Biomass combustion with ORC for decentralized bioenergy applications: A techno-economic approach

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Abstract

The use of biomass for decentralised energy production has undergone a significant development the last years. The fact that this fuel is CO_2-free provides many advantages in European and world aims for sustainable energy sources. Biomass trigeneration is a relatively new concept, which has the potential to improve the bioenergy economics for areas with warm climate, for which traditional biomass cogeneration was unfeasible. This concept can be applied with various energy conversion technologies, among others the biomass combustion coupled with the Organic Rankine Cycle process. The fact that ORC is a proven technology for waste heat applications provides advantages for its coupling with combustion. This combination is examined in the present study, in terms of the financial yield of an ORC tri-generation project. The concept of ORC biomass trigeneration is applied for a case study in Greece and interesting results regarding the cost and the profitability of the project are presented.

Keywords: ORC, biomass, bioenergy, decentralized energy generation, trigeneration, techno-economic assessment

Biomass combustion and ORC: Technology description

The most common way to convert biomass into heat and power is its combustion. The heat from biomass combustion can be further transferred into a water-steam cycle, or an Organic Rankine Cycle (ORC), producing power and heat.

The ORC process is a Rankine cycle process, in which organic medium is used instead of water. Due to the low temperature evaporation temperature of the organic medium, this process is appropriate for low temperature waste heat applications like for example geothermal plants, solar thermal processes, but also for biomass combustion applications.

The main advantage of the use of ORC in biomass combustion processes is that this technology is appropriate for decentralized applications and it is the only proven method for power generation up to 1 MWel. The electrical efficiency

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of the ORC process lies between 6-17%. This efficiency is linked with the maximum heat recovery and the thermal efficiency of the boiler. Examples of ORC plants can be found in central Europe (Stadtwärme Lienz Austria 1000 kW_{el}, Sauerlach Bavaria 700 kW_{el}, Toblach South Tyrol 1100 kW_{el}, Fußach Austria 1500 kW_{el}).

The following figure presents the Combined Heat and Power production when biomass combustion is combined with the ORC process. More specifically, the heat produced in the combustion chamber is transferred to a thermal oil which is first preheated from the exhaust gas. The thermal oil generates the organic steam which is expanded in the expander. The condenser of the process is feeding the District Heating (DH) network in which, the heat produced can be either used for heating purposes, or, with the use of absorption chillers, for cooling applications.

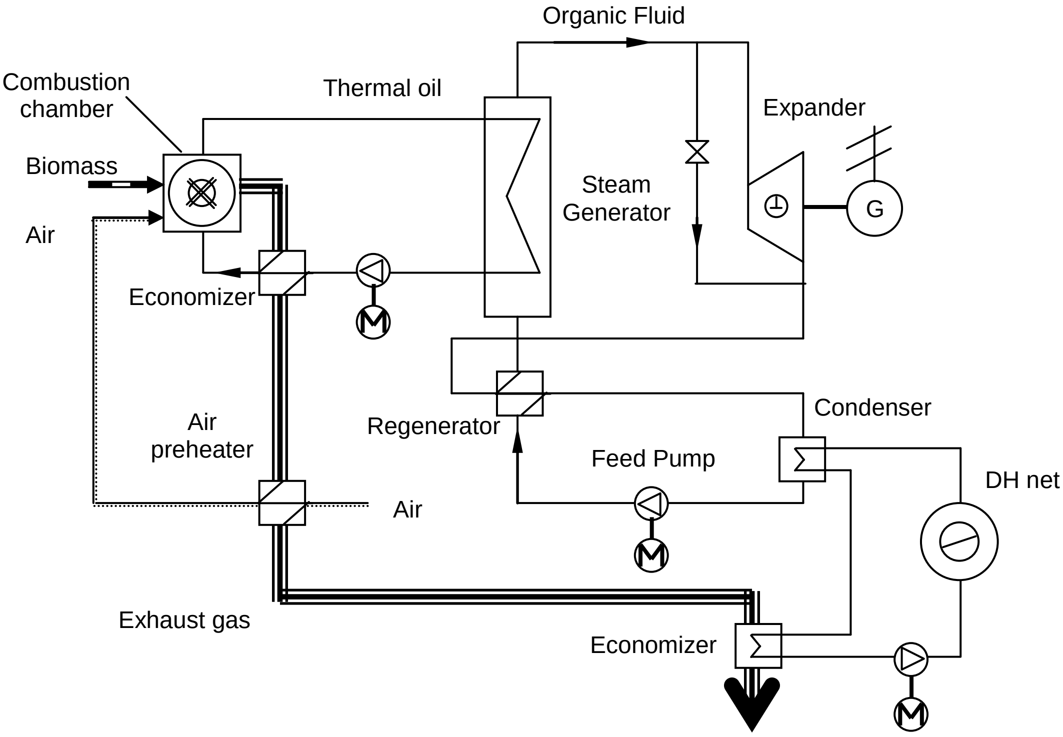

Fig. 1: CHP production with biomass combustion and ORC

When calculating the efficiency of an ORC process, also the boiler efficiency of the thermal oil boiler has to be taken into consideration. This leads to low electrical efficiencies of the system (6 to 17%) [1].

