Development of sustainable ORC applications in the tertiary sector: a case study in the Mediterranean climate

To cite this article: L Cirrincione *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1106** 012016

Development of sustainable ORC applications in the tertiary sector: a case study in the Mediterranean climate

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Abstract. In recent decades, climate change strong advancement has led many countries, especially the most developed ones, to a greater sense of environmental responsibility. On a global, European and national level, adaptation/mitigation strategies and actions aimed at improving energy-environmental sustainability and resilience in the tertiary sectors have been increasingly intensified. In this sector, therefore, plays a fundamental role the integration/introduction of technologies able to operate an efficient conversion of energy, such as indeed Organic Rankine Cycle (ORC) plant, other than renewable energy sources, in order to reduce both energy consumption and pollutant emissions. Within this scenario, the aim of this work is to investigate the potential application of a cogeneration ORC system powered by solar collector and geothermal sources, by evaluating its energy, environmental and economic advantages and limitations. To this purpose a case study involving the coverage of the energy needs of a hotel located in Catania (Southern Italy) has been simulated and analyzed. The outcomes put in evidence the importance of the operative conditions in optimizing the productivity of an ORC plant, especially when associated with renewable energy sources, although at the moment investment and supply costs are still quite high.

1. Introduction

In recent decades, climate change strong advancement has led many countries, especially the most developed ones, to a greater sense of environmental responsibility. On a global, European and national level, adaptation/mitigation strategies and actions aimed at improving energy-environmental sustainability and resilience have been increasingly intensified. Among these, some of the most relevant are the UN Sustainable Development Goals (SDGs) and Agenda for Sustainable Development [1,2], the EU environmental and climate energy related action plans [3,4] and the Italian national energy and climate strategies [5].

Within this scenario, the tertiary sector represents one of the most energy-consuming and polluting, hence deserving adequate attention [6,7]. Therefore, improving energy savings and efficiency in the tertiary sector would contribute to strengthen the country energy security, as also encouraged by the EU [4].

As part of the tertiary activities, tourism in Italy represents a significant share of the tertiary sector energy consumers, being an important economic driver characterized by persistent growing trend in recent years [8]. Specifically, most of the energy (up to 50%) is spent on air conditioning, followed by domestic hot water (DHW) and kitchen uses [9]. Consequently, in recent years such matter has been addressed also by the academic community [10], focusing mainly on technologies and solutions to increase energy savings through passive measures, as most tourist facilities consist of existing and/or historic buildings [11,12]. Hence, although some studies have started to focus also on active measures to reduce energy consumption [13] this topic still needs to be properly investigated.

Based on the above reported considerations, in the tertiary sector, therefore, plays a fundamental role the introduction of renewable sources that allow to reduce traditional greenhouse gas (GHG) emitting plants. The use of renewable sources, in turn, requires the development of technologies that can adequately integrate their physical and thermodynamic characteristics, in order to operate an efficient conversion of energy. One of the technologies that have been recognized as having such potential is the Organic Rankine Cycle (ORC) plant, which, by allowing the conversion of energy into useful work using a thermal source at low or medium temperature, couples well with the thermal power produced by renewable sources (e.g. solar and geothermal) [14-16].

The purpose of this work is to investigate the potential application of ORC, evaluating both its advantages and limitations (in terms of configuration and operating conditions), on a case study involving the coverage of the energy needs of a hotel located in Catania (Southern Italy) through the use of a cogeneration system powered by solar collector and geothermal sources.

The assessment reported in this paper, which also includes an economic analysis, although in this case concerns a specific application context, can be a good starting point to implement tools to provide useful operational guidance for decision-making processes of public and private administrations, in order to allocate in the most convenient way their resources to improve energy and environmental sustainability of the tertiary sector [17-19].

2. Materials and Methods

2.1. The case study

The case study is a hotel located in the Sicilian city of Catania in Southern Italy, a place therefore characterized by a Mediterranean climate profile, "Csa" according to the classification of Koppen-Geiger [20]. The hotel has a total area of 5403 m^2 and consists of 150 rooms, common areas (i.e. the rooms used to serve the hotel as lobby, laundry, relaxation area, etc.), conference room, restaurant and kitchen, divided on five floors.

For the calculation of the annual energy needs and the peak power required by the structure (Table 1) it has been taken as reference a "typical" hotel for tourism and business located in southern Italy and active all year round [21]. In particular, an average transmittance of the envelope of 1.35 W/m^{2}K was used, while for the windows (double glazed) a value of 2.83 W/m^{2}K was considered.

