Technical and Economic Analysis of Thermal Energy Storage in the Biomass CHP Plants with ORC Technology

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***Abstract* - The investments in units of electricity production from the renewable energy sources have an increasing trend in the European Union countries. The production of electricity from renewable energy sources and cogeneration is promoted by various support mechanisms. The quota obligation system and tradable green certificates was implemented in Romania. In the case of biomass, the support scheme provides two green certificates for each MWh delivered to the public electricity network and additional one green certificate if the electricity is produced in high efficiency cogeneration. For cogeneration plants, demand for useful heat is the essential condition in the qualification of electricity production in high efficiency cogeneration. A solution to provide the demand for useful heat and compensation of load variations over time is the storage of thermal energy. The paper presents the technical and economic analysis of the heat storage systems integration for a cogeneration unit with organic Rankine cycle (ORC) and biomass fuel. The use of thermal energy storage in the heating network of the ORC unit may allow connection of new consumers without disrupting the operation of current consumers. The increased heat consumption delivered of the cogeneration unit will allow the qualify for a larger amount of electricity in high efficiency cogeneration.**

Cuvinte cheie: *stocare energie termică, ciclu Rankine organic, cogenerare de înaltă eficiență, biomasă, scheme de sprijin.*

Keywords: *thermal energy storage; organic Rankine cycle (ORC); high efficiency cogeneration; biomass; support schemes.*

I. Introduction

Currently, capacities of cogeneration production of medium and small power from renewable energy sources are being developed and expanded to reduce CO2 emissions and dependence on fossil fuels [1]. The combination with thermal energy storage can increase the efficiency of cogeneration because the heat produced can be stored if not needed at that time, instead of reducing production.

The ability to use variations in sales prices of electricity and optimize revenue requires flexibility in starting, off and partial charging of the cogeneration units. The addition of a heat storage system will increase the flexibility of a cogeneration plant. The flexibility refers to the capacity of an installation to face changes. The thermal storage systems will allow the cogeneration unit to work continuously and, consequently, avoid repeated startups and stops which may harm the cogeneration unit. It will also allow it to extend the period of operation of the cogeneration unit with beneficial effects on the primary energy economy and the greenhouse gas emissions.

II. Promotion of High Efficiency Cogeneration for Biomass CHP Systems from Romania

To stimulate the production of electricity from renewable energy sources (RES-E) and cogeneration there are different support instruments [2,3]. The support schemes can be differentiated into investment support and operating support. The operating support can further be subdivided into price-based support (feed-in tariff, price premium, fiscal incentives) and quantity-based support (green certificates and mandatory quota systems).

Figure 1 shows how they were applied different support instruments in the European Union (EU) countries [4]. The current discussion within EU Member States about various renewable promotion schemes focuses on the comparison of two systems, the feed-in tariff (FIT) system and the quota regulation in combination with a tradable green certificate (TGC) market.

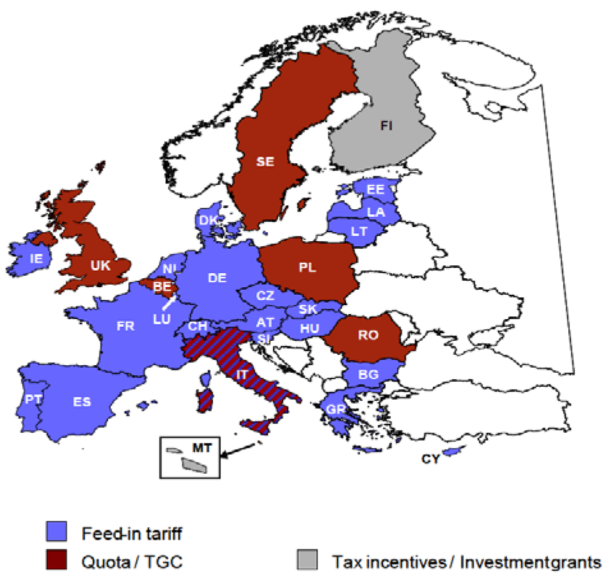


Fig. 1. Support schemes adopted by EU countries for electricity produced from renewable sources (Source: [4])

The classical feed-in tariff consists of a fixed price per kWh of electricity production paid to qualified electricity generators. Quantity-based support schemes adhere to the opposite philosophy compared to price-based support: the regulator stipulates the quantity level to be achieved and leaves the formation of the price to the market.

Directive 2004/8/EC creates a framework for the promotion and development of high efficiency cogeneration of heat and electricity based on a useful heat demand and primary energy saving. Promoting cogeneration has as its objective to reduce greenhouse gas emissions as a result of primary energy saving.

The system of mandatory quotas and tradable green certificates was adopted in Romania. The green certificates are traded on the green certificates market, distinct from electricity generated from renewable energy sources. The lifetime of the support scheme is 15 years. In the case of biomass, the support scheme provides two green certificates for each MWh delivered to the public electricity network and additional one green certificate if the electricity is produced in high efficiency cogeneration (Table I).

