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Performance Analysis of a Small-Scale ORC Trigeneration System Powered by the Combustion of Olive Pomace

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Abstract: The utilisation of low- and medium-temperature energy allows to reduce the energy shortage and environmental pollution problems because low-grade energy is plentiful in nature and renewable as well. In the past two decades, thanks to its feasibility and reliability, the organic Rankine cycle (ORC) has received great attention. The present work is focused on a small-scale (7.5 kW nominal electric power) combined cooling, heating and power ORC system powered by the combustion of olive pomace obtained as a by-product in the olive oil production process from an olive farm situated in the central part of Italy. The analysis of the employment of this energy system is based on experimental data and Aspen Plus simulation, including biomass and combustion tests, biomass availability and energy production analysis, Combined Cooling Heat and Power (CCHP) system sizing and assessment. Different low environmental impact working fluids and various operative process parameters were investigated. Olive pomace has been demonstrated to be suitable for the energy application and, in this case, to be able to satisfy the energy consumption of the same olive farm with the option of responding to further energy users. Global electrical efficiency varied from 12.7% to 19.4%, depending on the organic fluid used and the working pressure at the steam generator.

Keywords: renewable energy; biomass; olive pomace; combustion; ORC; working fluid

1. Introduction

Using fossil fuels has negative environmental impacts due to greenhouse gas emissions and air pollution problems. For this reason, in order to satisfy the continuous increase in energy demands and to reduce the environmental impact, the replacement of fossil fuels with renewable and sustainable resources is necessary. Biomass is considered an ideal energy source, thanks to its availability and its clean relationship with the environment [1,2]. Environmental analysis demonstrated that the biomass conversion processes can give a good performance [3,4]. A wide variety of biomass exists, e.g., food crops, energy crops, municipal solid wastes, green wastes and agricultural residues [5,6]. The use of biomass wastes avoids the "biomass vs. food" contrast [7] and solves the problem of waste disposal. In the Mediterranean areas of Europe, agro-industrial activities are very important, and a lot of residue is produced.

Among the major activities is the olive oil industry. Olive oil production generates a significant number of by-products, solids and liquids. It has been estimated [8] that one hectare of olives produces about 5000 kg of olives and, from these, about 2250 kg of olive pomace can been obtained.

The production process of olive oil typically brings an oily component, a solid residue and an aqueous component given by the water content of the olive pulp [9].

Anaerobic fermentation of the aqueous component, which has a high biochemical oxygen demand (BOD), has been suggested as a mean of solving this problem [10]. Although the solid residue does not present such a serious environmental problem, the option of producing a clean gaseous fuel composed of a residue that can be used as a fertiliser rich in nitrogen should be well thought out [11]. The global annual olive pomace production has been estimated at around 400 million tons on a dry basis [8].

For the management of mill solid wastes, some solutions have already been explored in the literature [10,12]: animal feed, biogas production, extraction of useful materials and fertilisers. Pelletising residue olive oil to increase the density and energy was also investigated. However, this solution is affected by the high oil content of the pomace, which reduces the quality of the pellets [13].

Biomass combustion is one of the most promising ways to reuse it, however it is necessary to consider the limits due to the low thermal efficiency of olive pomace [13]. In the literature, several studies have been reported on the combustion of olive mill wastes for energy production, alone or in combination with other fuels. Miranda et al. [14] investigated the combustion characteristics of solid mill waste (kernels, pulp and olive pomace) with different proportions of semi-solid waste (such as mill wastewater). Their results showed that the combustion of olive stones and olive-pomace gives a good efficiency and a reduced presence of non-combusted components, while lower combustion efficiencies were obtained in the case of pulp. Atimtay and Topal [15] have estimated co-combustion of various blends of olive pomace with lignite coal using various excess air ratios. Their study showed that with an air ratio of 40%–50%, considerable amounts of CO and non-fuelled hydrocarbons are formed, and the combustion efficiency drops to 84%–87%. According to the results, the combustion efficiency increased with an increasing excess air ratio. The authors suggested the addition of secondary air within the freeboard to improve the efficiency of the combustion process. This solution was also considered by Varol and Atimtay [16]. Combustion efficiencies in the range of 83.6%–90.1% were obtained from olive pomace.