Table 1. Annual energy needs and the peak power required by the structure

	Energy demand	Peak power
Electricity	1372 MWhe/y	198 kWe/y
Cooling	726 MWht/y	170 kWt/y
Heating	188 MWht/y	109 kWt/y

2.2. System set-up

The system consists of a cogeneration ORC plant to meet both the electrical and thermal needs of the facility. Power is supplied to the ORC plant through the use of thermal energy from a geothermal well, which is the primary energy source, and a solar thermal plant, as the secondary energy source, both realizable near the hotel property. In particular, it is expected that in the geothermal well, 150 m deep and consisting of a hot rock layer, are installed heat exchangers capable of producing hot at 95 °C to be used in the first phase of heating of the hydraulic circuit that will subsequently feed the evaporator of the ORC. While for the solar thermal system is expected to use a string of evacuated tube collectors with high efficiency (capable of operating at temperatures up to 130 °C), connected to a single storage tank, which aims to collect the heat removed from the collectors and provide it to the supply circuit from the ORC.

With regard to the production capacity of renewable energy sources, these have been estimated at 550 kWt and 345 kWt per year for the geothermal and solar thermal plants, respectively.

The ORC plant has been designed to allow the superheating of the organic fluid to a temperature of 90 °C, with which it starts an expansion phase in the turbine that allows the production of a determined mechanical power, depending on the efficiency of the thermodynamic cycle and the thermal energy supplied to the plant. The driving shaft to which the ORC turbine is connected carries out a bipartition of the energy, feeding at the same time an alternator, which generates the electrical energy required by the hotel, and a compressor, which starts the reversible heat pump that provides for the conditioning of the rooms. Therefore, the cooling and the heating of the rooms take place by means of a pre-existing reversible heat pump which would be powered by a share of mechanical energy produced by the ORC. A natural gas backup boiler is also present. Figure 1 shows the system configuration.

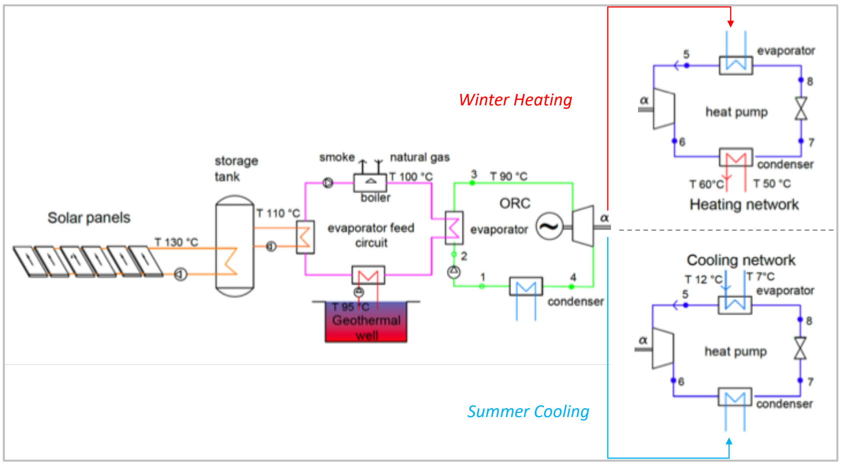

Figure 1. System configuration for summer cooling (down right) and winter heating (up right).

2.3. Simulations

To meet the purpose of this work, firstly a comparative (and sensitivity) analysis was performed evaluating the effects of the choice of organic fluid on the performance of the ORC. Specifically, the working fluids analyzed are: ammonia, R134a, R245fa, butane, isobutane, toluene, n-pentane, cyclohexane, R1233zd(E) and isopentane. To this purpose, the analytical-computational simulation model that described the thermodynamic behavior of the system, in order to evaluate the plant producibility in reference to the hotel thermal load of the hotel, was developed using Engineering Equation Solver (EES) computational software [22].

After identifying the best performing fluid, the study was further investigated by deriving the hourly electricity production of the ORC, so as to identify the hourly surpluses and/or deficits that the hotel must balance through the sale or purchase of electricity from the national power grid.

Subsequently, a sensitivity analysis was carried out for evaluating how the variation of the maximum temperature (T_{max}) at the outlet of the ORC evaporator, in a range between 80 °C and 110 °C, affects the efficiency of the whole plant. A further sensitivity analysis was carried out by keeping the required peak cooling capacity constant (169.65 kWt) and varying the electrical energy utilization factor α (between 0.3 and 0.7) that takes into consideration the distribution of energy produced by the turbine, studying how it affects (in addition to the control parameters) also the coverage of the electrical energy requirement.