TABLE I.
THE RES TYPE AND NUMBER OF GREEN CERTIFICATES ALLOCATED IN ROMANIA [5]

RES type	Type of power plant/group	Number of GC/MWh (initially)	Reduction (Government Decision no. 994/2013)
Wind energy	New	2 GC until 2017 1 GC as of 2018	0.5 GC until 2017 0.25 GC as of 2018
Solar energy	New	6 GC	3 GC
Biomass, Biogas, Landfill gas, Bio-liquid, Geothermal	New	2 GC	-
	High efficiency cogeneration (additional to the 2 GC)	1 GC	-
Hydraulic energy – used in power plants with installed power ≤10 MW	New	3 GC	0.7 GC

The qualification of electricity production in high efficiency cogeneration for a cogeneration unit is based on the primary energy saving compared to separate production with alternative technologies in similar conditions and the same amounts of useful heat and electricity.

The primary energy saving (PES) is defined as the difference between primary energy demand of separate generation of power and heat, and primary energy demand of combined generation.

Depending on the power of the group in cogeneration the conditions for accessing the support scheme are:

a) $Pe \leq 1$ MW, $PES > 0$;
b) $1 < Pe \leq 25$ MW, $PES > 10\%$;
c) $Pe > 25$ MW, $PES > 10\%$ and overall efficiency $> 75\%$.

The green certificates issued confirms of primary energy savings obtained and can be traded on a green certificates market, separate from the electricity market.

The advantage of the green certificate scheme is that producers in cogeneration are stimulated to find solutions for economic functioning.

The Romanian Energy Regulatory Authority has the task to monitor the costs and the income resulted from the RES-E production activity for producers that benefit from the green certificate support scheme, looking forward to change the scheme for the newcomers if there is a trend in overcompensation.

The revision mechanism of the number of certificates resulted from the overcompensation analysis is based on the annual recalculation of the number of green certificates/MWh (during the period in which the support scheme is being applied) so that the Internal Rate of Return (IRR), for each technology, for the newcomers, at an aggregated level, is equal with the IRR reference value resulted from the cost benefit analysis established when the promoting system was authorized. If the IRR increases with more than 10% than the reference level, the government would reduce the number of green certificates for that specific technology.

III. THE EVOLUTION OF THE INSTALLED CAPACITY OF RES-E IN ROMANIA

The installed power structure in the power plants of the National Power System (NPS) is 24738 MW while the available power on 2017/10/01 was 20956 MW [6]. The electricity from renewable energy sources (RES-E) represents a total capacity of 5190 MW (20.97%).

The installed capacity in RES-E (wind power plants, photovoltaic power plants, hydroelectric power plants with an installed capacity that is not larger than 10 MW, biomass power plants) is presented in Figure 2. The production of electricity in Romania in the 2016 year from RES-E has been of 13.52%. (Figure 3).

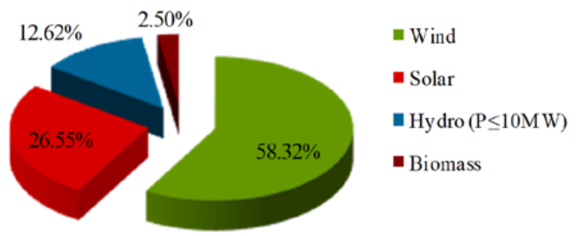


Fig. 2. The installed capacity of RES-E in the 2017 year [6].

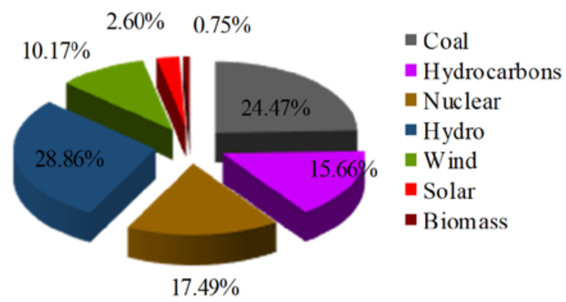
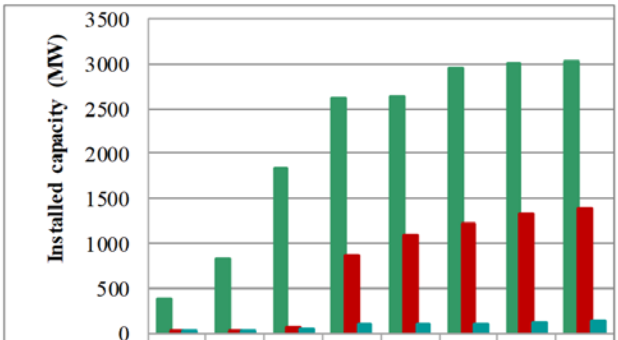


Fig. 3. The structure of electricity production in Romania in the 2016 year depending on the primary energy source [6].

The evolution of the installed power in units of electrical energy production from renewable energy sources, in 2010-2017, is presented in Figure 4.