The potential utilisation of solid olive mill wastes in combined heat and power (CHP) plants has been investigated by several authors [17–20] who highlighted the economic viability of such plants. The organic Rankine cycle (ORC) is one of the preferred and most studied CHP systems because of its reliability, versatility and low maintenance needs [21]. The ORC system can be considered a valuable application, also because the combustion is external with respect to the power generation system and unrelated to the features of the fuel.

The working fluid plays a key role in the ORC process. Organic fluids have higher pressures and lower boiling points compared to steam and since most of them are dry or isentropic fluids they do not require superheating before expansion [22]. Many studies have been carried out to select the best working fluids. Liu et al. [23] discovered that some working fluids at specific evaporations and condensation temperatures showed a similar thermal efficiency and the thermal efficiencies were found to increase with the critical temperature of the working fluid. Wang et al. [24] analysed the performance of the ORC system with different working fluids and showed that R245fa and R245ca are the most environment-friendly working fluids. Cataldo et al. [25] proposed to choose the fluid which has a low value of critical temperature and a high value of the latent heat of vaporisation. However, no single pure fluid has been found as optimal for the ORC due to the strong interdependence between the optimal working fluid, the working conditions and the cycle architecture [21].

Another important aspect to take into account is the heat transfer efficiency of the evaporator [26]. The pinch point temperature difference is often used to analyse the coupling heat transfer in the evaporator. Chen et al. [27] suggested a method to optimise the operating parameters of an ORC with a constrained inlet temperature of the heat source and the pinch point temperature difference in the evaporator.

The growing energy consumption of the agricultural field requests a fast evolution of the technologies aimed to biomass waste energy conversion because the application of more sophisticated processes and technologies within the chain of the agricultural and food industries requests more and more resources [28,29].

The aim of the present work is to evaluate the potential of olive pomace produced in a mill located in Central Italy as an energy resource, which represents the considered case study, whose combustion feeds an ORC unit combined with an absorption chiller. After the preliminary analysis of the biomass waste, the energy performance achieved by a small size CCHP ORC system powered by olive pomace combustion was investigated, considering various working fluids and different operating conditions.

2. Materials and Methods

2.1. Raw Materials

The olive pomace considered for the study derives from an Italian mill, located in Province of Rieti northeast of Rome. Composition and lower calorific value of the olive pomace has been evaluated, to determine a possible use as biofuel. Olive pomace (OP) samples at different stages (S1, S2, . . . , S5) were taken, and for each stage, the analysis was carried out both on the surface of the olive pomace and at 25 cm depth inside the olive pomace. The first stage was the period between the olive pomace production and two weeks afterwards. The second stage began at the end of the first stage and lasted for two weeks. The third stage began at the end of the second stage and lasted two weeks as well. In Table 1, the results of the samples analysis during the first and the third stage are reported because only the conditions at the beginning and at the end of the ripening process were of interest for our study.

Table 1. Biomass proximate and ultimate analysis.

Biomass		Proximate Analysis (%wt, Dry Basis)			Ultimate Analysis (%wt, Dry Basis)				LHV (MJ/kg)	HHV (MJ/kg)	Moisture (%wet)
		Ash	Volatile Matter	Fixed Carbon	C	H	N	O			
S1	OP surface 1st stage	2.9	78.1	19	50.86	8.22	1.20	36.82	21.86	23.55	18.00
S2	25 cm OP depth 1st stage	3.3	77.9	18.8	51.96	8.49	1.46	34.79	22.71	24.45	19.00
S3	OP surface, 3rd stage	3.8	77.6	18.6	52.90	8.94	2.54	31.82	23.75	25.59	14.6
S4	OP surface, 3rd stage	3.6	77.7	18.7	58.28	8.92	2.35	26.85	26.13	27.97	17.4
S5	25 cm OP depth, 3rd stage	3.5	77.6	18.9	56.73	8.13	2.92	28.72	24.62	26.30	16.8

Biomass samples were analysed according to the principles of the standard ISO 18134-1:2015 [30], and moisture content values of the samples were determined. Ash content values were determined according to the standard of ISO 18122:2016 [31].