In addition, to assess the economic feasibility of this system, also considering the potential annual energy savings achievable, an analysis was carried out by evaluating the Net Present Value (NPV), the

PayBack Time (PBT) and the profitability index of the investment. These incidences have been estimated considering a working life of 25 years, with an annual maintenance cost of €11 270. For the costs relating to the consumption of electricity and natural gas, inflation rates of 1.9% and 2.8%, respectively, have been considered. It was, in addition, taken into account a bonus of 27 815 €/year for a duration of 5 years for the solar collector system, based on incentives and tax deductions issued by the Italian governments specifically aimed at the energy efficiency enhancement [23]. While an interest rate of 2% was used to assess the discounted cash flow trend. With regard to energy savings on an annual basis, different operating conditions were simulated, varying the nominal thermal power of the system between 700 kWt and 550 kWt, depending on the average monthly thermal loads required for room conditioning.

Finally, an assessment of the environmental benefits, in terms of reduction of annual CO_{2eq} emissions related to the use of both the ORC plant and of the renewable sources feeding it, was also carried out. Specifically, with reference to the national energy mix, conversion factors of 435 g_{CO2eq}/kWhe and 57.3 g_{CO2eq}/MJ were considered for electricity and natural gas, respectively [24].

3. Results and Discussions

3.1. Fluids performance comparison

The obtained results show that the best performances are those related to R134a, with a thermal efficiency of 12%, which, however, turns out to be a fluid that is being phased out due to recent environmental regulations. Therefore, ammonia and toluene, characterized by efficiencies greater than 10%, can be considered valid alternatives, while the other fluids show more or less equivalent efficiencies, around 9%.

As regards operating pressures (Figure 2), the outcomes suggest that, with the exception of ammonia and R134a, most fluids operate at relatively low maximum pressures (2-6 bar), just above atmospheric pressure. Working at lower pressures can be a positive factor in that it makes it easier to manage the plant and also saves money during installation and maintenance. The fact that toluene and cyclohexane work at sub-atmospheric minimum pressures would instead represent a problem since it would favor phenomena of atmospheric air suction inside the plant components, with consequent mixing of the refrigerant fluid with the air, compromising the reliability of the entire plant.

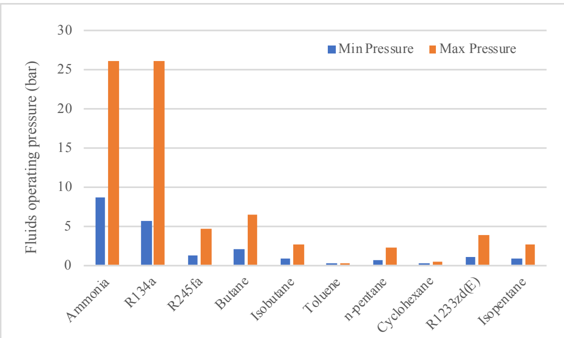

Figure 2. ORC operating pressures for the analyzed fluids.

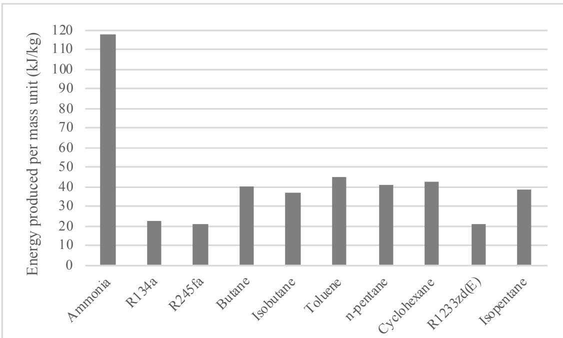

Figure 3. Work per unit flow rate produced by the ORC as a function of the working fluid.

As the simulations revealed a heterogeneity of the flow rates used by each working fluid with the same thermal power set, it was appropriate to estimate the useful work produced per unit of flow rate (i.e. the energy produced per unit of mass, kJ/kg). The results (Figure 3) showed that ammonia is the fluid that produces the most useful work (118 kJ/kg), significantly higher than the other considered fluids. Therefore, ammonia was chosen as the working fluid of the ORC for the following simulations.

3.2. Electric load coverage

The results of the simulations have shown that the representative profile of the hourly demand for electricity of the hotel for a typical day of reference has an almost constant trend during the year, showing 2 time slots (10-14 and 18-22) characterized by a greater demand for electricity (peak value 198 kWe) and a time slot at night (22-7) in which it is recorded a minimum demand, below 50 kWe. The local production of electrical energy of the ORC plant varies, however, between summer and winter (depending on the thermal load of the hotel) and together with it also varies the coverage of the daily electrical load.

