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A tri-generation plant fuelled with olive tree pruning residues in Apulia: an energetic and economic analysis.

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Abstract

This paper presents the energetic and economic analysis of a virtuous example consisting of a tri-generation system fuelled only with olive tree pruning residues and planned to be located next to Bari Airport (Apulia, Italy). The main goal is to demonstrate the feasibility and convenience of producing cooling, heating and electrical power from olive tree pruning residues in those regions characterized by a high availability of this kind of biomass, such as Apulia. A strategic location was selected, namely Bari Airport (Apulia), and this paper demonstrates the economic convenience of installing a commercially available Organic Rankine Cycle (ORC) unit of 280 kW_e that is capable of satisfying the thermal demands of the airport, with the addition of an absorption chiller for air conditioning in the airport buildings. First it is verified that the quantity of olive tree pruning residues available in the area surrounding the airport fully can satisfy the plant demand of feedstock. Then a detailed description of the components of the plant is provided. The performance of the plant is therefore evaluated in order to assess the thermodynamic competitiveness of a tri-generative system fuelled with this type of biomass. Finally, a detailed economic analysis is carried out with the aim of demonstrating the advantages that the plant can assure in terms of payback period (PBP), net present value (NPV) and internal rate of return (IRR). Two different typologies of government incentives are considered. In both of which, the PBP is 6 years with an IRR of about 21% and this points out the great economic attractiveness of the project. From an ecological point of view, the plant can ensure a remarkable reduction in CO₂ emissions.

28 *Keywords*

29 Agricultural residues, tri-generation, Organic Rankine Cycle, economic analysis.

30

31 **Nomenclature**

a	<i>potential availability of residues</i>	
C_c	<i>chipping cost</i>	$[\text{€}/\text{t}]$
C_f	<i>fuel cost required for the transportation</i>	$[\text{€}/\text{t}]$
$C_{\text{feedstock}}$	<i>overall cost for feedstock procurement</i>	$[\text{€}/\text{year}]$
C_h	<i>harvesting cost</i>	$[\text{€}/\text{t}]$
C_l	<i>cost for loading and unloading the feedstock</i>	$[\text{€}/\text{t}]$
C_t	<i>transportation cost</i>	$[\text{€}/\text{t}]$
f	<i>pruning frequency per year</i>	
H_{dry}	<i>lower heating value of dry biomass</i>	$[\text{kcal}/\text{kg}]$
H_i	<i>lower heating value of wet biomass</i>	$[\text{kcal}/\text{kg}]$
h	<i>enthalpy</i>	$[\text{kJ}/\text{kg}]$
P	<i>pressure</i>	$[\text{bar}]$
P_{el}	<i>total electrical power</i>	$[\text{kW}]$
P_m	<i>weight of the feedstock transported</i>	$[\text{t}]$
Q_c	<i>total useful cooling power</i>	$[\text{kW}]$
Q_{ol}	<i>mass of olives per year</i>	$[\text{t}/\text{year}/\text{hectare}]$
Q_{pr}	<i>mass of wet by-product (pruning residues)</i>	$[\text{t}/\text{year}/\text{hectare}]$
Q_{th}	<i>total useful thermal power</i>	$[\text{kW}]$
T	<i>temperature</i>	$[\text{°C}]$
U	<i>percentage of humidity</i>	
Y	<i>ratio of the by-product to the olive yield</i>	
$\dot{m}_b$	<i>mass flow rate of fuel</i>	$[\text{t}/\text{year}]$
η_{el}	<i>overall electrical efficiency</i>	
η_g	<i>total efficiency</i>	

Acronyms

<i>CCP</i>	<i>combined cooling and power</i>
<i>CHP</i>	<i>combined heating and power</i>
<i>CCHP</i>	<i>combined cooling, heating and power</i>
<i>IRR</i>	<i>internal rate of return</i>
<i>NPV</i>	<i>net present value</i>
<i>PBP</i>	<i>payback period</i>

32

33 **1. Introduction**

34 For over twenty years, governments have taken a number of actions to solve the environmental problem
35 concerning greenhouse gas emissions and global warming caused by the excessive consumption of fossil

36 fuels. Energy policies implemented to date have been promoting renewable energy exploitation, providing
37 full support by means of a number of incentives [1]. Such policies have already led to a significant change in
38 the energy mix, which is continuously replacing conventional fuels with renewable energy sources. European
39 countries planned to meet the 2020 targets on renewable energies thanks to such a relevant paradigm shift in
40 renewable energy exploitation [2]. Biomass is a form of renewable energy that can effectively be utilized to
41 reduce the impact of the energy production from fossil fuels on the global environment and can be converted
42 into useful forms of energy by using different processes. Several techniques, plants and devices for
43 extracting energy from waste biomass are available. The techniques for energy extraction from waste
44 biomass can be grouped in the following “families”: Combustion, Pyrolysis/Gasification, Bio-processing.
45 Biomass energy systems can generally provide several advantages such as a low carbon footprint and a lower
46 delivered energy cost compared to fossil fuels. In biomass-fuelled power plants the electricity generation is
47 usually coupled with the production of heating and/or cooling with the aim of increasing the overall
48 efficiency, since the electrical efficiency is low in the plants fuelled with biomass.

49 Despite the energetic use of agricultural wastes can play an important role in reducing the consumption of
50 fossil fuels, such a practice is not so widespread as expected in those regions having large availability of
51 agricultural residues [3]. This paper is focused on a particular type of agricultural residues largely diffused in
52 farms of the Mediterranean region, namely olive tree pruning residues, and aims to demonstrate that their
53 energetic use can be very profitable in a tri-generation system, also thanks to the recent advances both in the
54 tri-generation technology and in mechanical and management systems for harvesting, packaging and
55 transportation [4]. It is planned to realize the tri-generative power plant in a region having a large quantity of
56 oil olive crops, namely Apulia (south of Italy). The plant will be capable of satisfying the entire thermal and
57 cooling demands of the buildings of Bari Airport as well as part of the electrical energy required by the
58 Airport.

59 This paper aims to assess the feasibility and profitability of this system for tri-generation from the direct
60 combustion of olive tree pruning residues. As starting point the availability of biomass in Apulia, particularly
61 in the zone nearby the plant location, is quantified and compared with the needed amount of feedstock for the
62 plant operation. Then the components of the proposed tri-generative plant are described in details. A
63 thorough economic analysis is finally exposed in order to evaluate the economic convenience of the project.

64 In conclusion an estimation of the annual quantity of CO₂ that can be saved by the proposed plant is also
65 provided.

66 2. The agro-energetic Apulian model

67 *2.1 Potential of olive tree pruning residues for energy generation in the Mediterranean region*

68 The simultaneous generation of electricity, heating and cooling from olive tree pruning residues in tri-
69 generative plants can be instrumental in increasing energy production from renewable sources. The Apulian
70 context best fits this objective, by virtue of the high percentage of cultivated fields of olive trees and the
71 consequential great quantity of pruning residues that are usually unemployed and burned on fields.

72 In the European Community, olive groves are mostly present in the Mediterranean region. In fact,
73 Mediterranean countries, led by Spain, produce 10 million tons of olives per year, which is 75% of the world
74 production [5]. The Italian cultivation of olive trees is diffused above all in southern and insular regions
75 where about 80% of the Italian production of olives and oil olive is obtained. As a matter of fact, the Italian
76 region having the greatest extension of olive cultivated land is Apulia with 377.550 hectares, followed by
77 Calabria (194.887 ha) and Sicily (161.967 ha). Ever-increasing advances and research studies on the olive oil
78 production technology demonstrate the importance of olive oil production upon Italian economy [6].

