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Research article

Investment analysis of gas-turbine combined heat and power systems for commercial buildings under different climatic and market scenarios

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Abstract

The aim of the proposed work is to investigate the technical and economic suitability of a gas turbine combined heat and power system in commercial buildings. These systems are widely recognised as a promising technology to provide significant fuel savings and carbon emissions reduction where they have been widely used in industrial settings due to the relatively constant electrical and thermal loads required for industrial processes. However, CHP deployment has been relatively stagnant over the last few decades due to challenges such as poor planning and policy measures, energy market changes and regulatory barriers. In this context, a preliminary system design and optimisation procedure has been developed based on a sensitivity analysis of different scenarios of building loads, market and weather conditions. The optimisation is performed considering several technical and environmental parameters (e.g., energy and exergy efficiencies and primary energy saving), as well as economic indexes (e.g., net present value, pay-back period, profitability, etc.). This allows assessment of the suitability of the investment for different market price scenarios under different heating degree days demand scenarios. The analysis is carried out using an Italian case study as it exhibits a wide range of heating degree days variability, while subject to a single pricing market. Results show that strong correlations occur between the technical and economic performance indices and the weather conditions for all considered configurations. The methodology and conclusions, if coupled with the possibility of applying clustering techniques to determine common patterns of energy consumptions in building blocks, represent a powerful toolset to carry out preliminary techno-economic assessment of a combined heat and power system.

Keywords: Cogeneration (CHP), Commercial buildings, Heating degree days (HDDs), Investment analysis, Energy and exergy analysis

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Nomenclature

Variables

β	Pressure ratio
d	Day
ΔT_{ml}	Logarithmic mean temperature difference [K]
E	Exergy [kJ/kg]
ε	Component effectiveness
h	Hour / Enthalpy [kJ/kg]
I	Irreversibility [kJ/kg]
$\dot{m}$	Mass flow rate [kg/s]
η	Efficiency / Component isentropic efficiency
p	pressure [kPa]
P	power [kW]
Q	Heat flow rate [kW]
r	Discount rate [%]
s	Entropy [kJ/(kgK)]
S	Entropy generation [kJ/K]
T	Temperature [°C]
U	Global Heat Transfer Coefficient [W/(m^{2}K)]
VC	Variable cost [€]
y	year
W	Work [kJ]

Acronyms

CAPEX	Capital expenditure [€]
CDD	Cooling Degree Days [°C]
CF	Cash flow [€]
DCF	Discounted cash flow [€]
DEC	Decommissioning cost [€]
FEX	Foreign exchange rate [$/€]
HDD	Heating Degree Days [°C]
HRU	Heat Recovery Unit
INV	Investment [€]
IRR	Internal Rate of Return [%]
LCOE	Levelised cost of electricity [€/kWh$_e$]
LHV	Low Heating Value [kJ/kg]
NG	Natural gas
NPV	Net present value [€]
PBP	Pay-back period [years]
PEC	Component cost [€]

PES	Primary Energy Saving
PI	Profitability Index [-]
VOM	Operating and management costs [€]

Subscripts

0, ref	reference state
a	air
b	base
c	compressor
cc	combustion chamber
cs	cooling system / cooling set point
e	electric / electricity
ex	exergy
g	gas
gt	gas turbine
j	index / year
hs	heating system / heating set point
i	inlet
id	ideal
max	maximum
mech	mechanic
nom	nominal
o	outlet
ph	pre-heater
t	turbine
x	index
w	water

Highlights

- CHP techno-economic performance is correlated with the climatic conditions.
- HDDs are driving parameter for the profitability of CHP systems in buildings.
- CHPs are resilient to increases in energy market prices.
- The design of CHP systems is influenced by the investment policy adopted.

1. Introduction

Fuel cost volatility, security of supply and environmental issues associated with increasing energy use have led to mandatory energy efficiency targets and energy regulatory frameworks being established within the European Union (EU) [1,2]. The Energy Efficiency Directive 2012/27/EU [1] deals with much of the legislation surrounding energy efficiency, emissions reduction and monitoring. In this context, Article 14 [1] sets out provisions for the promotion of combined heat and power (CHP) systems, or cogeneration, in EU member states integrating the previous EU directive Directive 2004/8/EC [2].

CHP systems consist of the simultaneous production of electrical and thermal energy from a single fuel source (e.g., natural gas). The primary energy savings associated with simultaneous dual energy production can be relevant if compared with separate generation technologies, and it generally ranges from 10% to 30% [3] for optimised systems, depending on the specific configuration and application. Moreover, the simultaneous presence of both electrical and thermal loads (which is essential for CHP installations) and the possibility of selling excess electricity to the network make these technologies very promising as a solution for overall energy savings and carbon emission reductions.

Notwithstanding, CHP deployment has been relatively limited worldwide: global electricity production from CHP systems reduced from 14% in 1990 to approximately 10-11% in 2000 [4], whereupon it has remained relatively stagnant since [5]. There are a variety of reasons preventing the growth of CHP systems worldwide, including poor planning and policy measures, energy market failures and difficulties in establishing the true value of cogeneration, amongst others [6]. Since the economic suitability of cogeneration is heavily dependent on the "spark gap" (i.e., the difference in the market price of gas and electricity), the uncertainties related to market forecasting has led to a lack of knowledge about benefits and savings associated with these systems, as can be depicted from the IEA reports [4,7]. Moreover, regulatory and utility barriers are often cited as other leading causes for the poor uptake of CHP and, while regulatory frameworks have evolved over time to deal with these issues, many still remain. As mentioned in [4], to realise the full potential of CHP (and district heating), substantial financial incentives are not generally needed, but there is a requirement for the effective use of “modest, targeted policies to systematically address barriers” instead. In order to establish such policies and instil confidence in investors of CHP projects, there must be a stable and effective regulatory framework in place [5].

Generally, a proper assessment of CHP systems must be carried out starting from the preliminary design stage and considering all technical and economic (i.e., financial and markets) aspects involved in each specific application. These multidisciplinary assessments must be aimed at understanding the technical and economic suitability of a CHP system, leading to a preliminary optimisation of the design and operation strategies before an actual detailed design is carried out for each specific application.

CHPs are suitable for a wide variety of applications in large residential, commercial and industrial sectors, provided there is an outlet for the electrical and thermal energy. The building sector is of particular interest, since it accounts for more than 40% of overall energy demand worldwide [8], with an expected increasing trend over the coming decades, as reported in Szalay and Csoknayai [9]. In particular, under the current trend of the global climate change, global residential heating demand is expected to decrease by 34%, while cooling demand will increase by 72% [10]. Therefore, substantial energy savings are achievable within buildings to reduce the environmental impact of the built environment over the next decades.

CHP plants are used globally and are widely accepted in industrial settings due to the relatively constant electrical and thermal loads required for several industrial processes. According to Çakir et al. [11], CHP may result in a consistent energy conservation, usually ranging from 10% to 30%. Bianco et al. [12] investigated the feasibility of a cogeneration plant for a food processing facility, showing that PES values greater than 10% can be achieved.

On the other hand, commercial and residential buildings often experience much greater seasonal (and daily) variations in energy consumption [13], which leads to the need for more complex optimisation of the CHP design and operation [14]. Generally, commercial buildings are particularly suitable for CHP installations due to their relatively large and predictable heating, cooling and electrical loads [6]. These predictable loads can ensure CHP systems achieve sufficient operating hours, making them environmentally and economically effective [15].

Consequently, considerable research efforts have been made to understand the technical aspects of CHP installations in buildings and successful installations have been achieved [6]. As for instance, Biglia et al. [16] examined numerically the techno-economic feasibility of an internal combustion CHP system in a large hospital in Italy, showing that significant energy and cost savings can be achieved. Similarly, Armanasco et al. [17] demonstrated that a CHP plant is a favourable solution from both energetic and economic point of view for the industrial sector, with primary energy savings greater than 10%. Mago et al. [18] investigated primary energy consumption (PEC), potential emission reductions and operational costs of a CHP system in different commercial buildings in Chicago (USA). The results highlighted the importance of guaranteeing that the CHP covers a high portion of the building thermal demand, to have satisfactory primary energy savings (PES) and consistent emission reductions.

Although much work has focused on the technical aspects of CHP design and operation, the influence of building load profiles and climatic conditions on CHP off-design economic performance has not been examined comprehensively since little attention has been given to the impact of such conditions on the long-term profitability of CHP installations. In addition, CHPs are not necessarily energy-saving systems, where their energy and exergy performances depend solely on the specific building load. This is highlighted in Chen et al. [19], who analysed numerically the off-design performance of a small-scale CHP turbine system for reference commercial buildings. The authors showed that the fuel energy saving ratio tends to be negative when the load level of the system decreases below the 30% of the full nominal load, and they highlight the importance of a careful off-design assessment of the CHP system on a building load base. Similarly, Thu et al. [20] demonstrated experimentally that

CHP off-design working conditions can lead to poor energy and exergy efficiencies, with reductions up to 50% of nominal values depending on the actual building load profiles. Consequently, the design stage is of paramount importance to determine the correct optimised CHP size and its operating strategies, considering the specific application and off-design working conditions.

In this context, building thermal energy profiles and climate conditions play important roles in determining whether a CHP installation is suitable or not. Addressing this challenge requires proper methodologies able to assess all technical, economic and investment aspects affecting the CHP performances. Different technical indexes (such as PES and exergy efficiency) are generally considered for assessing the thermodynamic performance of CHP systems. Notwithstanding, being an efficient CHP system (i.e., high PES value and low carbon emissions) is not necessarily sufficient to guarantee the long-term profitability of the investment associated with the CHP system [12]. Running comprehensive techno-economic assessments is therefore paramount to identify best economically-optimised solutions depending on the specific application. Such analyses require the introduction of further external and non-technical variables - such as market context, uncertainties in future energy prices, regulatory framework, etc. - which may strongly influence the economic case of CHP systems [6].