In particular, during the summer season (Figure 4) the coverage is 50-100% at night, 20-25% during the daytime (when hotel activities are more intense, kitchens and restaurants are active) and 250% only in the first part of the afternoon (which generates a surplus of electricity to be sold to the national grid). As far as the winter season is concerned (Figure 5), the coverage is 50-150% during the night hours (in some hours surpluses are generated to be sold to the national grid) and 10-50% during the day hours.

This analysis highlighted how important it is to be able to provide a flexible cogeneration factor, so that local electricity production can be increased when the need for thermal energy for space conditioning decreases.

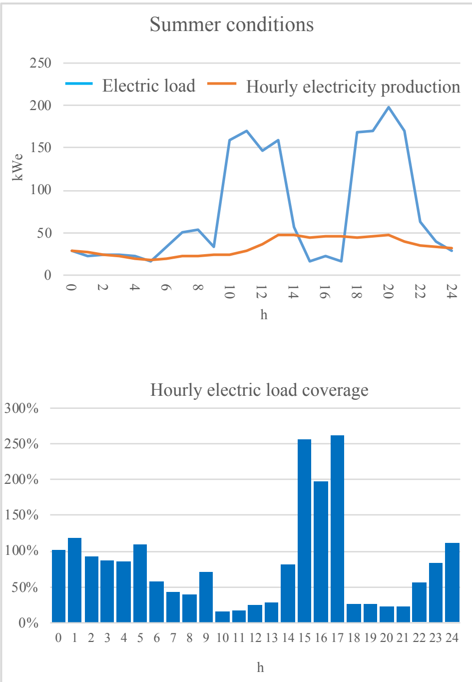

Figure 4. Comparison, on an hourly basis, between plant electricity production and hotel electrical load (top), and electrical load coverage percentages (down) during summer.

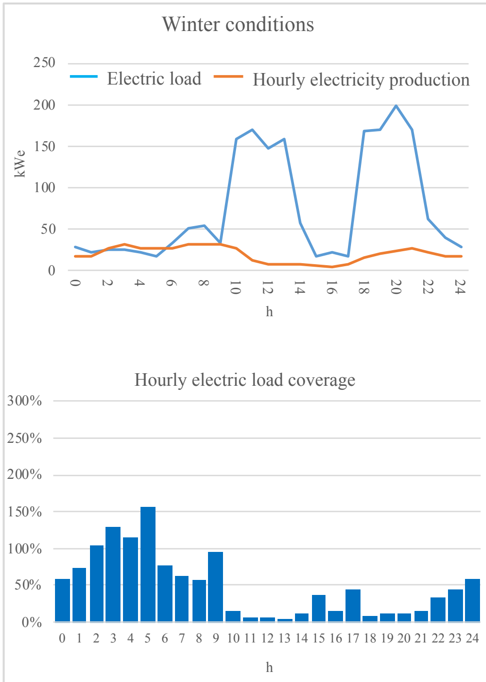

Figure 5. Comparison, on an hourly basis, between plant electricity production and hotel electrical load (top), and electrical load coverage percentages (down) during winter.

3.3. Sensitivity analysis

The results of the sensitivity analysis as a function of T_{max} at the outlet of the ORC, show that as the temperature increases, the efficiency of the fluid tends to increase by about 5%, again highlighting the potential of ammonia as a working fluid for ORC plants even at higher temperatures (100-110 °C), which would allow to evaluate the hypothesis of adopting a reduced expansion phase and use a heat recuperator to make possible the cogeneration for the production of DHW.

The second sensitivity analysis, regarding the trend in the degree of coverage of the hourly electric load as a function of the utilization factor for electricity α, showed that:

- for α = 0.3, the production of electrical energy is insufficient (-57%), i.e. the plant cannot adequately satisfy even the minimum requirement of electrical energy during the night hours;
- for 0.3 < α < 0.7, the system can satisfy the electrical load at night but only partially during daylight hours;
- for α = 0.7, the plant generates surpluses during the night and in the early afternoon, selling large amounts of electricity to the power grid and also managing to cover much of the electricity demand during peak load periods.

3.4. Economic analysis

The economic analysis is aimed at understanding the economic viability behind the investment in this technology while also taking into account the potential annual energy savings that can be achieved.

With regard to energy savings on an annual basis, the results obtained (Figure 6 and Figure 7) show that if, on the one hand, increasing the thermal power supplied to the ORC plant (kWt) favors an increase in the annual production of electricity (MWhe), on the other hand, it also increases the energy required from renewable sources which (due to the unsustainability of the thermal load) would require the help of the backup boiler, thus leading to an increase in gas consumption (Nm^3), and therefore the related supply costs.