79 Every year, in these zones, farmers have the problem of disposing, at their own expenses, of tons of pruning
80 residues. In [7], the management of pruning residues is considered: the authors argue that pruning residues,
81 despite having generally represented a disposal problem, can become a real opportunity for additional
82 revenue if an energy recovery of such wastes is performed, using them as fuels for energy production; thus,
83 in addition to eliminating the problem of disposal, the future commercialization of such agricultural wastes
84 can be a source of income rather than a cost for farmers.

85 In the past, the inefficiency and low availability as well as the high costs of harvesting machines were all
86 limiting factors in exploiting tree pruning residues. A large part of such residues was usually burned on
87 fields, while only the thickest branches were recovered by farmers and used as fuel-wood [8, 9]. A change in
88 farmers' mentality is now possible by virtue of recent advances in designing harvesting machines, which are
89 more reliable and efficient than in the past, thus allowing farmers to be able to perform collection and
90 harvesting processes effectively in terms of cost and time. In this regard, new industrial pruning harvesters

capable of overcoming the limits of common small units were tested in [7], showing that the introduction of the industrial technology can be instrumental in increasing the energetic use of pruning residues. More effective strategies in managing such residues can help farmers better exploit older and smaller size machines, especially in small farms and in those groves where steep terrain and/or irregular spacing do not allow the profitable use of large industrial harvesting units [7].

2.2 Availability of feedstock and plant demand

This section aims to assess whether the availability of raw material meets the requirements of the plant presented here, which is going to be realized at Bari Airport.

It should be noted that the by-product present on a field cannot entirely be used for energetic valorisation because of the permanence time on the field and weather conditions during the harvesting as well as the plot of the land (dimension and form). In order to evaluate the net potential availability of olive tree pruning residues in Apulia accounting for all of these factors, a valid calculation method was recently proposed in [10, 11]. This method quantifies the quantity of olive tree pruning residues per hectare per year by means of the following equation:

$$Q_{pr} = Q_{ol} \frac{Y}{f} \cdot \frac{a}{100} \quad (1)$$

where Q_{pr} (t/year/hectare) is the mass of wet by-product (pruning residues) per hectare that is yearly obtainable, Q_{ol} (t/year/hectare) is the mass of olives per year obtained in the field, Y is the ratio of the overall by-product to the overall olive yield, f is equal to the pruning frequency per year and a is the potential availability (%) that takes into account the characteristics of harvesting techniques and field as well as climatic conditions.

Once coefficients a and f are known, equation (1) allows calculating the precise value of Q_{pr} achievable from a specific zone, provided that factor Y is properly estimated. To accomplish this task, two equations have been retrieved in [10], specifically one for the provinces of Bari and Foggia and the other one for the provinces of Lecce, Brindisi and Taranto. These formulations calculate the by product/product ratio, Y , as a function of the yield of olives, Q_{ol} (expressed in t/year/hectare):

$$Y = 0,566 + \frac{1,496}{Q_{ol}} \text{ for Bari and Foggia} \quad (2)$$

$$Y = 0,365 + \frac{1,401}{Q_{ol}} \text{ for Taranto, Lecce and Brindisi} \quad (3)$$

Using Equations (1), (2) and (3), it is possible to depict the regional map of the net pruning residues available per year, as shown in Fig.1. In addition, Fig.1 shows their energetic potential (expressed in tep/year), which was obtained by multiplying Q_{pr} and the lower heating value (H_i) calculated through equation (4):

$$H_i = H_{dry} \left(1 - \frac{U}{100} \right) \quad (4)$$

where H_{dry} is the lower heating value of dry biomass (kcal/kg) and averages 4200 kcal/kg for pruning residues, U is the average humidity percentage present in the residuals collected on the field. This approach has general validity and can be applied to other zones of Italy as well as other European countries, provided that coefficients a , U and f , along with the relation between Y and Q_{ol} , are tuned in relation to the specific zone.

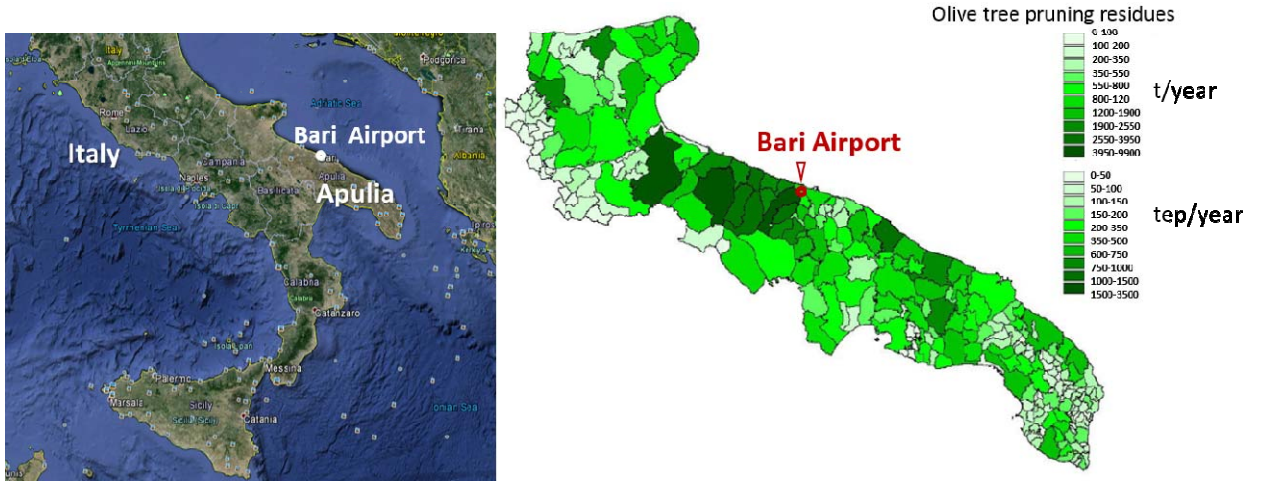


Figure 1: Plant location along with the distribution of olive pruning residues (t/year) and their energetic potential (tep/year) in Apulia.

The plant has been designed to ensure an electrical power (P_{el}) of about 280 kW. Using the expression of the electrical efficiency (η_{el}) and knowing the lower heating value of the fuel, the quantity of biomass needed for the plant operation covering a period of a year can be retrieved from the analytical expression of η_{el} :

$$\eta_{ei} = \frac{F_{ei}}{\dot{m}_b H_i} \quad (5)$$

129 where $\dot{m}_b$ denotes the fuel mass flow rate. Considering that the plant is expected to operate 8000 hours per
 130 year and that its electrical efficiency is equal to 11,2% (as reported in the following section), and assuming
 131 the lower heating value of pruning residues present on fields equal to 2540 kcal/kg (according to equation 4
 132 and assuming 40% humidity remained in residuals on fields), it results that $\dot{m}_b$ is equal to 6800 t/year.
 133 Such a feedstock demand must fully be satisfied by the farms surrounding the airport. In this regard, Table 1
 134 reports the production of tree pruning residues in the municipalities nearest the plant location (average
 135 distance < 20 km), along with their average distances from the plant. The quantities of pruning residues in
 136 each municipality were calculated by multiplying the hectares of land covered by olive trees and the value of
 137 Q_{pr} resulting from equation (1). The total production of pruning residues resulting from Table 1 is 12.656,02
 138 t/year, which is well above the plant demand, thus demonstrating that a very small area is sufficient to fully
 139 satisfy the plant demand. In particular, the complete production of tree pruning residues in Modugno (569,47
 140 t/year), Bari (771,18 t/year) and Bitonto (4.986,49 t/year) together with a small part of the production in
 141 Giovinazzo (472,86 t/year) are capable of satisfying the annual demand of the plant. Only taking into
 142 account these four municipalities, the average distance from the plant can be calculated as a weighted mean
 143 (in which the weights are the quantity of tree pruning residues) and results to be equal to 10,1 km.