Hydrogen, nitrogen and carbon concentrations on a dry basis were determined according to ISO 16948:2015 which describes the method for the determination of total carbon, hydrogen and nitrogen contents in solid biofuels [32]. The Lower Heating Value (LHV) was calculated for each sample of olive residue analysed, starting from the Higher Heating Value (HHV) and hydrogen content, and, in particular, the HHV was determined using the following formula [33]:

$$HHV = 0.3941\ C + 1.1783\ H + 0.1005\ S - 0.1034\ O - 0.0151\ N - 0.0211\ Ash \quad (1)$$

The abovementioned analysis results include both higher and lower heating values of the samples of biomass and results of the proximate and ultimate analyses of the olive pomace under investigation.

After the days elapsed between the first stage and the third stage, the contact with air (sample 3 and sample 4) eased the fermentation process which degraded the chemical and physical properties of biomasses. This is the reason why the ash content in sample 2 increased compared to sample 1 and then decreased in the following ones. Sample 4 had the highest C% concentration because of the presence of fungus and microorganisms from fermentation despite the increment of the ash content.

2.2. Combustion Process Model

For the model developed in the present study, the Aspen Plus process model simulator was used. The following assumptions were considered for the simulation:

- the process is steady-state and isothermal [34];
- drying and pyrolysis take place instantaneously and volatile products mainly consist of H_2, CO, CO_2, CH_4 and H_2O [35,36];
- char is 100% carbon [37];
- all gases behave ideally.

The flowsheet of the simulation, developed in Aspen Plus, is shown in Figure 1.

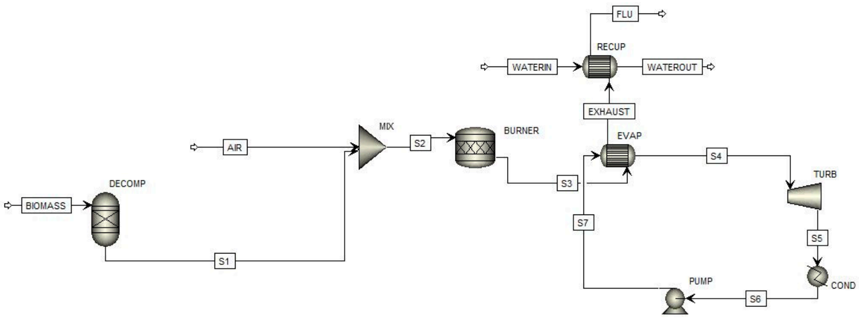

Figure 1. Flowchart of the plant evaluated in this study.

The stream BIOMASS was considered a non-conventional stream, as defined by its proximate and ultimate analysis. The BIOMASS stream goes to the RYIELD reactor used to simulate the decomposition of the unconventional feed into its conventional components (carbon, hydrogen, oxygen, sulphur, nitrogen, and ash by specifying the yield distribution according to the biomass ultimate analysis in Table 1 [1]. Off-products from DECOMP move into a mixer MIX in order to add the oxidising fluid, composed of pure air, to the combustible, and then the resulting mixed stream S2 goes into the BURNER, which simulates the combustion process. The fumes out of the combustor move to the ORC, composed of an evaporator called EVAP, a turbine called TURB, a condenser called COND and a pump called PUMP. The exhausted fumes out of the EVAP move into an exchanger called RECUP that generates the cogeneration effect: the heat from the fumes heats up a mass of water until a fixed value is reached.

Equations (2)–(7) are the chemical reactions considered in this work for the combustion process [38].

$$C + 2H \rightarrow CH \tag{2}$$

$$C + O \rightarrow CO \tag{3}$$

$$C + 0.5O \rightarrow CO \tag{4}$$

$$H + 0.5O \rightarrow H\,O \tag{5}$$

$$N + 3H \rightarrow 2NH \tag{6}$$

$$CH + 2O \rightarrow CO + 2H\,O \tag{7}$$

The following Table 2 showed the Aspen units of the flowchart presented in Figure 1.

Table 2. Description of Aspen Plus flowsheet unit operation presented in Figure 1.

