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Waste Heat Recovery Technologies on Optimized CHP-BESS Plant: A Performance Comparison Between Organic Rankine Cycle and H_2O-NH_3 Absorption Plant

Raffaele Iossa*, Alfredo Gimelli, Ali Karimi, Massimiliano Muccillo

Industrial Engineering Department, University of Naples Federico II, Naples 80125, Italy

Corresponding Author Email: raffaele.iossa@unina.it

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ABSTRACT

Combined, heat, and power (CHP) plants, integrated with battery energy storage systems (BESS), represent a feasible solution to meet electric and thermal demand with a single fossil primary energy source. In this work, a comparative analysis of two waste heat recovery technologies for a hospital was performed. An ammonia-water absorption, power, and cooling (APC) system and an organic Rankine cycle (ORC) plant were combined within an optimized fossil primary energy saving (PES) oriented battery-integrated cogeneration system, characterized by natural gas internal combustion engines, which waste heat is recovered inside the APC and ORC plants. A control strategy was implemented to optimize the efficiency of the system, prioritizing cooling or electric power production based on hourly Hospital's demand. The APC-based trigeneration configuration reaches a 20% of PES and a 24% reduction in CO_2 emissions, while the ORC-based trigeneration system performs a 19% improvement in PES and a 23% reduction in CO_2 emissions, compared to the hospital separate production of the same amount of energy. The simple payback (SPB) period for both configurations increases slightly, moving from 3.23 years for the optimized CHP-BESS plant to 3.3 years for the APC-based configuration and 3.4 years for the ORC-based plant.

1. INTRODUCTION

The last decade has highlighted how climate change is deteriorating the biological and economic sustainability of many sectors worldwide. Continuously shifting and irreversible weather patterns influences the integrity of ecosystems in numerous ways, including fluctuations in species abundance, changing in distribution ranges, alterations in activity patterns, and variations in microhabitat utilization. Additionally, climate change is increasing antimicrobial resistance, posing a significant threat to human health by amplifying the incidence of resistant pathogenic infections. Concurrently, diseases transmitted through various vectors such as water, food, and air, as an example is the coronavirus pandemic, are on the rise [1]. Inside the health sector the sensibleness for the risks linked to the climate change is increasingly growing, not only due to its impact on the human health but also because it represents one of the major polluters, responsible for 5.2% of global emissions [2]. Policy priorities [3, 4] play a critical role inside healthcare sector, aimed to balance the supporting investments in low-carbon technologies with the one in medical facilities, where pervasive unmet basic healthcare needs persist alongside underdeveloped healthcare systems [5]. This work presents a techno-economic comparison between two technologies for waste heat recovery from an optimized combined heat and power (CHP) plant, integrated with a battery energy storage system (BESS), aimed at minimizing fossil primary energy (PES). The comparison is based on the hourly energy demand of the Italian Hospital facility CROB (Oncological Reference Center of Basilicata).

2. THE CROB HOSPITAL

Table 1. Electric, thermal, and cooling annual energy and max peak power required by the CROB Hospital's facility

Annual billed electric energy	MWh	6.275,693
Electric power peak	MW	2.028
*Annual billed thermal energy	MWh	7.028,215
Thermal power peak	MW	1,621
Annual calculated cooling energy	MWh	1.644,938
Cooling power peak	MW	1,172

*Average billed lower heating value for the gas methane: 9.58 kWh/Nm^3.

The CROB Hospital, located in Basilicata (Italy), is one of the most important healthcare points in Italy, focused primarily on the diagnosis, treatment, and management of various types of cancer. The hourly average electric, thermal, and cooling demand of the Hospital [6] is shown in Figure 1, obtained through a combination of on-site measurement and numerical integration, which annual energy and peak power required are reported in Table 1. The thermal power demand is covered by natural gas thermal boilers, at the average temperature of 55℃, while the electric demand is satisfied by the electric local grid, in which is included the hospital's cooling demand, provided by electric heat pumps (characterized by COP=3), at the average temperature of 5°C.

