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A simplified approach for energy system design in buildings and its application to a case study

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Abstract. The present study proposes an easy-to-use procedure for the preliminary design of energy systems for existing buildings based on easily available consumption data. The approach is then applied to a case study represented by the Rector's headquarter of the University of Cagliari. With the aim of analysing a complex case, the building has been chosen among those with unknown thermal and electrical load subdivision. The feasibility study and subsequent preliminary sizing of a Combined Heat and Power (CHP) system serving the building started through seasonal comparison of electricity consumption data, which also allowed for the subdivision of the building's electrical and thermal loads and the definition of the electrical base load. The design of the cogeneration system was conducted through the analysis of the electric and thermal demand of the building with quarter-hour resolution, compared among different seasons. The application of the model to the case study allowed for a preliminary design and techno-economic feasibility assessment of implementing a Combined Cooling, Heating and Power (CCHP) system. Besides highlighting the valuable insights that can be obtained through observation and analysis of energy power curves, this paper presents energy indicators that can be utilized to populate benchmarks' databases for comparable buildings.

1. Introduction

Buildings are a significant contributor to both worldwide energy use and greenhouse gas emissions: in fact, in 2021 they accounted for approximately one-third of the world's energy consumption and 27% of the total energy sector emissions, reaching a value of 40% in Europe, which corresponds to 36% of CO_2 emissions [1–3]. In addition, between 2021 and 2030, there is a projected 20% increase in global floor area in the buildings sector together with a strong growth in service demand [3]. Minimum performance standards are progressively growing, coinciding with the escalation of the employment of energy-efficient and renewable technologies, while the power industry is undergoing decarbonization. According to [4], the Net Zero carbon Scenario requires a 24% reduction in buildings' energy consumption by 2030, which can only be achieved by improving their energy efficiency at a rate of 5% per year from 2020 to 2030, a significant increase from the previous decade. Implementing renewable energy sources, electric and thermal storage devices, integrated control systems and electric vehicle chargers in buildings are the most significant steps towards achieving these targets: the International Energy Agency estimates that renewable energy in buildings could provide up to 30% of the world's energy needs and reduce CO_2 emissions by up to 1.7 gigatons per year by 2030 [5].

Despite the growing interest in renewable energy solutions for buildings, their design is often rough and leading towards costly mistakes and lost opportunities for energy savings and GHG reductions. Avoiding a proper phase of planning and analysis can lead to a lack of understanding of the building's energy needs and usage patterns, resulting in systems that are either oversized and underutilized or undersized and unable to meet demand. On the other hand, to the authors' knowledge, scientific research in the field of energy system design for buildings is currently oriented towards either increasingly precise methods for the design of integrated energy systems [6] or towards optimization methods for building energy modeling and simulation (BEMS)[7–9], including mixed-integer programming and metaheuristic methods. It is well known that conducting such detailed designs during the preliminary stages of a project may not always be economically feasible, particularly for professionals or small and medium-sized enterprises. To reconcile the divergent perspectives discussed, the present investigation proffers a straightforward methodology for conducting the preliminary design of energy systems for extant structures, leveraging readily accessible consumption data. The proposed methodology allows for rapid quantification of thermal and electrical consumption, as well as determination of seasonal hourly energy flows, without the need for a detailed building modeling. As a result, it becomes possible to consider in preliminary phases even CHP and CCHP systems as alternatives to Photovoltaic (PV) systems, which are the most widely implemented technology in the building sector.

To exploit the potential of the proposed model, the possibility of implementing a CCHP system to a specific case study, namely the Rectorate at the University of Cagliari, was studied. Apart from the specific case where the constraints of the historical district forbid the installation of a photovoltaic system, cogeneration have several worthwhile advantages compared to PV: 1) PV systems are highly dependent on sunlight and weather conditions, making them less reliable and consistent than CHP systems, which can operate continuously and independently of external factors; 2) PV systems require large amounts of space to generate significant amounts of electricity, while CHP systems require smaller spaces and produce both heat and electricity; 3) if not provided with Electrical Energy Storage (EES) systems, PV do not either guarantee power during night, in the event of a grid outage nor improve the overall reliability of the electricity supply [10]. 4) PV systems require significant amounts of materials and minerals, such as silicon, which can be environmentally damaging to extract and process, while CHP systems typically use more common materials and have a lower environmental impact [11] 5) PV systems installation in historical buildings or relevant areas, require authorizations that are often difficult to obtain; 6) Albeit cogenerators are mainly fossil-fueled, with a not negligible environmental impact, “H_2 ready” cogenerators (powered up to 20-25% hydrogen) are already on the market.

Given that cogeneration can reduce energy costs in office buildings by up to 50% and decrease greenhouse gas emissions by up to 40% [12], several directives have been issued by the EU on the promotion of cogeneration in the last 20 years. Italy adopted these lines through the “High-Efficiency Cogeneration” (whose Italian acronym is CAR) qualification of certain cogeneration systems which guarantees priority access to the grid, tax breaks and access to the White Certificates market (energy efficiency certificates). The latter is an Italian policy instrument aimed at promoting energy efficiency: many companies are "obligated" by law to achieve energy savings targets and they can meet their obligations by purchasing White Certificates from energy efficiency projects.

2. System modelling

The methodology herein illustrated, proposed as a fast preliminary design approach for energy systems, is based on the minimal data set reported in Table 1.

Table 1. Minimal data set.