Aspen Plus Name	Block ID	Description
RYIELD	DECOMP	Yield reactor—converts the non-conventional stream "BIOMASS" into its conventional components
MIXER	MIX	Mixer—mixes oxidising fluid with S1 stream, which represents combustible fluid
RSTOIC	BURNER	Rstoic reactor—simulates the combustion process
HEATX	EVAP	HeatX—represents the evaporator of the ORC
-	RECUP	HeatX—heats up the temperature of the water until the utilisation level is reached
TURBINE	TURB	Turbine—represents the turbine of the ORC
HEATER	COND	Heater—represents the condenser of the ORC
PUMP	PUMP	Pump—represents the pump of the ORC

2.3. ORC-Based CCHP System Model

The CCHP is composed of an ORC system coupled with an absorption chiller aimed at cooling. In particular, the ORC is composed of the evaporator (EVAP), condenser (COND), turbine (TURB) and pump (PUMP). Low-boiling working fluid is pressurised in the pump and then flows into the evaporator. Within the evaporator, the working fluid receives heat from the combustion process and evaporates. After the vaporisation of working fluid, it moves into the turbine and a mechanical power is then produced by means of expansion. Finally, the working fluid is cooled within the condenser at a low pressure of the cycle, and the pump restarts the cycle again. The assumptions of the present evaluation are reported in Table 3 [24], and the pressure drops within the thermodynamic cycle are shown in Table 4 and vary depending on the working fluid.

Table 3. Organic Rankine cycle (ORC) system conditions.

Heat source temperature (°C)	500
Heat source mass flow rate (kg/h)	200
Isentropic efficiency of turbine	0.85
Mechanical efficiency of turbine	0.75
Isentropic efficiency of pump	0.80

Table 4. Selected working fluids for organic Rankine cycle.

Working Fluid	Fluid Type	Condensing Pressure at 30 °C (bar)	Critical Temperature (°C)	Critical Pressure (bar)	ODP
R245fa	Isentropic	1.77	154.29	36.50	0
R245ca	Isentropic/dry	1.21	174.58	39.30	0
Cyclobutane	Isentropic	1.83	187.05	49.88	0
Cyclopentene	Isentropic/dry	0.61	234.11	48.05	0

The Aspen Plus model simulated the operations of the CHP system and the available and residual downstream exhaust thermal power was converted into cooling power by means of a Yazaki absorption chiller and determined by means of its COP (coefficient of performance) declared by the manufacturer.

The performance of the system is strictly dependent on the properties of the working fluid which can be typically categorised as dry, isentropic and wet according to the slope of the saturation curve in an S-T diagram. It can be respectively positive, infinite or negative. The dry or isentropic working fluids allow to avoid the superheating, which is usually needed to prevent the impingement of liquid droplets on the turbine blades, increasing the economic efficiency of the ORC systems [24]. For this simulation, dry and isentropic organic fluids are chosen. The adopted criteria for the fluid selection were: trifling ozone depletion potential (ODP), higher critical temperature and higher critical pressure. In this way, fluorinated alkanes such as R245fa and R245ca were selected for their application in many operating plants nowadays. Then, cyclobutene and cyclopentene were selected for the critical parameters fit to the range of the heat source temperatures [38]. The characteristics of the working fluids used in the simulation are reported in Table 4 [39].

Finally, the considered absorption chiller is a 35 kWc and 0.7 COP Yazaki WFC SC 10 which receives part of the exhaust thermal power. The available exhaust thermal power is overabundant with respect to the 50 kWth thermal power required by the Yazaki unit. The functional scheme of the overall system has been shown in Figure 2.