Moreover, detecting the most suitable economic indicator(s) to assess and compare different technical solutions is central for such analyses and requires a careful evaluation of the market where the system will be located in. A vast number of indexes can be used for assessing the economic suitability of a project. For instance, the Handbook of Financial Engineering [21], considers the Net Present Value (NPV), Pay-back Period (PBP) and Internal Rate of Return (IRR) as the most well-known and commonly used indicators (See Section 2.2.2 for more details). It is also important to consider that the choice of the economic index adopted reflects the global strategy of the investors and it might result in different outcomes of the optimisation process, as demonstrated in Bianco et al. [12] and Dumont et al. [22].

Generally, one of the main research limitations is that the economic analysis of CHP systems is presented as an ''*ex-post*'' validation without detailing the market assumptions underpinning the selection of specific economic indexes [12]. Limited consideration is generally given to fuel and electricity price forecasting, both of which have been found to significantly affect the economic viability of CHP systems, due to their intrinsic uncertainties over time [23].

Generally, there is a lack of rational assessment procedures for the comprehensive evaluation of CHP system [24] accounting for the different techno-economic-investment aspects influencing their preliminary design. In fact, a wide-ranging comparison between different investment scenarios linking CHP optimisation outcomes with CHP design characteristics, climatic conditions and market context is relatively scarce, specifically for gas-turbine CHP systems in buildings. These aspects are of particular importance for buildings where the seasonal load variation, related to fluctuations in weather conditions and user profiles, makes the economic optimisation even more challenging, requiring the adoption of accurate methodologies.

Commencing from the considerations and research gaps outlined above, the aim of the present paper is to investigate the suitability of a gas turbine CHP unit for commercial buildings by adopting a comprehensive approach involving all relevant technical, economic, environmental and market aspects. Specifically, the paper focuses on the influence of technical CHP design parameters on the CHP techno-economic performance considering off-design working conditions and different climatic locations. This aspect is of particular importance since the CHP system in building applications may experience strong variations of their operating conditions which must be taken into account since the very beginning of the techno-economic suitability assessment.

Moreover, the paper combines technical aspects with the economic analysis by linking directly the investment cost with the thermodynamic specification of the detected design with the aim of performing long-term economic assessment of the investment aimed at analysing and optimising the CHP design for different market and investment scenarios. The influence of boundary conditions, such as climatic conditions and commodities market prices, on the CHP techno-economic optimisation and its long-term profitability is therefore investigated. Finally, the influence of investment policies on the CHP system design and optimisation depending on specific environmental and economic scenarios are assessed.

It is important to observe that subject is intrinsically multidisciplinary, since it involves engineering and modelling aspects, as well as, it includes economic perspectives by introducing market forecasting scenarios and investment policy framework. Merging technical, market and investment policy aspects makes the paper comprehensive and relevant for the building energy sector and CHP system deployment. The considerations and the conclusions reported in this paper represents a useful guideline for building energy managers, owners and investors in order to assess, design and optimise potential CHP installations in the context of various building demand profiles at the very early design stage.

2. Approach

This section is outlined as follows:

- Section 2.1 provides a detailed description of the benchmark commercial building used as reference case.
- Section 2.2 defines the CHP system configuration and the numerical model developed.
- Section 2.3 describes the market context considered for carrying out the techno-economic analysis.

2.1 Case Study

The case study considered in the present work consists of a benchmark commercial building (section 2.1.1) which is supposed to be retrofitted with the CHP system described in section 2.2. The building is modelled using EnergyPlus and several simulations are carried out for each climatic location (described in section 2.1.2) in order to determine its hourly energy consumption profiles presented in section 2.1.3. The details of the analysis carried out is described in the following sections.

2.1.1 Benchmark building

The reference commercial building consists of a 12-storey large office building equipped with a gas boiler and with two water-cooled chillers to supply the heating and cooling demands. The main building characteristics are detailed in Table 1.

Each floor is divided in to five separate thermal zones: a core and four perimeter zones. Partition walls within the building are of 2x4 steel frame construction with a gypsum board finish. The roof is of flat roof construction, with insulation entirely above deck. The surface area of the roof is assumed to correspond to the building footprint. Additionally, a parking lot, of area 30,201 m^2, is included where lighting loads must be considered. There are no skylights or tubular daylight devices installed in the building and there are no obstructions surrounding the building to cause shading. Interior lighting levels vary with time and day and the maximum lighting power densities are determined using the "space-by-space" or "whole building area" method as set out in [26]. External lighting and building service equipment (e.g., elevators) are also considered to determine the overall electric consumption of the building.

Table 1: Building and heating/cooling system characteristics [25].

	Unit		**Value**
Internal volume	m^3		178,176
Total floor area	m^2		46,320
Aspect ratio	-		1.5
Floor to floor height	m		3.96
Floor to ceiling	m		2.74
Windows to wall ratio	-		0.38
Glazed area	m^2	Overall	4,636
		North/South	1,391
		East/West	927
Average U-value	$W\ m^{-2}\ K^{-1}$	Wall	0.857
		Roof/Floor	0.357
		Windows	3.236
Nominal air exchange	% vol		0.10
Hot water demand	litres/day/pers		3.8
Hot water supply temperature	°C		43
Occupancy level	m^2/pers		18.6

All the electricity required is directly imported from the grid and no renewable energy systems are installed. The reference building was simulated using EnergyPlus [27] for different climatic locations in Italy to determine yearly energy consumptions, as described in the following section. In the subsequent analysis, these load profiles are considered constant on an annual basis.

2.1.2 Climatic boundary conditions

Several climates are considered in this paper, to evaluate the effects on the building load profiles and on the techno-economic performance of the proposed CHP system. Heating and cooling degree days (HDD and CDD respectively) are used to establish hot, cold and mild climates. These values are calculated using the mean daily degree-hours (MDDH) method [28], based on weather data obtained from the EnergyPlus™ weather database [29].

$$HDD_t = \sum_{d=1}^{D_t} \left[\frac{1}{24} \sum_{h=1}^{24} \left(T_{b,hs} - T_{e,h} \right)^+ \right]_d \qquad (1)$$

$$CDD_t = \sum_{d=1}^{D_t} \left[\frac{1}{24} \sum_{h=1}^{24} \left(T_{e,h} - T_{b,cs} \right)^+ \right]_d \qquad (2)$$

Table 2: Classification of climatic conditions for the selected locations.

Location	**Yearly average temperature** [°C]	**HDD** (T_b=20°C) [°C]	**CDD** (T_b=24°C) [°C]	**Köppen-Geiger climate classification [31]**
Trento	1.2	6846	0	Humid subtropical
Milan	12.4	3097	107	Humid subtropical
Rome	15.3	2160	167	Mediterranean
Palermo	18.0	1310	176	Hot Mediterranean

Italy was chosen for this study as it shows a wide variation of climatic conditions [30] over its territory, while exhibiting a unified market condition. The HDD and CDD are the main parameters used in establishing the climate type, however the Köppen-Geiger climate classification [31] is also reported as reference. The HDDs, CDDs and the climatic classification of each location are listed in Table 2, while Figure 1 reports their monthly temperature distributions.

2.1.3 Demand profiles

The aforementioned building was modelled using EnergyPlus and several simulations were carried out for each climatic location in order to determine its hourly energy consumption profiles. Since the building remains the same for each simulation, any changes in energy consumption is as a direct result of climatic conditions. The simulation results, summarised in a monthly format, are shown in Table 3 and Figure 2.

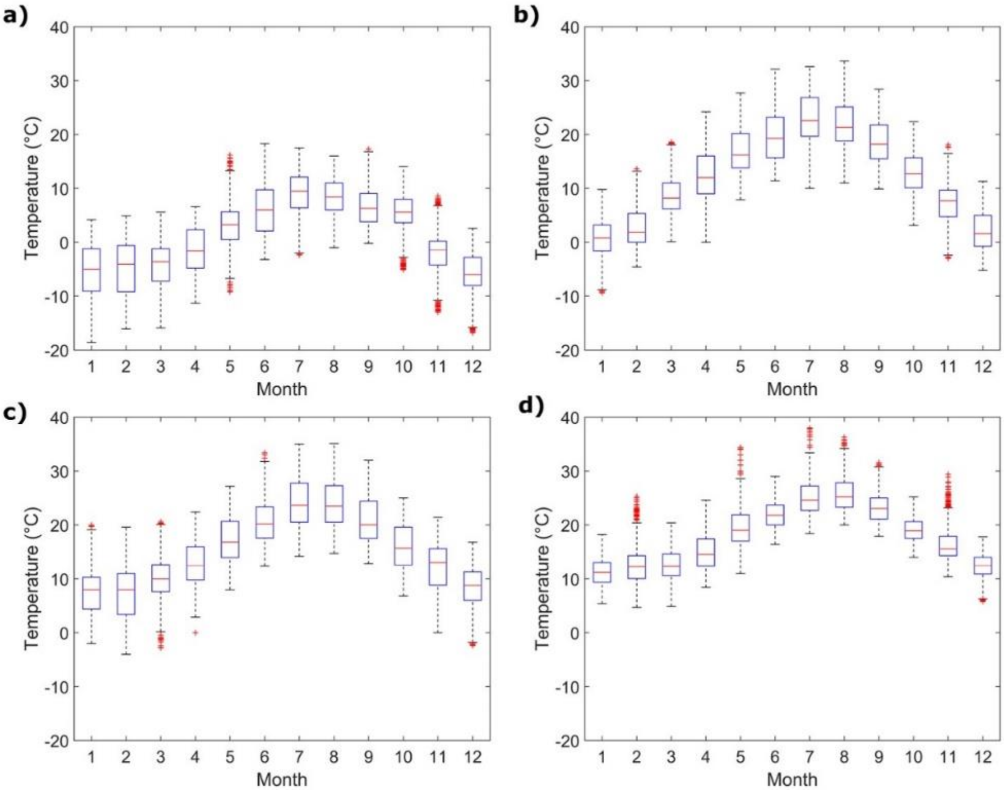

Figure 1: Ambient temperature distributions: (a) Trento, (b) Milan, (c) Rome and (d) Palermo.

Table 3: Classification of the climatic conditions at the selected locations.