Parameter	Description	Notes

E	Electricity demand of the building	with the highest time res.[1]
$COP_{O,AC}$	Coefficient Of Performance for offices Air Conditioning	
$EER_{O,AC}$	Energy Efficiency Ratio for offices Air Conditioning	
$EER_{DC,CS}$	Energy Efficiency Ratio for Data Center Cooling System	
$\dot{E}_{DC,R}$	Nominal power of the Data Center IT equipment	Not essential
T_{amb}	Ambient temperature evolution	Not essential

To design an energy system, it is first essential to determine the building's heating, cooling, and electricity demand, making this way possible to assess the potential of CHP, heat recovery (HR) and integrated uses of Thermal Energy Storage (TES) systems. For buildings where heat is provided by a boiler, thermal meters or, at least, fuel flow meters are sufficient for calculate thermal demand. Differently, the cooling and heating demands for buildings where thermal demand is fulfilled with heat pumps, can be evaluated through a seasonal analysis of electricity consumption. In fact, the share of the electricity needed to meet thermal demand, for each hour of the mean seasonal working day, can be evaluated as the difference between maximum or mean hourly electric power during winter or summer and maximum or mean hourly electric power during middle season, when thermal demand is zero. The most precautionary approach to evaluate the electric power for air conditioning is to calculate it as the difference between maximum hourly electric power during winter or summer and mean hourly electric power during middle season, but this can lead to oversize the thermal demand. For this reason, considering that the proposed methodology is proposed for a preliminary phase, the authors suggest using mean hourly values, as following:

$$\dot{E}_{O,AC,S} = \dot{E}_S - \dot{E}_{MS} \quad (1)$$

$$\dot{E}_{O,AC,W} = \dot{E}_W - \dot{E}_{MS} \quad (2)$$

where $\dot{E}_{O,AC,S}$ and $\dot{E}_{O,AC,W}$ are the mean hourly electric power for air conditioning systems during summer and winter, while $\dot{E}_S$, $\dot{E}_W$ and $\dot{E}_{MS}$ are the mean total hourly electric powers during summer, winter, and middle season. Saturdays, Sundays, and holidays should not be considered, to avoid too low, not representative, average values. It can however happen that real starting and ending dates of thermal seasons could differ from the "conventional" ones, and therefore seasonal-based data separation could be difficult. A bar-chart of the peak electric power of the entire period can be useful to define these dates correctly.

Starting from $\dot{E}_{O,AC,S}$ and $\dot{E}_{O,AC,W}$ it is possible to calculate the building thermal load during winter ($\dot{Q}_{O,AC,W}$) and summer ($\dot{Q}_{O,AC,S}$) through the mean hourly COP and EER values of the installed equipment. If hourly values of air temperature and nominal power of air conditioning equipment are available, COP and EER values can be calculated with a low level of approximation as a function of these parameters as described by the UNI EN 14511 standard. The study of the mean hourly power curves also allows to identify the presence of a building base load and to quantify it. This load, that is consumed 24-hour and it is usually the one firstly studied for energy efficiency reasons, can be reasonably assumed equal to the nighttime-hours power consumption.

Buildings in the tertiary sector often include data centers. In this case, the base load can be furthermore split into IT devices consumption and cooling system consumption. Given the nominal power of the data center cooling system, the hourly correlations between ambient temperature and data center power consumption can lead to define the temperature-dependent increase of the base load. The nighttime hours of the base load, as well as holidays or Sundays, are particularly suitable for this analysis

[1] Usually, electricity suppliers or local distributors provide to their customers electricity demand curves with a resolution of fifteen minutes.

since they are not affected by other factors that may influence the power consumption (the data center power load due to IT devices is constant during off-work hours). The correlation formula is reported below:

$$Correl(T_{amb}, \dot{E}) = \frac{\Sigma(T_{amb} - \overline{T_{amb}})(\dot{E} - \bar{\dot{E}})}{\sqrt{\Sigma(T_{amb} - \overline{T_{amb}})^2 (\dot{E} - \bar{\dot{E}})^2}} \tag{3}$$

correlations between ambient temperature and consumption well apply to data centers, even for such short time resolutions, because, unlike the areas of buildings for human permanence, their high ventilation flow rates greatly attenuate the effects of building inertia, temperature phase shift and attenuation. Through the latter correlation it is possible to define a regression curve that describes the trend of the data center cooling load as a function of the outdoor temperature: the temperature-dependent load variation is entirely due to the cooling system. This curve can be used to estimate the data center cooling load trend even during daylight hours, when the cooling system consumption variations may otherwise appear to be due to other activities.

The choice of the energy system heavily depends on existing spatial and environmental constraints. The most comprehensive case of producing both electric and thermal energy will be discussed in the following, detailing the well-established preliminary procedure for designing a CHP system.

To assess the feasibility of installing a cogeneration system, it is convenient to utilize technical data from devices already on the market. Manufacturers typically provide information on net electrical power output ($\dot{E}_{CHP}$), net heat output ($\dot{H}_{CHP}$) power of the fuel consumption ($\dot{F}_{CHP}$), electrical ($\eta_{E,CHP}$) and thermal ($\eta_{H,CHP}$) efficiencies, based on load and for different values of supply and return temperatures. Usually, data are provided and partial loads.

For the preliminary sizing of the system herein considered, the heat produced by the CHP system can be considered as directly used for heating, even if in a realistic plant configuration heat exchanger losses and circulators consumptions should not be neglected.

When sizing a CHP system and choosing its operational strategy, two different approaches can be chosen: the first one is to prioritize the electricity demand ($\dot{E}_D$), fulfilling it even if it causes heat waste ($\dot{H}_{LOSS}$), the other one is to prioritize the thermal demand ($\dot{H}_D$), with electrical production being considered secondary. The second approach is the one which maximizes the CHP efficiency indexes but, during periods of excess electricity production, electricity is feed-in the grid ($\dot{E}_{GRID}$):

Approach 1: $$\dot{E}_{CHP} = \dot{E}_D;\ \dot{H}_{CHP} = \dot{H}_D + \dot{H}_{LOSS} \tag{4}$$

Approach 2: $$H_{CHP} = \dot{H}_D;\ \dot{E}_{CHP} = \dot{E} + \dot{E}_{GRID} \tag{5}$$

The second approach is economically better if the building's electricity demand on thermal demand ratio is constant across the day, thus avoiding the feed-in. Otherwise, it can be convenient to install a parallel of smaller cogenerators, to ensuring that the system operates for most of time at an optimal load level, resulting in higher energy savings and reduced environmental impact.

In the tertiary sector, buildings typically require heating during winter and cooling during summer. A basic cogeneration system can supply both electricity and heat, but it can be provided with an absorption heat pump to become a trigeneration system, allowing for extended operation during summer months and/or meeting the cooling demands of data centers during each season. Commercial hot-water-fired absorption chiller solutions are characterized by conversion efficiencies related to the incoming heat approximately of 60-70% [13].