Town	Tree pruning residues production (t/year)	Average distance (km)
Modugno	569,47	9
Bari	771,18	10
Bitonto	4.986,49	10
Giovinazzo	1.937,61	13
Bitetto	1.292,99	15
Bitritto	423,23	15
Binetto	337,58	18
Palo	2.337,47	15
Tot	12.656,02	-

Table 1: Tree pruning residues production in the nearest municipalities and their distances from the plant

3. DESCRIPTION OF THE PLANT

3.1 Electrical and thermal demands of the airport

The designed plant is a tri-generative system employing a commercially available ORC for simultaneous production of electricity and useful heat combined with an absorption chiller used to generate chilled water for air conditioning. Figure 2 depicts the thermal power required by the airport buildings during the year: it is concentrated in months comprised between November and April with a maximum demand of 410.000 kWh in January. The electrical demand of the airport, as depicted in Figure 3, is always present during the year and is subjected to an increase in the summer season, due to the air conditioning, with a peak of 1.000.000 kWh in July and August.

In the hot seasons (May, June, July, August, September, October), chilled water is needed to cool the buildings of the airport, whilst the thermal power required by the thermal users of the buildings is null. Contrarily, in the cold seasons (November, December, January, February, March, and April) the demand for cooling power is zero, while the buildings need useful thermal power. Because of such a thermal and cooling demand of the buildings during the year, it is not possible to perform a complete tri-generation, with the power plant assuming a combined cooling and power (CCP) configuration in the hot season and a combined heating and power (CHP) configuration in the cold season.

The power plant has been designed in order to satisfy the maximum thermal demand, which occurs in January. Considering the overall number of hours over which this thermal demand is distributed, the maximum thermal power provided by the plant must be equal to about 1500 kW. In a similar way, the maximum cooling power achievable by the plant has been set equal to the maximum cooling power demanded by the buildings in July, namely 500 kW. As a result, the absorption chiller of the plant has been chosen so as to provide a maximum cooling power of 500 kW.

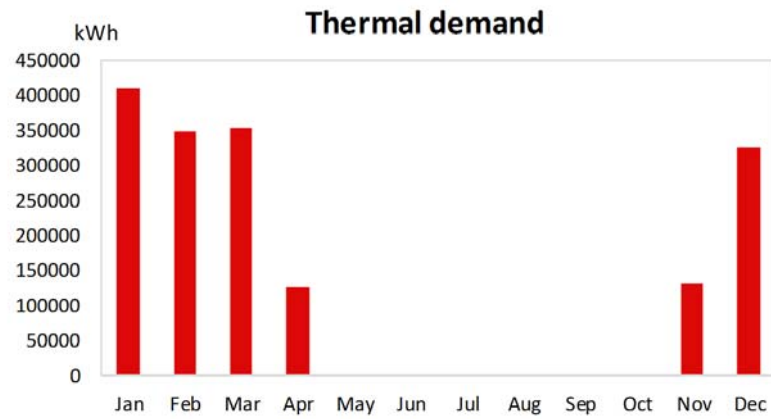


Figure 2: Airport thermal demand.

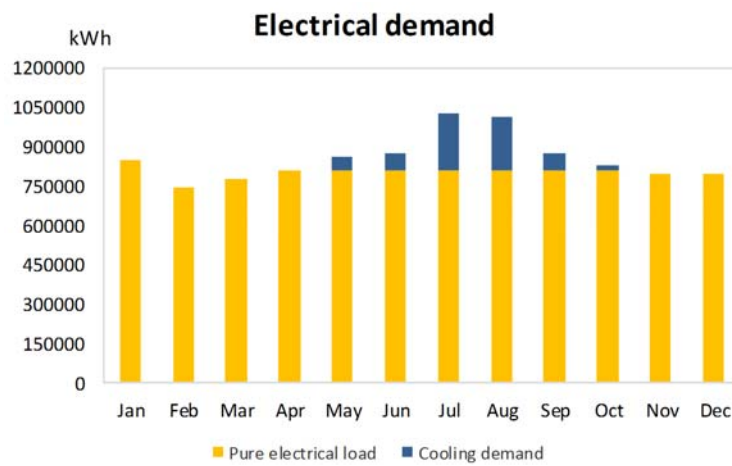


Figure 3: Airport electrical demand.

3.2 Plant layout and components

Figure 4 shows the layout of the plant along with the state point information. The main sub-systems of the plant, namely the biomass combustor, the ORC unit, the thermal users and the absorption chiller are analysed in the following sub-sections.

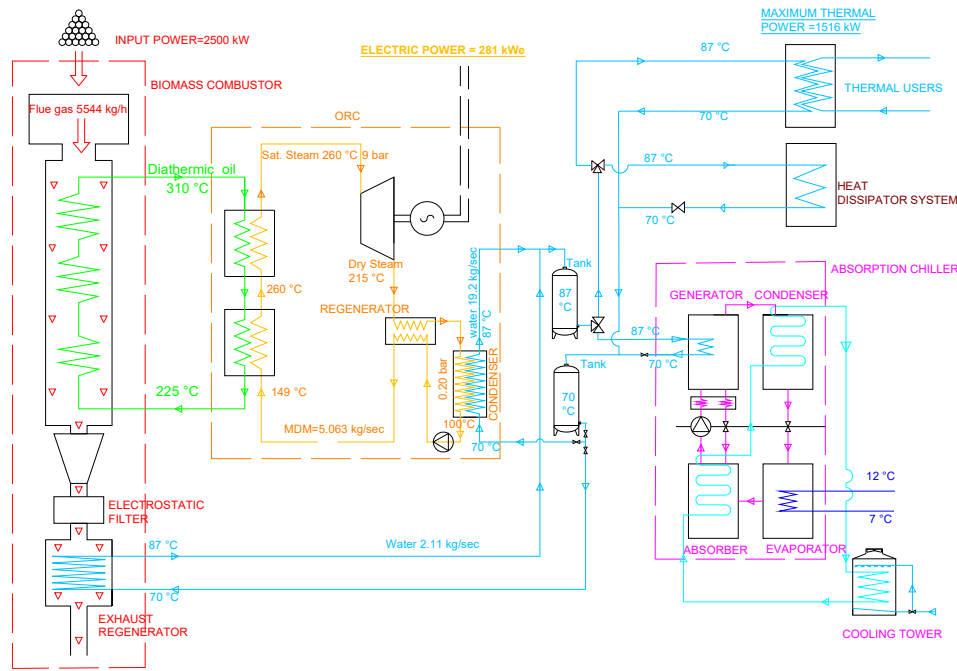


Figure 4: Plant layout with state point information

BIOMASS COMBUSTOR

On the left of Figure 4, the schematic representation of the biomass combustor (dashed red box) is reported, where the top black box indicates the combustion chamber. This is fed with pre-dried pruning residues by means of a pneumatic system, which allows burning bigger size pieces of wood as well as leaves and tree barks.

The biomass combustor is equipped with radiative and convective heat exchangers at its top for transferring heat from the flue gases generated from the combustion to the diathermic oil (denoted by the green line), thus increasing its temperature. After exiting the heat exchanger, the flue gases are subjected to particulate and ash elimination. To accomplish this task, a cyclone and an electrostatic filter, which is at present the best method of separation for the smallest particles, are placed downstream of the heat exchanger.

Before being discharged into the atmosphere, the flue gases flow through a final heat exchanger (referred to as the exhaust regenerator) which allows increasing the overall efficiency of the plant by recovering most of the residual thermal energy of the exhaust gases.

