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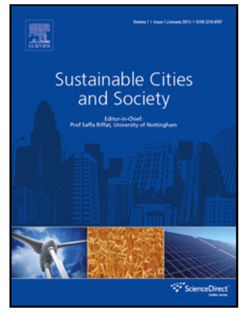

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Improving energy efficiency of commercial buildings by Combined Heat Cooling and Power plants

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Highlights

- Combined Heat, Cooling and Power plants are proposed as retrofit solutions for improving energy efficiency of commercial buildings.
- A big *Do It Yourself* shop located in the northern part of Italy was assumed as a case study.
- The analysis is based on real energy consumption data available from ad-hoc energy audits.
- A flexible *profit-oriented* management strategy is applied for operating the CHCP plant.
- Results showed that CHCP systems could help to reduce energy consumptions and greenhouse gas emissions in the commercial sector.

ABSTRACT

Commercial buildings play a key-role in the energy consumption of the building sectors. Recent statistics have shown that as the number of commercial buildings is continuously increasing, their effects on energy consumption are expected to grow. These buildings are characterized by high energy demand mainly due to lighting and HVAC requirements. Rooms of energy saving exist by considering that: (i) electricity demands and HVAC requirements occur simultaneously during the day and (ii) both demands are currently satisfied by using separate energy systems. It is apparent that the adoption of polygeneration systems could represent a valid solution to achieve energy savings. To this aim, the paper investigated the profitability of a trigeneration system for commercial buildings, considering a big *Do It Yourself* shop located in the northern part of Italy, as case study. The analysis was based on (i) energy consumption data collected by energy-audits and (ii) a profit-oriented management strategy for the trigeneration systems proposed in literature. Results showed that trigeneration represents a profitable energy conversion system thanks to revenues achieved by selling surplus electricity and the support of financial mechanism for "*High-Efficient*" eligibility. In comparison with the currently adopted energy conversion systems, important reductions in energy consumption and CO_2 emissions are observed.

Keywords: Combined Heat Cooling and Power, Commercial building, Energy Saving, Energy systems design and operation.

NOMENCLATURE

a,b	(€/kW) and (€)	Constants for linearized cost figures of a component
Capacity	(kW)	Nominal Capacity of Prime Mover or Absorption Chiller
COP	(dimensionless)	Coefficient of Performance
D	(kWh)	Thermal, Cooling or Electricity Hourly Demand
E	(kWh)	Electricity Produced on yearly basis
F	(kWh)	Energy Supplied to CHP or Auxiliary unit
H	(kWh)	Heat recovered on yearly basis
HLV	(kJ/kg) o (kJ/Sm^3)	Heating Low Value
i	(dimensionless)	Interest Rate
MP	(€/kWh) or (€/ Sm^3)	Market Price of electricity or Natural Gas
RefEη	(dimensionless)	Reference efficiency for electricity production
RefHη	(dimensionless)	Reference efficiency for heat production
RISP	(MWh)	Primary Energy Saved
WhC	(dimensionless)	Number of White Certificates
Z	(€)	Cost for equipment purchase

Subscripts

abs Referred to Absorption Chiller

buy Referred to electricity bought from the grid

c "Cooling" referred to Total Supply Spread indicator and Cooling Demand

CHP Referred to heat and electricity produced in "cogenerative" mode

comp Referred to "component" in capital cost equation

e Referred to electricity

hp Referred to "heat pump"

nonCHP Referred to electricity not produced in "cogenerative" mode

ref Related to "reference"

sell Referred to electricity sold to the grid

th Referred to "Thermal" in Total Supply Spread and Thermal Demand

waste Referred to heat recovered from the CHP unit and "wasted" in an emergency radiator

Greek Symbols

η (dimensionless) Efficiency

μ (kg_{CO2}/kWhel) Emission Factor of electricity consumed from the grid

Acronyms

AHU Air Handling Unit

CHP Combined Heat and Power

CHCP Combined Heat, Cooling and Power

DPBT Discounted Payback Time

ESFL	Energy Supplied at Full Load
ET	Electricity Tracking mode
HT	Heat Tracking mode
HVAC	Heating, Ventilation and Air Conditioning
ICE	Internal Combustion Engine
LL	load level of a component
NPV	Net Present Value
PES	Primary Energy Saving
PHR	Power to Heat Ratio
RTU	Rooftop Unit
SS	Spark Spread
TSS	Total Supply Spread

1. INTRODUCTION

Buildings are responsible of a significant share of the total primary energy demand. For instance in European Union (EU), this sector affects for the 40% of the total energy consumption [1]. In particular, recent statistics on the total primary energy consumption reveal a relevant role of the commercial and public service: in fact, as shown in Figure 1, this sector contributes to the consumption of 288 MTOE in the last available year (i.e. 2017), which represents 14.53 % of the total primary energy consumption in Europe [2].

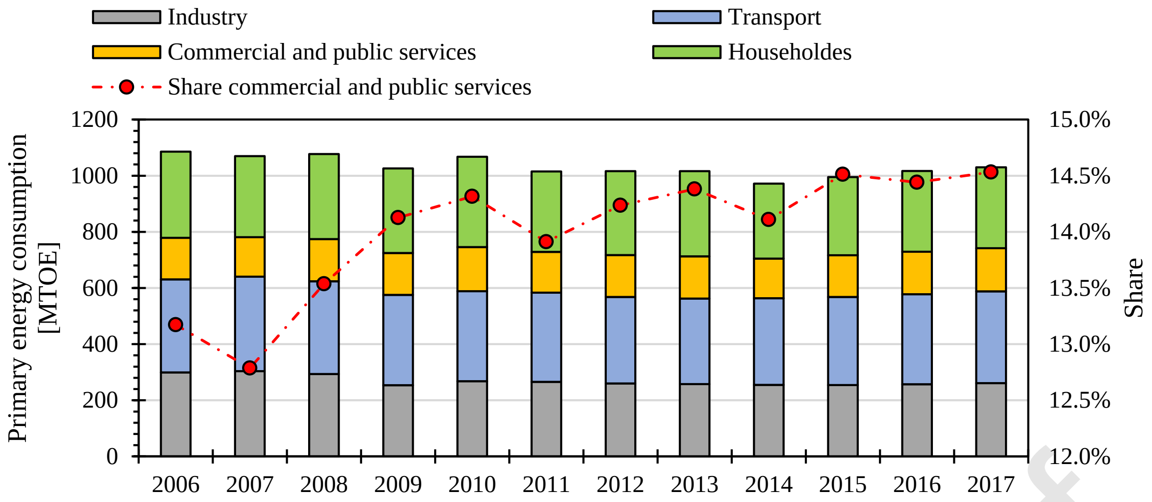


Figure 1. *Annual primary energy consumption in Europe by sector and share of the commercial and public services sector*

In Figure 2 energy carriers adopted to satisfy the primary energy demand of commercial and public sectors are shown. It is possible to observe an increase of the electricity consumption and the progressive adoption of renewable energy sources as well [2]. Conversely, the use of district heating grid is almost stable, whereas the utilization of fossil fuels has a slowly decreasing trend. More specifically, according to the last available year (i.e. 2017) the share of energy carriers was composed by 46.69 % electricity, 29.35 % natural gas, 6.25% heat, 10.39 % oil and derivates, 6.39 % renewables and finally 0.79% other sources.

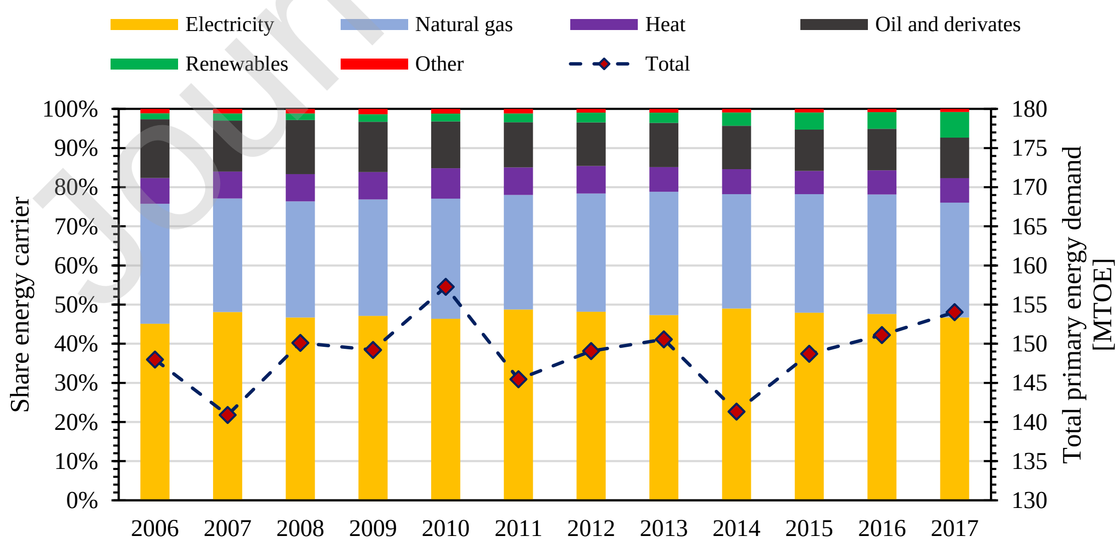


Figure 2. *Energy carriers used in commercial and public services sectors*

In this context, it is interesting to analyze the role played by big shopping centers. It is estimated that the total shopping center floorspace in Europe covers a surface of 166.5 million of square meters, with an annual increase rate of 2.3% [3]. Focusing in the Italian context, Figure 3 underlines a growing trend of commercial activities, such as malls (shopping centers for all products) and supermarkets (mainly food). The Italian malls and supermarkets cover a surface of 3.58 and 10.12 millions of square meters, respectively, representing altogether the 8.23% of the European total shopping center floorspace [3], [4].