Location	Peak electrical load	Peak heating load	Annual electricity demand	Annual thermal demand
Units	kW	kW	MWh	MWh
Trento	1306	2045	4890	2419
Milan	1985	2067	5830	924
Rome	1973	1285	6350	408
Palermo	2009	649	6778	210

Trento (Figure 2a) is observed to exhibit the greatest HDD of the four locations, and, consequently, shows the greatest heating demand, with a peak heating load of 2,045 kW occurring in February (Table 3). This heating demand is very seasonal due to the mild summers and cold winters, while the electrical load is relatively constant and appears to have little seasonal variability. On the other hand, Palermo shows negligible heating demand, while it has considerable cooling requirements due to its very mild winters and hot summers (Figure 2d). Palermo has the greatest average electrical energy consumption of all the locations considered, with a peak of 2009 kW (Table 2). Both Milan and Rome weather conditions are in between of the other two localities (Figure 2b,c). As a mild climate, Milan has a reasonable amount of heating and cooling demand throughout the year, while Rome experiences a slightly milder climate to that of Palermo and therefore has small amounts of seasonal heating demand and larger cooling demands.

These energy consumption profiles will be used for the subsequent analysis aimed at designing and optimising a CHP system as a replacement for the standard system. The benchmark building will also work as reference for the economic analysis carried out in the following sections.

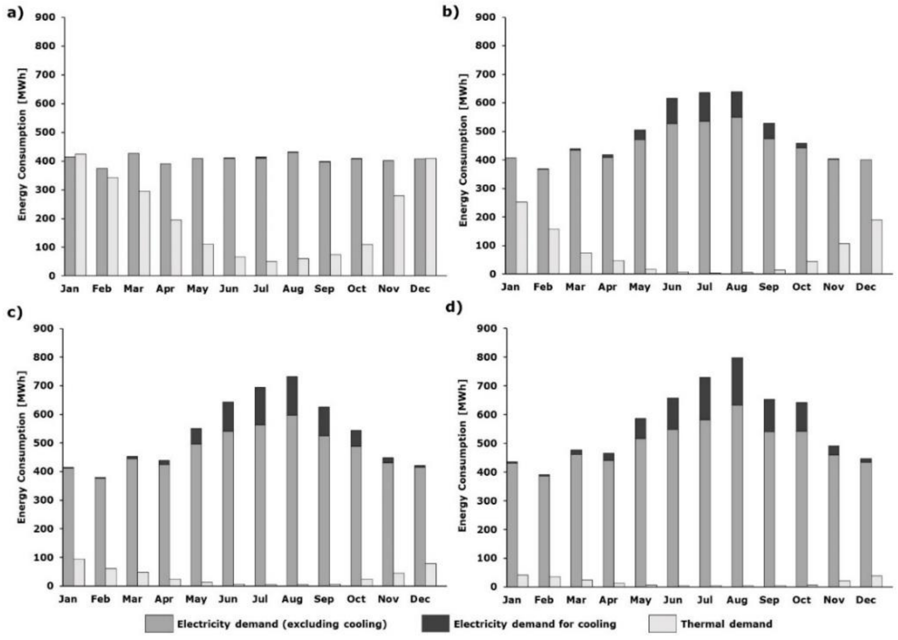

Figure 2: EnergyPlus demand profiles: (a) Trento, (b) Milan, (c) Rome and (d) Palermo.

2.2 CHP design

The building is characterised by variable thermal and electrical loads which introduces uncertainty about the economic suitability of a CHP system. In the present work, a gas turbine CHP system was chosen to retrofit the reference system. A typical gas turbine has a turbine inlet temperature (TIT) above 800 °C and the exhaust gases are between 430 °C and 540 °C [32], making them suitable for potential heat recovery for use by the building.

The power generated by the CHP system is used to reduce the imported electricity by the building, while the remaining part is bought from a power supplier. If electricity production exceeds the building demand, the surplus is sold to the market. Gas boilers are installed as backup in case the CHP is not able to supply all the thermal power required by the building.

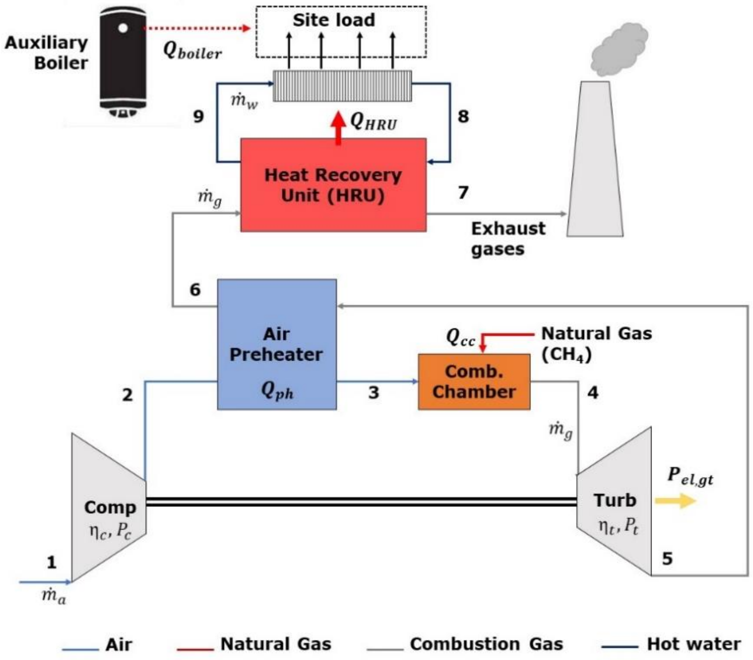

Figure 3: CHP system schematic.

The gas turbine cycle is modelled as a Brayton cycle as shown in Figure 3. A numerical model of the CHP system was developed in Matlab®, which consists of a set of energy balance equations characterising each system component, to define each thermodynamic state point. A steady state regime is considered for all processes, while fluid potential and kinetic energies and pressure losses are neglected. The main governing equations are reported in Table 4.

Table 4: Governing equations adopted in the present work [12]

Component	**Governing equations**	
Compressor	$P_c = \dot{m}_a(h_2 - h_1)$	(3)
	$\eta_c = \dfrac{(h_{2,id} - h_1)}{(h_2 - h_1)}$	(4)
	$M^* = \dfrac{\dot{m}_a}{\dot{m}_{a,0}} \dfrac{p_{in,0}}{p_{in}} \sqrt{\dfrac{T_{in}}{T_{in,0}}}$	(5)
	$N^* = \dfrac{N}{N_0} \sqrt{\dfrac{T_{in,0}}{T_{in}}}$	(6)
Preheater	$Q_{ph} = \dot{m}_a(h_3 - h_2) = \dot{m}_g(h_5 - h_6)$	(7)
	$\epsilon = \dfrac{Q_{ph}}{Q_{ph,id}}$	(8)
Combustion chamber	$Q_{cc} = \dot{m}_{fuel} LHV_{fuel} = \dfrac{\dot{m}_g h_4 - \dot{m}_a h_3}{\eta_{cc}}$	(9)
	$\dot{m}_g = \dot{m}_a + \dot{m}_{fuel}$	(10)
Turbine	$P_t = \dot{m}_g(h_4 - h_5)$	(11)
	$\eta_t = \dfrac{(h_4 - h_5)}{(h_4 - h_{5,id})}$	(12)
	$P_e = P_{net}\eta_{mec}\eta_{el} = (P_t - P_c)\eta_{mec}\eta_{el}$	(13)
HRU	$Q_{HRU} = \dot{m}_a(h_6 - h_7) = \dot{m}_w C_{p,w}(T_{w,out} - T_{w,in})$	(14)
	$\epsilon = \dfrac{Q_{HRU}}{Q_{HRU,max}}$	(15)

Off-design performance working conditions are introduced by using gas turbine maps derived from [32]. These maps, shown in Figure 4, include efficiency and pressure ratio characteristic curves related to corrected mass flow ratio and non-dimensional rotational speed (Eq. 5 and Eq. 6, Table 3). In particular, Figure 4a shows the variation of the compressor pressure ratio as function of the rotational speed and of the air mass flow rate, while Figure 4b shows the compressor efficiency as function of the rotational speed and pressure ratio. Finally, Figure 4c shows the turbine efficiency as function of the pressure ratio and rotational speed. These maps reflect the performance of a small-scale gas-turbine outside the standard working conditions.

The nominal gas mass flow rate flowing through the turbine is determined from the nominal turbine power, as suggested in [11]. The gas turbine efficiency can be calculated as follows:

$$\eta_{gt} = \frac{P_{el}}{Q_{cc}} \tag{16}$$

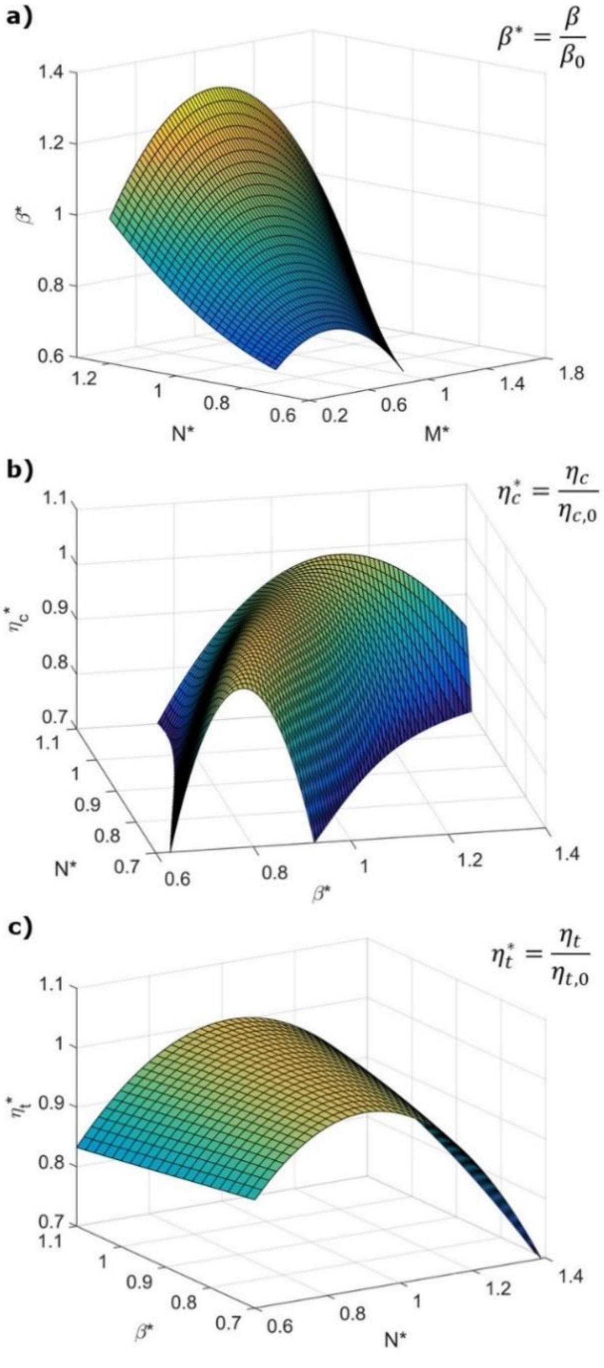

Figure 4: (a) Compressor pressure ratio, (b) compressor efficiency, and (c) turbine efficiency maps [32].