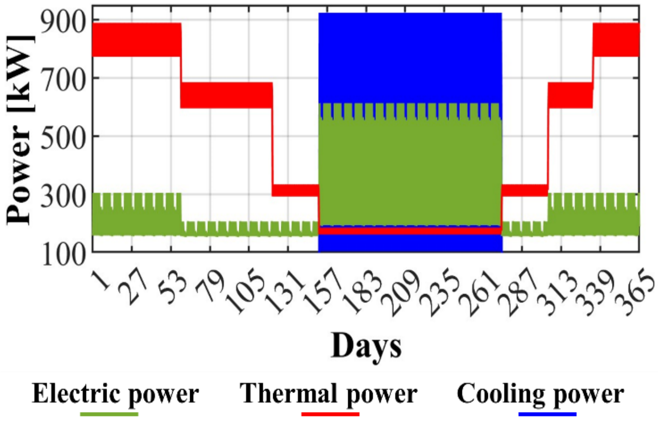

Figure 1. Daily CROB Hospital's power demand

3. OPTIMIZED CHP-BESS PLANT

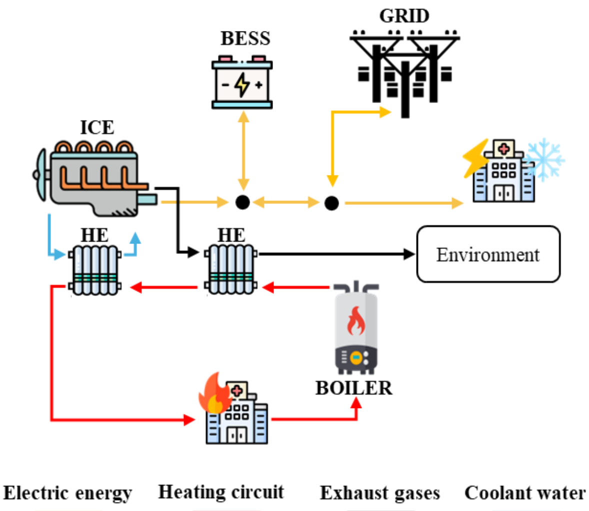

Figure 2. Optimized CHP-BESS plant scheme

During the last years the role played by cogeneration plants inside the healthcare sector is of primary importance, ensuring energy demand during electric grid or renewable plants faults, while reducing emissions and energetic costs. Gimelli et al. [6] implemented a genetic algorithm based - vector optimization methodology [7] to determine the optimal size of a modular CHP-BESS plant (Figure 2) for the CROB Hospital, aimed to maximize the PES index in comparison to the conventional separate production of equivalent energy. The electric power produced by the natural gas internal combustion engines, in cogeneration asset, covers the Hospital's electric demand, which exceeding power is stored inside the BESS or sold to the local grid; the thermal power coming from the exhaust gases and from the coolant water and lubricant oil, covers the Hospital's thermal demand. Anytime the CHP-BESS plant is not able to meet the required load of the Hospital, the natural gas boiler is turned on and the electric power is imported from the local grid. According to the PES hourly evaluation, a proper engine's on/off control strategy has been implemented in the work. During a specific time interval, the decision to turn on or off the engines is based on the fossil primary energy saving performed by the plant to meet Hospital's hourly demand. In fact, every time the PES>0, the engines are turned on, assuring a fossil primary energy saving; if the PES<0, the engines are off and the Hospital's demand is covered by the separate production of energy. Although CHP plants can work at partial loads [8], with relative several electric and thermal power output, this study has been based on the assumption that partial loads are not taken in account. So, the gas engines operate only at the nominal point. The details of optimal solution are reported in Table 2, the plant is characterized by three ICEs, each one delivering 443 kW of electric power at the nominal working point; the total recoverable thermal power is 523.56 kW, which 68% (356 kW) comes from the exhaust gases (at the constant temperature of 350°C), the remaining 32% (168 kW) comes from coolant water and lubricant oil (at the constant temperature of 90°C). The system is coupled with a small BESS, with 68 kWh of capacity.

Table 2. Characteristics of the optimized CHP-BESS system

CHP Plant Operation Time	h/year	8760
ICEs Total Number	#	3
ICE Nominal Electric Power	kW	443
ICE Recoverable Thermal Power from Exhaust Gases @350°C	kW	356
ICE Recoverable Thermal Power from Coolant Water and Lubricant Oil @90°C	kW	168
BESS Capacity	kWh	68

4. WASTE HEAT PLANTS FOR ENHANCED TECHNO-ECONOMIC PERFORMANCES

After the recoverable thermal power coming from the CHP system is exploited to meet Hospital's thermal demand, the exhaust gases are still characterized by high temperature and recoverable thermal power. In this work, starting from the optimized CHP-BESS solution, the energetic and economic outcomes obtained through two waste heat recovery plants are presented: an organic Rankine cycle (ORC) plant and an absorption, power, and cooling (APC) system, both fueled by engines' exhaust gases.