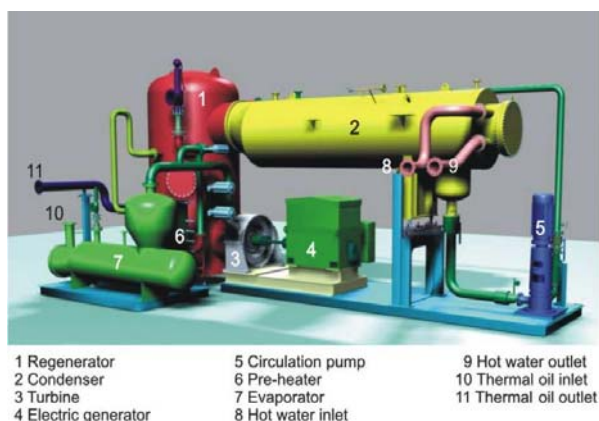
In order to reduce the NO_x emission (the limit value established by the normative is 200 mg/Nm^3), the strategy consists in the introduction of a certain quantity of urea in the combustion chamber, so that NO_x can react with the injected urea to form molecular nitrogen. To optimize the chemical reaction between urea and

195 NO_x , the temperature and reaction time must properly be controlled. The best range of temperature is
 196 between 800 and 1100 °C, with the optimum being equal to 1000 °C, while the best residence time ranges
 197 from 0,2 to 0,5 seconds.

198 ORC

199 The choice of an ORC system results from its peculiar characteristics, specifically: the turbine isentropic
 200 efficiency can be as high as 90%, the turbine can rotate at very low rotational speed and, as a result, can
 201 directly be connected to the electric generator without the need for a gear reducer. Furthermore, the turbine
 202 blades are subjected to low usury thanks to humidity absence during the steam expansion, and the system
 203 ensures short time for maintenance and long life of the components because this technology is nowadays
 204 mature and reliable. All these advantages have contributed to make ORC systems the most widespread
 205 technology for small-scale combined heating and power generation from biomass [12-13]. However, thanks
 206 to recent technological advances in designing gas to gas heat exchanger [14-16] and micro water-steam
 207 expanders, it was demonstrated in [17] that the employment of small combined cycles as a valid alternative
 208 to ORC systems for CHP from biomass will be feasible in the near future and will be able to guarantee
 209 competitive thermodynamic performances.

210



211

212 *Figure 5: CAD representation of the ORC unit [18].*

213 A CAD representation of the selected ORC unit is shown in Fig. 5. This unit is commercially available [18]
 214 and has been selected among commercially available units in order to satisfy the maximum thermal demand
 215 of the airport while ensuring the maximum possible electrical efficiency. In fact, the unit is capable of
 216 generating an electrical power of about 281 kW with an efficiency of 16.4%, which is very high level of

performance despite the small-scale application and despite the very high condensation temperature required by the thermal users. The thermodynamic cycle of the ORC is reported in Fig. 6 along with all the values of pressure, temperature and enthalpy; Fig. 7 shows the heat exchange both in the boiler (which is made up of an economizer and an evaporator) and in the condenser (which also comprises a de-superheater). Both graphs have been retrieved by the authors using the data provided by the manufacturer. More details regarding the performance parameters of the ORC unit are provided in Table 2.

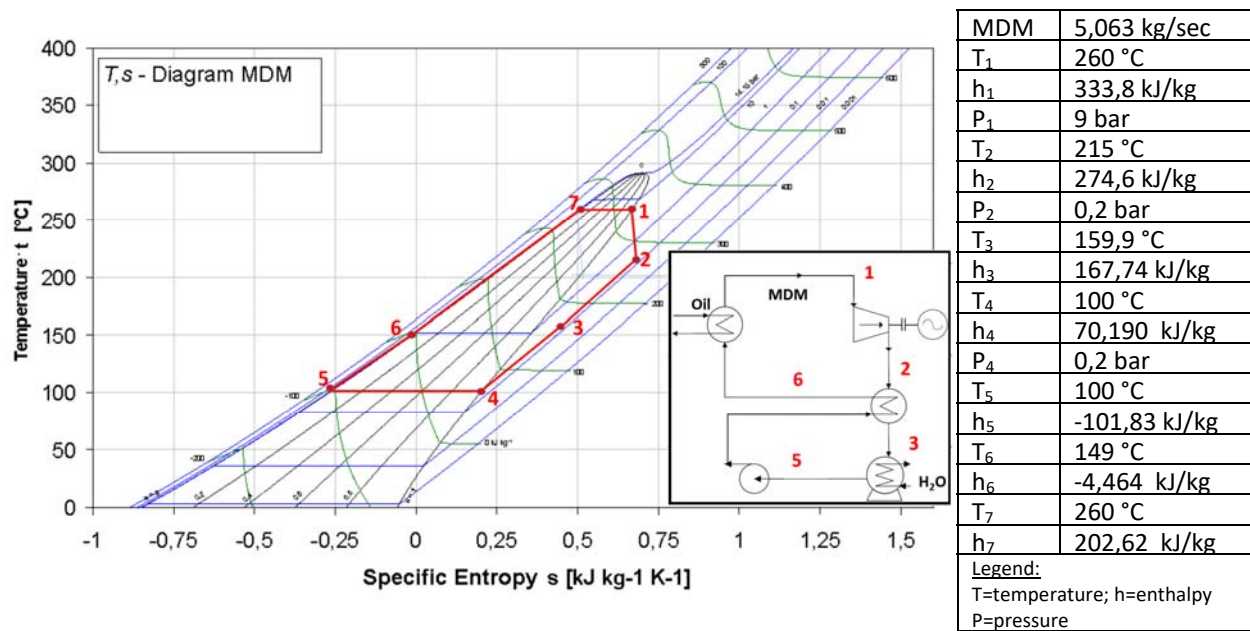


Figure 6: Thermodynamic cycle of the ORC

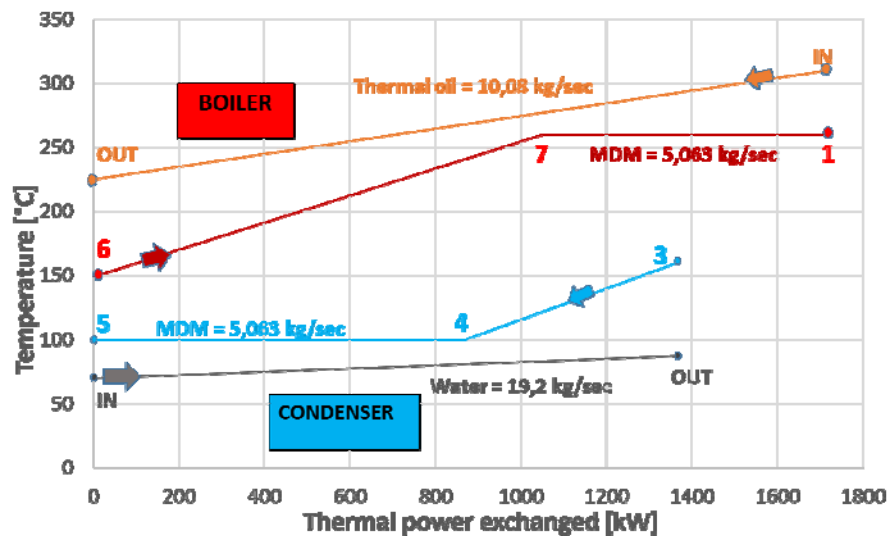


Figure 7: Temperature vs thermal power in the boiler (top) and condenser (bottom)

228 The proposed application is a high temperature configuration, as the heat source comes from the biomass
229 combustion. As occurs in most of the commercially available ORC units to be used in high temperature
230 applications (i.e. biomass combustion), the working fluid is not directly coupled to the flue gas, but a thermal
231 oil is used as a thermal vector between the combustor and the ORC, in order to privilege safety and
232 economic aspects. Indeed, the use of the thermal oil allows avoiding local overheating and allows the heat
233 exchanger to operate at atmospheric pressure, as also discussed in [19]. Moreover, the adopted temperature
234 (about 310°C) for the hot side of the thermal oil (therminol 66) ensures a very long oil life. The utilization of
235 the thermal oil also allows operation without requiring the presence of licensed operators.