However, even if the efficiency of the ORC is low, it has some advantages, like the fact that the system can work without maintenance, which leads to very low personnel costs. Furthermore the organic working fluid has, in comparison with water, a relatively low enthalpy difference between high pressure and expanded steam. This leads to higher mass flows compared with water. The application of larger turbines due to the higher mass flow reduces the gap losses compared to a water-steam turbine with the same power. The efficiency of an Organic Rankine Cycle turbine is up to 85 % and it has an outstanding part load behavior [2].

For numerous organic fluids the expansion of the turbine ends in the region of superheated steam [3]. This avoids drop erosion and allows a reliable operation and a fast startup of the cycle.

The selection of the appropriate working fluid is very important for the ORC process. This is related to the heat input level application. The most commonly used medium for biomass combustion is octamethyltrisiloxane (OMTS). For this fluid, thermal as well as total efficiency for high temperature ORC applications, as biomass combustion, is relatively low. Therefore, a lot of research is done the last years in order to use other working fluids, in order to achieve higher efficiencies [4].

Economics of Biomass Combustion - ORC Plant

Brief Model Description

In the NTUA an optimization model has been developed. This model is a tool that has the ability to simulate a biomass-to-energy supply chain, taking into consideration not only the upstream biomass supply chain (up to the energy conversion facility), as most of the researchers do, but also the downstream supply chain of the energy products generated, such as electricity, heat and cooling.

The energy conversion facility may be a CHP (Combined Heat and Power) or a trigeneration plant, and provision is made to incorporate the investment and operational costs of a district heating or/and district cooling network. The energy conversion unit consists of two distinct technological devices: a base-load biomass co-generation unit and a peak-load biomass heat boiler, to cover the peak heat loads, as is the common practice in similar cases.

The simulation model has been coupled with an optimization module, which optimizes the major design and operational characteristics of the whole system, by determining the optimal values of a set of variables.

Investment analysis

The investment analysis criterion used as the objective function of the optimization problem is the Net Present Value of the investment, due to its inherent advantages, its common use as a project appraisal method in business practice and its widespread use in relevant cases in the literature. Apart from the Net Present Value, other investment analysis criteria, such as the Internal Rate of Return and Pay Back Period have also been calculated for the optimum system parameters determined by the optimization method.

Case study

This paper presents the results from the implementation of the model for a case study that concerns the investment analysis of an ORC trigeneration power plant, given the demand of a specific customer for heat and cooling. The customer is considered to be a local community using heat mainly for space heating and domestic hot water applications, whereas cooling is primarily used for space cooling. The heating and cooling demand is highly dependent on the climatic conditions (ambient temperature), therefore it is characterized by high variability. The biomass-to-energy conversion facility is considered to operate at heat-match mode, as the main objective of the power plant in similar cases is to fully satisfy the thermal and cooling needs of the customers. The electricity generated during the operation of the co-generation (base-load) module of the power plant is always absorbed by the national grid, due to the favorable legislative framework that gives priority to renewably generated electricity.

The main revenue sources of the power plant under consideration are electricity sales to the national grid, heat and cooling provided to the customers via a district heating network, as well as trading of the Emissions Reduction Units (ERU's).

A base-load co-generation module and a biomass boiler for peak-load heat production comprise the energy exploitation module. Heat produced from the abovementioned devices will be transferred by the main district heating pipeline to a position near the final consumers. A terminal point follows, containing heat exchangers and absorption chillers to produce cooling using heat as primary energy source. The same distribution network is used for district heating and cooling. The plant is assumed to operate in heat-match mode, to serve the heating and cooling needs of the customers. The electricity produced will be sold directly to the grid, at prices determined by the Greek energy authority.