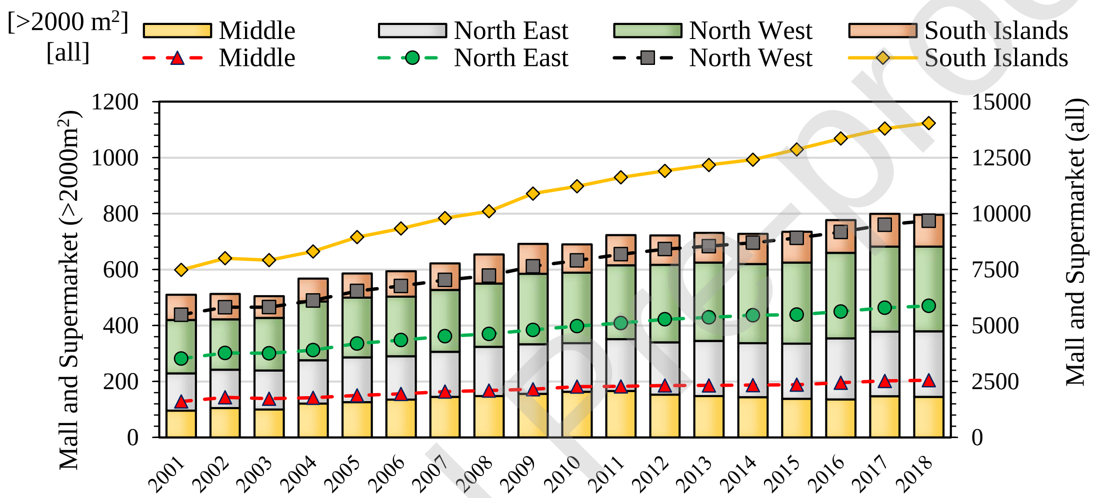


Figure 3. *Number of shopping centers over sixteen years in Italy*

From previous data, it is apparent that improving the energy performance of commercial building sectors could contribute to the sustainable development of cities. For these reasons, the investigation of energy saving techniques to be implemented is of utmost importance and some studies have been focused to this aim.

In big shopping centers, the energy consumption is mainly due to the lighting systems designed to enhance goods qualities and due to the HVAC systems in order to assure indoor comfort of customers [5], [6]. In order to minimize the primary energy consumption, all plants should be correctly sized and properly managed. For instance, a little increase of the indoor temperature setpoint during summer reduces considerably the energy demand of the building. However, this aspect should be carefully evaluated for commercial reasons, such as the limitation of the outdoor lighting in malls can dissatisfy the customers [7], [8]. Thus, excluding the potential modulation of the operative conditions of the existing plants, the remaining solutions are related to the adoption of new devices, materials and control systems in order to reduce the primary energy consumption [9]. About lighting plants, LED lamps are currently spreading worldwide, replacing the old lamps (mainly fluorescent and high-pressure sodium) thanks to the greater energy efficiency. This technology allows also for the modulation of the artificial luminous flux as function of the natural contribution through skylights and windows [10]. Focusing on the indoor temperature and air quality control, several approaches can be adopted to obtain a reduction of the primary energy demand:

- Improve the thermal resistance of the buildings' envelope [11];
- Install heat exchangers in order to recover the heat from exhausted air [9];
- Replace the old Air Handling Units (AHU), Roof Top Units (RTU) and chillers with more modern and energy saving ones [12] .

In detail, the energy performance of the buildings' envelope has a relevant role, based on the local climatic conditions. In existing buildings, common techniques adopted are the realization of thermal isolation by the addition of special layers and the replacing of the old windows with the new double and triple glazed windows [13]. In new buildings, the free cooling can be promoted by the realization of a solar chimney [14], [15]. Focusing on HVAC plants, heat exchangers represent nowadays a commercial solution to recover a significant ratio of the sensible heat from the exhaust air. New technologies are also under development in order to recover also a part of the latent heat [16]. In the last years, a significant increase of the energy efficiency of AHU, RTU and chiller has been achieved thanks to the introduction of new control techniques, such as the adoption of inverters to modulate the thermal power output as function of the real requirement [17].

As previously shown, retrofit interventions in commercial building are mostly carried out according to a fragmented approach, which involve: (i) improvement in the energy performance of the envelope, (ii) installation of low-consuming energy conversion systems or (iii) adoption of renewable energy-based technologies for electricity generation such as photovoltaic panels. However, opportunities of energy savings exist by considering that commercial buildings are usually characterized by simultaneous electricity and thermal demands which are usually satisfied by using separate and obsolete systems. With this respect, cogeneration (CHP) or trigeneration (CHCP) systems could represent a solution for reducing the energy consumption in this sector.

Even though CHP or CHCP are not new concepts, for long time they represented a viable option to improve the energy efficiency only in industrial processes, where regular load profiles allowed for reducing risks due to high capital expenditures. However, design and operation of CHP/CHCP systems for the building sector is a very complex issue mainly due to the highly variable energy demand on a daily basis. To this regard, the design of grid-connected systems covering a variable energy demand cannot be effectively optimized without the optimization of management strategy: indeed, these two aspects are interrelated and algorithms for the integrated optimization of design and operation have been proposed. For instance in [18], a tool for efficient design and operation of polygeneration-based energy microgrids serving a cluster of buildings was proposed and then applied to a case study [19]. Other published papers proposed stochastic optimization of design [20] and operation [21] of cogeneration systems.

Furthermore, it is widely recognized that the adoption of this technology should be encouraged by making it more economically attractive, either by increasing the expected returns or decreasing the risks of such investments. From a legislative point of view, EU Directives

2004/8/EC [22] and 2012/27/EU [23] recognized the key-role played by cogeneration for decreasing the primary energy consumptions and the related greenhouse gas emissions. Also, in Directive 2004/8/EC the concept of "*High Efficient*" CHP plants was introduced for those systems which fulfil some precise criteria in terms of energy efficiency and reduction of primary energy consumption [22]. In these cases, CHP/CHCP systems are supported by a financial mechanism aimed to help investors by increasing revenues and reducing risks associated to the investments. Few published papers have been focused on CHP (or CHCP) systems for commercial buildings. In 2004, Zogg et al. [24] evaluated the benefits of cogeneration for different types of commercial buildings in the United States of America by taking into account the available commercial technologies. For the selected case studies, the authors highlighted that promising primary energy saving could be reached but the high investment required by CHP systems could represent a barrier to their spread. In [25], Gonzales and Nebra considered natural gas-fueled CHP systems for industries and commercial sectors in Peru. The authors asserted that these plants could be a very promising energy saving solution in Peru, since diesel and coal-based technologies are still popular.

In [26], Carragher et al. investigated gas turbine-based CHP systems for commercial buildings considering the effects of market and climate conditions. Optimal sizes were determined according to different climate conditions.

It is relevant to observe that previous studies were mainly focused on the design of CHP systems by relying on energy consumption data from ad-hoc simulations and not on realistic operation of commercial buildings. Other analyses, conversely, usually assumed hotel buildings as reference case studies.

It is interesting to evaluate energy savings potential and profits that could be achieved when CHCP plants are proposed as energy systems for big shopping centres. In fact, these buildings are equipped with plants used with a relevant capacity factor, due to a high number of working days and operation of plants close to nominal capacities. Therefore, the introduction of more efficient solutions could lead to significant annual energy savings.

Furthermore, the construction of new shopping centres usually involves opening of other activities in same territory like cinemas, restaurants, dental clinic etc [27]. Thus, the introduction of polygeneration systems in big shopping centres could represent a starting point to plan a small energy district. In this way, different energy carriers can be shared in order to satisfy the total primary energy demand in a more rational way than in case where the electricity and thermal demands are met by separate plants. For instance, larger CHCP plants may be installed on commercial buildings and serve also a cluster of buildings in a small area nearby, by distributing electricity and heat recovered from the primed mover through ad-hoc networks [28]. At least two benefits could be recognized: (i) CHCP plants could improve the energy sustainability of small areas of cities and (ii) the adoption of larger plants could reduce the risks related to the high investments, since the unitary costs of CHCP plants are usually reduced by the high scale factors in the market.

In this paper, the profitability of CHCP plants is investigated for an existing commercial building in the northern part of Italy by assuming the criterion proposed in [29] for design and operation of polygeneration systems. The study was based on real energy consumption data of the case study in order to achieve more robust results. The paper was structured as follows:

- in the second section, some notes on the multi-objective criterion followed for the design and operation of CHCP system are provided; then, details on the “High Efficiency” eligibility criteria are provided.
- In the third section, a detailed description of the case study is given, focusing on the current energy conversion systems adopted to meet electricity demand and HVAC requirements.

- In the fourth section, details on the CHCP plant proposed for the case study are provided;
- In the last section, results of this analysis are shown and discussed.