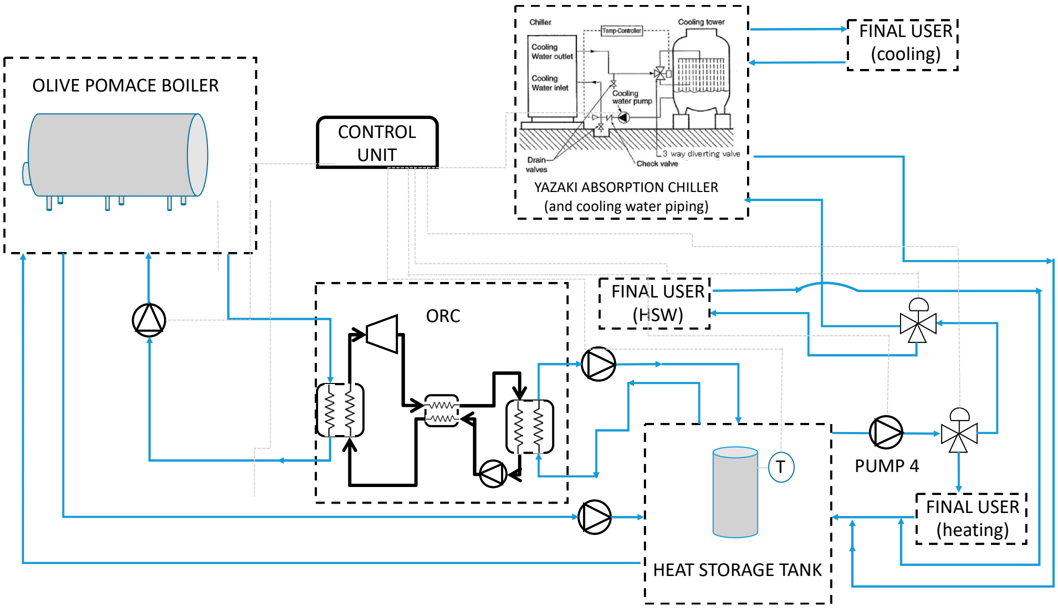

Figure 2. Functional scheme of the ORC-based trigeneration system.

3. Results and Discussion

3.1. Combustion Products

The examined mill produces 200,000 kg of olive pomace per year. As a consequence, 5000 h of operation per year have been considered with a biomass flow rate consumption of 40 kg/h. The process parameters of the burner are 500 °C and 1 bar.

3.2. Mechanical, Thermal and Electrical Efficiencies

The first results of the simulation are reported in Table 5, showing the comparison of the working fluids analysed in terms of 5 system performance. The thermal duty Q of the combustion product (stream S3) is equal to 75 kW, and for each working fluid, the thermal duty Q of the exhausted fumes out of evaporator (stream EXHAUST), the power P produced from the expansion in turbine and the mechanical and thermal efficiency of the cycle η and η, respectively, were investigated, varying the pressure of the pump. Then η is calculated according to Equation (8), where p_{pump}(bar) is the pressure of the pump, ΔP_{pump} (kW) is the power required by the pump, P (kWe) is the electrical power produced and Q_{evap} (kW) is the thermal power required by the evaporator. Then η is calculated according to Equation (9). η is calculated considering an alternator efficiency equal to 0.97 [40].

$$\eta_{mecc} = \frac{P_{expansion} - W_{pump}}{Q_{evap}} \tag{8}$$

$$\eta_{therm} = \frac{Q}{Q_{source}} \tag{9}$$

Table 5. Comparison of the working conditions of the selected working fluids.

p_{pump} (bar)	R245fa		R245ca		Cyclobutene			Cyclopentene		
	20	**30**	**20**	**30**	**20**	**30**	**40**	**20**	**30**	**40**
$Q_{exhaust}$ (kW_{th})	65.41	65.22	61.91	61.20	64.00	63.20	63.00	61.00	59.30	59.00
ΔP_{pump} (kW)	0.21	0.31	0.19	0.28	0.37	0.57	0.78	0.36	0.56	0.75
$P_{expansion}$ (kW)	3.62	4.01	4.52	5.01	4.33	5.00	5.30	5.92	6.51	6.93
P_{el} (kW_e)	3.41	3.80	4.30	4.85	4.17	4.85	5.12	5.72	6.30	6.68
η_{mecc}	13.10%	14.51%	14.34%	15.60%	14.91%	16.72%	17.80%	17.80%	19.00%	20.00%
η_{therm}	70.30%	70.00%	66.60%	65.81%	68.81%	68.00%	68.00%	65.00%	63.70%	63.52%
η_{el}	12.77%	14.10%	13.93%	15.12%	14.41%	16.20%	17.20%	17.20%	18.40%	19.40%

From the comparison of the working fluid conditions, shown in Table 5, it is possible to ascertain that the mechanical power release by the turbine is comprehended between 3.62 kW and 6.9 kW, depending on the organic fluid used and the pressure of the pump. The lower value is 3.62 kW for the R245fa at 20 bar of pump pressure, and the highest value is 6.9 kW for the cyclopentene at a pump pressure of 40 bar. The mechanical efficiency varies from a minimum of 13.1% for the R245fa at a pump pressure of 20 bar to a maximum of 20% for the cyclopentene at a pump pressure of 40 bar. The thermal efficiency ranges between 63.5% to 70.3%, where the minimum value is for the R245fa at 20 bar of pump pressure, and the maximum one is for the cyclopentene at 40 bar pump pressure. Furthermore, Q is enough to allow a small size cogeneration.