4.1 Organic Rankine cycle plant

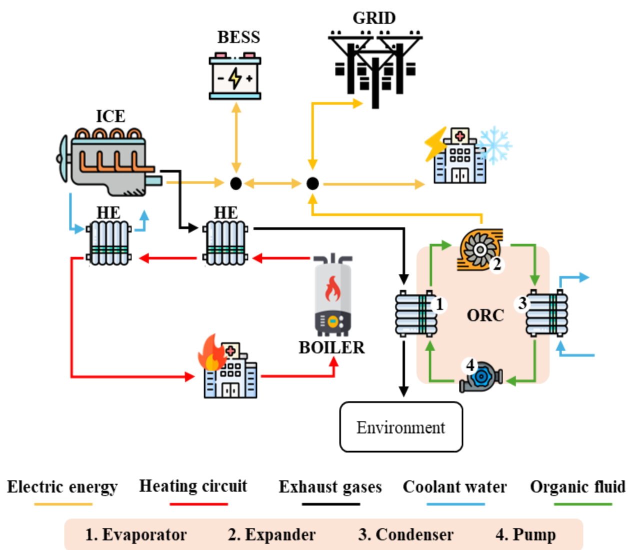

Figure 3. Layout of the CHP-BESS-ORC plant

Between 2016 and 2020, the ORC market observed a 40% increase in installed capacity and a 46.5% increase in the number of installed plants, totaling over 2700 installations. Additionally, the first few months of 2021 saw the construction of more than 452 MW and 189 plants, with further projects planned for the coming years [9]. The organic Rankine cycle plants result in one of the most relative and practically realizable technology [10] inside the energy transition panorama, as they increase the overall efficiency of energy production [11] and provide flexible and customizable energy solutions. Karimi et al. [12] performed a numerical techno-economic analysis integrating an ORC plant within the optimized CHP-BESS solution obtained in Tufano et al. [7] for the CROB Hospital, which layout is shown in Figure 3.

The engines' exhaust gases of the CHP plant, after covering the Hospital thermal demand, are sent inside the evaporator (1) of the ORC plant where the thermal power is given to the R245FA organic fluid, expanding inside the scroll expander (2), for the electric power production, and condensing inside a condenser (3), before restarting the thermodynamic cycle with the feed pump (4). The electric power produced through the ORC plant is integrated inside the hourly CROB's demand if required, stored inside the BESS, or sold to the electric grid. The thermodynamic model has been tuned and validated on the experimental data of a small ORC test-rig reported in the study by Accorsi [13], characterized by a nominal electric power of 3 kW. To appreciate the energetic and economic impact on the Hospital's energetic demand, the numerical model has been scaled-up, which characteristics are reporter in Table 3. Its nominal working point is characterized by input thermal power equal to the mean value recoverable from the engines' exhaust gases, after covering Hospital thermal demand.

Table 3. Characteristics of the ORC plant [10]

Nominal Thermal Power Input	kW	350
Evaporator Area	m^2	4.38
Condenser Area	m^2	4.38
Nominal Electric Power	kW	25

As result, the energy conversion efficiency of the ORC plant, defined as the ratio between the nominal electric power production (25 kW) and the nominal thermal power input (350 kW), is equal to 7.14%.

4.2 Absorption, power, and cooling plant

CHP plants are designed to meet at the same time electricity and heating demand, while providing a constant energy source during the electric grid fails inside the Hospitals. However, of particular concern is the increasing demand for cooling power, which is expected to triple globally from 2016 until 2050 [14]. Indeed, the utilization of air conditioners currently contributes to 10% of the world's electricity consumption and is forecasted to emerge as one of the primary catalysts for the electric global demand [14]. Thermally driven refrigeration systems emerge as a solution for the cooling power production, fueled by waste heat coming from upstream thermal power plant or industrial processes. Absorption systems represent a widespread technology, excelling in converting thermal to cooling power [15], adaptable to various thermal sources, particularly renewable sources (such as solar [16]) or waste heat. The main commercial applications are characterized by LiBr-H_2O (lithium bromide – water mixture) and NH_3-H_2O (ammonia - water mixture) as working fluids [17]: the first one represent a longstanding and well adopted technology, which single-stage configuration achieves a COP between 0.7-0.8 [18]; the second one exhibits a lower COP, around 0.6-0.7, but is characterized by ammonia, an environmentally benign fluid, with zero global warming and ozone depletion potential [19]. Braccio et al. [20, 21] reported an exergoeconomic analysis on an ammonia-water absorption chiller prototype, integrated with a partial admission turbine for the electric power production. In this work, the thermodynamic model of the APC system, tuned on the experimental data [20], has been integrated into the optimized CHP-BESS solution, which layout is reported in Figure 4.