236 The working fluid is a siloxane, namely MDM (octamethyltrisiloxane, molecular formula = $C_8H_{24}O_2Si_3$,
237 critical temperature = 290 °C, critical pressure = 14.20 bar, molecular weight = 236.5 kg/kmol). The
238 siloxanes are the most used molecules in high temperature CHP applications, because they have the desired
239 characteristics that best fulfil the high working temperatures [20]. The use of MDM as the working fluid
240 results from the fact that MDM is the most suitable in cycles having high condensation temperatures. In fact,
241 in the proposed plant the condensation temperature must be of the order of 100 °C to satisfy the needs of the
242 heating network (hot water at 87 °C is needed in the plant). Despite the very high condensation temperature,
243 the use of MDM allows the back-pressure of the turbine to be kept as low as possible, by virtue of its very
244 low condensation pressure at 100 °C (20 kPa). As a result, the working fluid can be expanded in the turbine
245 to 20kPa, and, at this exit pressure, the temperature of the steam is still very high (215 °C). This temperature
246 level makes the employment of the regenerator mandatory in order to maximize the efficiency of the cycle.

247 THERMAL USERS AND ABSORPTION CHILLER

248 In the condenser of the ORC system, the working fluid disposes of the remaining heat to the cooling water
249 (azure line) which is used either in an additional heat exchanger for thermal uses or in the absorption chiller
250 (purple dashed box) using a solution of lithium bromide salt and water for cold generation. When the thermal
251 power produced by the plant exceeds the demand for chilled water or useful thermal power, the excess
252 thermal power is dissipated through a heat dissipator.

253 In the configuration proposed, two insulated water tanks are used to regulate the flow of the hot water used
254 as thermal vector for the absorption chiller and for the thermal user: a large part of the hot water (at 70 °C) is
255 sent from the bottom tank to the condenser of the ORC cycle, while the remaining part is sent to the exhaust

regenerator. The hot water exits these two devices at higher temperature (87 °C) and is conveyed into the top tank, which is used to distribute the hot water either to the thermal user or to the generator of the absorption chiller. Finally, the hot water at lower temperature (70 °C) exiting either the generator or the thermal user is delivered back to the bottom tank in order to have a continuous operation mode. In Figure 4, the heat dissipator system is depicted below the heat exchanger indicating the thermal users; the heat dissipator is activated by acting on a three-way valve, which is also capable of regulating the thermal power to be dissipated according to the demand of either the thermal users or the absorption chiller.

On the right hand side of Figure 4, it is possible to observe the components of the absorption chiller, specifically the absorber coupled with the generator, the condenser, the lamination valve and the evaporator. In the configuration proposed for the absorption chiller, a cooling tower is used to dispose of the heat transferred to the condenser coolant. The choice of an absorption refrigerator instead of a compressor refrigerator results from the fact that the former allows the recovery of the surplus heat; furthermore, an absorption refrigerator does not need a compressor to realize the refrigeration cycle, which results in a substantial reduction in the electric power compared to a standard compressor refrigerator. It should be noted that novel and effective studies have been conducted in order to recognise the optimum hot water temperature for absorption chillers [21, 22].

The selected unit is a commercially available lithium bromide absorber that is capable of providing the maximum efficiency (72%) with a hot water temperature of 87 °C. This choice was made in order to maintain the same condensation temperature of the ORC both in Summer and in Winter. This choice allows the ORC unit to operate constantly at its design conditions and allows the complexity of the regulation system to be reduced.

3.3 Efficiency analysis

All the components of the power plant shown in Fig. 4 are commercially available, and their performance parameters are clearly indicated by the manufacturer. Table 2 reports the specifications along with the setting chosen for the biomass combustor, the exhaust regenerator and the ORC system. As indicated in this table, a great part (2141 kW) of the input power (2500 kW) is transferred to the diathermic oil according to the efficiency of the heat exchanger (85,6%), while the residual thermal energy of the exhaust gases is partly recovered through the exhaust regenerator and is transferred to the hot water (maximum thermal power

recovered = 150 kW). Not all the thermal energy transported by the diathermic oil (2141 kW) can be transferred to the ORC, because of the efficiency of the heat exchanger of the ORC system (80%); as a result, the thermal power in input to the ORC results to be equal to 1710 kW. For this value of input power, the chosen ORC system is capable of producing 281 kW_e, while a thermal power of 1366 kW is still available in form of hot water exiting the condenser. The overall efficiency (including both the electrical and the thermal power produced) of the ORC system, excluding the heat exchangers and the other components of the plant, is equal to 0,96.

The setting shown in Table 2 is valid both for the summer season, when only air conditioning is needed (combined cooling and power configuration), and for the rest of the year, when the absorption chiller is unnecessary and the thermal energy transferred to the water in the condenser can be recovered only for thermal use (combined heating and power configuration).

Table 3 reports the setting regarding only the former case (combined cooling and power configuration). In this case, it is noteworthy that cold water at 7 °C is available for the cooling system with a maximum cooling power of 500 kW. The electrical efficiency (η_{el}) is defined by equation (5) and is equal to 11,2%, while the overall efficiency (η_G) is 31,2% according to equation (6):

$$\eta_G = \frac{P_{el} + \dot{Q}_c}{\dot{m}_b H_t} \quad (6)$$

where $\dot{Q}_c$ denotes the cooling power. In contrast, Table 4 reports the setting regarding the latter case (combined heating and power configuration), when chilled water is not needed. In this case, a maximum useful thermal power of 1516 kW can be produced (35,5 kg/s of hot water at 87 °C) in January. The maximum overall efficiency, η_G , results to be equal to 71,8%, according to equation (7):

$$\eta_G = \frac{P_{el} + \dot{Q}_{th}}{\dot{m}_b H_t} \quad (7)$$

where $\dot{Q}_{th}$ denotes the useful thermal power.

The maximum potential of the proposed plant in the two different configurations is also illustrated by the bar charts of Figure 8 for completeness.

Plan component	Description	Value
Biomass combustor	Input power	2500 kW
	Thermal power transferred to the Diathermic-oil	2141 kW
	Heat exchanger efficiency	85,6%
	Mass flow rate of the flue gases	5544 kg/h
Exhaust regenerator	Flue gas temperature at the exhaust regenerator inlet	220 °C
	Flue gas temperature at the exhaust regenerator outlet	100 °C
	Maximum mass flow rate of water entering the exhaust regenerator	2,11 kg/s
	Water temperature at the inlet of the exhaust regenerator	70 °C
	Water temperature at the outlet of the exhaust regenerator	87 °C
	Maximum thermal power transferred to the water	150 kW
	Efficiency of the exhaust regenerator	81%
ORC	Thermal power transferred to the working fluid	1713 kW
	Gross electrical power of the steam turbine	300 kW
	Net electrical power	281 kW
	Turbine isentropic efficiency	85%
	ORC overall electrical efficiency	16,4%
	Mass flow rate of cooling water (condenser)	19,2 kg/s
	Temperature of the water at the condenser inlet	70 °C
	Temperature of the water at the condenser outlet	87 °C
	Thermal power achievable in the condenser	1366 kW
	ORC thermal efficiency	80%
	ORC efficiency (thermal+electrical)	96%