2. NOTES ON THE CRITERION FOR DESIGN AND OPERATION OF CHCP SYSTEMS

Design of cogeneration and trigeneration systems is usually carried out by using "*heuristic method"* as the *Energy Supplied at Full Load* (ESFL). This method relies on users' *duration curve* of heat demand for the selection of the size of the prime mover to be installed in the CHP plant. Duration curve relates the heat demand level with the annual number of hours when such a demand is observed [30]. This approach selects the size of the prime mover which allows for maximizing the energy supplied by running it at its full capacity. It is apparent that undersize or oversize of the prime mover is avoided, while providing a good compromise between the following requirements: (i) the capability to cover a good fraction of annual heat demand by operating the CHP unit at high Load-Levels (LL), and (ii) the achievement of satisfactory overall energy conversion efficiency [30]. When considering the design of CHCP systems, duration curve of the "*Aggregate Thermal Demand"* (ATD) is used instead of the duration curve of heat demand. As shown in Eq. 1, the ATD represents the total heat load resulting by summing up (on hourly basis) the "*direct*" heat load, which is related to the thermal demand for air conditioning and domestic hot water production, and the ‘‘*indirect heat load'',* which represents the heat needed to feed an absorption chiller used to satisfy the entire cooling demand.

$$ATD = D_{\mathrm{th}} + \frac{D_{\mathrm{c}}}{COP_{\mathrm{abs}}} \qquad (1)$$

In Eq. 1, COP_{abs} is the coefficient of performance of an absorption chiller fuelled by the heat recovered from the prime mover of CHP unit. D_{c} and D_{th} refer respectively to user's cooling

and thermal demands. It is evident that the adoption of the ATD curve instead of the heat demand duration curve allows for increasing the number of operating hours of the prime mover during the year, since the cooling demand is also satisfied by using a trigeneration setup (CHP unit and absorption chiller) instead of electrically-driven systems like chillers or rooftop units.
When CHP (or CHCP) systems operate in the field, the amount of electricity and heat produced does not match instantaneously with the users' electricity and heat demand. For this reason, a management strategy of the prime mover is required. Two strategies for operating CHP systems are usually adopted, which are indicated as *Electric Tracking* mode (ET) and *Heat Tracking* mode (HT). Each one indicates which output of the plant (i.e. electricity or heat) is "prioritised" to control the prime mover [31]. It can be shown that the HT mode allows for achieving higher primary energy saving, since no excess heat is produced, and the electricity surplus is instantaneously exchanged with the grid. Conversely, when adopting a ET mode, a fraction of the heat recovered from the prime mover has to be dissipated during those hours characterized by high electricity demand and moderate heat demand, which eventually affects the primary energy saving achieved [30]. However, some economic benefits could not be exploited when a HT mode is adopted. In fact, during hours characterized by high selling prices of electricity but low thermal demand, the adoption of HT mode obligates the modulation of both thermal and electrical power outputs in order to meet thermal demand. As stressed in [30], in these hours, it could be more profitable to maintain higher power productions in order to avoid the purchase of electricity or even sell the electricity surplus to the local grid. Hence, CHP unit should be operated at a LL higher than the one resulting from HT mode even though an amount of heat produced by the CHP unit is rejected via an emergency radiator. However, it was proven that this energy loss slightly affects the achieved total primary energy saving [29].

Based on the previous consideration, a *profit-oriented* management criterion was proposed in [29] and here briefly described. For a sake of clarity, a synthetic diagram is shown in Figure 4.

After the selection of the nominal capacity of the CHCP prime mover according to the ESFL criterion, decisions about the convenience should be made about its operation or shutdown. To this aim, the *Total Supply Spread* indicator is defined for both cooling and heating periods. In Eq. 2 the *thermal Total Supply Spread* (TSS_{th}) is defined for heating period. This indicator is the ratio between the cost sustained respectively by "separate" and "combined" production of 1 kWh electricity and the corresponding amount of heat recovered.

$$TSS_{th} = \frac{\dfrac{3600}{\eta_{ref,t} \cdot PHR_{CHP} \cdot HLV_{fuel}} \cdot MP_{fuel} + MP_{e}}{\dfrac{1}{\eta_{e,CHP}} \cdot \dfrac{3600}{HLV_{fuel}} \cdot MP_{fuel}} \quad (2)$$

In Eq. 2, MP_{fuel} and MP_{e} are respectively the market prices of fuel and electricity. $\eta_{ref,t}$ is the reference efficiency for the separate production of heat. $\eta_{e,CHP}$ is the electric nominal efficiency of the CHP plant. PHR_{CHP} is the power to heat ratio of the prime mover and HLV_{fuel} is the low heating value of the fuel used by the plant. The 3600 factor is introduced due to different energy units adopted in the variables. For example, in case of natural gas, the units are: MP_{e} (€/kWh), MP_{fuel} (€/Sm^3), and HLV_{fuel} (kJ/Sm^3).

In Eq. 3 the *cooling Total Supply Spread* (TSS_{c}) is defined to evaluate the profitability achievable when the heat is used to feed an absorption chiller used to meet the cooling demand.

$$TSS_{c} = \frac{MP_{e}\left(1 + \dfrac{COP_{abs}}{PHR_{CHP} \cdot COP_{abs}}\right)}{\dfrac{1}{\eta_{e,CHP}} \cdot \dfrac{3600}{HLV_{fuel}} \cdot MP_{fuel}} \quad (3)$$

In Eq. 3 COP_{abs} is the coefficient of performance of an absorption chiller used to meet user's cooling demand and fuelled by the heat recovered from the prime mover of the CHP plant.

From previous definitions of TSS, it follows that if these indicators are greater than one, costs sustained for operating a separate energy production system are greater than ones of a CHCP system, and so the use of CHCP plant is more convenient. Conversely, when the TSS is lower than one, the CHCP system should be switched off as its operation is not more profitable.

Once decided if it is convenient or not to operate the CHCP system, it is necessary to evaluate if it is better to strictly operate the plant in HT mode or in a flexible mode, thus allowing for a surplus heat production. To this purpose, a ‘‘marginal power supply analysis” is performed by the introduction of the *Spark Spread* (SS) indicator as defined in Eq. 4. In detail, SS represents the ratio between the purchasing price of electricity and the cost sustained for its production by using a CHP plant. It is interesting to observe that $SS < TSS$ by comparing Eq. 4 to Eqs. 2 and 3.

$$SS = \frac{MP_{\mathrm{e}}}{\frac{1}{\eta_{\mathrm{e,CHP}}} \cdot \frac{3600}{HLV_{\mathrm{fuel}}} \cdot MP_{\mathrm{fuel}}} \tag{4}$$

By combining the aforementioned indicators, three operating scenarios for CHP/CHCP systems can be identified, as shown in Figure 4. In particular:

- when $SS > 1$ (and consequently $TSS > 1$), the CHCP unit can be operated at full-load regardless user’s thermal demand and the surplus heat produced by the prime mover is dissipated via an emergency radiator. Indeed, in comparison with the selling price of electricity, the fuel price is so low to justify the utilization of CHCP unit as a traditional fossil fuel supplied generator and producing thermal energy as a secondary benefit. Therefore, it is profitable to sell the surplus electricity produced by the CHP plant to the grid;
- when $SS < 1$ and $TSS > 1$, the combined heat and power production is still profitable but the CHCP unit should be operated in heat-tracking mode, as no profit is achieved by selling electricity to the grid;

- *TSS* <1 (and consequently also *SS* <1), no profit is achieved by using a CHCP system with respect to a separate production system, therefore the prime mover should be switched off.

It should be stressed that the proposed criterion accounts also for a technically feasible CHP operation like the minimum part-load operation (LL_{min}) of the prime mover. For instance, for a reciprocating internal combustion engine (ICE), the minimum part-load operation ranges among 30% - 40% of the nominal capacity. In order to account for this limit, those hours characterized by demands which require the CHP unit to operate below the minimum part-load operation (LL_{min}) value, are excluded from the analysis.

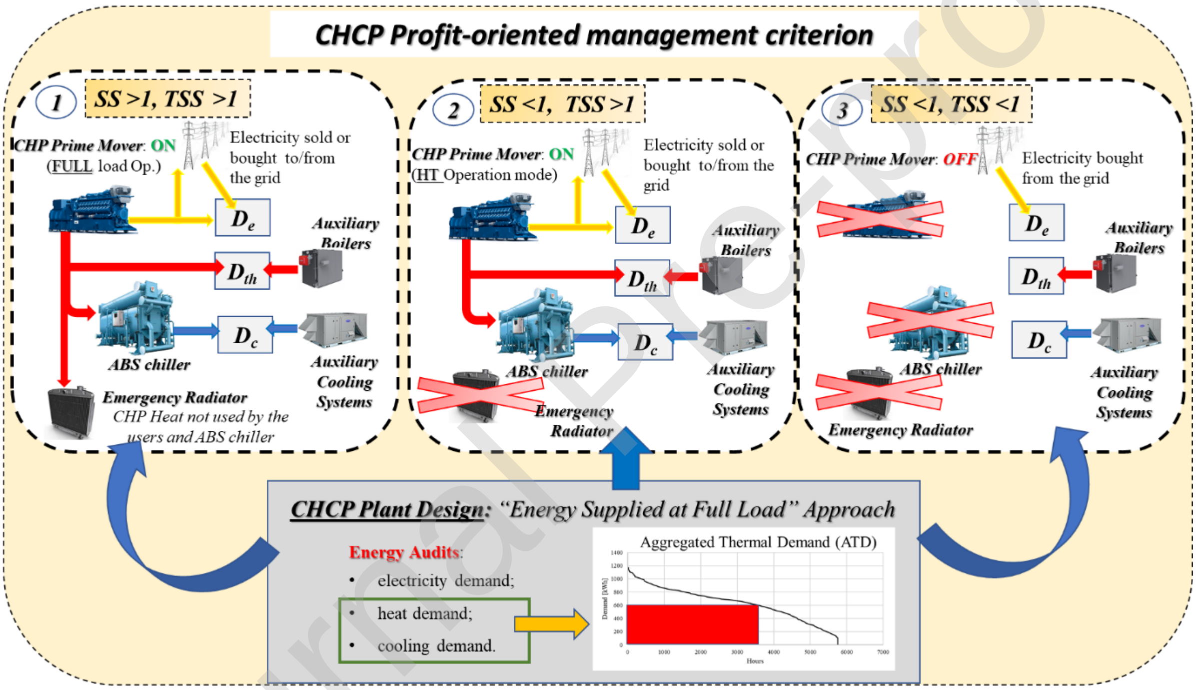


Figure 4. *Flexible profit-oriented* CHCP management strategy: summarizing scheme

2.1 Notes on "*High-Efficient"* eligibility of CHCP plant according to Italian legislative framework

One of the most important concept introduced by the Directive 2004/8/EC is the eligibility of CHP systems as "*High Efficient*" cogeneration plant [22].