The fuel source is a mix of locally available woody biomass types, in order to reduce the transportation cost. Using a combination of biomass types instead of a single type may have considerable logistical advantages and cost reduction [5,6]. These woody biomass types have similar characteristics and heating value, can be handled with the same equipment and are considered agricultural residues with no important alternative use, therefore they can be purchased in relatively low price. The price has been assumed to be 30€/t_{wet} for all biomass types, including loading cost to the transportation vehicles. The main data used for the case study is presented in Table 1.

n_{el}	14%
n_{th}	75%
n_{total}	89%
Power-to-Heat Ratio	18,7%
Size of Reference Plant (kWel)	1000
Investm. cost of ref. plant (€/kWel)	2760
Subsidy on investment	40%
COP absorption chiller	0,733
Operational & Maintenance cost (% of inv. Cost /yr)	3,5%
DH forward temperature	92°C
DH return temperature	65°C
Electricity purch. price (€/MWh)	68,42
Oil price – for heating	0,5

(€/kg)	
Price of tCO2 (€/tCO2)	15
Heat consumers	300
Average distribution network length per consumer (m)	20

Table 1 Main case study data

Results

ORC technology offers a solution of low capital requirement and relatively low Operational & Maintenance cost. Furthermore, ORC usually comes in pre-assembled modules, thus significantly reducing installation time and cost. Additionally, the standardization of ORC modules reduces the risk associated with performance and reliability. The paper aims at clarifying the technological aspects of ORC for decentralized bioenergy applications, while at the same time investigating the economics of a biomass trigeneration application through the case study application.

The ultimate aim of the model is to maximize the total system financial yield. Therefore, calculations have been performed to satisfy the end customer heat and cooling needs in an optimum way [6]. The optimum values for the variables of the problem are presented in Table 2. One can see that mainly almond and peach tree prunings are used as fuel sources, while olive tree prunings are also used, but in smaller quantities. Factors that lead to this fuel mix include the special distribution and availability of each biomass type, the purchasing price, the moisture content, the availability period and the energy content.

CHP nominal electrical power (kW)	390
CHP nominal thermal power (kW)	2090
Boiler nominal thermal power (kW)	985
Olive tree prunings (t/yr)	1200
Almond tree prunings (t/yr)	2113
Peach tree prunings (t/yr)	2334

Table 2 Optimum variable values

In Table 3 the energy generated each month is presented. The biomass boiler is utilized for three months per year to deliver peak load thermal power, the main peak taking place during the summer. It is interesting that the cooling load determines the overall peak for the specific application. This fact bears a significant importance, as it reveals that cooling demand may have higher peak than heating in south Europe, therefore shifting the traditional dimensioning practices of district heating plants form the winter peak load to the summer peak load, in the case of trigeneration.

As far as electricity generation is concerned, the power plant generates 2738,5 MWh per year. This result is in accordance with the assumptions made for fixed Power-to-Heat Ratio in partial loads and heat-match operation of the power plant.

Month	**Electricity (MWh)**	**Thermal CHP (MWh)**	**Thermal Boiler (MWh)**
Jan	281,0	1505,1	47,3
Feb	255,0	1366,1	0,0
Mar	217,6	1165,8	0,0
Apr	134,0	717,8	0,0
May	154,6	828,0	0,0
Jun	274,9	1472,4	0,0
Jul	281,0	1505,1	511,9
Aug	281,0	1505,1	506,9
Sept	263,0	1408,9	0,0
Oct	136,8	733,1	0,0
Nov	178,8	958,1	0,0
Dec	281,0	1505,1	0,0
TOTAL (yearly)	2738,5	14670,7	1066,2

Table 3 Energy generated by ORC

As it was stated before, the main purpose of this work is to examine the investment yield of ORC in a specific case study application. The main results of the investment analysis performed for the optimum parameter values are presented in Table 4.

NPV (€ $*10^6$)	1,61
IRR	14,8%
PBP (years)	9,9
Investment (€ $*10^6$)	2,67

Table 4 Investment analysis results

The application of ORC technology will result in a 1,61 million Euro Present Value. While the number is positive, and therefore at first glance acceptable, one should also examine other yield indicators before reaching a conclusion. The relatively low initial capital requirement for ORC power plant results for good performance of ORC in terms of the Internal Rate of Return value, which is an investment analysis criterion that mainly influences investors with short-term perspective. The IRR of almost 15% is a value that could trigger investors' interest, though private investors may find it relatively low to compensate for the uncertainty inherent in the project. The pay back period of 10 years could be considered very high for renewable energy applications, as other renewable energy sources may perform better, and this could be a factor limiting private investors' interest. However, non-profit organizations, such as municipalities, may still find these figures appealing for a project that could improve the local communities' living standards.