To evaluate if the CHP system can be defined as High-Efficiency Cogeneration, with reference to Italy, the in-law equations and minimal requirements are provided below. To be eligible for tax breaks and White Certificates [14], cogeneration systems must meet a minimum overall efficiency $\eta_{GL,CAR}$, defined as the ratio of the energy output (electricity and heat) to the energy input (fuel). The overall efficiency, calculated with reference to an entire year, must be higher than 75-80% depending on several factors.

$$\eta_{GL,CAR} = \frac{E_{CHP|year} + H_{CHP|year}}{F_{CHP|year}} \quad (6)$$

Moreover, to access the White Certificates scheme, cogeneration systems up to 1 MWe must have a positive PES (Primary Energy Saving) index. PES is a measure of the primary energy savings achieved by a project, expressed as a percentage of the primary energy consumption of a reference scenario. The PES calculation has to be performed using a standardized methodology, known as the Technical Regulation for Energy Efficiency (RTIEE), which was established by the Italian Ministry of Economic Development, with reference thermal ($\eta_{H,REF,PES}$) and electric ($\eta_{E,REF,PES}$) efficiencies of the separated production of heat and electricity regulated by [15]. The calculation of White Certificates in Italy is based on [16], and considers the average conventional efficiency of the Italian electricity ($\eta_{E,REF,WC}$) and heat ($\eta_{H,REF,WC}$) production systems. It's interesting to note that the reference efficiencies reported in the two abovementioned decree are different each other.

When evaluating the profitability of an investment in its early stages, it is widely acknowledged that one the most effective approach is to utilize yearly cash flow analysis. This technique involves identifying all relevant costs and revenues associated with the investment, and then calculating the net cash flow for each period:

$$CF = -C_C - C_{O\&M} - C_F - C_O + R_{El} + R_{INC} + S_E + S_H \quad (7)$$

that includes the capital cost (C_C), operation and maintenance costs ($C_{O\&M}$), the cost of fuel (C_F), other marginal costs (C_O) (i.e., insurance, property taxes, environmental compliance), revenues from electricity sales to the grid (R_{El}), incentives from programs such as white certificates (R_{INC}), the savings of purchasing electricity from the grid (S_E) and heat in the case of district heating (S_H).

The net cash flows are discounted to their present values using an appropriate interest rate, which enables the calculation of important economic indicators such as the Payback Period (PP), Net Present Value (NPV), etc. useful to evaluate and compare each other different solutions. If capital and O&M costs are unknown, IRENA offers a publicly available database on RES costs [17].

3. Case study

The University of Cagliari was established in the 17th century. Less than a century later, the Savoy chose to give it a new location considering Carlo Emanuele III's intent to reorganize the Sardinian universities. The Rectorate's structure design was therefore commissioned to engineer Belgrano, and construction ended in 1780. The building, which is known as Palazzo Belgrano, represents the case study of the present work. It has three floors above the ground level, and an attic, and its nowadays use is for offices. Specifications of the building geometry are reported in Table 2

Table 2. Specification of the Rectorate geometry

Gross area	10,500 m^2
Gross volume	48,000 m^3
S/V	0.22
Net area	7,000 m^2
Net air-conditioned area	2,000 m^2
Net air-conditioned volume	8,000 m^3

With reference to the building's technological systems, HVAC system is mainly represented by reversible heat pumps, while lighting system consists of neon lamps for the common spaces and LED lamps for offices. On the ground floor of the building is located one of the University's data centers, whose consumption share on total is not negligible, even more so it operates 24h. Residual electrical consumption of the building are represented by PCs, printers, and other office equipment.

The simplified breakdown of energy fluxes of the building is shown in Figure 1. The electrical power input to the building ($\dot{E}$) can be divided into the electrical power used by the offices ($\dot{E}_{O}$) and the data center ($\dot{E}_{DC}$). The electrical power used by the offices can be further divided into power used for air conditioning ($\dot{E}_{O,AC}$) and power used for other purposes (residual - $\dot{E}_{O,R}$). Similarly, the electrical power used by the data center ($\dot{E}_{DC}$) can be further divided into power used for its cooling system ($\dot{E}_{DC,CS}$) and power used for other purposes (residual - $\dot{E}_{DC,R}$). Since the HVAC system is powered by electricity, thermal powers ($\dot{Q}_{O,AC}$, $\dot{Q}_{DC,CS}$) can be calculated through the cooling and conditioning systems electrical powers ($\dot{E}_{O,AC}$, $\dot{E}_{DC,CS}$).

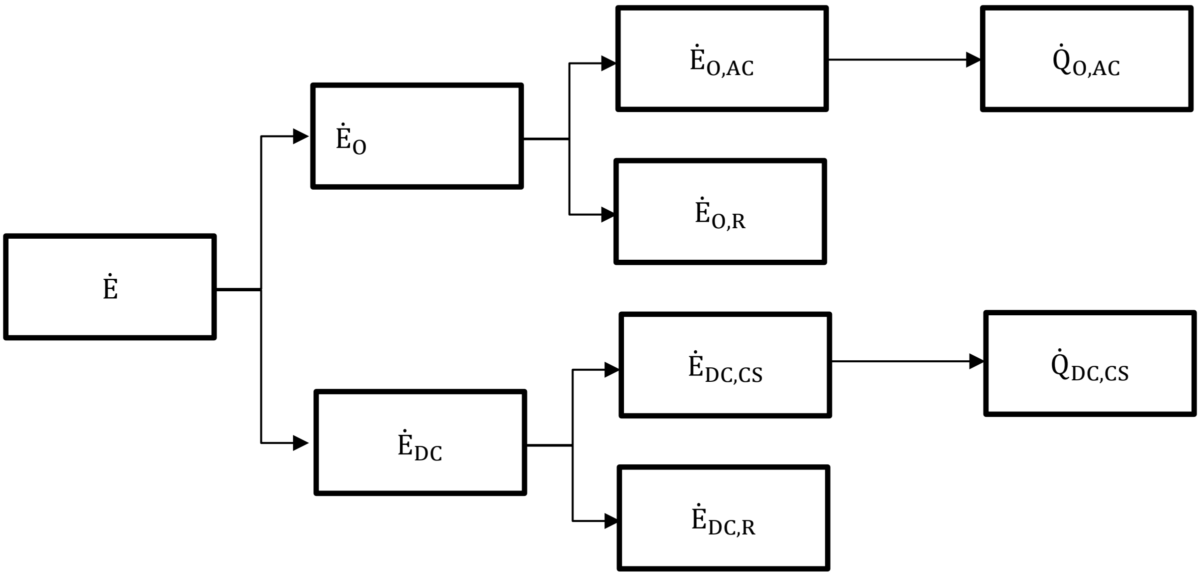

Figure 1. Simplified breakdown of energy fluxes of the Rectorate.