The main assumptions, parameters and constraints introduced in the present work are reported in Table 5 [12, 13].

Table 5: Boundary conditions [12-13, 22]

Parameter	Symbol	Unit	Value/Range
Reference ambient pressure	p_1	kPa	101.325
Nominal pressure ratio	β_0	-	4-12
Turbine inlet temperature	TIT	°C	800-1100
Discharged exhaust gas temperature	T_7	°C	≥120
Nominal compressor efficiency	$\eta_{c,0}$	-	0.85
Nominal turbine efficiency	$\eta_{t,0}$	-	0.915
Combustion chamber efficiency	η_{cc}	-	0.97
Preheater effectiveness	ε_{ph}	-	0.85
Mechanical efficiency	η_{mech}	-	0.99
Electric efficiency	η_{el}	-	0.95
Turbine power	P_t	MW	0.03-1
Natural gas low heating value	LHV	MJ/kg	46.25

2.2.1 Exergy analysis

Exergy analysis has become common place in many design and optimisation studies [33,34] as it is considered a very useful tool in establishing inefficiencies in complex thermodynamic systems. When carried out on a component by component basis, as is done in this study, it can provide an insight into which components have the greatest effect on the total system efficiency, due to their internal irreversibilities. Exergy, or availability, is the maximum useful work that can be obtained from a system at a given state with respect to reference conditions [35]. Exergy can be destroyed during a process due to entropy generation, because of its intrinsic irreversibilities, which can be calculated as in Eq. 17.

$$I = T_0 S_{gen} \geq 0 \tag{17}$$

Exergy at a specific thermodynamic state *i* can be defined as follows:

$$E_i = \dot{m}[(h_i - h_0) - T_0(s_i - s_0)] \tag{18}$$

where the index *0* denotes the reference state, i.e., ambient temperature and pressure in the present work.

The exergy balance equation of a steady state process can be expressed as shown in Eq. 19, where W is the work rate of the control volume, Q_j is the heat transfer rate at the temperature T_j through the boundary, and I is the total exergy destruction rate during the process. The terms $\dot{m}_{i,x}E_{i,x}$ and $\dot{m}_{o,x}E_{o,x}$ are the exergy flow rates entering (inlet, subscript *i*) and exiting (outlet, subscript *o*) the control volume.

$$\sum_j \left(1-\frac{T_0}{T_j}\right)Q_j - W + \sum_x \left(\dot{m}_{i,x}E_{i,x}\right) - \sum_y \left(\dot{m}_{o,x}E_{o,x}\right) - I = 0 \qquad (19)$$

Therefore, the system exergy efficiency (or "second-law efficiency") can be defined as follows:

$$\eta_{ex} = \frac{\sum E_{used}}{\sum E_{supplied}} = 1 - \frac{\sum I + \sum E_{lost}}{\sum E_{supplied}} \qquad (20)$$

2.2.2 Investment analysis

To perform an economic assessment of a proposed CHP system, it is necessary to determine the capital expenditure (*CAPEX*). In the present work, the cost associated with each system component was calculated as function of the thermodynamic parameters utilising the equations shown in Table 6 [36]. The total capital cost can be calculated as follows:

$$CAPEX_{1994\,USD} = PEC_c + PEC_{ph} + PEC_{cc} + PEC_t + PEC_{HRU} \qquad (21)$$

Since the equations in Table 6 are based on 1994 USD, the CAPEX must be converted to the present-day value. Using a mean inflation rate (*i*=2.3%), the 1994 value is compounded to present-day, and then converted to Euro value using the prevailing (2018) foreign exchange rate (FEX = 1.2 \$/€).

$$CAPEX_{2018\,EUR} = FEX_{USD/EUR} \cdot CAPEX_{1994\,USD}(1+i)^y \qquad (22)$$

The total variable cost VC can be calculated as the sum of all cost associated with the CHP system operation less the potential revenue from selling electric energy over the considered year.

$$VC_{CHP,j} = \left(VC_{fuel} + VOM\right)_{CHP,j} + VC_{BOILER,j} + VC_{GRID,j} - VR_{EG,j} \qquad (23)$$

where the term $\left(VC_{fuel} + VOM\right)_{CHP,j}$ represents the yearly variable cost of the CHP system, determined as the sum of the fuel consumption (i.e., NG) and VOM costs. $VC_{BOILER,j}$ and $VC_{GRID,j}$ are the variable costs associated with potential energy integration from existing boilers and electric network, occurring when the CHP fails in covering the whole building demand. $VR_{EG,j}$ represents the possible variable revenues related to the CHP, which includes the amount of energy sold into the grid and potential government subsidies.

Table 6: Cost functions [36]

Component	**Cost function**	**Constants**
Compressor	$PEC_c = \left(\frac{C_{11}\dot{m}_a}{C_{12}-\eta_c}\right)\cdot\beta\cdot log(\beta)$	$C_{11} = 71.10\ \$/(kg/s)$ $C_{12} = 0.9$
Preheater	$PEC_{ph} = C_{41}\left(\frac{\dot{m}_g(h_5-h_6)}{U\Delta T_{ml,ph}}\right)^{0.6}$	$C_{41} = 4122\ \$/m^{1.2}$ $U = 18\ W/(m^2K)$
Combustion chamber	$PEC_{cc} = \left(\frac{C_{21}\dot{m}_a}{C_{22}-\frac{p_4}{p_3}}\right)[1 + exp(C_{23}T_4 - C_{24})]$	$C_{21} = 46.08\ \$/(kg/s)$ $C_{22} = 0.995$ $C_{23} = 0.018\ K^{-1}$ $C_{24} = 26.4$
Turbine	$PEC_t = \left(\frac{C_{31}\dot{m}_a}{C_{32}-\eta_t}\right)\cdot log(\beta)\cdot[1 + exp(C_{33}T_4 - C_{34})]$	$C_{31} = 479.34\ \$/(kg/s)$ $C_{32} = 0.92$ $C_{33} = 0.036\ K^{-1}$ $C_{34} = 54.4$
HRU	$PEC_{HRU} = C_{51}\left(\frac{Q_w}{\Delta T_{ml,HRU}}\right)^{0.8} + C_{52}\dot{m}_w + C_{53}\dot{m}_g^{1.2}$	$C_{51} = 6570\ \$/(kW/K)$ $C_{52} = 21{,}276\ \$/(kg/s)$ $C_{53} = 1184.4\ \$/(kg/s)$
Note: Data based on 1994 data (USA \$).		

To establish the economic suitability of the proposed CHP system, the variable cost $VC_{CHP,j}$ must be compared with the standard system installed in the reference building scenario ($VC_{REF,j}$), where heat is supplied by gas boilers and electricity is bought from the grid. Therefore, the yearly cost saving (i.e., yearly cash flow, CF) is calculated as shown in Eq.24. If the cash flow CF is positive, the CHP system guarantees lower operational costs than the reference scenario.

$$CF_j = VC_{REF,j} - VC_{CHP,j} \tag{24}$$

The CHP economic suitability is assessed considering the operating life of the system (i.e., 20 years) and by means of several economic indexes [12,22]:

- Net Present Value (*NPV*), defined as the difference between the discounted cash flow (*DCF*) during the operating life and the initial capital cost (Eq. 25). The term DCF can be calculated as shown in Eq.26, where r is the discount rate (assumed equal to 10% [12]) and N is the CHP operating life in years.

$$NPV = -CAPEX + DCF \tag{25}$$

$$DCF = \sum_{j=1}^{N} \frac{CF_j}{(1+r)^j} \tag{26}$$

- Pay-Back Period (PBP), which is the time required to recover the capital exposures or, in other words, the time during which the capital invested is at risk. It can be calculated as shown in Eq.27 where the variable is the time "t".

$$NPV = 0 \rightarrow CAPEX = \sum_{t=1}^{N} \frac{CF_j}{(1+r)^t} \tag{27}$$

- Internal Rate of Return (IRR) is the value of the discount rate which would result in NPV=0. It can be calculated by using Eq.27 by setting *r* as the unknown variable.
- Profitability Index (PI) is a measure of the efficiency of the investment and it is expressed by the ratio between the DCF and the initial capital cost.

$$PI = \frac{DCF}{CAPEX} \tag{28}$$

- Levelised Cost of Electricity (LCOE), Eq. 29, determines the unit price of electricity produced by the CHP system over its lifetime. The calculation takes into consideration the capital cost, lifetime operating costs as well as decommissioning costs, assumed equal to 25% of the capital cost in accordance with [37-39].

$$LCOE = \frac{\sum_{j=1}^{N} \frac{VC_{CHP,j} + INV_j + DEC_j}{(1+r)^j}}{\sum_{j=1}^{N} \frac{P_{e,j}}{(1+r)^j}} \tag{29}$$

2.3 Market context

To fully evaluate the economic performance of the CHP system over its life, the evolution of energy prices during the CHP operating life must be considered. In the present work, the evolution of electricity and gas prices are calculated using the method outlined in [12], while the price forecasting is taken from [40]. For both gas and electricity prices, three different price scenarios are considered, namely "*low*", "*medium*" and "*high*". The *low* scenario sees an initial reduction followed by a rise in energy prices, while the medium scenario considers a regular evolution of the market. Finally, the high scenario envisions more demanding market conditions with greater increases in energy prices over the considered period. According to the afore mentioned assumptions, electricity and gas prices scenarios are shown in Figure 5.