Before evaluating the high-efficient eligibility, it is necessary to understand if the total amount of electrical power produced by the CHP plant can be considered as "generated" in a cogenerative mode or not. To this aim, it is first required to calculate the total energy efficiency of the CHP plant η_{tot} as shown in Eq. 5.

$$\eta_{\text{tot}} = \frac{E_{\text{plant}} + H_{\text{CHP}}}{F_{\text{plant}}} \tag{5}$$

where E_{plant} and F_{plant} represent respectively the total amount of gross electricity produced and fuel consumed by the plant and H_{CHP} is the useful heat recovered. According to legislative requirements [22], η_{tot} must be compared with a threshold efficiency, whose value for gas turbines and internal combustion heat engines is fixed at 0.75 by law.

To this regard, two situations may occur:

1. The total efficiency of the plant is equal or higher than the corresponding threshold. In this case the total amounts of electricity production and fuel consumption are assessed as "from CHP", i.e. $E_{\text{plant}} = E_{\text{CHP}}$ and $F_{\text{plant}} = F_{\text{CHP}}$;
2. The total efficiency of the plant is lower than the corresponding threshold. In this case the plant is virtually divided into two sub-units, "CHP" and "nonCHP"; the total electricity production and fuel consumption are consequently split into two fractions, one related to the "CHP" sub-unit indicated as E_{CHP} and the other related with the sub-unit assumed in "nonCHP" operation:

Once calculated H_{CHP}, E_{CHP} and F_{CHP}, in order to verify whether the plant should be assessed as "High-efficient CHP" or not, a *PES* (Primary Energy Saving) index must be calculated, as shown in Eq. 6.

$$PES = \left(1 - \frac{1}{\frac{CHPH\eta}{RefH\eta} + \frac{CHPE\eta}{RefE\eta}} \right) \cdot 100\% \tag{6}$$

In Eq. 6, *CHPHη* and *CHPEη* are respectively calculated as H_{CHP}/F_{CHP} and E_{CHP}/F_{CHP}, while *RefHη* and *RefEη* represent the reference efficiencies used for units producing separately heat and electricity. These efficiencies are fixed depending on the fuel consumed and the year of construction of the CHP plant. As concerns the heat recovery, reference efficiency values for heat production depends on the stream used as heat transfer medium (i.e. direct use of combustion gases or production of steam or hot water). As regards the reference electrical efficiency, it depends also on the average air temperature of the country where the plant is installed, and the electrical power output voltage of the CHP system. In order to be assessed as "High-Efficient CHP", the Directive 2004/8/EC indicates as efficient cogeneration any CHP plant fulfilling the following condition: any plant with an installed capacity above 1 MW_e must achieve PES = 10%, and any positive value for small and micro-scale CHP, respectively below 1 MW_e and 50 kW_e [22].

Once verified the "High-Efficient" eligibility of the investigated CHP plant according to European Directive, it is possible to quantify the economic revenues obtainable by the national support mechanism. For instance, in Italy the amount of revenues obtained by a "High-Efficient" CHP plant are calculated proportionally to the "RISP" indicator (defined in Eq. 7) [32], which quantifies the energy saving (measured in MWh) by the adoption of the CHCP system in comparison with the separate production. This indicator considers thermal and electrical efficiency of the reference separate energy conversion systems, indicated as $\eta_{\mathrm{T,ref}}$ and $\eta_{\mathrm{E,ref}}$ in Eq. 7, which are calculated according to the legislative framework provided in [32], and which are different from the ones used in Eq. 6.

$$RISP = \frac{H_{\mathrm{CHP}}}{\eta_{\mathrm{T,ref}}} + \frac{E_{\mathrm{CHP}}}{\eta_{\mathrm{E,ref}}} - F_{\mathrm{CHP}} \tag{7}$$

For example, in 2005 [33] a specific instrument was introduced in Italy to certify the energy saving achieved in an energy system after carrying out some actions aimed at improving its energy performance. This tool is usually known as "*Energy Saving Certificate*" or equivalently "*White Tag*" or "*White Certificate*" (WhC). In detail, 1 WhC is equal to 1 ton of equivalent oil (TOE) of primary energy saved and it issued by the Italian agency "Gestore dei Servizi Energetici". In particular, once quantified the RISP achieved, according to Eq. 7, the number of White Certificates obtainable is equal to:

$$WhC = K \cdot 0.086 \cdot RISP \tag{8}$$

In Eq. 8, the factor 0.086 is used to convert MWh in TOE. The coefficient *K* is a function of CHP plant size and the corresponding values are reported in [32]. It is important to observe that once qualified as "High Efficient" plants, CHCP systems are supported by this mechanism only for 10 years from the beginning of its operation [34].

3. DESCRIPTION OF THE CASE STUDY

As previously mentioned, the case study is a big *Do It Yourself* (DIY) shop located in Milan, in the Northern part of Italy (latitude 45.57° N, longitude 9.36° E). The sale area has a gross surface of about 6830 m^2, with an average height of 7.8 m. The warehouse and the offices cover respectively a surface of 930 m^2 and 410 m^2. The following systems are currently installed to satisfy the HVAC demands:

- the sale area of the shopping centre is equipped with 6 rooftop units (RTUs), having the technical specifics provided in Table 1. During winter, two boilers fuelled by natural gas (740 kW thermal nominal capacity each) are used to satisfy air conditioning demand. Indeed, in addition to the refrigerant circuit all RTUs are equipped with a water battery which is supplied by the hot water produced by boilers.

- Boilers are used also to supply the warehouse and the office. In particular, eight heaters are installed inside the warehouse, of which two with a rated power equal to 31.2 kW (0.4 kW electricity, 5500 m^3/h) and the other 21.33 kW (0.3 kW, 3300 m^3/h).

Table 1. Technical features of rooftop units currently installed in the investigated DIY shop

	Number of units	*Rated Air flow rate* [m^3/h]	*Refrigerant*	*Cooling Mode** [kW]	*Heating Mode** [kW]	*Electric Power Consumption* [kW]
RTU_1	1	40000	R407C	226.3	240.0	80
RTU_2	2	27000	R407C	169.5	165.0	64
RTU_3	2	21000	R407C	136.4	165.0	42
RTU_4	1	6000	R407C	37.3	30.0	15

****Reference conditions***: (a) *cooling mode*: External temperature 35°C, RH 45%; Internal temperature 26°C HR 50%, (b) *heating mode*: External temperature 5°C; Internal temperature 20°C, water temperature 70/55°C

3.1 Energy audit of the case study: results

In order to reduce the risk related to the high investment cost of polygeneration systems, an accurate energy audit is usually performed. With this regard, thermal, electrical and cooling demands are usually determined by analysing the energy bills (i.e. gas and electricity) and by carrying out interview at plant's owner. In Figure 5, for the case study, monthly electricity and gas consumptions are shown and calculated based on electricity bills provided by the owner. About the total electricity demand, the shopping centre started a measuring campaign few years ago, in order to monitor the energy consumption from which it was possible to identify irregularities in the operation of plants and plan promptly extraordinary maintenance interventions. Therefore, hourly data on the total electricity consumption are also available.

First of all, natural gas (represented by the dashed purple line in Figure 5) is consumed during wintertime and it is only used by the boilers to produce hot water in order to supply the air heating coils installed within each RTUs. Then, the orange line in Figure 5 shows the overall monthly electricity consumption and it encompasses electricity uses mainly for the HVAC systems and for lighting. Indeed, the electricity consumption for HVAC plants was evaluated in the following way:

- Lighting plants were characterized by step function operating profiles; therefore, it was possible to evaluate the electricity consumption by the knowledge of the installed power, the number of working days and data on solar radiation (only for the outdoor lighting);
- Some electrical loads were assumed to be constant during all year, as an example the electricity consumption for the air exchange of technical rooms;
- Other loads were related to the working hours, like the electricity consumptions for elevators, cash registers and other machines;
- Therefore, the difference between the hourly total electricity consumption and the sum of all the other loads profile is due to HVAC plants.

Cumulating these hourly data, the monthly trend for the HVAC systems (shown by yellow rectangles in Figure 5) was evaluated in the year. It is worth noting that the electricity consumed for air conditioning purposes during wintertime is due to the RTU fans which are used to supply air flow to the heating coils.

In Figure 6, daily profile for electricity consumption are compared for two days in winter and summer. As shown in the graph, most part of the energy demand is limited during the day in both cases, and the great difference in value is due to the RTUs operation during summer.