The Rectorate of the University of Cagliari is situated in the historic city center, where the installation of photovoltaic panels is not permitted due to conservation constraints for historic districts. Therefore, the discussion presented below considers the implementation of the proposed model for designing a CCHP system, which could be positioned under an existing canopy in the parking lot of the building. Currently, the necessary backup for the data center electricity supply is provided by a 2004 diesel generator that is nearing the end of its lifespan. Such a system, being independent of the electric grid, would enable the University to avoid the expense of acquiring a new diesel generator.

4. Results

This paragraph shows the results of the application of the proposed methodology to the case study represented by the Rectorate of the University of Cagliari. Consumption data are referred to August-December 2022 and the time resolution is 15 minutes.

A bar-chart of the peak electric power of the entire period considered, useful for properly identify the real starting and ending dates of thermal seasons and therefore to distinguish the seasonal consumptions of the building, is shown in Figure 2. With reference to the case study, as reported in Figure 2, cooling-demand season clearly ended on day 46 (September, 16 – identified by point (1)) while heating-demand season began on day 113 (November, 22 – identified by point (2)). Cooling, no HVAC and heating periods are therefore clearly defined.

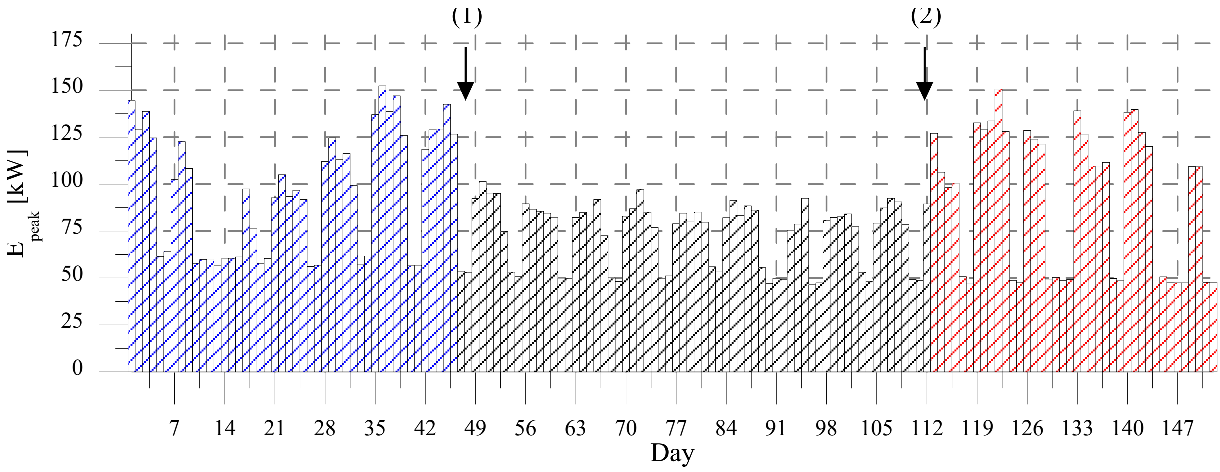

Figure 2. Peak electric power of the considered period.

Starting from the data classification abovementioned, Figure 3 represents the mean and maximum hourly electric power during thermal demand seasons (a) and no thermal demand season (b). Figure 3 demonstrates that heat and cooling demands of the building are very similar and that the building base load is clearly identified (around 50 kW, depending on season).

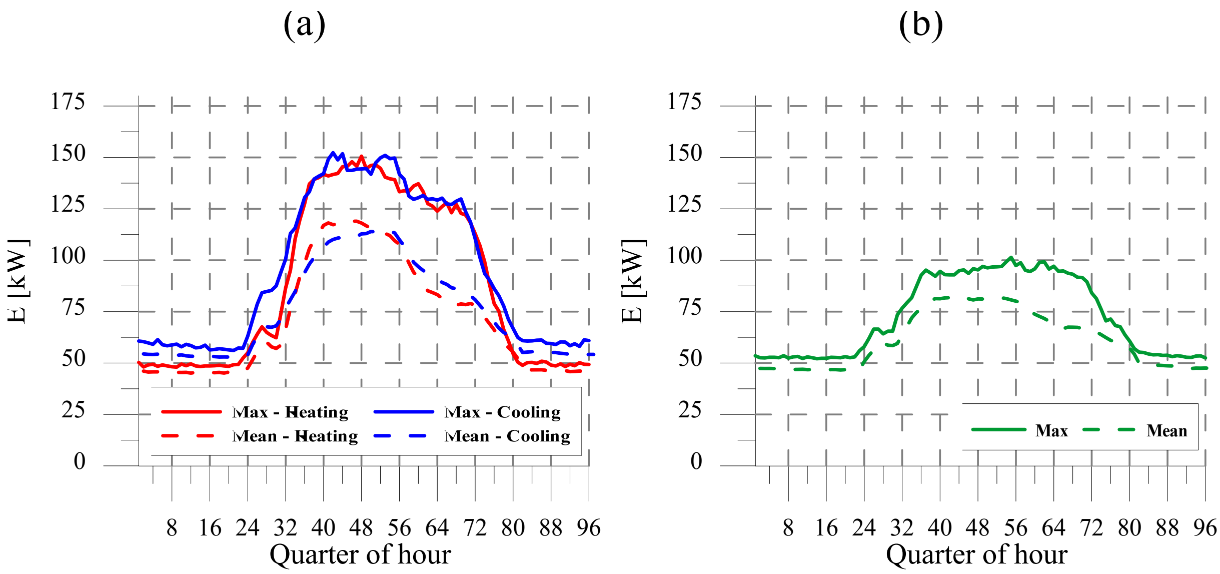

Figure 3. Mean and maximum hourly electric power during thermal demand seasons (a) and no thermal demand season (b).