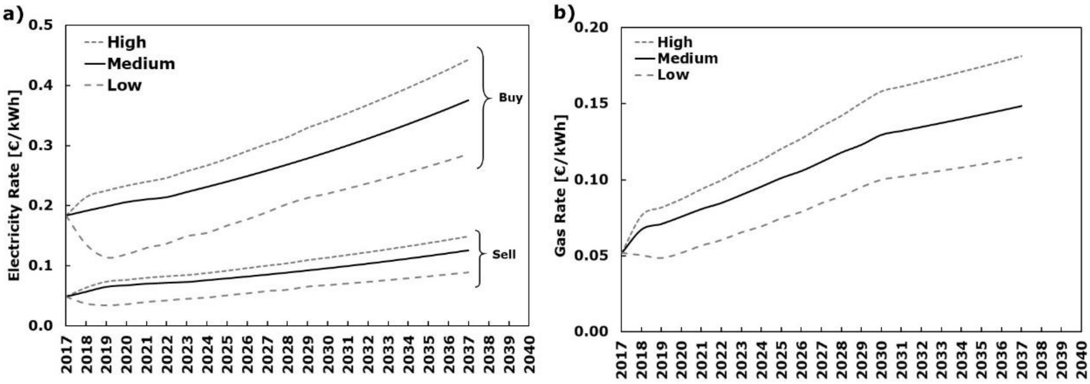

Figure 5: Price evolution of (a) electricity rates and (b) gas rates on the Italian market.

The evolution of the final price paid by the consumer is then determined by applying the relative year on year change of the import price of natural gas to the current Italian rate. In other words, it is assumed that all taxes, levies and standing charges remain constant and changes in price are due to commodity fluctuations only, as suggested in [12].

High efficient CHP units are also entitled to subsidies in accordance with the EU legislation [1,2], which introduced a standard methodology to calculate the primary energy saving, as follows:

$$PES = 1 - \frac{Q_{cc}}{\frac{P_e}{\eta_{el,ref}} + \frac{Q_{user}}{\eta_{t,ref}}} \tag{30}$$

where $\eta_{el,ref}$ and $\eta_{t,ref}$ are the reference electric and thermal efficiencies, assumed to be equal to 0.522 and 0.90 respectively

[12]. PES is used in the present work to assess the eligibility of the CHP plant to access the support scheme, in accordance with the Italian legislation (PES > 0 for P_{nom}<1 MW, PES >10% for greater sizes).

3. Results and discussion

In this section, a techno-economic assessment of the CHP system is outlined with the aim of identifying optimal system sizes (i.e., net power installed) based on different performance metrics. Therefore, a sensitivity analysis of various system technical parameters - i.e., pressure ratio and nominal power installed, which are the main parameters influencing the overall CHP system cost [12, 13] – was carried out. Then, the influence of different market scenarios and investment policies parameters on the CHP economic performance was investigated.

The main outcomes obtained from the technical and economic optimisations are reported in the following section 3.1 and 3.2 respectively. Section 3.3 presents the results obtained by extending the analyses to further Italian locations to highlight the influence of the climatic conditions on the techno-economic performance of the CHP system.

3.1 Technical analysis

The technical assessment focuses on the primary energy savings (PES) achieved by the CHP system, since PES it is a direct measure of the overall efficiency of the system and is the main parameter in evaluating subsidy eligibility. Figure 6 shows the trend of PES values obtained for different pressure ratios as a function of the net power installed. First, it can be noted that PES shows a general negative trend as a function of the system size. This trend is easily explained by the fact that PES is strictly related with the CHP thermal heat utilised by the building: greater CHP sizes lead to greater amounts of thermal energy dumped (such scenarios are considered to be oversized systems), which results in poorer overall system efficiencies. In fact, these systems are particularly suitable for applications with constant yearly heat demand since they allow a better exploitation of the heat generated.

On the other hand, buildings can present considerable seasonal variations of heating energy demand, with peaks in winter and low values in summer, which ultimately affects system performance. Moreover, since the amplitude of this seasonal variation depends on the climatic region considered, the design and optimisation of the CHP system is subject to this variation. It can be noted in Figure 6a that Trento, the coldest location considered in this work (HDD = 6846), is the only location able to achieve positive PES values (for low system size), resulting from the higher building thermal demand (Figure 2a) which allows for greatest utilisation of the turbine exhaust gases. Warmer regions, i.e., Milan, Rome and Palermo (HDD = 3097, 2160, 1310, respectively), show negative PES values (Figure 6b,c,d), making the CHP system ineligible for potential subsidies. Moreover, it can also be observed in Figure 6 that systems with higher pressure ratios show lower PES values for higher system sizes. This phenomenon is related to the gas-turbine thermodynamic cycle: the increase of the pressure ratio leads to a lower temperature of the exhaust gas at the turbine outlet, which affects the amount of available thermal energy.

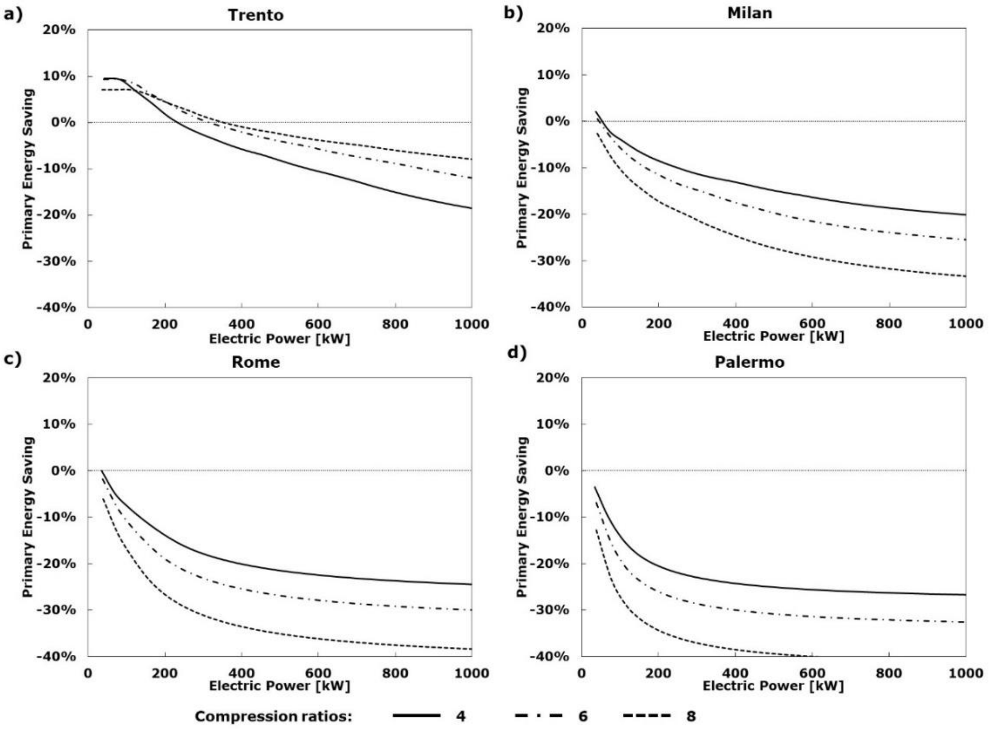

Figure 6: Primary energy savings for (a) Trento - HDD=6846, (b) Milan – HDD=3097 (c) Rome – HDD=2160 and (d) Palermo – HDD=1310.

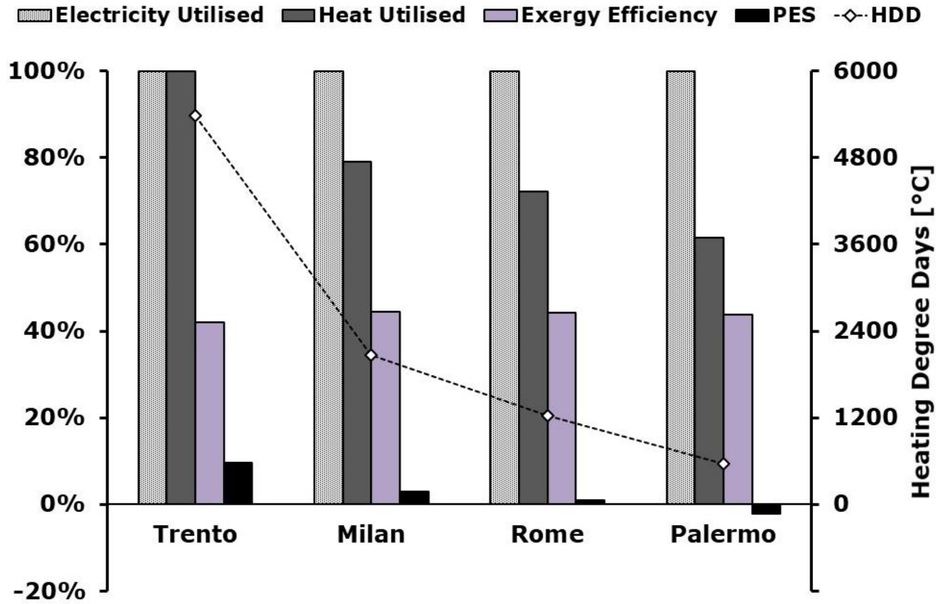

Figure 7: CHP power and thermal energy production utilised onsite, primary energy saving and exergy efficiency.