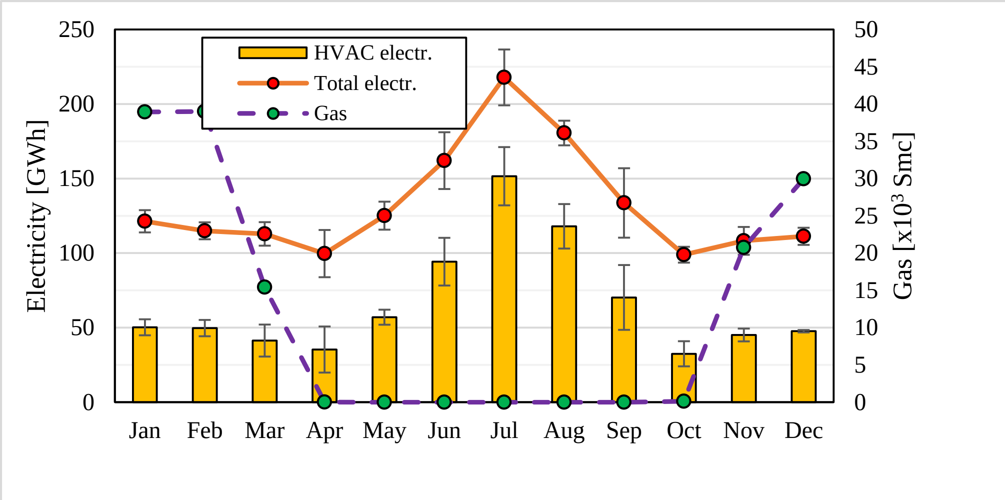


Figure 5. Monthly Gas and Electricity Consumption of the case study

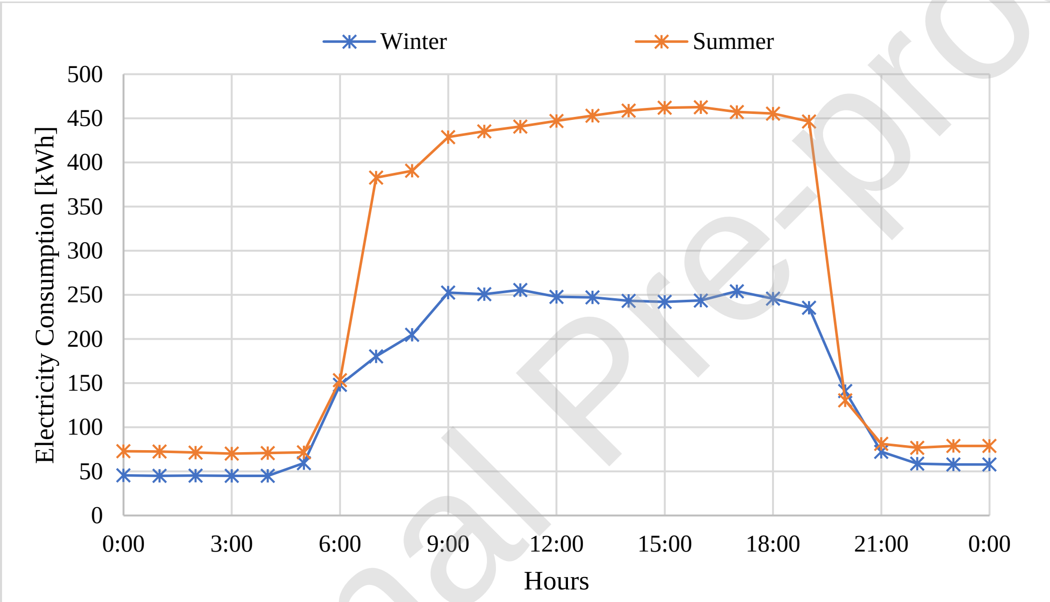
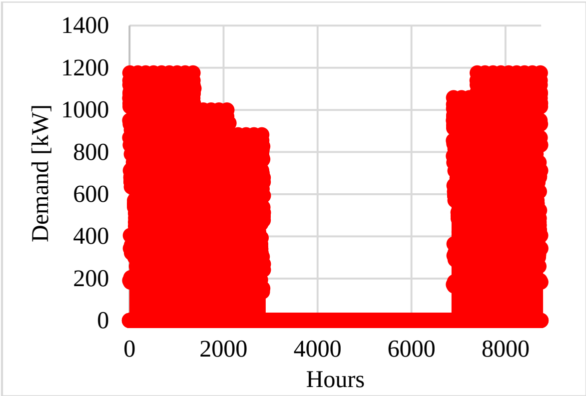
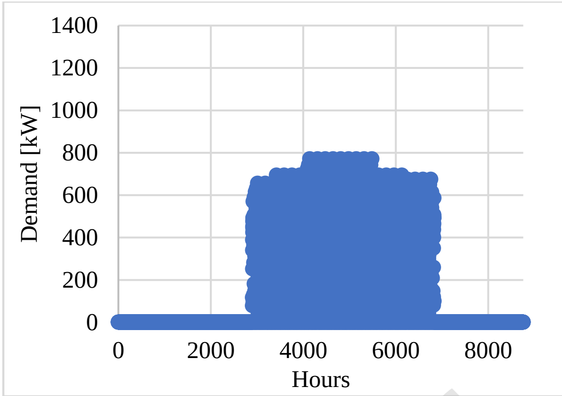


Figure 6. Electricity Consumptions (HVAC plus other uses) in typical summer and winter days

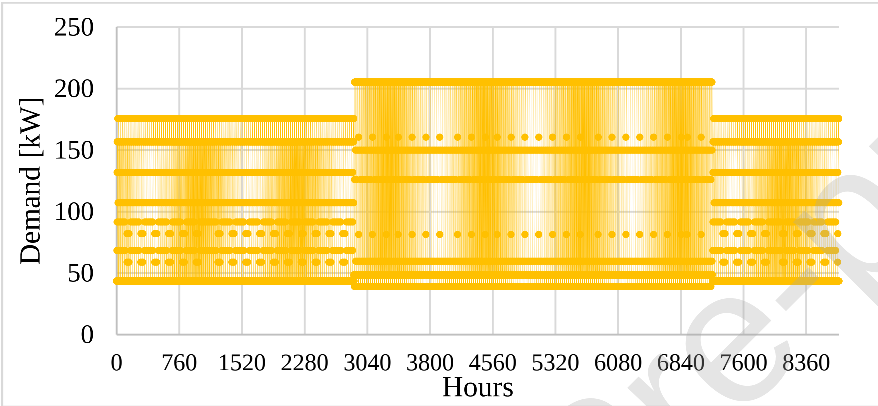
In Figure 7a-c, the yearly heating, cooling and electricity demands are shown. The maximum thermal demand (Figure 7a) is observed during December and January, which corresponds to nearly 1200 kW. Conversely, as shown in Figure 7b the maximum value of cooling demand is around 800 kW and it occurs during August when the maximum request for air conditioning is observed. As concerns electricity demand profile shown in Figure 7c, this trend accounts only for the lighting systems consumption.



(a)



(b)



(c)

Figure 7. Annual demand profiles for **(a)** heating, **(b)** cooling and **(c)** electricity.

4. DESCRIPTION OF THE PROPOSED CHCP SYSTEM

A simplified scheme of the CHCP system assumed for the case study is shown in Figure 8. An internal combustion reciprocating engine (ICE) was considered as the prime mover. The heat recovered from the ICE is supplied to an Air Handling Unit (AHU) to heat air used for space heating during winter. Conversely, during the summer, the heat recovered is used by an absorption chiller (ABS) which produces 7 °C cold water, which is fed to the AHU in order to cool down warm air for space cooling. An emergency radiator is also included for those hours when the CHP is operated at full load and the user's heat demand is lower than the heat recovered from the prime mover. Existing boilers and RTUs, which are currently used for satisfying HVAC requirements, cover the remaining fraction of thermal and cooling demand not met by the CHCP system. The overall system is connected to the grid in order to exchange electrical power during deficit or surplus hours.

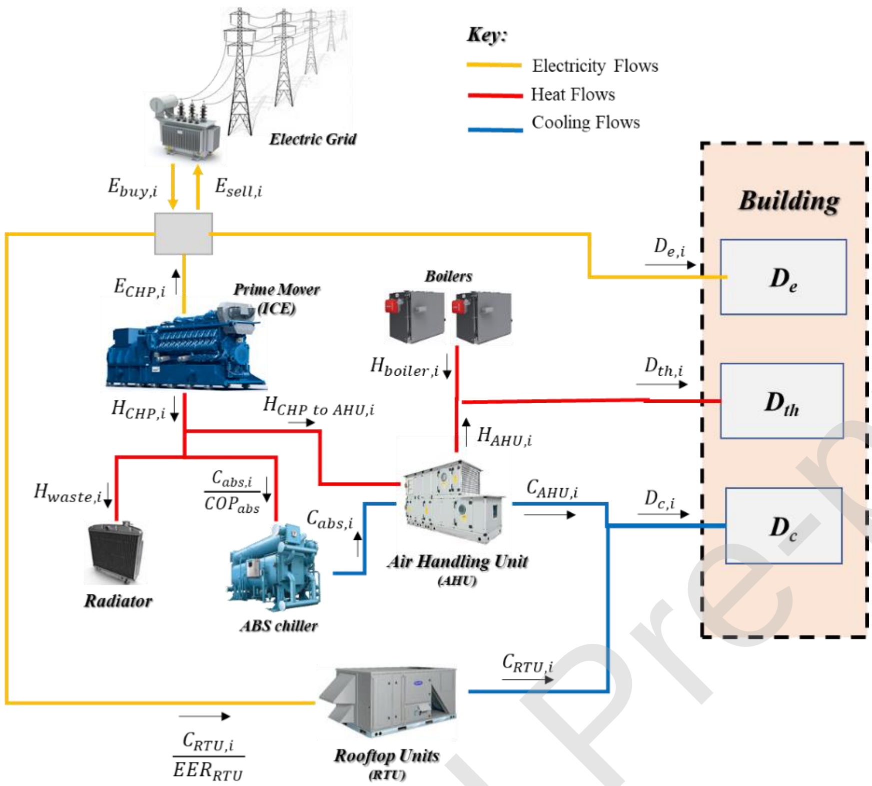


Figure 8. Reference scheme for reciprocate engine-based CHCP plant

In order to carry out an economic analysis, it was necessary to estimate costs sustained for equipment purchase (here indicated as Z_{comp}), and prices of fuels and electricity consumed by the plant. As concerns equipment purchase, cost figures were determined on the basis of Eq. 9.

$$Z_{comp} = a_{comp} Capacity + b_{comp} \tag{9}$$

In Eq. 9 the variable ‘‘*Capacity*’’ indicates the nominal capacity of the component (such as the nominal thermal output of the CHP unit or the nominal cooling capacity of the absorption chiller). The parameters a_{comp} and b_{comp} are determined by means of regression analyses on large databases of equipment costs available from previous research activities [35]. For the case study the following values were assumed: a_{CHP} =734.93 €/kW and b_{CHP} =142,475 € for the prime mover, a_{ABS} =126.71 €/kW and b_{ABS} =53,349 € for the absorption chiller. Maintenance costs of the ICE were also accounted for by assuming an average 0.015 €/kWh$_e$.