Before going to the next step of the procedure (identify the share of electricity needed to meet thermal demands), it is necessary a preliminary focus on the building's base load and its potential correlations with ambient temperature. Given the range of the building base load, Figure 4(a) shows the correlation with ambient temperature. In particular, a strong correlation[2] was found during night hours (9 p.m. to 4 a.m.). The results of the correlation analysis and the subsequent definition of the regression curve can be observed in Figure 4(b), which shows the seasonal power consumption trends of the data center

[2] Correlation coefficient: 0.86 – number of data analyzed: 1.368.

throughout a day. It is evident that the temperature increase has a significant impact on power consumption, with a nearly 20% growth between winter and summer. Additionally, the graph highlights the influence of temperature during the central hours of the day, where power consumption increases by up to 10%.

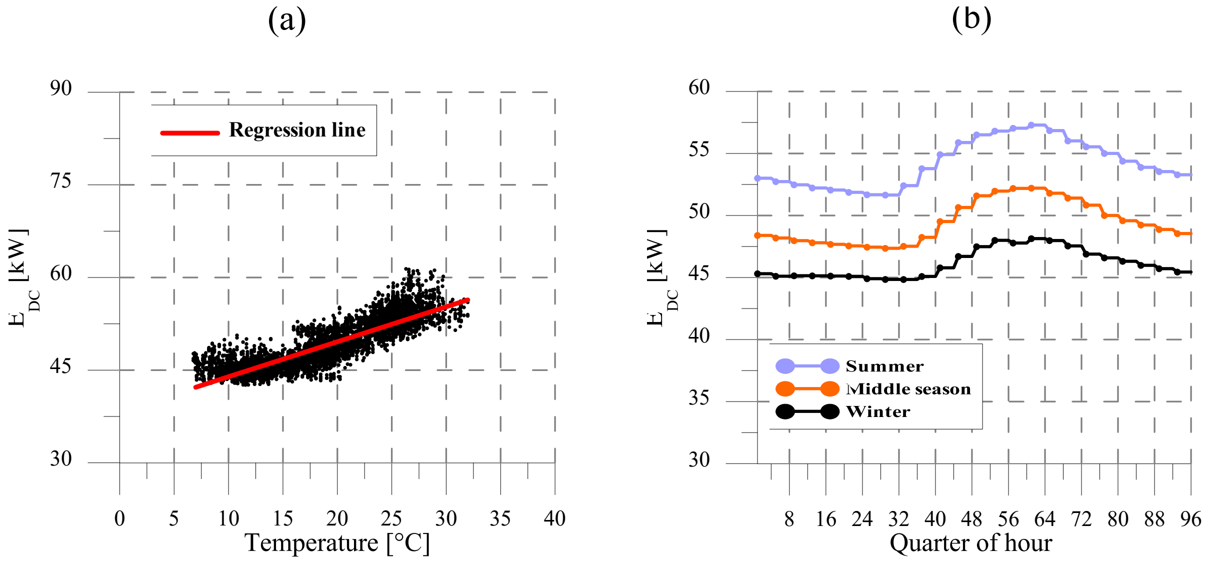

Figure 4. Correlation analysis results (a) and seasonal power consumption trends of the data center throughout an entire day (b)

Through the steps of the previously described procedure, it was possible to obtain Figure 5, which represents the mean hourly energy flows of Figure 1 during winter (a), summer (b) and middle season (c). During winter, the electrical power due to heating ($\dot{E}_{O,AC}$) starts averagely at 8 a.m., reaches its maximum around 12 p.m. and then gradually decreases down to zero at 8 p.m. It's interesting to notice that the electrical power used for other purposes in the offices ($\dot{E}_{O,R}$) starts at 6 a.m.: this is caused by the cleaning personnel of the building, that switch-on all the buildings lights. This way can be also deduced that the installed power for lightning in the building is around 12-18 kW. During summer, tendencies are similar, except for the maximum of the electrical power due to air conditioning ($\dot{E}_{O,AC}$), which is reached two hours later with respect to winter. During the middle season, $\dot{E}_{O,R}$ trend follows the occupancy levels of the building.

In addition to the specific objective of this research work, the application of the model to real data has also allowed the calculation of the main energy indicators for the building, such as electric power to gross area and thermal power to net AC volume, which are reported in Table 3 with the aim to increase the benchmark database for similar buildings.

Table 3. Energy indicators of the Rectorate

			Average value (working hours)			Maximum value		
			Winter	Summer	Middle season	Winter	Summer	Middle season
Electric power to gross area	$\frac{\dot{E}}{A_g}$	[W/m^2]	8.8	8.9	6.9	11.3	10.9	7.8
Offices thermal power to net AC volume.	$\frac{\dot{Q}_{O,AC,W}}{V_{AC,n}}$	[W/m^3]	8.6	5.9	-	15.9	10.3	-