Table 2: Specifications of the biomass combustor, exhaust regenerator and ORC valid both for the combined cooling and power configuration and for the combined heating and power configuration

	Summer configuration (electricity + cooling)	
Absorption chiller	Maximum mass flow rate of hot water through the generator	9,77 kg/s
	Temperature of hot water entering the generator	87 °C
	Temperature of hot water exiting the generator	70 °C
	Maximum thermal power transferred to the generator	695 kW
	Maximum mass flow rate of cold water through the evaporator	23,89 kg/s
	Temperature of cold water at the evaporator inlet	12 °C
	Temperature of cold water at the evaporator outlet	7 °C
	COP	72%
Plant efficiency	Net electrical power	281 kW
	Useful thermal power	-
	Maximum cooling power	500 kW
	Electrical efficiency	11,2%
	Maximum overall efficiency	31,2%

Table 3: Specifications of the absorption chiller and efficiency parameters valid for the summer configuration (combined cooling and power configuration)

	Winter configuration (electricity + heating)	
Thermal user	Maximum mass flow rate of hot water available for thermal users	21,31 kg/s
	Temperature of hot water available for thermal users	87 °C
	Temperature of hot water returning to the bottom tank	70 °C
Plant efficiency	Net electrical power	281 kW
	Maximum thermal power available for thermal use	1516 kW
	Cooling power	-
	Electrical efficiency	11,2%
	Maximum overall efficiency	71,8%

Table 4: Specifications of the thermal users and efficiency parameters valid for the combined heating and power configuration

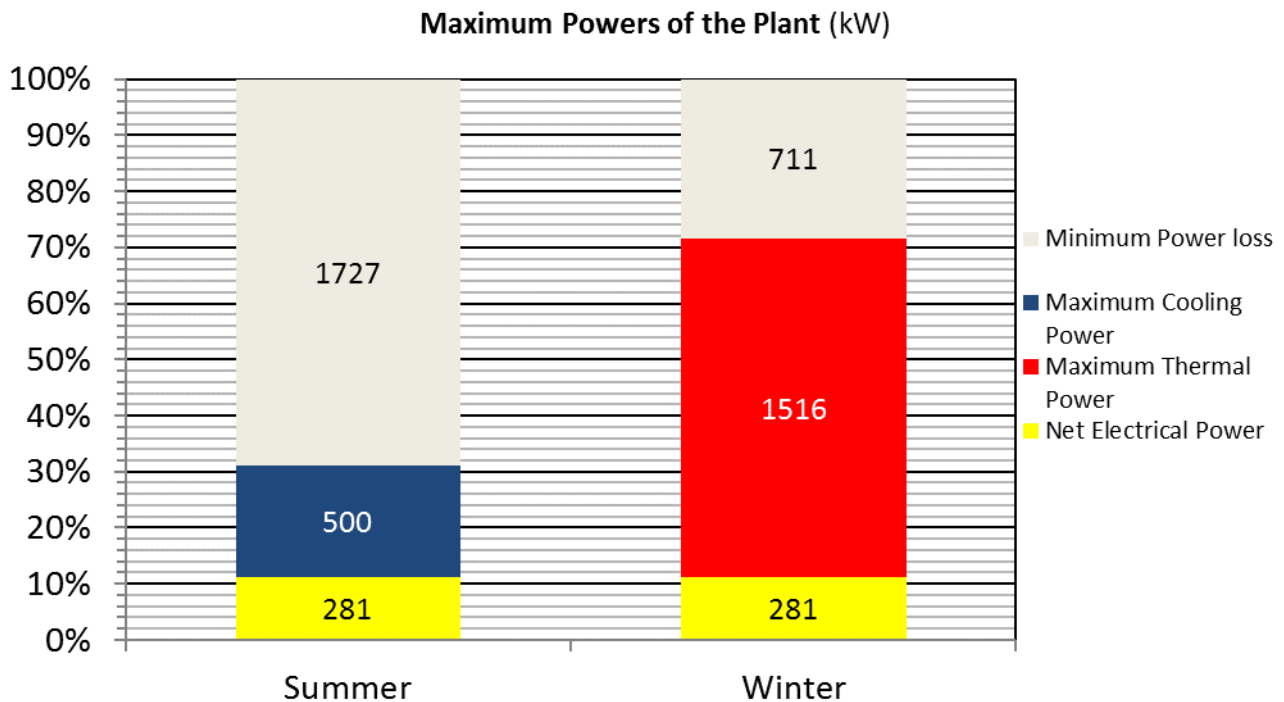


Figure 8: Maximum potentiality of the plant in the summer season (cooling and power) and in the winter season (heating and power).

Figure 9 shows how the overall efficiency of the plant changes with the months. The partial load strategy consists in producing the same electrical power (281 kWe), while dissipating the excess thermal and cooling power through proper dissipation systems. In this manner the ORC operates at its design conditions so that the efficiency of the ORC is not reduced at partial loads; as a result, the electrical energy obtained from biomass is always the maximum possible. This strategy is also justified by the large availability of feedstock in the zone surrounding the airport (see Section 2).

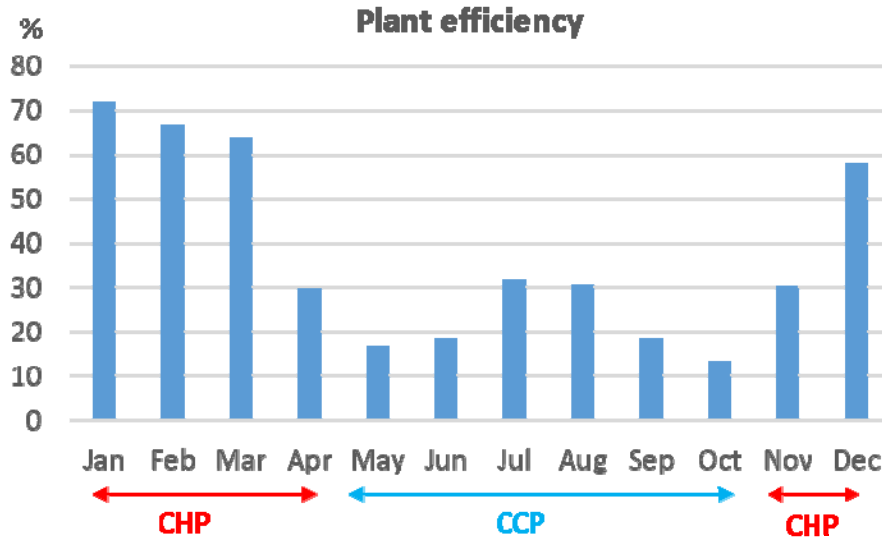


Figure 9: Overall efficiency vs months

4. ECONOMIC ANALYSIS

In this section the economic advantages that the plant can ensure are analysed. In particular, the payback period (PBP), the net present value (NPV) and the internal rate of return (IRR) are evaluated. To accomplish this task, it is necessary to quantify the periodic cash flow of the investment, in terms of annual costs and incomings.

4.1 Cost estimation

The main costs to be sustained are the overall cost for the realization of the plant and the annual cost required for the procurement of the necessary feedstock.

The cost of the plant, given by the sum of the costs of the components and the installation costs, amounts to 2.900.000 €.

The yearly cost for due to the procurement of the necessary feedstock ($C_{feedstock}$), expressed in €/year, can be calculated as follows:

$$C_{feedstock} = \dot{m}_b * (C_h + C_t + C_c) \quad (8)$$

where $\dot{m}_b$ is the fuel mass flow rate, C_h is the harvesting cost (expressed in €/t), C_t is the transportation cost (expressed in €/t) and C_c is the chipping cost (expressed in €/t).