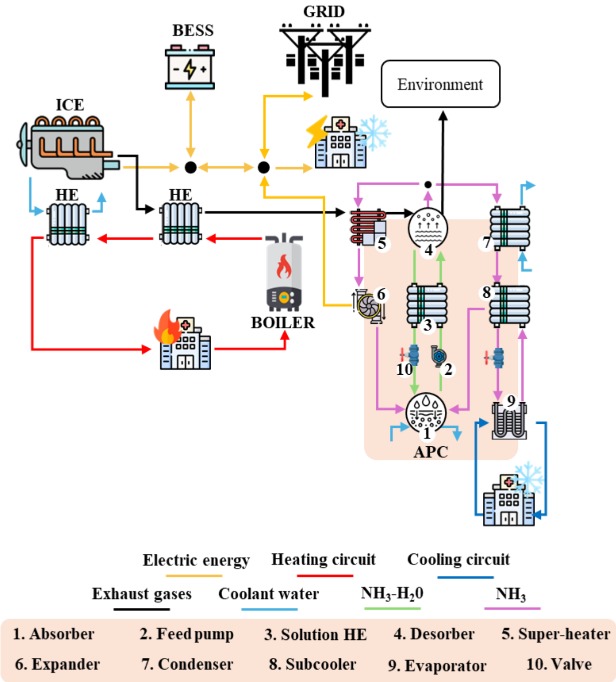

Figure 4. Layout of the CHP-BESS-APC plant

The ammonia rich liquid solution at the absorber outlet (1) is pumped into the desorber (2) where part of the exhaust gases' waste heat is recovered, allowing the partial desorption of ammonia vapor. Based on the hourly Hospital's electric and cooling power demand, the ammonia vapor is divided between two lines: on the electric power production line, the ammonia rich solution is superheated (5) through the thermal energy coming from exhaust gases (before being sent to the desorber), increasing the temperature of the vapor before entering the turbine (6), in order to avoid condensation during expansion and increasing the mechanical (and electric) power production efficiency; on the cooling production line, an intermediate temperature source allows ammonia vapor condensation inside the condenser (7), then pre-cooled in a sub-cooler (8) using the fluid coming out from the evaporator, where the cooling circuit allows to cover the hourly Hospital's cooling demand. The electric and cooling production lines both mix inside the absorber (1) where the ammonia is absorbed in the water rich solution, by an intermediate temperature source. The experimental plant [20] is characterized by 7 kW of cooling power and 0.1 kW of electric power, respectively in closed electric line and closed cooling line. To appreciate the impact of the APC plant into the Hospital building, the numerical thermodynamic model has been scaled-up, which characteristics are reported in Table 4. The nominal working point corresponds to the one characterized by the same thermal power input of the ORC plant, in order to compare the performances of both plants with the input thermal power of the heat source.

Table 4. Characteristics of the APC plant

Nominal Thermal Power Input	kW	350
Absorber Area	m^2	30
Desorber Area	m^2	51.22
Evaporator	m^2	20.79
Condenser	m^2	30.11
Solution HE	m^2	14.89
Subcooler	m^2	6.41
Super-heater	m^2	0.03
Maximum Cooling Power	kW	210
Maximum Electric Power	kW	21.15

As result, the scaled-up APC system is characterized by two energy conversion efficiency: the ratio between the maximum cooling power production (210 kW) and thermal power input (350 kW) represents the COP of the system, equals to 0.6; while the ratio between the maximum electric power production (21.15 kW) and thermal power input represents the electric efficiency of the system, equals to 0.06.