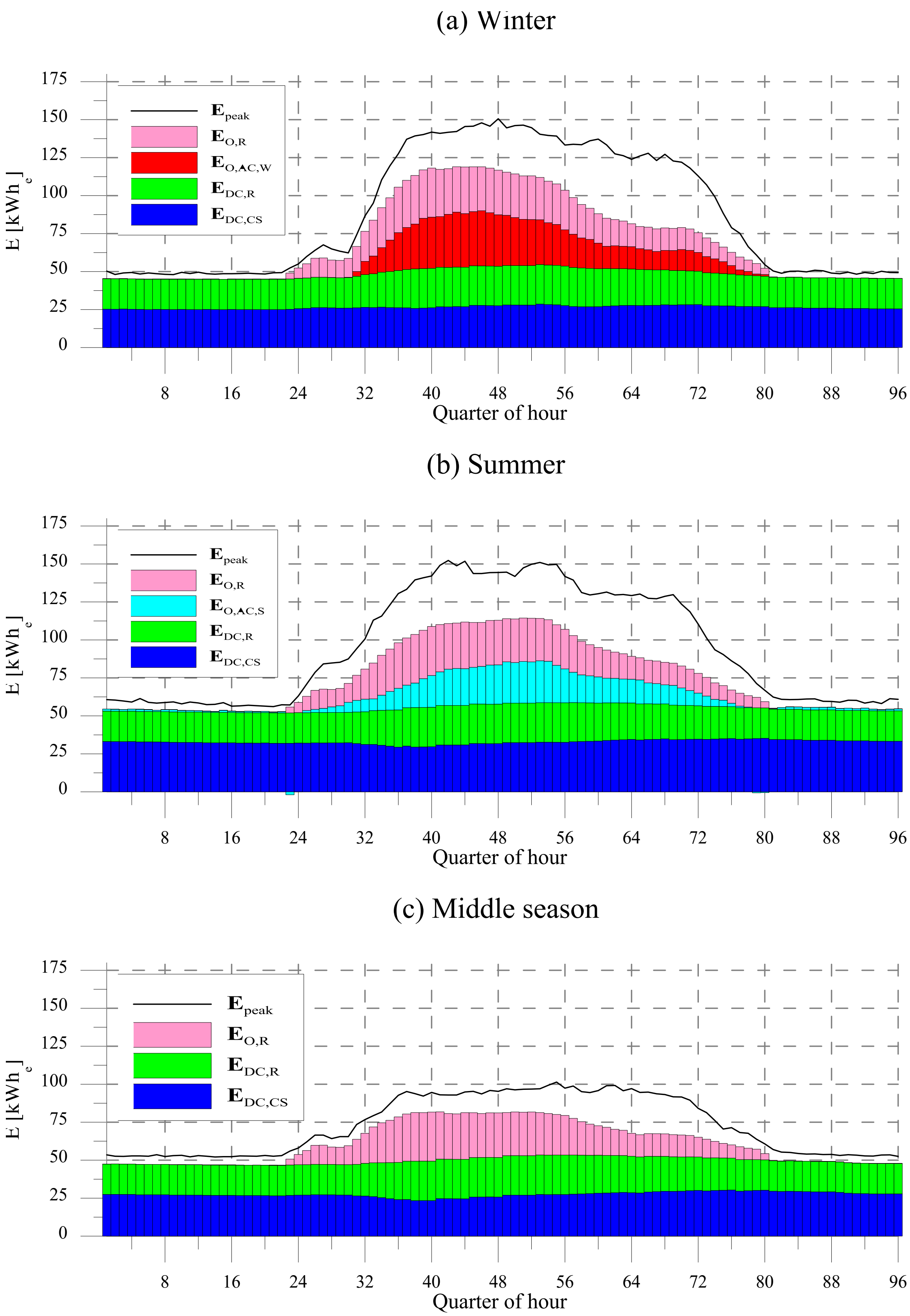

Figure 5. Mean and peak hourly energy fluxes

In the perspective of evaluating a cogeneration system, Figure 6 represents the simultaneous requests for office heating ($\dot{Q}_{O,AC,W}$) and electricity ($\dot{E}_{O,R}$+ $\dot{E}_{DC}$) of the Rectorate during an average winter day. In the present work, COP and EER have been assumed equal to the minimum values imposed by Italian legislation [18]. As it can be seen, the electricity demand varies from a base load of about 45 kW up to a maximum of about 80 kW during the central hours of the day while the heat request is null during the night hours and grows rapidly during the central hours of the day, passing from 0 up to 200 kW in less than 4 hours. The differences in base load and slopes of the two curves are not optimal for a 24-hour operation of a cogeneration plant. In fact, under the assumption of using the cogenerator for the entire day, the heat generated from it should be dissipated during the night. Additionally, since the $\dot{E}/\dot{Q}$ ratio greatly varies between morning and afternoon hours, the cogenerator would operate off-design for several hours of the day.

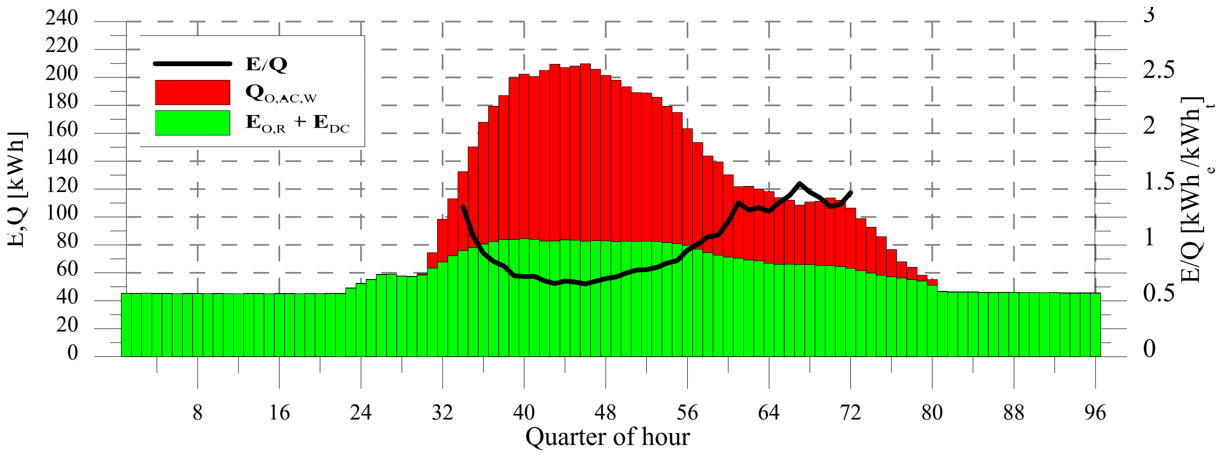

Figure 6. Simultaneous requests for heat and electricity during an average winter day

For the previously reported reasons, rather than hypothesizing to install a single cogenerator sized for the maximum heat demand, it has been assumed to install more smaller cogenerators in parallel, this way ensuring that the overall system operates at an optimal load level, resulting in higher energy savings and reduced environmental impact. The simulation of the energy system performance has been carried out considering a commercial H_2 ready micro-cogenerator [19] powered by LPG (methane is still difficult to supply in Sardinia), whose nominal values for different supply and return temperatures [°C] are reported in Table 4. Figure 7 reports the power and efficiency curves as a function of the load conditions. Two pairs of supply and return temperatures are provided: 50/30 °C and 90/70 °C. Specifically, the 50/30 °C range aligns with the heating demand, whereas the 90/70 °C range corresponds to the input requirements of an absorption chiller, which will be further discussed. The global efficiency of the 50/30 °C solution greatly benefits from the recovery of waste heat from the exhaust condensation. Start-up of the cogeneration has been set for a minimum load of 50%.