342 The cost of harvesting depends on the machines used for this purpose. In this analysis, a machine (referred to
 343 as the baler) capable of both collecting tree pruning residues and grouping them into cylindrical bales, as
 344 with the forage waste, is considered. This machine was constructed for forage and in a second time modified
 345 for olive tree pruning residues. A bale has a diameter of 1.50 m and a width of 1.20 m, the medium weight
 346 varies between 400 and 450 kg, and the time necessary to produce a bale is about 15 minutes. According to
 347 the specification provided by the manufacturer, the operation costs for the harvesting operation can be
 348 estimated to be $C_h = 26 \text{ € /t}$.

349 The overall transportation cost per tons of feedstock (C_t) is given by the sum of the cost of the fuel required
 350 for the round trip (C_f) and the cost for loading and unloading the feedstock (C_l), divided by the weight of the
 351 feedstock transported (P_m):

$$C_t = \frac{C_f + C_l}{P_m} \quad (9)$$

352 According to typical vehicles for transportation of feedstock, the maximum weight of feedstock that can be
 353 loaded on the vehicle amounts to $P_m = 18 \text{ t}$.

354 To calculate C_f , the average speed of the vehicle during the round trip can be assumed equal to 30 km/h with
 355 a fuel consumption equal to about 40 €/h in the case of transporting 18 t of feedstock, which results in a fuel
 356 cost per km equal to 1,33 €/km. The distance of a round trip can be taken equal to the average distance of the
 357 farmers from the plant, namely 10,1 km (see Section 2.2). With these assumptions, C_f amounts to about 26,9
 358 € (multiplying 1,33 €/km by 20,2 km, considering the round trip). With regard to C_l , the time to load and
 359 unload 18 t of feedstock can be assumed equal to 1 hour (45 minutes necessary to load and 15 minutes to
 360 unload); if these operations are performed manually, C_l averages 25 €, according to the average salary of a
 361 worker [23].

362 Hence, substituting $C_f = 26,9 \text{ €}$, $C_l = 25 \text{ €}$ and $P_m = 18 \text{ t}$ in equation (9) results in a total transportation cost
 363 (C_t) equal to 2.9 €/t.

364 The chipping stage allows obtaining a solid biofuel in the form of chips with dimensions suitable for the
 365 biomass combustor. The cost of the chipping phase can be estimated to be equal to $C_c = 5 \text{ € /t}$.

366 In conclusion, it has been demonstrated that $C_h = 26 \text{ € / t}$, $C_f = 2,9 \text{ € / t}$ and $C_c = 5 \text{ € / t}$. Substituting these
367 values in Equation (8) and considering that $\dot{m}_b = 6800 \text{ t/year}$, the cost required for the procurement of the
368 necessary feedstock amounts to $C_{feedstock} = 230.500 \text{ € / year}$.

369 4.2 Incomings estimation

370 The main incomings are represented by the avoided costs of hot water ~~generation~~ and electricity generation.
371 The first contribution can be calculated from the examination of the annual thermal demand of the airport
372 shown in Fig. 2, which amounts to $1.680.000 \text{ kWh}_{th}$. Considering that 1 Nm^3 of methane averagely costs
373 $0,30 \text{ €}$ and that the quantity of methane required to produce $1.680.000 \text{ kWh}_{th}$ is about 159.200 Nm^3 according
374 to the current technology, it results that the cost avoided for thermal power production is equal to $47.760,00$
375 € / year .

376 The avoided cost of electricity-results from the fact that the overall electrical energy required by the airport is
377 partly provided by the power plant. The plant produces an electrical power of 281 kW over 8000 hours , so
378 the overall electrical energy provided to the airport buildings results to be equal to $2.248.000 \text{ kWh / year}$. In
379 addition, the plant allows saving an electrical energy of 610.000 kWh necessary for the cooling of the
380 buildings (see Fig.3). Summing up these two contributions and considering that the current price of
381 electricity in that area is $0,12 \text{ € / kWh}$, the overall avoided cost of electricity is $342.960,00 \text{ € / year}$.

382 Further incomings are given by government incentives, which can be grouped into two categories
383 independent from each other. The first one is equal to 75% of the overall capital cost of the plant and regards
384 CCHP biomass –fuelled plants built in the south regions of Italy with a capital cost comprised between 2 and
385 25 millions of Euros. With this incentive, the initial plant cost of $2.900.000,00 \text{ €}$ is lowered to $725.000,00 \text{ €}$.

386 The other one regards all CCHP biomass –fuelled plants and ensures a bonus per every KWh_e produced
387 during the initial 15 years. The bonus is equal to 0.227 € / kWh_e in the first year and then is reduced by 2% per
388 year.

389 4.3 Analysis of the investments

390 The estimation of costs and incomings achieved in Sections 4.2 and 4.3 allows evaluating the annual cash
391 flow of the investments. Figure 10 shows the annual cash flow during a period of 15 years: the situation
392 regarding the first kind of incentive is depicted in red, while the other case is plotted in blue.

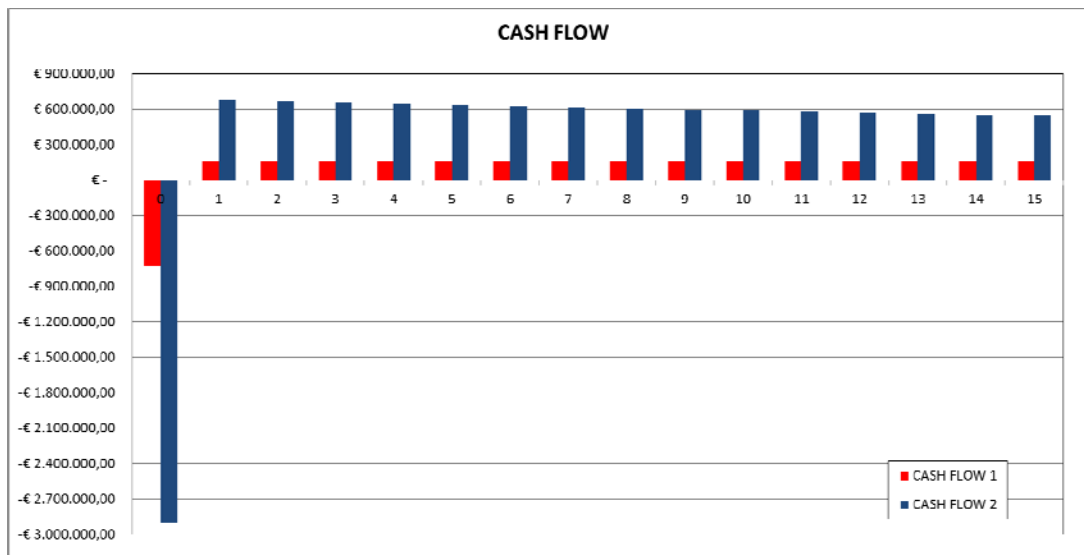


Figure 10: Annual cash flows of the investment vs number of years, considering the two typologies of government incentives separately.

The first type of incentives leads to having an initial outlay lower than the second type, but also a lower annual cash flow in all the subsequent years. This results from the fact that the first type of incentives only ensures a reduction in the initial cost of the plant, whilst the second type gives a bonus for each electrical kWh produced, thus ensuring additional annual incomings for the subsequent 15 years.

The calculation of the payback period and net present value can be instrumental both in evaluating the profitability of the investment and in recognizing which of the two typologies of government incentives is more suitable. These indicators are plotted in Figure 11 for both categories of incentives, with the assumption that the discount rate is equal to 8%. It can immediately be noticed that the investment has a PBP value of 6 years for both cases; furthermore, we can state that the second typology of government incentives (a bonus for each electrical kWh produced) ensures more gains than the first one. In fact, at the end of the 15th year the NPV is 646.399,00 € in the first case and 2.386.248,00 € in the second one.