As concern electricity prices, according to the national legislation in Italy, electricity is purchased at a Unique National Price (‘‘PUN’’, in Italian), formed on hourly basis on the competitive market which accounts also for transmission/distribution fees and taxes. Conversely, the surplus electricity produced by a CHP plant is sold at an hourly ‘‘Zonal energy price’’, which generally may differ from the PUN. In the present analysis, electricity prices observed in the year 2018 were considered [36].

As concerns the price of natural gas consumed, the following values were assumed for this analysis:

- NG consumed by boilers in a separate production: 0.35 €/Sm^3;
- NG consumed to fuel efficient cogeneration: 0.25 €/Sm^3

In order to properly quantify the avoided CO_2 emissions by using a CHCP system, the total emissions of a “separate” and “combined” energy systems were compared as shown in Eq. 10. In particular, the following steps were taken:

- first, CO_2 emissions for a separate production (indicated as CO_2^{sep} in Eq. 10) were calculated by summing up emissions associated to the electricity purchase from the grid (consequently produced by the national power park) and the emissions due to NG combustion in boilers in order to meet the thermal demand. With regards to the electricity purchased from the grid, an emission factor μ_{CO2}^{grid} = 0.485 kg/kWh$_e$ was considered [37]. As concerns CO_2 emissions from natural gas boiler, an emission factor μ_{CO2}^{NG}= 0.19 kg/kWh$_{gas}$ was considered, for a dedicated boiler characterized by a thermal efficiency $\eta_{t,boil}$ = 0.9;

- then, the ''Total CO_2 emissions for the CHCP plant'' (indicated as CO_2^{comb} in Eq. 10) were calculated by summing up: (i) the CO_2 emissions from the CHP unit, indicated as $\mu_{CO_2}^{CHP} F_{plant}^{NG}$ in Eq. 10, where $\mu_{CO_2}^{CHP}$ and F_{plant}^{NG} are respectively the emission factor of the prime mover and the amount of natural gas used during its operation, (ii) emissions from natural gas auxiliary boilers, indicated as $\mu_{CO_2}^{NG} F_{aux}^{NG}$ in Eq. 10, where are respectively the emission factor of auxiliary boilers and the amount of natural gas used during their operation, and (iii) the additional CO_2 emissions provoked in centralized power plants when producing the net additional energy purchased from the grid (i.e. E_{purch}). This term can be either positive or negative, indicating the additional or avoided emissions in power plants due to the deficit or surplus of electricity when the power exchange with the grid is in prevalent purchasing or selling mode.

$$CO_2^{sav} = CO_2^{sep} - CO_2^{comb} = (\mu_{CO_2}^{grid} D_e + \mu_{CO_2}^{NG} \frac{D_{th}}{\eta_{t,boil}}) - (\mu_{CO_2}^{CHP} F_{plant}^{NG} + \mu_{CO_2}^{NG} F_{aux}^{NG} + \mu_{CO_2}^{grid} E_{purch}) \quad (10)$$

In order to simulate CHCP operation on an hourly basis, a model was built in Engineering Equation Solver [38]. The model included:

- equations for energy flows and for calculating SS and TSS indicators;
- hourly values of thermal, electricity and cooling demands of the building case study, which were imported from external tables thanks to a built-in function for data reading, already available in EES environment;
- hourly values selling and buying prices of electricity which were available also in external tables;

- the minimum part-load operation of the CHP prime mover, which required to switch off the prime mover in those hours characterized by thermal demand lower than the minimum thermal capacity provided by the prime mover.

5. RESULTS AND DISCUSSIONS

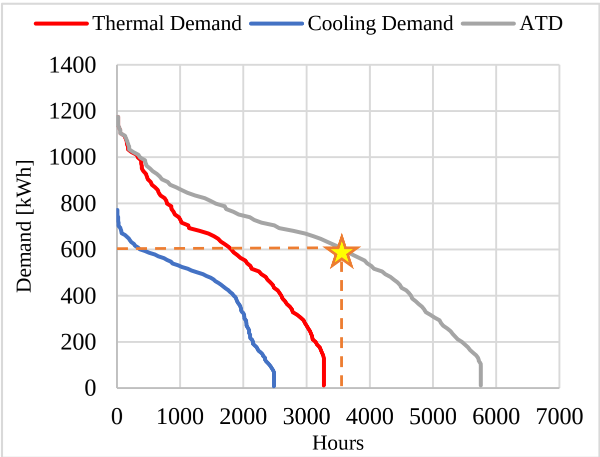
In this section the achieved results are shown and discussed. In particular, once selected the nominal thermal capacity of the prime mover of the proposed CHCP systems (shown in Figure 8), the following results are obtained:

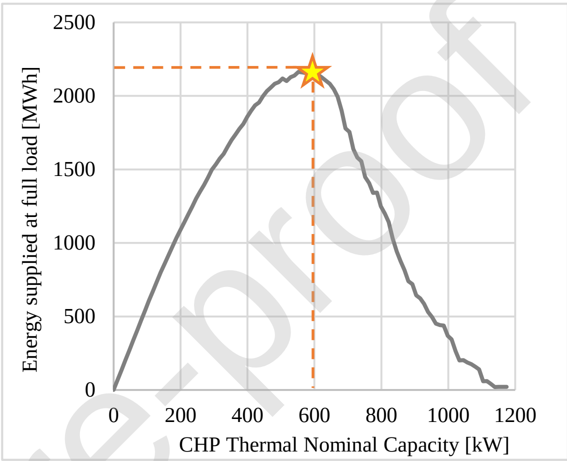
- for a typical summer day and winter day, the values of SS and TSS indicators are presented;
- for the same days, a description of CHCP plant operation is reported on an hourly basis, by focusing also on interactions of the CHCP system with the grid and on intervention of auxiliary systems;
- yearly energy, economic and environmental results of CHCP plant operation are exhibited;
- the eligibility of the investigated system as a *High-Efficient* cogeneration plant is finally discussed.

5.1 Description of the CHCP system of the case study

By applying the *Energy Supplied at Full Load* (ESFL) criterion to the ATD duration curve as explained in Section 2, it was possible to select the nominal thermal capacity of the internal combustion engine (ICE) for the case study. To this aim, duration curves of heat demand (red-colored line), cooling demand (blue-colored line) and aggregated thermal demand (grey-colored line) were determined and here shown in Figure 8a. All aforementioned curves were determined by using yearly cooling and thermal demands available from energy audits. In Figure 8b, the ESFL curve is shown, and the maximum (indicated by a yellow star) is observed for a thermal nominal capacity value equal to 600 kW_{th}. If a CHP prime mover of this size was selected, it would operate at full load for about 3750 hours, as shown in Figure 8a.

By analyzing ICEs sizes available on market, a 620 kW_{th} ICE fueled by natural gas and characterized by a 0.38 nominal electrical efficiency and 0.45 thermal efficiency was selected for the case study. Then, based on the nominal thermal capacity of the ICE to be installed, a 430 kW absorption chiller was selected.





(a) **(b)**

Figure 8. **(a)** Duration curve of thermal demand, cooling demand and aggregated thermal demand and **(b)** ESFL curve

5.2 Focusing on the CHCP flexible management strategy: results for typical winter and summer days

In Figure 9, values of Spark Spread (yellow-colored line) and the Total Supply Spread observed for two typical days (one in winter and one in summer) are shown. From the SS profile, it can be observed that values lower than 1 during night hours, i.e. from 8 pm to 8 am, because of low electricity prices. Conversely, values greater than 1 are observed from 8 am to around 8 pm. It is worth stressing that only one *SS* curve is shown for both winter and summer days, since no great variations in electricity prices were observed.

As concerns *TSS* values, different trends resulted when evaluating its values in winter and summer. It is possible to observe that:

- TSS_{th} and TSS_c are always greater than 1 from 8 am to 8 pm; therefore, according to the flexible management the utilization of the prime mover at the maximum load is a rational management strategy, even though a fraction of the heat recovered is wasted in an emergency radiator.
- different trends for TSS_{th} and TSS_c are observed in the remaining part of the day (i.e. during night hours). For instance, in summer, from 8 pm to 8 am, TSS_c is always lower than 1 (see Figure 4), thus it is suggested to switch CHP plant off. Conversely, during a typical winter night, TSS_{th} values are approximately equal to 1.1, hence the operation of CHP unit in HT mode is a rational management strategy.