Table 4. Technical data of the LPG-fuelled cogenerator (nominal conditions). The subscripts represent supply and return temperatures.

Electric power	$E_{50/30}$	20 kW	Electric efficiency	$\eta_{E50/30}$	31.7 %
	$E_{90/70}$	19 kW		$\eta_{E\ 90/70}$	30.0 %
Thermal power	$H_{50/30}$	45 kW	Thermal efficiency	$\eta_{H\ 50/30}$	71.4 %
	$H_{90/70}$	33 kW		$\eta_{H\ 90/70}$	52.0 %
Fuel consumption	F	63.4 kW	Global efficiency	$\eta_{GL\ 50/30}$	103.1 %
				$\eta_{GL\ 90/70}$	82.0 %

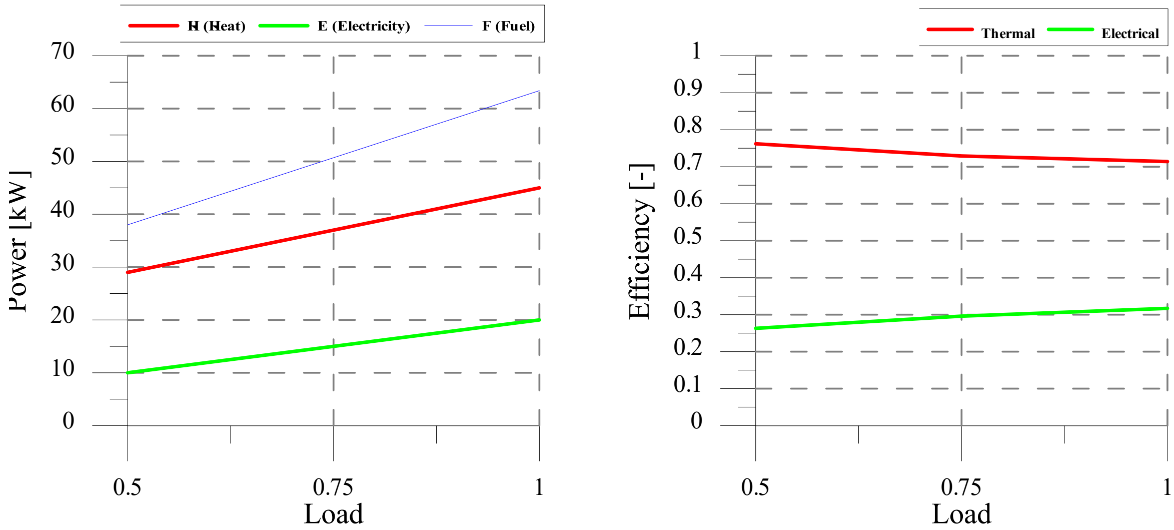

Figure 7. Power and efficiency curves of the cogenerator (temperature supply and return 50/30 °C)

Results of the simulation are reported in Figure 8 for an average winter day, with reference to heat (a) and electricity (b) demand and supply. As it can be seen, the chosen operational strategy has been to prioritize the thermal demand, with electrical production being considered secondary, for efficiency reasons. Three parallel cogenerators could be implemented, with the first unit on for more than 10 hours a day during winter, the second only for the 5-6 central hours of the day and the third for averagely only 1.5 hours per day.

(a) (b)

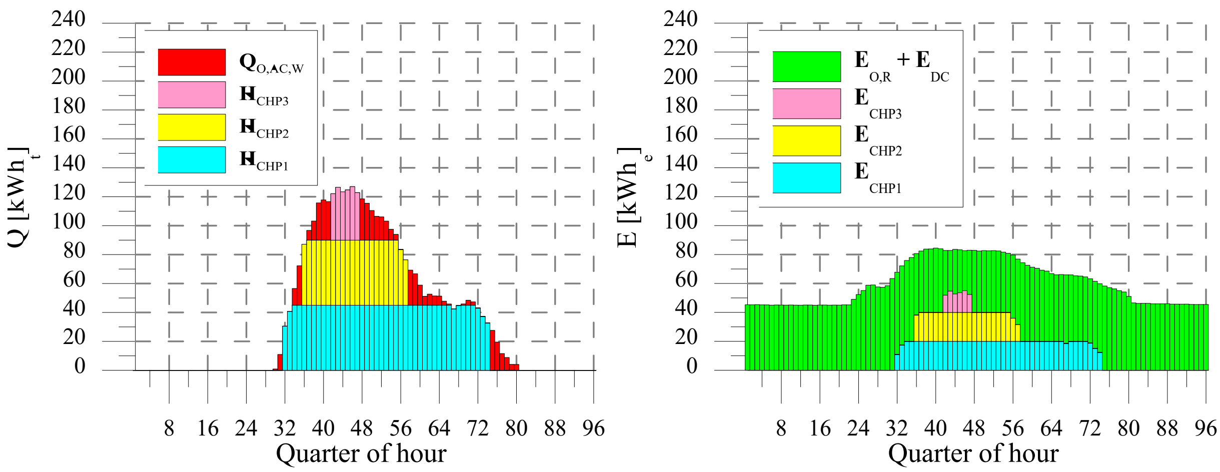

Figure 8. Heat (a) and electricity (b) demand and supply during an average winter day.

Obviously, the investment for the third unit, given these runtime hours, is certainly not cost-effective and therefore the following analysis refers to the solutions with only two cogenerators. The reference values of thermal and electric efficiencies considered for PES and White Certificates calculus are reported in Table 5. The latter consider the climate zone, the avoided network losses as a function of voltage and the share of self-consumed electricity. With the selected system configuration, yearly PES and $\eta_{GL,CAR}$ would be sufficient for defining the CHP as High-Efficiency Cogeneration (CAR).

Table 5. High Efficiency Cogeneration (CAR) and White Certificates reference efficiencies.