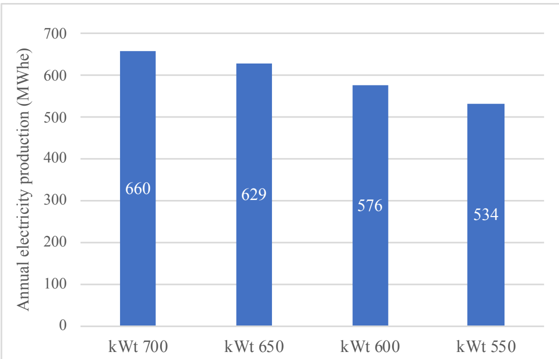

Figure 6. Electricity savings as a function of the thermal power required by the ORC.

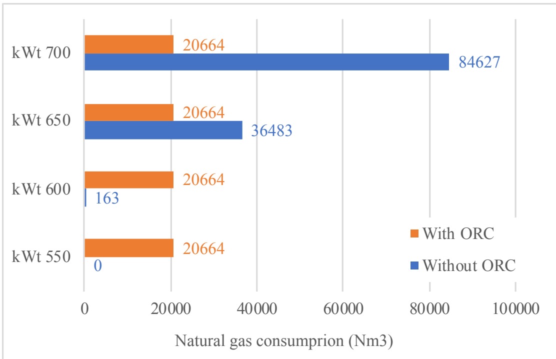

Figure 7. Variation in natural gas consumption for the different operating conditions.

Concerning the evaluation of the initial investment costs for the realization of the system layout (market analysis) the costs related to each section have been evaluated, obtaining a total cost of 1 426 888 €, consisting of: 320 000 € for the ORC, 600 000 € for the geothermal plant, 481,434 € for the solar thermal plant and 25 454 € for the ORC feeding circuit. As previously mentioned, the economic feasibility of the investment has been evaluated, for each of the operating conditions assumed above, through the analysis of the economic indices NPV, PBT and profitability of the investment, obtaining the values shown in Table 2.

Table 2. Investment economic parameters as a function of the power required by the ORC

ORC Thermal power	NPV (€)	PBT (years)	Profitability index
kWt 700	428 570	18	0.35
kWt 650	1 182 243	12	0.96
kWt 600	1 846 205	10	1.50
kWt 550	1 652 843	11	1.35

On the basis of the obtained results, it can therefore be deduced that the maximum economic performance is achieved when the ORC operates with a thermal capacity of 600 kWt. This demand is, in fact, almost entirely sustainable with only the capacity of renewable energy plants (reducing the use of natural gas purchase) and the savings of electricity are still quite high (576 MWh/year).

3.5. Environmental benefits assessment
Considering a working life of the plant of 25 years, the environmental benefits resulting from the saving of both electricity and natural gas used to supply the needs of the hotel have resulted in an avoided emission between 3 919 and 7 312 t_{CO2eq} depending on the operating conditions (Table 3), highlighting again as more advantageous the 600 kWt one.

Table 3. Avoided emissions as a function of the power required by the ORC

ORC Thermal power	Avoided emissions (t_{CO2eq})
kWt 550	6864
kWt 600	7312
kWt 650	6037
kWt 700	3919

4. Conclusions
In this work, the potential applications of the ORC cycle in the tertiary sector have been examined, considering the case study of a hotel structure located in Southern Italy. The analysis carried out has highlighted both the advantages and the criticalities deriving from the use of this technology, mainly related to the aspects concerning the design of the layout, the choice of the working fluid and the operating conditions.

The obtained results showed how, depending on the chosen configuration, it was possible to generate an excess of electricity during the winter season, and a partial coverage of the load during the summer season. While, from the environmental point of view, it was always possible to obtain relevant benefits in terms of saved CO_{2eq} emissions. Therefore, in order to optimize the operation and productivity of an ORC plant, not only the choice of the working fluid and the operating parameters are crucial, but also the conditions of use and the climatic context, especially in the case where the ORC is associated with renewable energy sources systems.

From an economic point of view, the overall performance is not particularly high if compared to the currently most widespread systems, especially since the purchase of an ORC plant is still particularly expensive. However, this technology is slowly establishing itself, along with a greater development and use of renewable energy technologies, so it is expected that the price of ORC will decrease over time, making this type of plant configuration more accessible.

In conclusion, although at the moment investment and supply costs are still quite high, ORC plants represent an intelligent solution whose potential, both in terms of large application and environmental sustainability, make their development promising. In particular, for the type of application that has been addressed in this work, i.e. the one concerning the energy coverage of hotels of a certain size.

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