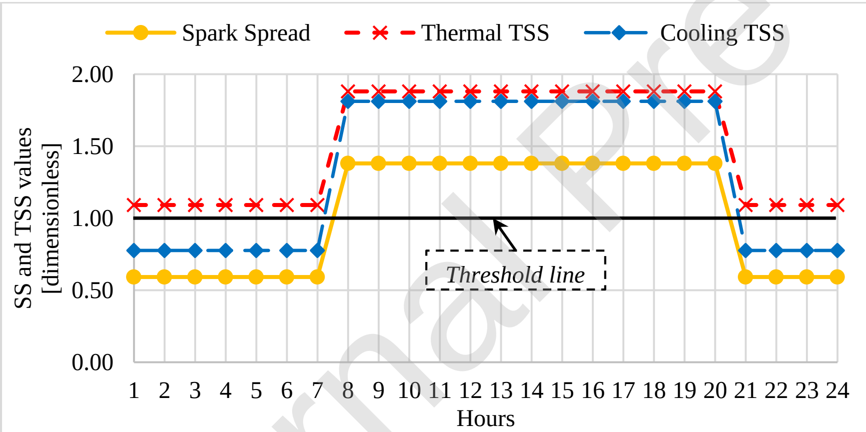
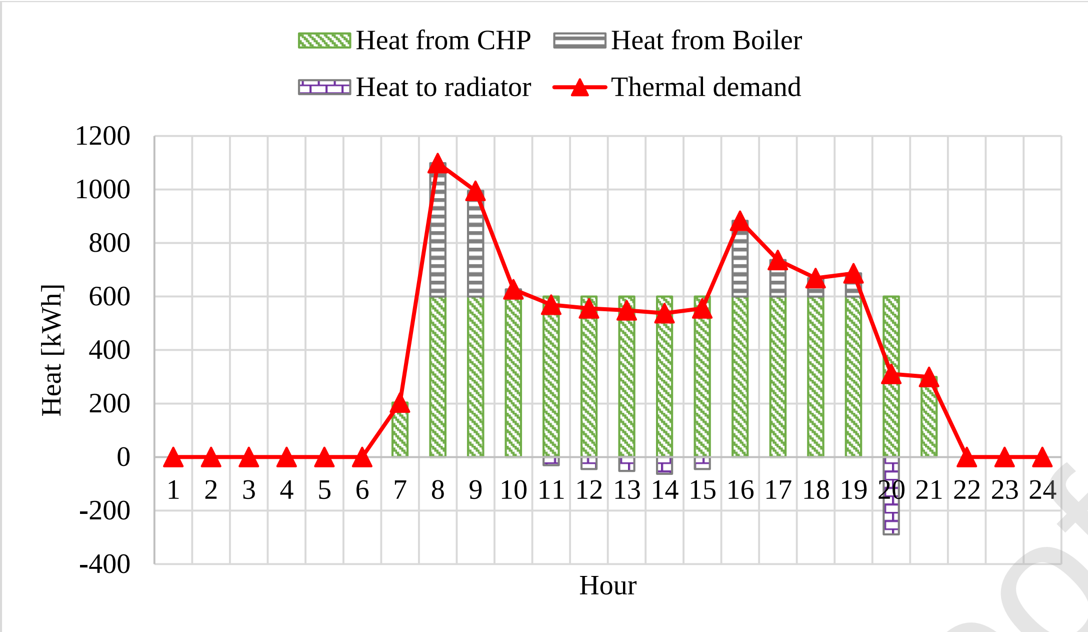


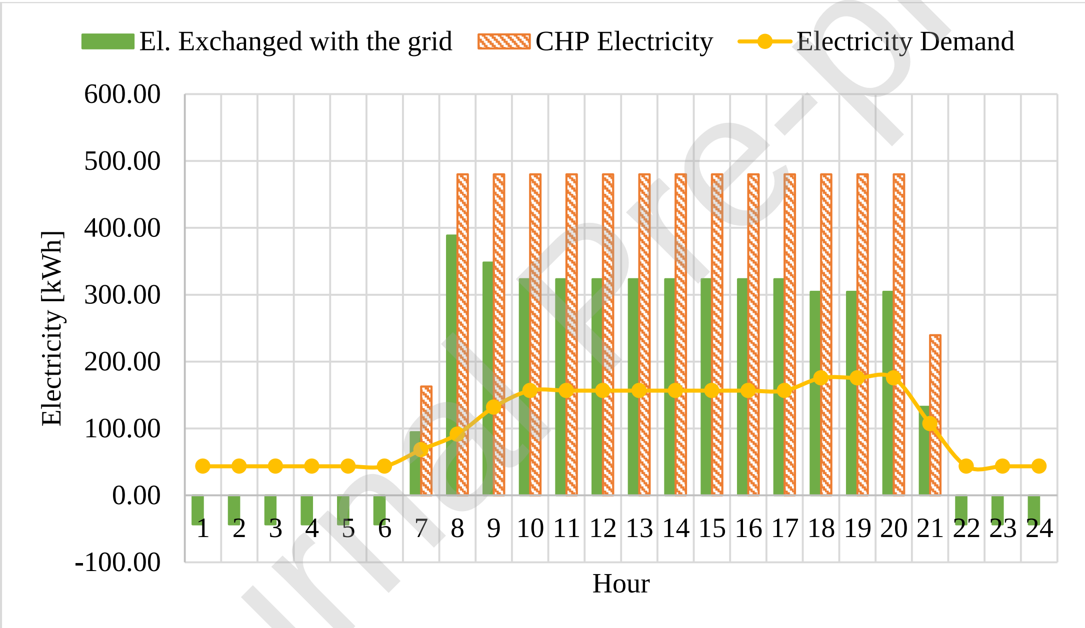
Figure 9. *SS* and *TSS* values calculated for a typical summer day and winter day

It is useful to investigate for the same days, all energy flows involved during the operation of the CHCP system. To this aim, in Figures 10a and 10b, daily results of CHCP operation in a typical winter day are presented. It is possible to observe that:

- During nighttime, i.e. from 10 pm till 6 am, since no thermal demand is observed (red line in Figure 10a), the CHCP systems is switched off and the low electrical load is entirely met by consuming low-cost electricity supplied by the grid.
- The maximum thermal demand is observed mainly at around 7-8 am when the plant is switched on and no internal heat gains (such as people) are present.
- From 7 am through 9 pm, the CHCP system is switched on. In particular, at 7 am, since TSS_{th} is higher than 1 and *SS* is lower than 1 as displayed in Figure 9, a HT strategy is followed. During this hour, the CHCP thermal capacity is controlled in order to satisfy the thermal demand (Figure 10a), being the electrical load balanced by exchanging power with the grid (Figure 10b).
- From 8 am to 8 pm, both *TSS* and *SS* values are greater than 1 (see Figure 9), and according to the proposed management strategy, the operation of CHP at its full capacity is very profitable. However, it is worth observing that during this time frame, the thermal demand is either higher or lower than the heat recovered from the CHP unit. For this reason, when the heat recovered is lower than the demand (for instance from 8 am to 10 am, in Figure 10a), the boilers provide the remaining fraction of demand not covered by the CHP unit. In the graph, this amount is indicated by grey-stripped rectangles. Conversely, when the heat demand is lower than the heat recovered by the CHP unit, the exceeding heat is wasted by a radiator.
- As evinced in Figure 10b, the electricity produced by the CHP unit is greater than the demand during the day hours; therefore, the fraction not consumed by the building is sold to the grid.



(a)

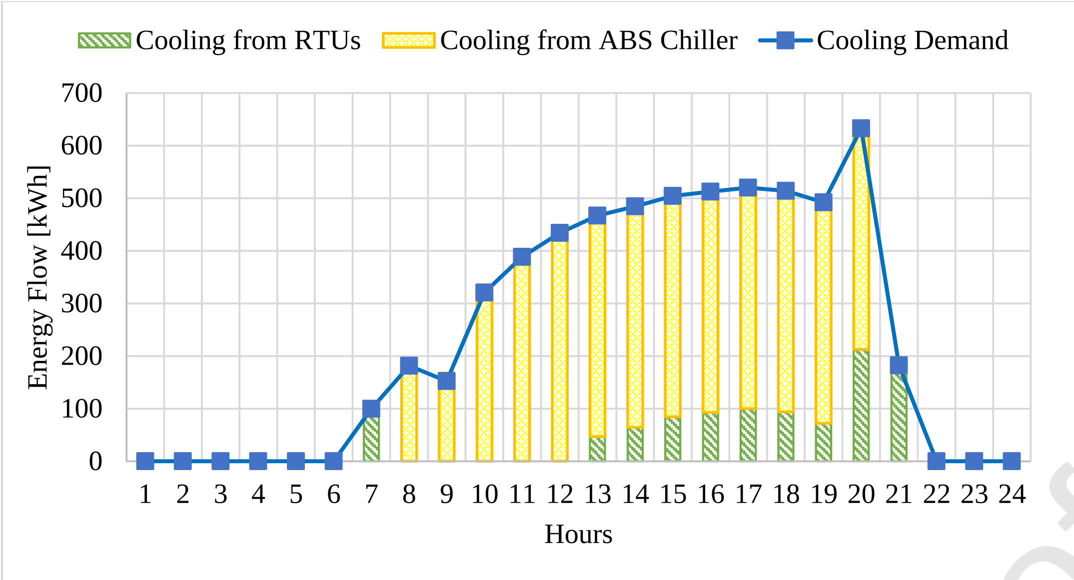


(b)

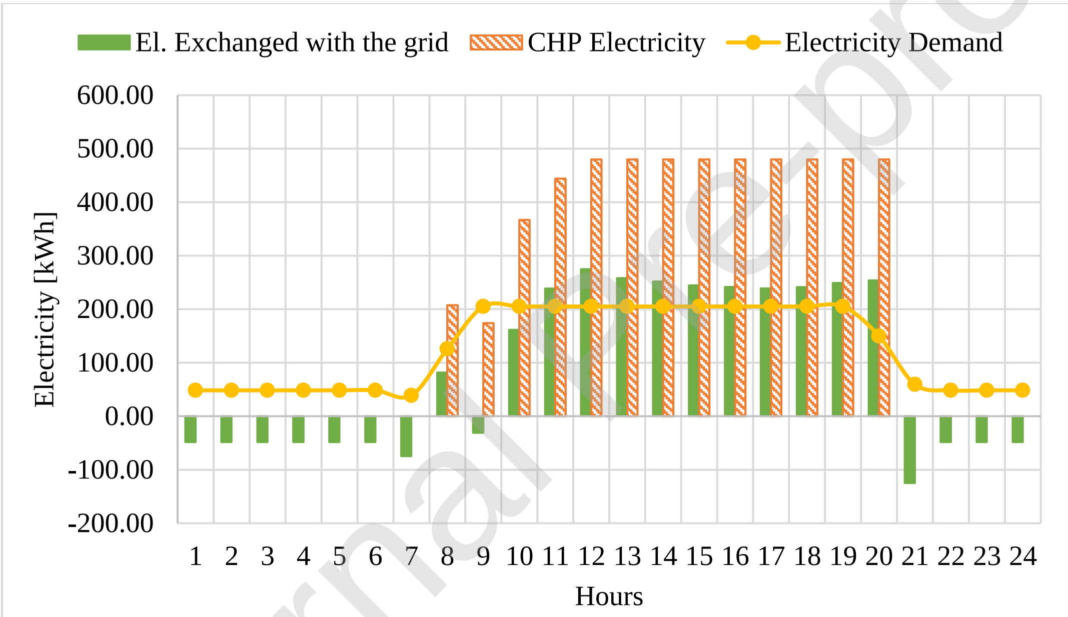
Figure 10. CHP operating results for a typical winter day: **(a)** energy flow involved while matching thermal demand **(b)** electricity flow