Parameter	Description	Value
$\eta_{H,REF,PES}$	reference thermal efficiency of the separated production of heat and electricity	0.89
$\eta_{E,REF,PES}$	reference electric efficiency of the separated production of heat and electricity	0.4079
$\eta_{H,REF,WC}$	average conventional efficiency of the Italian heat production park	0.90
$\eta_{E,SC,REF,WC}$	average conventional efficiency of the Italian electricity production park	0.4255

Table 6. Yearly results of the simulation of implementing a CHP system at Rectorate

E_{CHP}	32	MWh
H_{CHP}	72	MWh
F_{CHP}	101	MWh
$\eta_{GL,CAR}$	1.029	-
PES	0.36	-
$N°_{W.CERT}$	6.3	-
Energy injected into the grid	0	MWh

As previously stated, in the Rectorate operates a data center that requires continuous cooling throughout the year, 24 hours a day, 365 days a year (averagely 65 kWt during winter, 80 kWt during middle season and 100 kWt during summer). With the aim to increase the operating hours, the cogeneration unit has been integrated with an absorption chiller, thus achieving a CCHP system. Since this integration results in lower performance of the cogenerators due to the higher temperatures (90/70 °C) required by the absorption chiller, during winter the priority has been given to meeting the heating demand, with cooling being secondary. Technical data of the considered market-available absorption chiller are reported in Table 7.

Table 7. Technical data of the hot-water-fired absorption chiller (nominal conditions)

Cooling capacity	32.5 kW	Input (hot water) temperature	88 °C
Chilled water temperature	7 °C	Input (hot water) power	46.6 kWt

Yearly results of energies, global efficiency, PES, and the number of White Certificates obtainable in the CCHP scenario are reported in Table 8. Even if yearly PES and $\eta_{GL,CAR}$ would be sufficient for defining the CHP as High-Efficiency Cogeneration (CAR), the global annual efficiency of the cogenerator deviates significantly from its nominal values, passing from values above 1 of the CHP scenario (obtained recovering condensation heat from flue gases) to values around 0.85 of the CCHP scenario (off-design conditions and no recovery of condensation heat from flue gases).

Table 8. Yearly results of the simulation of implementing a CCHP system at Rectorate

E_{CCHP}	235	MWh

H_{CCHP}	426	MWh
C_{CCHP}	252	MWh
F_{CCHP}	780	MWh
$E_{CCHP,SC}$ (Self-consumed)	235	MWh
$E_{CCHP,EXP}$ Energy exported to the grid	0	MWh
Not purchased energy from the grid for thermal demand	106	MWh
$\eta_{GL,CAR}$	0.85	-
PES	0.26	-
$N°_{W.CERT}$	29	-

Table 9 reports the assumptions and the results on the economic profitability of the investment, carried out through a cash-flow analysis. Capital and O&M costs have been assumed as suggested by [20] for the cogenerator and [21] for the absorption chiller. Since the 2022 European energy crisis scenario would have resulted in overestimations, unitary LPG[3] costs [22] and electricity revenues [23] have been assumed equal to the Italian average prices in 2021, while for electricity savings, the cost actually incurred in 2021 was considered. To accurately account for the avoided cost of purchasing electricity, a grid loss factor of 10% was applied to the energy consumption (standard for low voltage electricity supplies in Italy). For the economic indicator calculations, an investment lifetime of 25 years, 10 years of revenues from white certificates and a discount rate of 5% have been assumed. The economic feasibility analysis revealed that the investment in the CCHP system is not viable (NPV (25y) < 0), mainly due to the costs of fuel, whose consumption is greatly affected by the low global annual efficiency. It is pertinent to emphasize that there exist non-economic advantages that can still confer value and justification to the investment: for instance, having such a system in the district where the rectorate is located could also help overcome the limitations on available power from the electricity provider. Additionally, the system could provide backup power and energy independence for the building's essential services. Therefore, a more comprehensive evaluation could be carried out, considering both the economic and non-economic benefits of the proposed system.

Table 9. Assumptions and results on the economic profitability of the investment.

Parameter	Description	Value
$C_{C,CHP}$	Capital Cost of the cogenerator	3,000 €/kWe
$C_{C,CHILL}$	Capital Cost of the absorption chiller	2,700 €/kWt
S_G	Savings from avoided purchase of a 50 kVA new generator for data center	25,000 €
$C_{O\&M,CHP}$	Operation and Maintenance Cost of the cogenerator	0.025 €/kWhe
$C_{O\&M,CHILL}$	Operation and Maintenance Cost of the absorption chiller	0.002 €/kWht
$C_{F,LPG}$	LPG Cost	0,623 €/l
R_E	Revenues from selling electricity to the grid	125.46 €/MWh
S_E	Savings from avoided purchase of electricity	210.90 €/MWh
$R_{INC,W.CERT}$	Revenues from a White Certificate (average 2021)	267.40 €
PP	Payback Period	>25 years
CF	Yearly cash flow (including White Certificates)	≈ 10 k€/year

[3] The impact of reduced excise duties on heating fuel consumption, which is available to Sardinia due to its insular condition, has been considered.

5. Conclusions

The aim of this study was to develop a simple and easy-to-use model evaluating seasonal energy flows of buildings and, therefore, to preliminarily size diverse types of electricity and thermal supply systems, even combined. The average seasonal hourly energy flows estimation is obtained only from the electrical power curves and a few easy assumptions. Some simplifications of the energy model are proposed, depending on the level of detail of the available data and the degree of approximation desired. The study was then extended to include preliminary technical and economic considerations for the feasibility assessment of a CCHP system, also considering the incentives available in Italy for this type of energy system. The model has been applied to a case study, represented by the Rectorate of the University of Cagliari, under the hypothesis of implementing a trigenerative system: thermal energy is used primarily for heating and subordinately, through an absorption chiller, for cooling a data center. The analysis demonstrates that the investment is not economically feasible, mainly due to the low global efficiency of the system, but it may lead to other non-economic advantages, such as providing extra and/or backup power and energy independence for the building's essential services.

The research development will be to validate the model, comparing it with on-site energy measurements and thermal modeling of the building, as well as to apply it to other university campuses to study different system layouts, including fuel cells, storage, and heat recovery.

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