5. MATHEMATICAL MODELLING FOR THE ENERGETIC AND ECONOMIC ASSESSMENTS

The logic integration between the thermodynamic models of the ORC plant and APC system within the optimized CHP-BESS model is shown in Figure 5. For every hour of the year the Hospital's electric, thermal, and cooling demand, together with the economic values assumed as constant, represent the main input for the numerical models. Every time the CHP plant is on, after covering the Hospital's electric and thermal demand, the remaining engines' exhaust gases thermal power is recovered inside the ORC plant for the production of electric power, integrated inside the hourly Hospital's electric demand, stored inside the BESS, or sold to the local grid. When the engines' exhaust gases thermal power is recovered into the APC system, a proper control strategy, based on the hourly Hospital's electric and cooling demand, splits the ammonia vapor between the electric and the cooling production line, always aimed to prioritize the cooling power production rather than the electric one, accordingly to the APC system performances in converting thermal power to cooling power with higher efficiency compared to the conversion efficiency in electric power. The cogenerated electric and thermal power is then integrated respectively with the external electric local grid and auxiliary boiler, in order to meet the hourly energetic Hospital's demand. At the end of the calculation, the main outcomes are represented by the PES index, the reduction of CO_2 emissions, and the SPB period, used to compare the performances of the proposed systems.

The Eq. (1) for the PES index takes into account all the energy flows occurring between the Hospital, the proposed integrated plant, and the auxiliary systems (electric grid and thermal boiler).

$$PES = \frac{E_{P,RS} - E_{P,PS}}{E_{P,RS}} \tag{1}$$

The fossil primary energy of the reference systems (separated production of the energy) ($E_{P,RS}$) is represented by Eq. (2).

$$E_{P,RS} = E_{P,TH} + E_{P,EL} + E_{P,EL\ EXC} \tag{2}$$

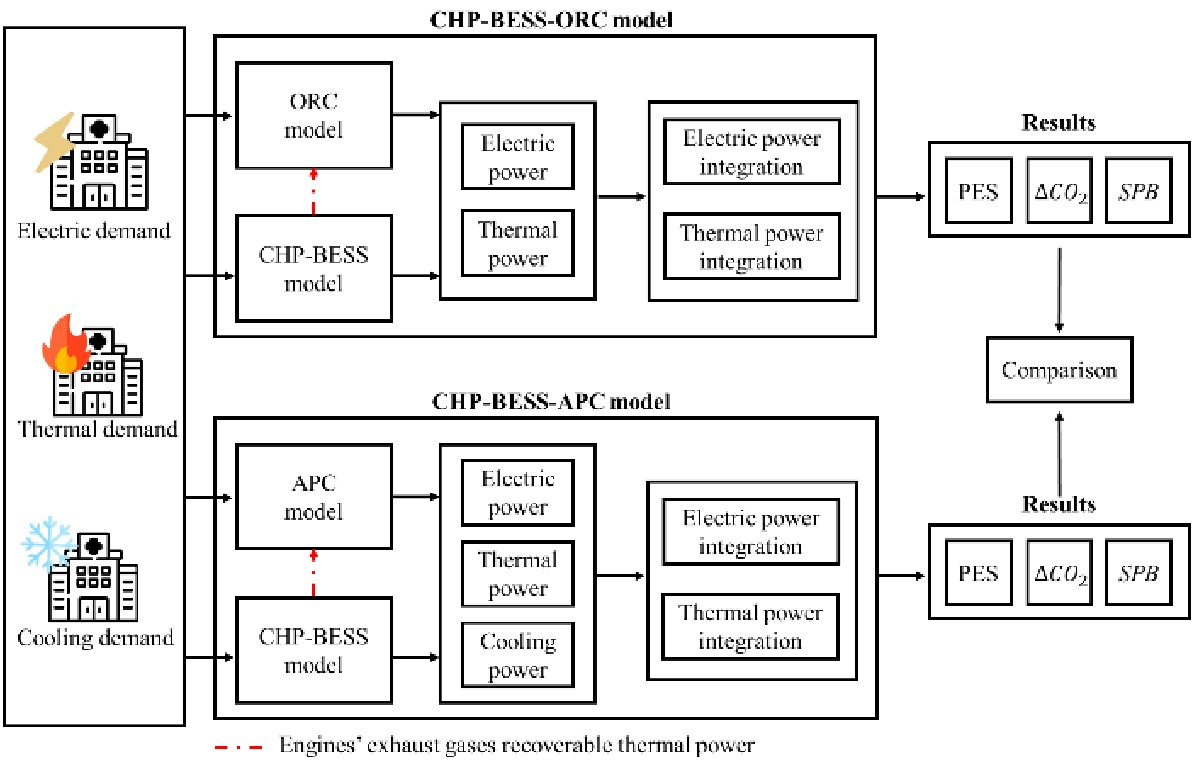

Figure 5. Workflow of the integrated CHP-BESS thermodynamic model with ORC and APC models