3.3. Sensitivity Analysis

A sensitivity analysis is carried out in order to evaluate the impact of the pressure pump on the trends of the mechanical and thermal efficiency for each working fluid considered. The trends resulted from the simulation are showed in Figures 3–6.

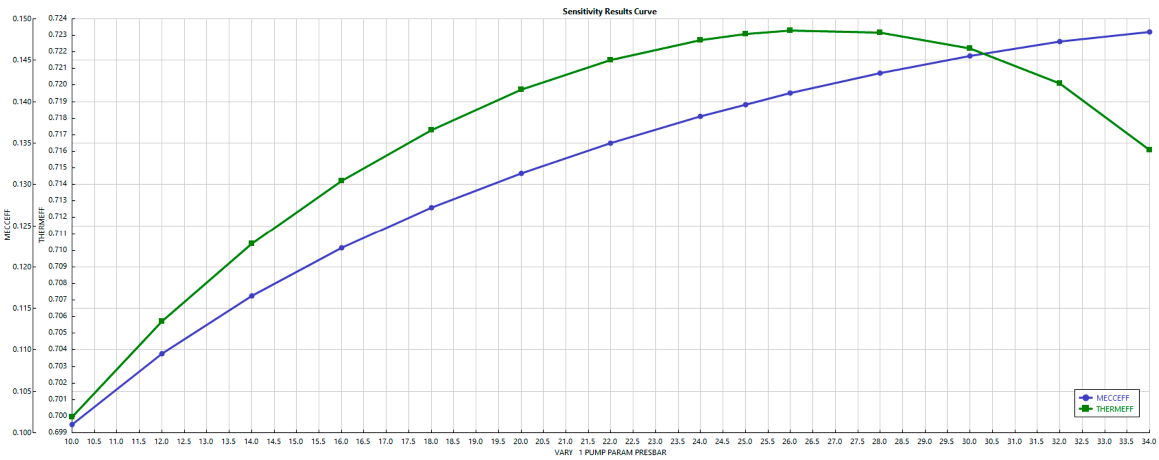

Figure 3. Mechanical and thermal efficiency vs. operating pressure. R245FA.

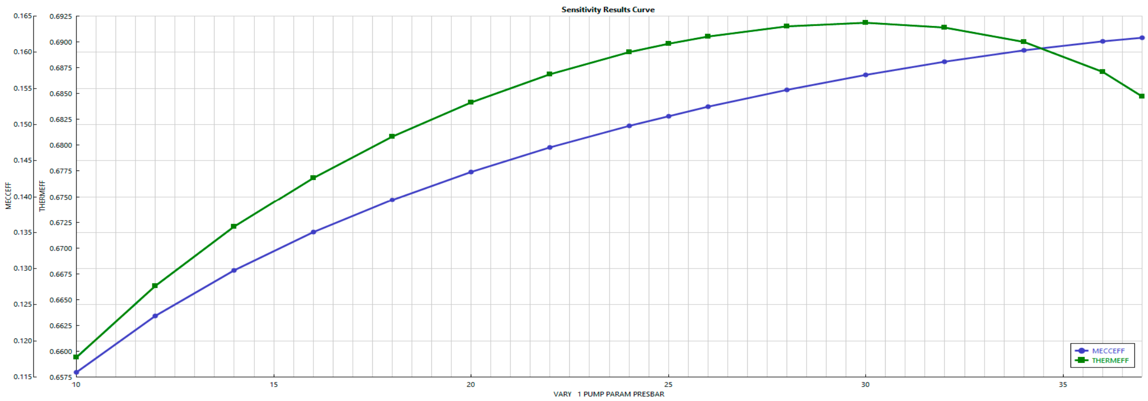

Figure 4. Mechanical and thermal efficiency vs. operating pressure. R245CA.