Figure 7 shows the percentage of both electricity and heat utilised by the building for the different locations analysed, in the case of a system sized for maximum PES. It can be observed that, while all the electrical energy produced is used to cover the building power demand (i.e., the system is undersized from an electrical point of view), the percentage of the utilised heat decreases depending on the climatic conditions of the location analysed (i.e., HDD). Therefore, PES values are strictly correlated with the amount of CHP thermal energy utilised by the building and it becomes negative for warmer climatic conditions (i.e., Palermo). Finally, it can be noted that the exergy efficiency is broadly similar (between 41.9% and 44.5%) for all locations considered.

3.2 Economic analysis

For each location, an economic assessment was carried out to determine the most suitable system size to maximise/minimise the economic indicators discussed in section 2.2.2.

Figure 8a presents the capital cost per unit of electrical power output of the CHP system, for each of the three compression ratios. Since the investment cost is directly correlated with the thermodynamic parameters, an increment of the compression ratio leads to higher investments due to the more expensive equipment required to handle these greater pressures. Furthermore, since higher average ambient temperature affects the performances of the compressor and the turbine (according to the maps shown in Figure 4) slightly greater investment costs are evident for warmer locations. Similarly, Figure 8b shows the LCOE values as function of the location and the compression ratio. As the LCOE is directly related to the capital cost of the system, a similar trend is observed between Figure 8a and 8b: greater LCOE values occur for higher compression ratio and for warmer locations (higher investment costs).

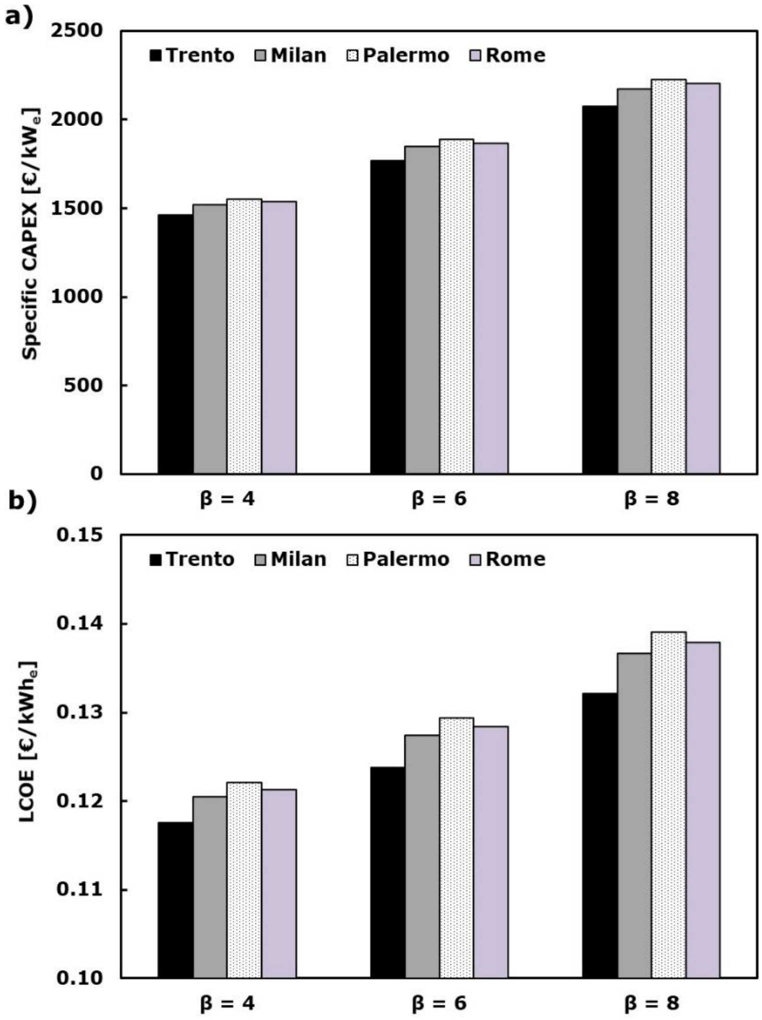

Figure 8: (a) CAPEX per nominal electric power installed and (b) LCOE values (medium price scenario) for different compression ratios and locations.

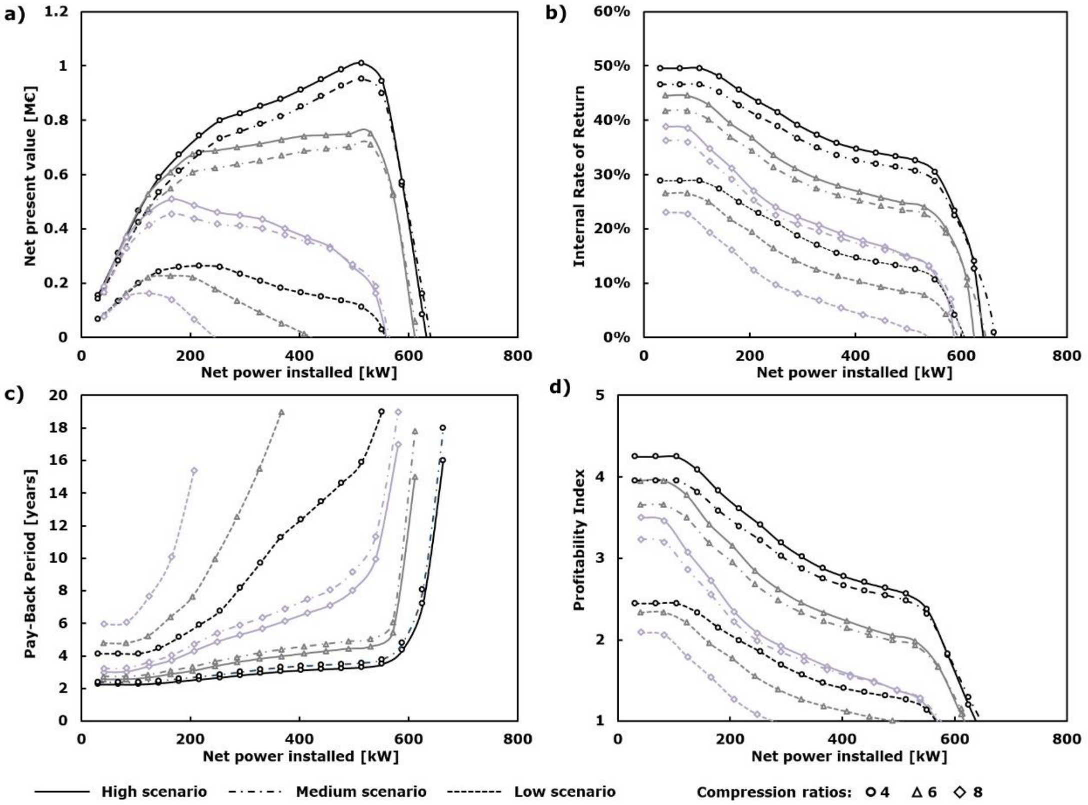

Figure 9: Economic indexes for different compression ratios and market price scenarios. (a) Net present value, (b) Internal rate of return, (c) Pay-back period and (d) Profitability Index. Locality: Trento.

An economic analysis, based on a 20-year assessment period, was carried out by considering the investment performance of the CHP system. Figure 9 shows the trend of the economic indexes for different compression ratios and market scenarios for Trento. It can be noted that lower compression ratios lead to better economic performances of all indexes, attributable to the better exploitation of the produced CHP thermal power. In particular, NPV profiles (Figure 9a) show maximum values of €952k, €711k and €455k for compression ratios equal to 4, 6 and 8, respectively (medium price scenarios). It is also possible to note that the correspondent optimal system sizes tend to decrease consistently when higher values of the compression ratio are used (i.e., $\beta=8$).

Generally, increasing the CHP size means greater electricity and thermal energy production. Notwithstanding, whereas electricity may be sold into the market, the seasonal load of the building limits the total amount of thermal energy exploitable, forcing the system to dump any overproduction. Thus, the cost saving associated with the thermal consumption reaches an asymptote, which depends on the specific building thermal load profile and corresponds to the maximum of NPV. The result is the reduction of the economic performance of larger systems.

In addition, the increase of system size leads to poorer performance of the other indexes: both the IRR (Figure 9b) and the PI (Figure 9d) trends decrease with the increase of the net power installed, as well as the PBP (Figure 9c) which exhibits a minimum for small system sizes. This result can be explained considering that, while NPV tends to favour larger systems so as to maximise the total revenue, the other indexes are a measure of the risk associated with the investment (IRR and PBP, even if in different ways) and of its overall performance (PI). Therefore, these indexes perform more favourably for smaller system sizes (low investment costs), which reduces the overall financial exposure and maximises the investment performance (further theoretical implications about using these economic indexes as optimisation criteria can be found in [12]).

Finally, Figure 9 shows the influence of different price scenarios on the CHP economic performance. It can be noted that more demanding market conditions (high scenario) lead to higher NPV (Figure 9a), IRR (Figure 9b) and PI (Figure 9d) and to lower PBP (Figure 9c) values for all compression ratios considered. Therefore, CHP systems are resilient to an increase of gas market price, as already demonstrated in [12]. Furthermore, since the fuel input (NG) is converted in both electrical and thermal energy reducing the energy wasted (i.e., higher efficiencies than conventional systems), the value of the energy harvesting is much higher with higher energy prices, leading to greater profitability of the investment.

Next, the influence of different climatic conditions on the economic performance of the CHP system are presented. Considering the NPV trends (Figure 10a), maximum values of the system size (i.e., electric power installed) can be detected. In particular, Trento shows the greatest system size (520 kWe approx.) which guarantees a NPV of about €950k over the 20 year period considered. For this system, almost all the electricity and a large proportion of the thermal demands are met by the CHP (as shown later in Figure 11).

Considering the other locations, the range of system sizes that are economically viable are reduced consistently: a reduction of optimum sizes and eventual NPV values occur with a clear negative trend from colder to warmer regions. Similar conclusions can be obtained by observing the trends of IRR (Figure 10b), PBP (Figure 10c) and PI (Figure 10d).