It is given by the sum of the fossil primary energy respectively required by the thermal boiler ($E_{P,TH}$) and the electric local grid ($E_{P,EL}$), in order to cover Hospital's thermal and electric demand, and the fossil primary energy of the exceeding electric energy ($E_{P,EL\,EXC}$) related to the proposed integrated plant. The Eq. (3) shows in detail the terms of the fossil primary energy for the reference system:

$$E_{P,RS} = \frac{E_{TH}}{\eta_{TH,ref}} + \frac{E_{EL}}{\eta_{EL,ref}} + \frac{E_{EL,EXC}}{\eta_{EL,ref}} \tag{3}$$

where, E_{TH} represents the yearly Hospitals' thermal energy demand; $\eta_{TH,ref}$ is the reference efficiency for the thermal boilers, assumed equals to 0.90; E_{EL} represents the yearly Hospital's electric energy demand; $E_{EL,EXC}$ is the yearly exceeding electric power related to the proposed systems; $\eta_{EL,ref}$ represents the reference efficiency of the local electric grid, assumed equals to 0.45.

The fossil primary energy of the proposed system ($E_{P,PS}$), shown in Eq. (4).

$$E_{P,PS} = E_{P,CHP} + E_{P,TH_{int}} + E_{P,EL_{int}} \tag{4}$$

It is obtained through the sum of the fossil primary energy required by the CHP system ($E_{P,CHP}$), and the sum of the fossil primary energy related to the integrated thermal energy ($E_{P,TH_{int}}$) and integrated electric energy ($E_{P,EL_{int}}$) respectively from the thermal boiler and electric local grid, in order to meet Hospital's demand. The Eq. (5) shows in detail the terms of the fossil primary energy for the proposed system:

$$E_{P,PS} = m_c H_i + \frac{E_{TH,INT}}{\eta_{TH,ref}} + \frac{E_{EL,INT}}{\eta_{EL,ref}} \tag{5}$$

where, $m_c H_i$ is the product between the yearly fuel mass required by the cogeneration system and the fuel lower heating value; $E_{TH,INT}$ represents the thermal energy integrated during the year by the thermal boiler to cover the Hospital's demand; $E_{EL,INT}$ is the electric energy integrated during the year by the local electric grid, to cover the Hospital's electric demand.

The economic comparison among presented integrated plants is based on the SPB evaluation, calculated as shown in Eq. (6).

$$SPB = \frac{IC}{\Delta C_{tot}} \tag{6}$$

The IC represents the investment cost of the proposed systems, reported in detail with Eq. (7):

$$IC = Cost_{CHP} + Cost_{BESS} + Cost_{WH} \tag{7}$$

where, $Cost_{CHP}$ and $Cost_{BESS}$ represent the investment cost of the optimized CHP-BESS solution [6]; $Cost_{WH}$ is the investment cost of the waste heat plants considered in this work: the ORC [12] or the APC [21] system. The investment costs are summarized in Table 5.

The ΔC_{tot} constitutes the annual cost saving, expressed with the Eq. (8).

$$\Delta C_{tot} = C_{tot\,RS} - C_{tot\,PS} \tag{8}$$

It is expressed as the difference between two aliquots: $C_{tot\,RS}$ is the total energy cost of the reference system (separate production of the same amount of energy), containing the annual electric and thermal energy required by the Hospital; $C_{tot\,PS}$ represents the total energy cost for the proposed system, considering the annual cost of the cogeneration's gas methane and the integrated electric and thermal energy respectively from the electric local grid and auxiliary boiler. In Table 6, the average cost of the gas methane, the imported and exported electricity, are shown based on the Italian pricing system.

Table 5. Investment costs of the proposed systems

CHP Plant	€	1.329.000,00
BESS	€	20.400,00
ORC Plant	€	47.754,00
APC Plant	€[3]	56.019,00

Table 6. Reference value of the energetic costs for the Italian pricing system [6]

Electricity Peak Power Cost	€/kW	28.36
Average Electricity Cost	€/kWh	0.121
Average Electricity Selling Price	€/kWh	0.093
Average Gas Methane Cost	€/Nm^3	0.39

More details about models and equations are reported in studies [6, 12, 21].