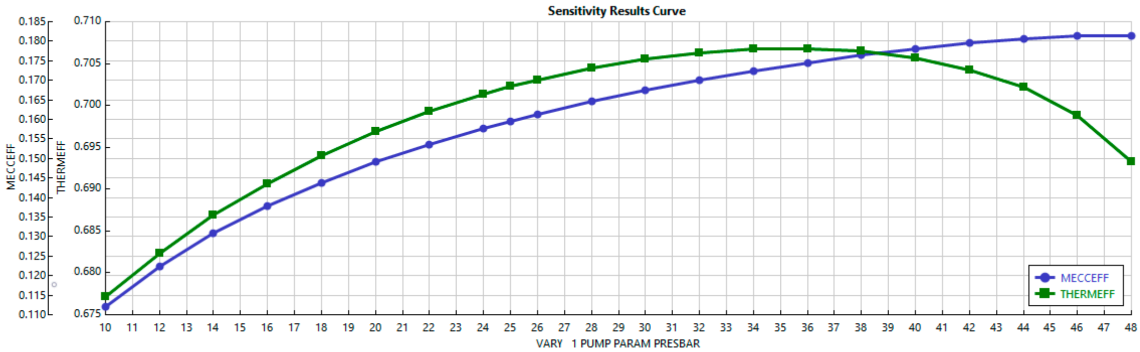

Figure 5. Mechanical and thermal efficiency vs. operating pressure. Cyclobutene.

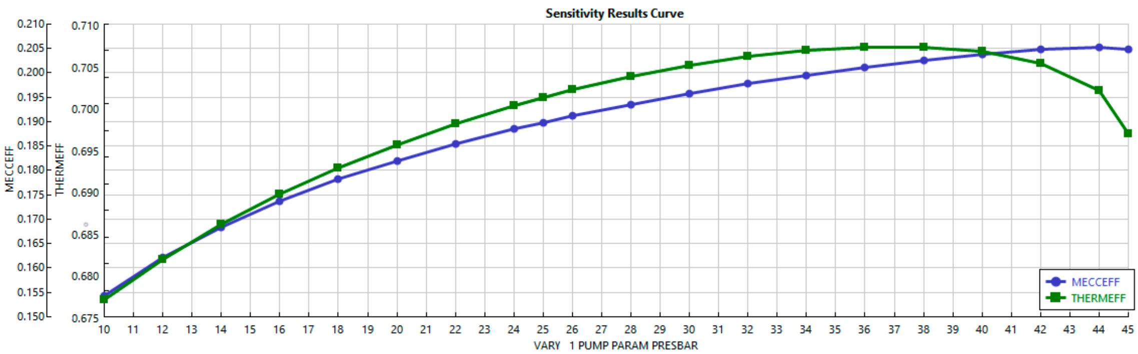

Figure 6. Mechanical and thermal efficiency vs. operating pressure. Cyclopentene.

Figures 3–6 shows a crescent trend for the mechanical efficiency with the rise of the cycle operating pressure included between 10 bar and the critical pressure for each considered working fluid. Instead, the thermal efficiency shows a crescent trend until a maximum is reached and after that a decreasing trend. In the cases of R245fa and R245ca, the mechanical efficiency increases from 10 bar to the critical pressure. In case of Cyclobutene, the efficiency is stable for a pressure higher than 46 bar and, in the case of Cyclopentene, the maximum of mechanical efficiency is reached at 44 bar and decreases between 44 and 45 bar.

3.4. Proposed Scenario

Considering operations of 5000 h/year, the working period could be split between hot season (from June to September), cold season (from 15th of November to 15th of April according to the relevant Italian decree [41]) and middle season (all other months). During the cold season, the thermal power Q from the exhaust stream could be used for heat uses as industrial processes, hot sanitary water, and space heating. During the hot season, it has been mostly considered as the thermal input to a Yazaki absorption chiller unit aimed to address the cooling needs. The remaining thermal power can be used for residual heat uses. The two scenarios proposed are reported in Tables 6 and 7, where Q (kWth) is the thermal power required for the cooler, P (kW) is the electrical power produced from the cooler, Q (kW) is the thermal power available for heating water and W (kg/h) is the flow rate of heated water.

Table 6. Hot season proposed scenario.