In Figures 11a and 11b, CHCP operation results in a typical summer day are shown. It is possible to observe that:

- During nighttime, i.e. from 10 pm till 6 am, since no cooling demand is observed (blue line in Figure 11a), the CHCP systems is switched off and the low electrical load (mainly due to lighting systems) is entirely met by consuming low-cost electricity from the grid.
- At 7 am, a no-null cooling demand is observed. However, as indicated in Figure 11a, the CHCP is still switched off. Indeed, since TSS_c is lower than 1 in this hour as proved in Figure 9, it is not profitable to operate the CHP system. Then, in order to meet the cooling demand, the RTUs are operated (see the green-stripped rectangle in Figure 11a).
- From 8 am to 8 pm, both *TSS* and *SS* are greater than 1: according to the proposed management strategy, the utilization of CHP at its full capacity is very profitable. However, it is worth observing that from 8 am to 12 pm the cooling demand is entirely satisfied by using only the absorption chiller. Conversely, from 1 pm to 8 pm, since the cooling demand is higher than the maximum cooling capacity deliverable by ABS chiller, RTUs have to be operated as well (see green-stripped rectangle in Figure 11a).
- As concern electricity produced by CHP system, in Figure 11b, the CHP electricity production is greater than the demand during the day hours; thence the fraction not consumed by the building is entirely sold to the grid.
- The maximum cooling demand is generally shifted towards 7 pm to 9 pm because of the greater number of customers during these hours.
- It is relevant to underline that for those hours characterized by low cooling demand, (i.e. from 8 a.m. to 9 a.m.) the CHP is operated at the minimum part-load achievable for the considered technology (i.e. $LL_{min} = 0.4$).



(a)



(b)

Figure 11. CHP operating results for a typical summer day: **(a)** energy flow involved while matching cooling demand **(b)** electricity flow

5.3 Yearly energy, economic and environmental results and "High-Efficient" eligibility of the investigated system

In Table 2 energy, economic and environmental results achieved on a yearly basis by the proposed CHCP plant are reported. In the first column, energy consumptions and economic costs sustained for operating the current energy systems (i.e. boilers and RTUs) are shown. Conversely, in the second column, results achieved by the CHCP plant operated following the flexible management strategy are presented. In particular, the following quantities are pointed out:

- the yearly natural gas consumption;
- the net annual exchange with the grid (positive when purchased and negative when sold);
- the annual cost sustained for electricity and natural gas purchase;
- the amount of heat supplied to the user by the CHCP unit and by the auxiliary boilers;
- the primary energy saving index PES achieved by the proposed management strategy;
- the amount of CO_2 emitted by the current energy conversion system and by the CHCP plant;
- the discounted payback period, the net present value NPV and the number of White Certificates obtained.

Table 2. Yearly results achieved by the CHCP system under investigation

	Current Energy System (Boilers and RTUs)	*CHCP System*
Yearly Natural Gas Consumption [m^3]	226.8	732.3
Natural Gas (NG) Cost [k€]	73.1	197.9
Net electric power exchange [MWh]	1653	-1101.8
Cost for electricity exchange [k€]	153.4	-40.2
Total Fuel Cost (Electricity + NG) [k€]	226.5	157.7
Heat by CHP recovery [MWh]	-	3119.2
Heat by Auxiliary boilers [MWh]	2173	334.8
Global Energy Efficiency	-	0.8
PES [%]	-	16.1
CO2 [tonn]	1215	852
Number of White Certificates	-	165
Discounted Payback Time [years]	-	4.9
Net Present Value [k€]	-	595.0

First of all, an increase in the yearly consumption of natural gas is observed for the CHCP plant in comparison with the current energy system due to the need to fuel the prime mover. Consequently, an increase of cost sustained for purchasing gas is observed. However, when considering net cost for electricity exchange in Table 2, it is possible to see that a negative values -40.2 k€ is obtained, which testifies that revenues, obtained from selling electricity to the grid, are greater than costs sustained for purchasing electricity. When comparing the total costs sustained (i.e. Electricity + NG) to operate the current energy system with the ones observed for the CHCP plant, a reduction of nearly 70 k€/year is observed.

As concern CO_2 emissions, a reduction of 363 tons of CO_2 is observed when comparing the proposed CHCP system to the current energy system.

Finally, it was evaluated if the proposed CHCP plant was eligible as "*High-Efficient"* plant according to criteria shown in subsection 2.1. The global efficiency of the CHCP plant resulted equal to 0.8, which is greater than the threshold imposed by law, i.e. 0.75 [23]; therefore, the entire electricity produced by the CHCP system was considered produced in a "cogenerative" mode. Then, the Primary Energy Saving Index (see Eq. 6) was calculated by using values reported in Annex II of European Directive 2011/877 [39]. In particular, since a natural gas-fuelled ICE was assumed for the case study, a $RefH\eta$ value equal to 0.9 and $RefE\eta$ equal to 0.525 were selected [39]. As reported in Table 2, the PES indicator assumed a positive value, i.e. 16.1%; thence the system is eligible as a high-efficient CHP plant.

At this point, it is possible to quantify economic revenues arising thanks to support mechanism "White Certificate" for a "High-Efficient" CHP plant operated in Italy. To this aim, the annual energy saved, indicated as "RISP" [32], was calculated by using in Eq. 7. In accordance to Italian legislative framework, the following reference values were assumed for a separate production system: an electric efficiency equal to 0.46 and a thermal efficiency equal to 0.9 [32]. The resulting amount of energy saved resulted equal to 1950 MWh. According to Eq. 8, the number of White

Certificates resulted equal to 165. Finally, by considering that the current market price of energy saving certificates is around 260.0 €/WhC [34], yearly revenues arising from this support mechanism accounted for about 42.9 k€.

In order to calculate the Net Present Values and the Discounted Payback time of the proposed investment, an 18 years operation of the plant and a 5% interest rate were assumed. As highlighted in Table 2, the Net Present Value resulted positive and equal to 595 k€. Also, the discounted Payback time resulted equal to 4.9 years, thus suggesting that a low risk is related to this investment.

Before ending this work, it is worth evaluating the sensitivity of PBT with the White Certificates market prices. To this regard, a sensitivity analysis was carried out and results are shown in Figure 12. In particular, the WhC prices ranged from 50 €/WhC to 400 €/WhC. It is possible to observe that the PBT obtained varied from 6.7 years down to 3.8 years. This result suggests that even if a decrease in WhC prices will occur with respect to current values, a low risk is still related to this investment.

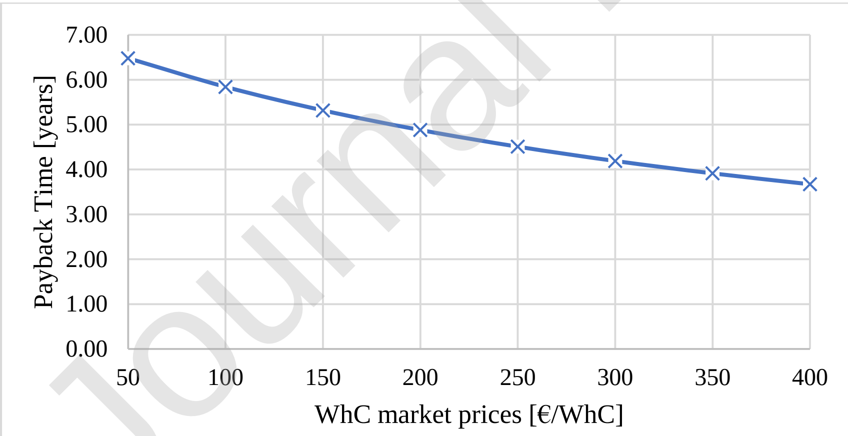


Figure 12. Sensitivity analysis of DPBT with market prices of White Certificates

6. CONCLUSION

This paper investigated the potential of installing CHCP systems for commercial buildings, where the high energy demands (usually for lighting and HVAC systems) are usually met by using a separate and obsolete energy conversion technologies. In this sector, great opportunities of profit exist by using cogeneration or trigeneration systems for satisfying both electricity and air conditioning demands which are simultaneously observed on a daily basis. However, even if an efficient trigeneration system is installed, it should be properly operated in order to achieve profitable energy saving. To this aim, a novel management criterion proposed in literature was used in this paper. As an example, a big *Do It Yourself* shop located in the northern part of Italy was assumed as a case study, where energy demands for lighting and operating HVAC systems were met by using separate energy systems such as boilers and rooftop units. A CHCP system was firstly designed by using a heurist method. Then, a flexible operation strategy was implemented which allows to maximize profits and to guarantee satisfactory primary energy savings. Results showed that CHCP systems could help reducing energy consumption in the commercial sectors along with other measures usually adopted as the installation of high-performing lighting systems. In addition, interesting profits are achieved thanks to: (i) the revenues arising from selling electricity during hours of high market electricity prices, and (ii) the financial support mechanism for "High-Efficient" CHP plant.

Conflict of Interest

On behalf of all authors, I also **declare** that we do not have competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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