6. RESULTS

The energetic and economic performances of the proposed systems, obtained through the development and integration of proper thermodynamic models, are reported in Table 7.

Table 7. Performances comparison of the proposed systems

		Optimized CHP-BESS	ORC	APC
PES	%	18	19 (+5.55%)	20 (+11.1%)
CO_2 reduction	%	22	23 (+4.54%)	24 (+9.1%)
Peak power from the grid	kW	1571	1554 (-1.08%)	1531 (-2.55%)
Peak power to the grid	kW	955	955 (0%)	968 (+1.36%)
SPB	years	3.23	3.29 (+1.89%)	3.3 (+2.2%)

The further engines' exhaust gases waste heat recovery, for the production of electric and/or cooling power, increases the fossil primary energy saving compared to the optimized CHP-BESS solution. In Figure 6, Figure 7, and Figure 8, the fossil primary power saving obtained through the integration of the proposed systems inside the Hospital is compared to the one required by the reference system (separate production of the same amount of energy). All the figures are characterized by the same trends: the highest values of fossil primary power saving obtained through the integration of the waste heat recovery plants, compared to the fossil primary power required by the optimized CHP-BESS solution, is during the summer, corresponding to the period where the Hospital's electric power required is the highest one because of the cooling demand of the electric heat pumps. However, the integration of the APC system inside the optimized CHP-BESS plant returns the highest fossil primary energy saving. Despite the APC system is characterized by a maximum electric power production of only 21.15 kW, compared to the 25 kW of the ORC plant, this result is achieved through its capacity to convert thermal to cooling power with higher efficiency (compared to the conversion of thermal to electric power), characterized by a COP of 0.6. So, every time the APC system produces 210 kW of cooling power (and this happens during the summer), considering the Hospital's electric heat pumps are characterized by COP equals to 3, the relative electric power saving obtained through the cooling power production of the APC system is equal to 70 kW, around 48 kW more than the ORC plant. Figure 9 reports the comparison between the daily averaged Hospital's cooling demand, during the summer, and the cooling power produced by the APC system, fueled by engine's exhaust gases, which corresponds am averaged maximum daily reduction of the Hospital's electric demand equals to 6%. The fossil primary energy saving obtained through the integration of the ORC and APC plants brings to the CO_2 emissions reduction, respectively of 4.54% and 9.1% compared to the one obtained through the optimized CHP-BESS solution. On the other side, despite the relative high investment costs of the waste heat recovery systems, the SPB slightly increase, moving from 3.23 year for the optimized solution, to 3.29 years for the integration of the ORC plant, till 3.3 years for the integration of the APC system.

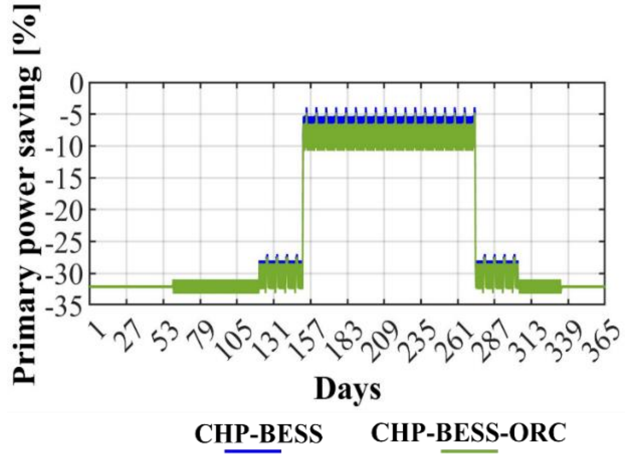

Figure 6. Fossil primary power saving comparison between the optimized CHP-BESS and the CHP-BESS-ORC plants

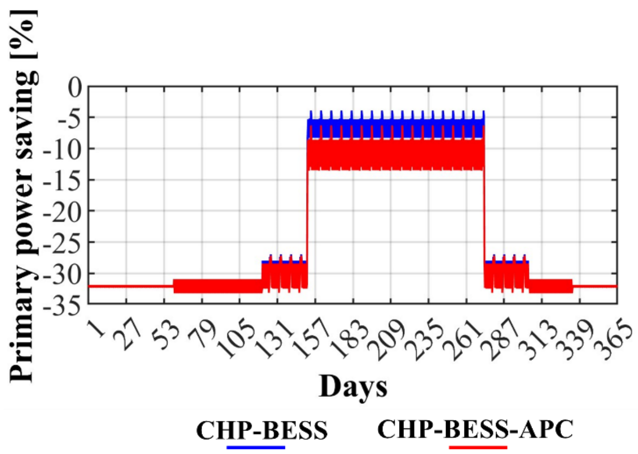

Figure 7. Fossil primary power saving comparison between the optimized CHP-BESS and the CHP-BESS-APC plants