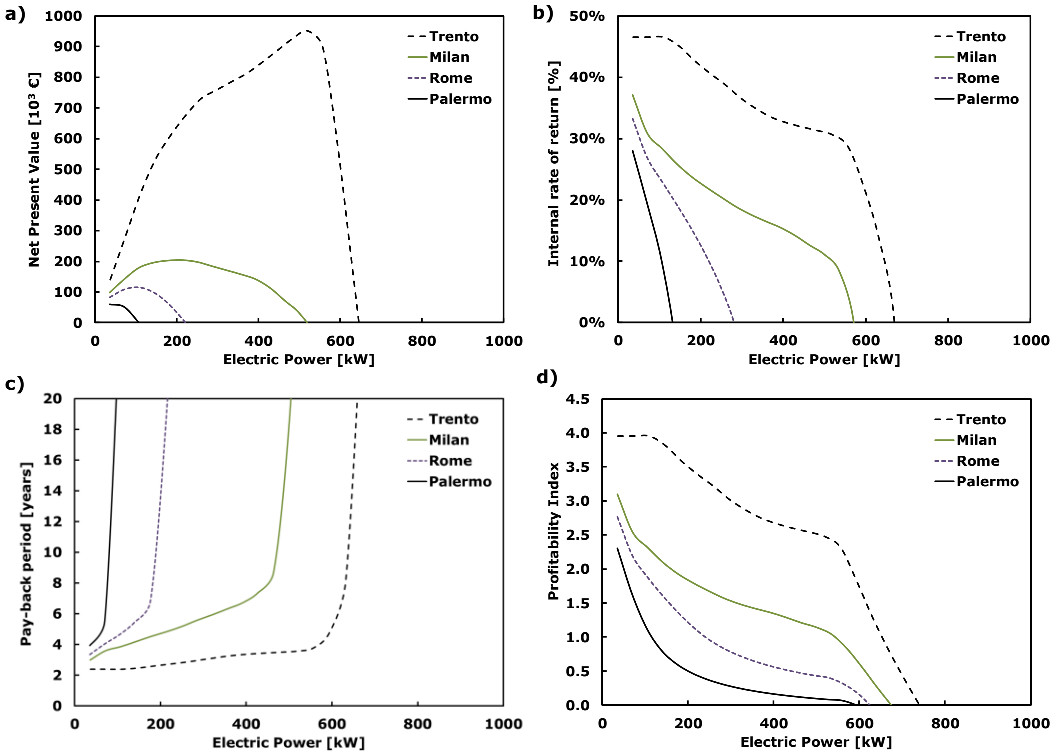

Figure 10: Economic indicator trends for each location: (a) Net present value, (b) Internal rate of return, (c) Pay-back period and (d) Profitability Index. β=4, TIT=900°C. Medium price scenario.

Generally, CHP systems installed in cold regions (i.e., Trento) have better economic performances than those installed in warm regions (i.e., Rome, Palermo) due to the higher building thermal demand. Greater system sizes lead to higher electrical and thermal energy production at the price of higher CAPEX and associated gas consumption. Even if excess electricity produced is sold to the market, with a consequent cash flow, much of the thermal energy will be wasted, providing no further cost savings. Thus, the increment of the revenue from exporting the additional electricity produced does not justify the increased capital and marginal costs, if no use of thermal energy can be detected.

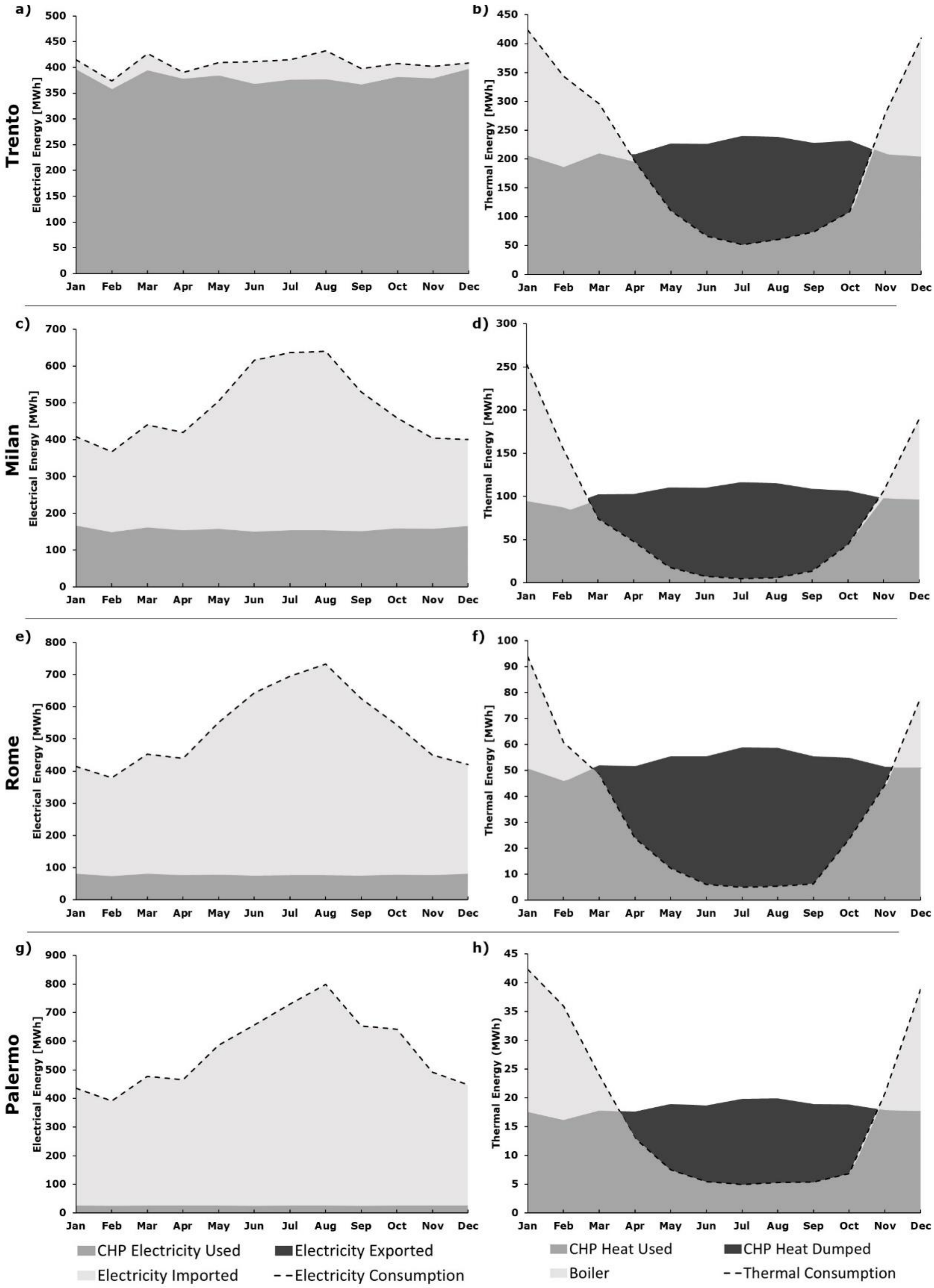

Figure 11: Monthly electricity (left) and thermal (right) energy profiles for Trento, Milan, Rome and Palermo. Systems sized by NPV maximisation. Note: y-axis ranges vary depending on location.

The importance of user loads is shown in Figure 11 where the building and CHP monthly electricity and thermal profiles are plotted. Since the CHP system is sized assuming the NPV as the optimisation criterion, the cold region (Trento) presents the highest net power installed which, in turn, leads to greater electricity production (Figure 11a), covering almost all the building demand (no electricity is sold into the market at a monthly level). On the other hand, since the CHP thermal energy available is almost constant through the year (the fluctuations shown are related to the external temperature variations which affect the turbine-compressor efficiencies), integration is required during the cold season, while part of thermal energy produced is dumped in the warm season (Figure 11b). Notwithstanding, the CHP can provide almost 70% of the yearly thermal demand of the building.

Considering the warmer locations (Figure 11c,d,e,f,g,h), a reduction in size and, consequently, in electrical and thermal energy production, occurs. Despite the size reduction, almost all thermal heat produced is not utilised during the summer period, reducing the value of the energy harvesting and, in turn, the overall profit associated with the system.

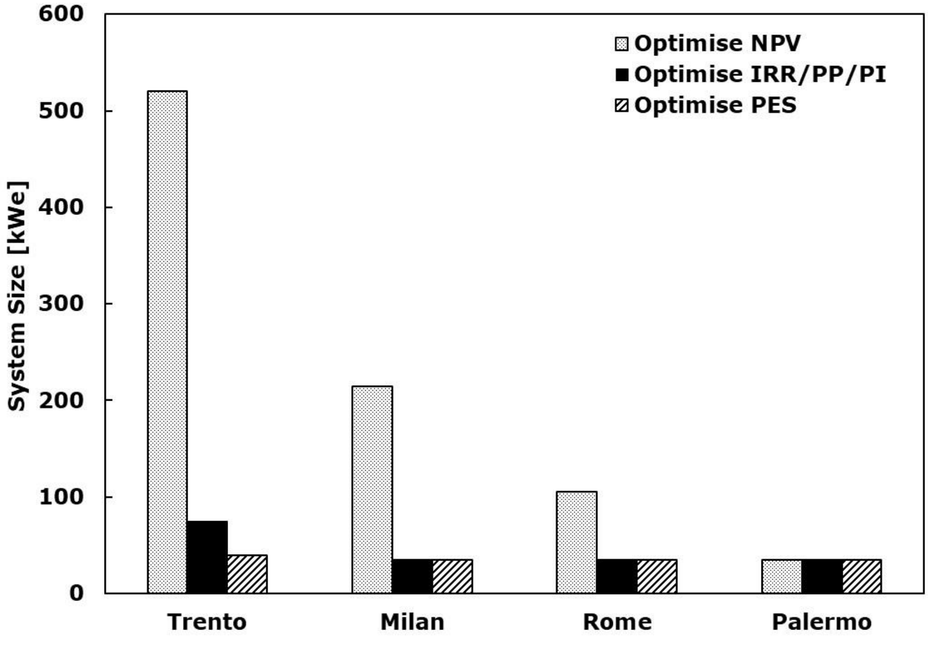

Figure 12: Selected system sizes for different optimisation criteria. β=4, TIT=900°C. Medium price scenario.