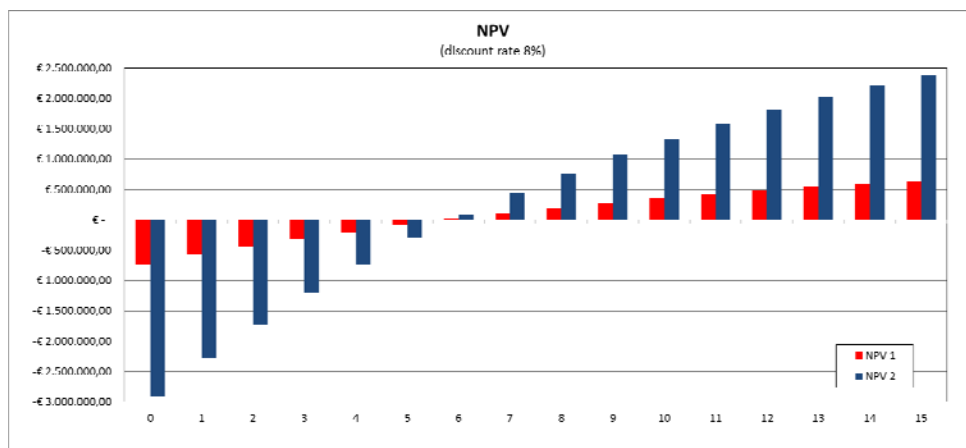


Figure 11: Net present value of the investment vs number of years for the two typologies of government incentives

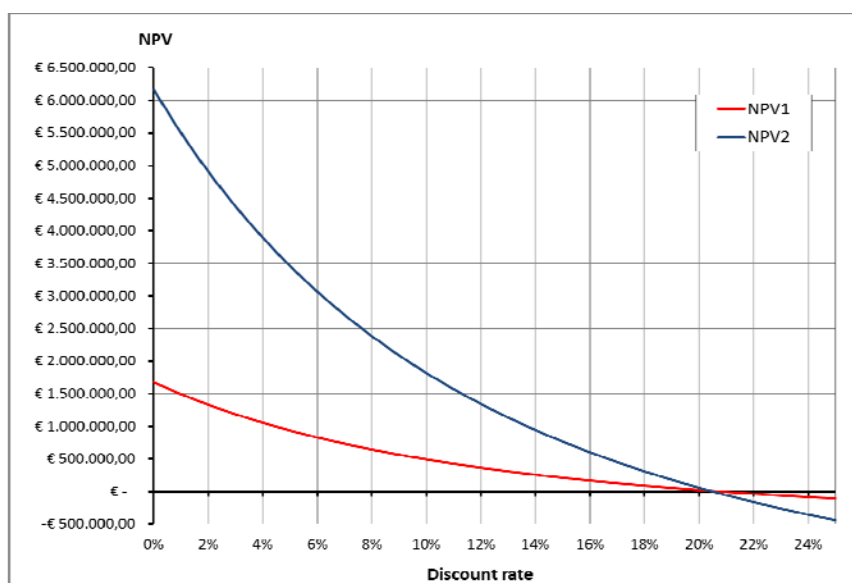


Figure 12: Net present value of the investment after the 15-th year, as a function of the discount rate for the two typologies of government incentives

These results can be generalized considering what happens at the changing of the discount rate. For both types of government incentives, Figure 12 shows the NPV of the investment after the 15-th year as a function of the discount rate. It is clear that this graph confirms that the second type of incentives is more convenient than the other one, regardless of the discount rate chosen.

From the examination of Figure 12, we can also appreciate the internal rate of return (IRR) of the investment. It is almost constant regardless of the typology of the incentive, being equal to about 21% in both cases. This value points out the profitability of the investment once again.

5. ECOLOGICAL CONSIDERATIONS

This final section evaluates the quantity of CO₂ that will not be released into the atmosphere after the proposed power plant is built at Bari Airport. To perform this evaluation, it must be considered that 1 Nm³ of methane weighs 0,7 kg, and 2,75 kg of CO₂ are normally produced per kg of methane in a stoichiometric reaction.

With regard to the heat generation, the quantity of methane required to produce 1.680.000 kWh is 159.200 Nm³, thus the annual quantity not released into the atmosphere will be 306.460 kg.

With regard to the electricity production, supposing a reference electrical efficiency of 0,60, it results that the methane necessary for the electrical generation is 316.050 kg. Thereby, the avoided release of CO₂ for

430 electricity generation will be equal to 869.140 kg. Overall, the mass of CO₂ avoided per year will be
431 1.175.600 kg.

432 In conclusion, it results that the proposed tri-generative plant can be very important in the Apulia context
433 from an ecological point of view. Furthermore, the plant can lead to a double ecological gain, because in
434 addition to avoiding the combustion of fossil fuels for energy production, it can also avoid that a lot of olive
435 pruning residues are burned on fields with considerable quantities of CO₂ released into the atmosphere. Such
436 a practise is prohibited by the Italian law and produces a great quantity of dioxin because of the low
437 temperature combustion, while the produced pollutants are almost completely eliminated in the biomass
438 combustor of the proposed tri-generative plant.

439

440 6. CONCLUSIONS 441

442 For over twenty years ever increasing attention has been given to the ecological problem in national politics.
443 One of the most effective ways to reduce CO₂ emissions is the use of biomass as fuel for energy production.
444 This research is focused on the energetic use of agricultural wastes in Apulia, in particular olive tree pruning
445 residues. At present, such agricultural residues are burned on Apulian fields (despite being prohibited by the
446 Italian law) with a consequential loss of possible energy exploitation.

447 In the real case considered, pre-dried olive tree pruning residues are directly used as solid fuel in a tri-
448 generative power plant of about 280 kW_e planned to be located near Bari Airport.

449 The Apulia context was analysed with respect to the availability of feedstock, finding that the resource of
450 biomass present in a very small area surrounding the plant location is sufficient to satisfy the energetic needs
451 of the plant. Afterwards, the plant was described in detail. It is composed of a biomass combustor, a co-
452 generative ORC system and an absorption chiller, which ensures chilled water in the summer. Moreover, to
453 reduce the quantity of pollutant components like NO_x and CO, an electrostatic filter will be positioned
454 downstream of the exhaust regenerator

455 In the winter season, when the production of chilled water is unnecessary, the plant will be able to produce a
456 maximum thermal power of 1516 kW in the form of hot water at 87 °C along with a net electrical power of
457 281 kW. In contrast, part of the thermal power can be transferred to the generator of the absorption chiller
458 with the aim of producing chilled water (maximum cooling power of 500 kW) in the summer season. In the

459 former case (combined heating and power configuration), the overall efficiency of the plant is 71,8%, while,
460 in the latter case (combined cooling and power configuration) the plant is able to produce electricity and
461 cooling power with a maximum overall efficiency of 31,2%.

462 The main economic advantages come from the avoided costs of electricity and methane necessary for
463 generating the thermal power. Two typologies of government incentives have been considered: according to
464 the first one, the government finances a percentage of the plant cost, contrarily, according to the other one,
465 the government provides a bonus for every electrical kWh produced. In both cases, the payback period is 6
466 years and the internal rate of return is about 21%, highlighting that the proposed project is highly convenient
467 from an economic point of view. From an ecological point of view, the plant is remarkably eco-efficient,
468 ensuring a reduction of 1.175.600 kg/year in CO_2 emissions.

469 Although this research activity is concerned with a specific zone, namely the area surrounding Bari Airport,
470 the results can be applied to other zones of the Mediterranean region, which has continuous availability of
471 residues from olive tree pruning practices.

472

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