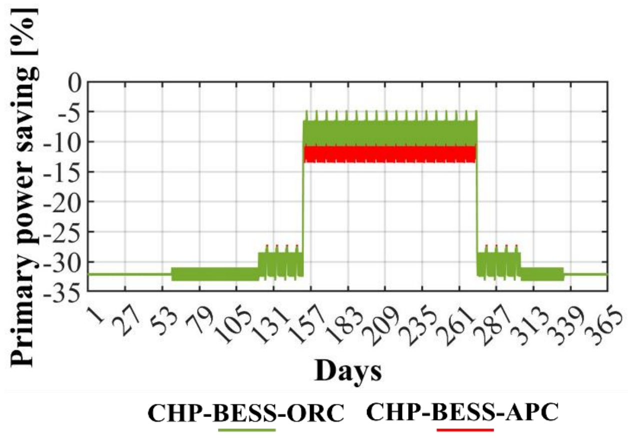

Figure 8. Fossil primary power saving comparison between the optimized CHP-BESS-ORC and the CHP-BESS-APC plants

However, the rapid increase of the SPB period is mitigated by two factors: the reduction of the peak power imported from the local grid that brings to a reduction of the energetic costs of the Hospital, while the increase of the peak power sold to the local grid increases the energetic costs of the hospital as long as the energetic contract with the electric producer grows because of the management of a higher peak of electric power.

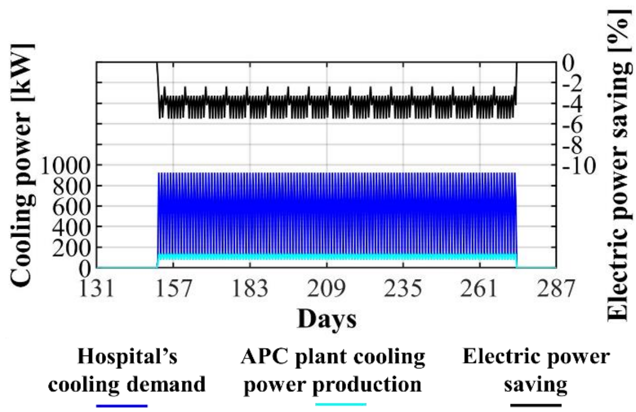

Figure 9. Daily averaged hospital's summer cooling demand, APC plant cooling production, and its relative electric power saving

7. CONCLUSIONS

The further recovery of the engines' exhaust gases waste heat for the electric and/or cooling power production, brings several energetic, environmental, and economic improvements, compared to the traditional systems of energy supply. The CHP-BESS solutions represent a starting point in the energy transition panorama for the healthcare buildings, as capable to reduce their environmental impact while allowing operations regardless of the power grid availability. However, to cover the forecasted energetic demand of the next years, many solutions for enhanced energy conversion efficiency are under investigation. The ORC and APC plants represent great solutions respectively for the electric and electric/cooling production, fueled by waste heat coming from upstream industrial processes or thermal power plants. Their integration inside a max PES-aimed optimized CHP-BESS solution has brought a PES and CO_2 reduction improvements, with a slight increase of the SPB. The characteristics of the APC plants are well suited when the cooling demand is consistent during the year, as its efficiency reaches the maximum value when converting thermal to cooling power despite to electric power; on the other side ORC plants should be preferred when the electric demand is dominant during the year, characterized by higher efficiency when converting thermal to electric power, compared to the one of the APC plants. However, the integration of these waste heat recovery plants inside an optimized CHP-BESS solution, altered the behavior and the outcomes of the system, which requires a new multi-input multi-variable optimization design process, in order to redefine the optimal layout capable to meet at the same time the maximization of the energetic and economic saving.

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NOMENCLATURE

APC	absorption, power, and cooling
BESS	battery energy storage system
CHP	combined, heat, and power
COP	coefficient of performance
ICE	internal combustion engine
ORC	organic Rankine cycle
PES	fossil primary energy saving
SPB	simple payback