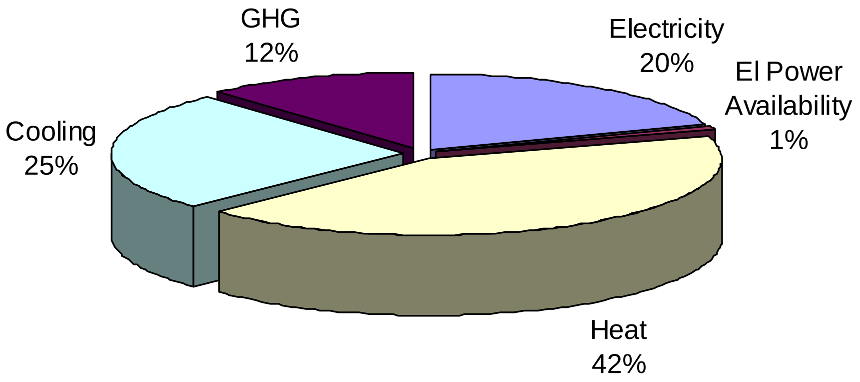

Fig. 2 Revenue breakdown

The revenue breakdown of the ORC power plant is shown in Fig. 2, where all the amounts are present values for the financial lifetime of the investment. It is obvious that revenue related to heat and cooling sales are by far the most important revenue streams, offering almost 67% of the total revenue. Therefore, it can be said that ORC bases its viability on heat and cooling income. Electricity accounts for 21% of the total income, including the power availability income, and greenhouse gas emissions trading contributes the rest 12%.

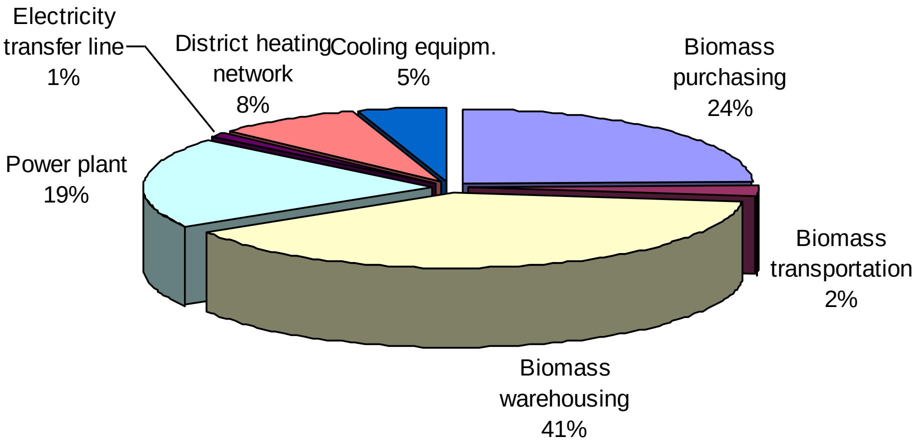

Fig. 3 Cost breakdown

Fig. 3 presents the cost breakdown, where all amount are expressed in present values. It is interesting to note that the main cost factor is the storage of biomass. This stems from the choice of an expensive type of storage for the biomass, namely closed warehouse with drying capabilities. However, one should keep in mind that this cost factor also includes the cost of handling, unloading and treating the biomass. Using this type of storage, ensures that biomass moisture level will be quickly reduced and therefore the danger of self-ignition as well as fungus and spores development, which are very dangerous for public health, will be significantly reduced. This solution has a very important cost, especially when seasonal biomass types are examined, as in this work, where very large amounts of fuel have to be stored to allow a year-round operation of the power plant. Therefore it is imperative that lower cost storage methods are also examined, in order to significantly reduce the related cost and increase the yield of the project.

The second in order of importance cost factor is biomass purchasing. It should be noted here that low cost biomass sources have been examined in this work. In the case of biomass types that have alternative use and a market price, as fuel wood or wheat straw, it is very probable that biomass purchasing cost would be the highest cost factor.

The ORC power plant investment, operation and maintenance accounts for only 19% of the total system cost, therefore proving the fact that ORC is a relatively low cost technology. The district heating network construction and Operation & Maintenance cost accounts for 8% of the total, whereas the cooling equipment accounts for 5%. Biomass transportation accounts for only 2% of the total cost, primarily because local biomass sources have been selected, therefore significantly reducing the mean travel distance, and secondarily because the loading and unloading stages are not included in this stage.

Conclusions

A presentation of the ORC technology has been performed in this work, both in terms of its technological characteristics, as well as the financial yield of a biomass ORC project, aiming at serving a specific heating and cooling demand.

ORC technology offers a solution of low capital requirement and significantly low Operational & Maintenance cost in comparison to other biomass energy exploitation technologies. Nonetheless, the notably low Power-to-Heat Ratio of the ORC technology results in reduced revenue from electricity generation. ORC is a well proven and used technology and the power plants usually come in pre-assembled modules, thus significantly reducing installation time and cost. Additionally, the standardization of ORC modules reduces the risk associated with performance and reliability, and this is a factor that may be critical for the decision of an investor, depending on his risk attitude [7].

Furthermore, it has been pinpointed that using closed warehouse as a biomass storage system results in extremely high cost, which is the main reason for the mediocre financial yield of the project examined in the case study. Despite the advantages of this storage method in health and safety issues, as well as the negligible material loss and the increase of the energy content of biomass, other lower-cost storage methods should be examined, like ambient storage or storage under low-cost pole-frame constructions [8].

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