Working Fluid	**R245fa**		**R245ca**		**Cyclobutene**			**Cyclopentene**		
p_{pump} (bar)	**20**	**30**	**20**	**30**	**20**	**30**	**40**	**20**	**30**	**40**
$Q_{exhaust}$ (kW_{th})	65.41	65.22	61.91	61.2	64	63.2	63	61	59.3	59
$Q_{chiller\_feeding}$ (kW_{th})	50	50	50	50	50	50	50	50	50	50
$P_{cooling}$ (kW_e)	35	35	35	35	35	35	35	35	35	35
Q_{heat_use} (kW_{th})	15.41	15.22	11.91	11.2	14	13.20	13	11	9.30	9
W_{water} (kg/h)	205	202	159	149	186	176	173	146	124	120

Table 7. Cold season proposed scenario.

Working Fluid	**R245fa**		**R245ca**		**Cyclobutene**			**Cyclopentene**		
p_{pump} (bar)	**20**	**30**	**20**	**30**	**20**	**30**	**40**	**20**	**30**	**40**
$Q_{exhaust}$ (kW_{th})	65.41	65.22	61.91	61.20	64	63.20	63	61	59.30	59
W_{water} (kg/h)	870	868	824	815	852	841	838	812	789	785

The results of the present case study indicated that the proposed approach is suitable for the energy supply of a farm, considering the yearly production shown in Table 8. As discussed, the use of different working fluids changes the distribution between thermal and electric energy. The cooling energy produced is the same because it was obtained by the combination of operating hours and the cooling power supplied by the absorption chiller. The latter is equal to the nominal cooling power of the absorption chiller as the thermal power feeding the absorber is always major than the required thermal power. The COP considered is also the nominal one. This representation of energy use can be different according to the energy consumption profiles depending on the kind of activity. The cooling energy production has been determined only for the hot season as for a residential user even if it could be differently distributed along the year according to possible industrial processes requiring cooling energy during the entire year. Table 8, regarding the yearly energy productivity of the CCHP system, shows that the Cyclopentene differs from the others in terms of the electric energy production. As a consequence, the thermal energy available for heating uses is smaller.

Table 8. Yearly energy production.

p_{pump} (bar)	**R245fa**		**R245ca**		**Cyclobutene**			**Cyclopentene**		
	20	**30**	**20**	**30**	**20**	**30**	**40**	**20**	**30**	**40**
Electric energy (MWh_e)	17	19	22	24	21	24	26	29	32	33
Thermal Energy (MWh_{th})	195	194	180	177	189	185	184	176	169	167
Cooling Energy (MWh_e)	58	58	58	58	58	58	58	58	58	58

4. Conclusions

In this work, the chemical composition and energy performance of the olive pomace has been analysed, showing a good value of LHV (around 22 MJ/Kg) and good values of the proximate and ultimate analysis. A trigeneration system composed of an ORC unit, powered by a biomass boiler, developed in Aspen Plus and coupled with an absorption chiller was investigated with different working conditions. Four dry/isentropic organic fluids were considered for their negligible ozone depletion potential, higher critical temperature and critical pressure, and a sensitivity study was carried out in order to determine the mechanical, thermal and electrical efficiency of the plant at varying operative conditions for each working fluid. The minimum and maximum level obtained whilst varying the organic fluid and the pressure of the pump were 13.1%–20.0%, 63.5%–70.3% and 12.7%–19.4% for mechanical, thermal and electrical efficiency, respectively. Furthermore, a heat recovery of the exhaust gas out of the evaporator was managed in order to heat up an amount of water (120 kg/h) to 85 °C temperature and feeding a 35 kWc absorption chiller. The present analysis deepened the coupling between an ORC CCHP system and olive pomace for the first time in the literature and lead to the conclusion that this biomass waste can be an effective and available by-product of the olive oil production process suitable for an energy-from-biomass-waste trigeneration system. In particular, the most important findings of the present work were:

- At a national level, considering an olive pomace production ratio of 2250 kg/ha and about 1052000 ha of Italy being occupied with olive trees aimed at oil production in 2017 [42], the energy potential of this energy system would be of 5.9 GWh, 31.1 GWh and 10.7 GWh, corresponding to a 0.286 Mtoe (Million Tonnes of Oil Equivalent) in terms of primary energy, which would give an important contribution to the overall primary energy national production.
- The triple energy could be used within the agricultural chain, representing a virtuous case of distributed generation.
- At a local level, the developed model shows that Cyclopentene is the most highly performing fluid in terms of electricity production, while R245fa is the least.
- The increasing pressure entails an energy benefit in terms of power production and electric efficiency, but the increasing trend is slower at the highest pressures of the considered range.

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