Figure 12 shows the comparison between the optimum system sizes obtained from the optimisation of each index for each location assuming a medium market price scenario. Since optimisation of IRR, PBP and PI all lead to similar system sizes, the results have been grouped together for the sake of clarity. As described before, maximising the NPV leads to the greatest CHP net power installed for all locations, with a decreasing trend from cold to warm localities. On the other hand, the optimisation of the other economic indexes tends to favour smaller sizes for all considered locations, in particular for the warmer regions where the minimum required system size is evident.

3.3 Extended analysis

The analysis has been extended to further Italian locations in order to understand better the influence of the weather conditions on the techno-economic performance of the CHP system. Similar to the prior analysis, the yearly thermal and electric demand profiles of the building was determined using EnergyPlus for each additional location. Then, the CHP system was optimised with respect to each parameter (PES, NPV, IRR, PBP and PI) for three different values of pressure ratio and using the medium price scenario as reference.

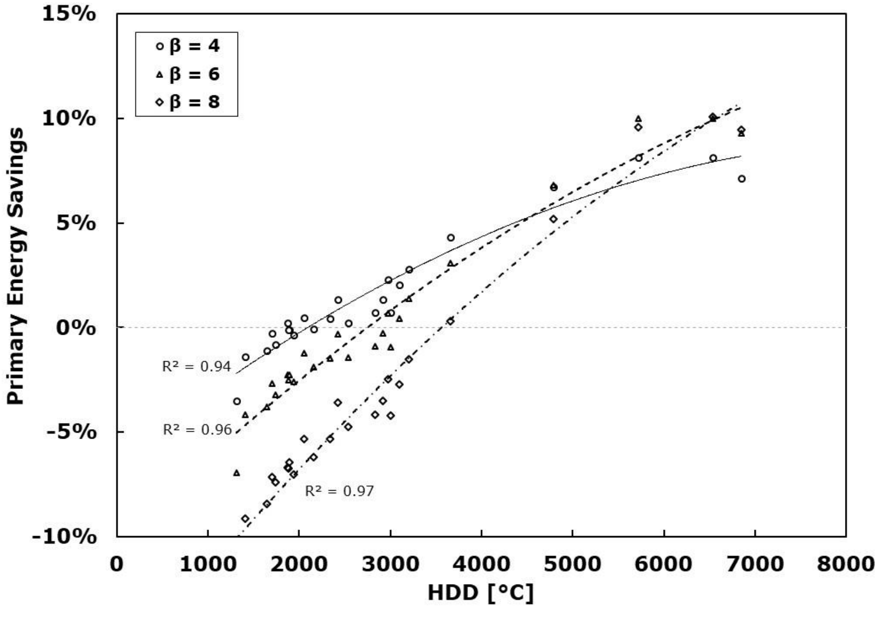

Figure 13: Primary Energy Savings (PES) as function of HDDs (System sized to maximise PES).

The obtained results were analysed and compared using HDD values as an index of climatic conditions. It is possible to observe in Figure 13 that a strong correlation exists between PES and HDDs. Since the building thermal demand can be directly correlated with the HDDs [28, 30], this trend confirms the direct correlation between PES and the building thermal demand. Generally, higher values of HDDs allow greater CHP optimal sizes, which in turn leads to a better usage of the thermal energy produced. Moreover, better performances can be obtained for lower pressure ratios: the PES becomes negative at HDD values of about 1900, 2900 and 3700 for pressure ratios of 4, 6, and 8, respectively.

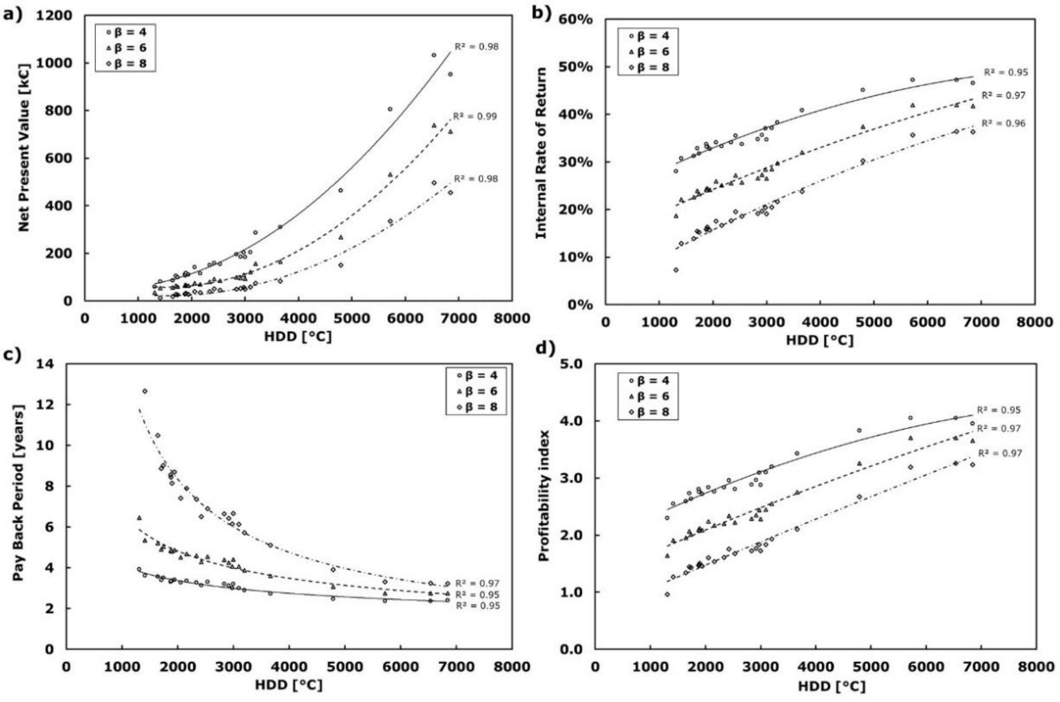

Figure 14 (a) NPV, (b) IRR, (c) PBP and (d) PI metrics as function of HDDs. (System sized to maximise the corresponding economic index)

Similar results were found for the analysis of the trends of the economic indices (Figure 14). Strong correlations ($R^2 > 0.96$) can be detected for all analysed economic indexes and pressure ratios. NPV trends (Figure 14a) show positive slopes against HDDs, while higher pressure ratios tend to be less profitable (due to the higher investment costs). Similar considerations can be done by observing IRR and PI values (Figure 14b,d). Finally, PBP profiles (Figure 5c) show negative trends against HDDs, with minimum values in the coldest regions of 2.4, 2.8 and 3.2 for pressure ratios of 4,6 and 8, respectively.

Therefore, the economic profitability of a CHP system can be directly correlated with the weather conditions of the location of the CHP system. Specifically, the building requirements, in terms of thermal energy, play a more important role than electricity demand during the design and optimisation stages, as demonstrated by the better profitability in colder regions.

4. Conclusions

The present paper investigated the techno-economic performance of a gas-turbine CHP unit for a large commercial building for different market price scenarios and a wide range of climatic conditions. A comprehensive analysis of the CHP system was carried out to identify optimal sizing depending on different profitability indicators (namely, PES, NPV, IRR, PBP and PI).

A key conclusion is that the intrinsic seasonal variation of the thermal energy demand of a commercial building block strongly affects the CHP technical performance. The PES index showed a general negative trend as a function of the system size, since a greater installed power leads to greater amounts of thermal energy wasted during the shoulder and summer seasons, which results in a poorer overall system efficiency. Since subsidy eligibility is directly linked to positive PES values, the analysis of the building thermal demand and the optimisation of CHP heat usage are paramount if access to such subsidies is sought. The present work provides some insight on how to perform this analysis and a guideline for researchers and engineers to achieving positive CHP thermal performances depending on building thermal demands, market context, investment policies and climatic conditions.

The investment (CAPEX) associated with the CHP installation is higher for greater system sizes and for higher pressure ratios, due to the increased complexity of the configuration. Values between €1500/kWe and €2200/kWe were found and depend on the site HDD value. The evaluation of the main economic indexes showed that different optimum configurations are evident depending on the performance indicator chosen.

NPV-optimisation leads to greater CHP sizes since it tends to maximise the amount of electricity generated whilst limiting the amount of thermal energy dumped. Optimum configurations were found based on HDD value and market scenarios, since a sharp deterioration of the investment is detected when a certain value of installed electrical power is reached, due to the oversupply of dumped heat (i.e., higher marginal cost but limited associated revenue).

NPV optimisation leads to the greatest CHP net power installed for all locations, with a decreasing trend from cold to warm localities. Similar results were obtained by optimising the CHP based on IRR, PBP and PI. Since they tend to reduce the capital exposure and the risks associated with the investment, by recouping capital costs as quickly as possible, small system sizes are preferred.

Generally, covering several techno-economic and market scenarios is paramount to get a more comprehensive perspective on a specific investment. Notwithstanding, the results highlighted that no univocal answers can be found, and the choice of the most suitable system will eventually arise from the investment policy adopted.

Moreover, the analysis confirmed that CHPs are resilient to increases in market prices, since better economic performance was obtained with more demanding market price scenarios.

Extending the investigation to further Italian locations, strong correlations ($R^2 > 0.96$) between the performance indexes and the weather conditions at the location, measured using the HDDs, were found. Therefore, HDDs, which are strongly correlated to the thermal demand of a building, can be used as a driving parameter to provide an indication as to the economic profitability of a CHP system for specific buildings.

It is important to state that the tool presented in this paper is intended for preliminary decision-making assessments. Fast key decisions can be analysed using this tool from the integrated analysis of the CHP system and building in the context of the various market and investment scenarios that designers may consider, when evaluating preliminary design options. Therefore, the methodology, results and conclusions outlined in the present paper represent a powerful guideline to carry out preliminary techno-economic assessments of CHP systems in commercial buildings considering different climatic conditions, investment policies and market scenarios.

Acknowledgments

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