	2010	2011	2012	2013	2014	2015	2016	2017
Wind	370	826	1822	2607	2624	2953	3007	3027
Solar	0	1	49	860	1091	1208	1324	1378
Biomass	23	25	40	87	96	100	121	130

Fig. 4. The evolution of the RES-E installed power in 2010-2017 [6].

The implementation of the green certificate support system and mandatory annual quotas had the effect increase of investments in in units of electricity production from renewable energy sources, especially wind power and solar power.

By type of biomass used, the installed capacity in biomass plants is distributed as follows:

a) wastes from forestry and related industries: 101.25 MW;
b) gas of fermentation from sludge and animal manure: 7.21 MW;
c) landfill gas: 4.76 MW;
d) biogas: 17.09 MW.

After the dispatching mode, the installed capacity in biomass plants is distributed as follows:

a) dispatchable groups: 29.65 MW;
b) non-dispatchable groups: 100.66 MW

A unit is considered dispatchable (may respond to a dispatcher) provision if its power falls into the following categories:

a) thermal power plants (including biomass): $P_{inst.} \geq 20$ MW;
b) hydro power plants: $P_{inst.} \geq 10$ MW;
c) wind power plant, photovoltaic power plant (ensemble of energy groups): $P_{inst.} \geq 5$ MW.

The integration of renewable energy sources is accompanied by specific challenges in operating the National Power System (NPS) and the electricity market.

After the integration of wind power plants in particular, there have been difficulties in operating of the NPS due to the sudden variations in their production of electricity.

The intermittent and unpredictable character of the renewable energy sources implies greater system reserves to ensure the balance between production and consumption of electricity. Also, a greater flexibility of the conventional power plants for the provision of balancing and ancillary services is required.

The electricity production from biomass has the advantage of good predictability as opposed to solar and wind sources whose production is unpredictable and fluctuating.

Under current and future operating conditions of the NPS a series of preventive actions are required to increase safety and efficiency in generating electricity, including the promotion of various energy storage systems. The investments in the storage systems expansion will allow increasing the share of renewable energy sources in total production of electricity.

IV. Increasing Energy Efficiency of the Organic Rankine Cycle on Biomass by Integrating Heat Storage in the Heating Network

The lack of correlation between the amounts of electricity and the heat supplied of the cogeneration unit and demand for electricity and heat represent a major concern in the implementation of the combined heat and power plants. More than that, a cogeneration system works most efficiently at a constant load, but the thermal and electrical requirements are not usually constant.

We analysed the possibility of implementation the thermal energy storage (TES) in the cogeneration plant with the ORC technology (Organic Rankine Cycle) and biomass fuel shown in Figure 5.

The technical characteristics in the nominal conditions are 1.3 MWe and 5.4 MWth.

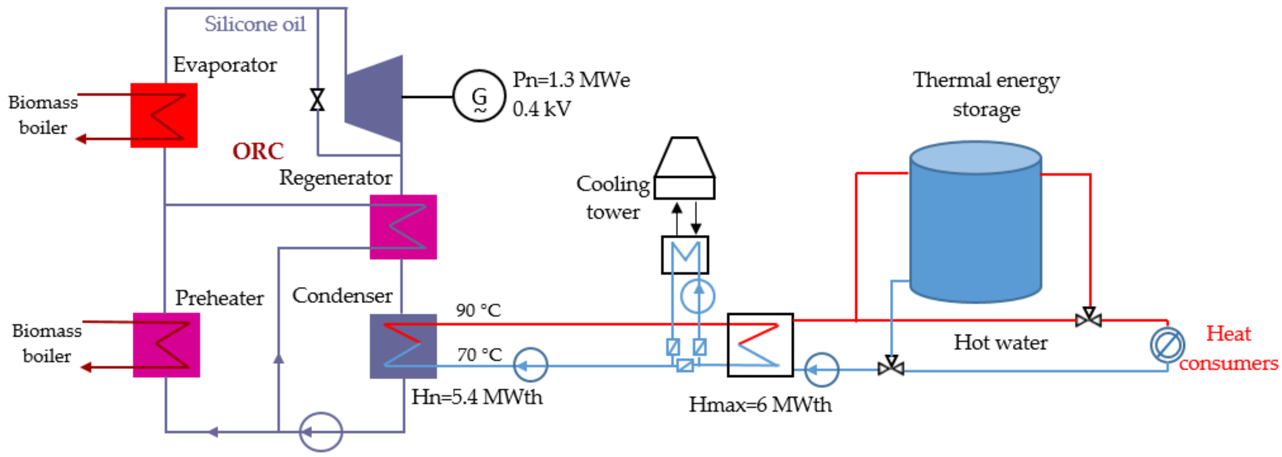


Fig. 5. TES position in the heating network of the ORC unit.

The used biomass comes from the industrial processing of wood (wood chips, bark, sawdust) and biomass from agriculture (straw). Heat delivered by the cogeneration plant is mainly used for industrial purposes (dryers for wood) and a small part for heating administrative buildings and production.

Because the demand for useful heat is less than the amount of the cogeneration unit heat produced, the qualified electricity in high efficiency cogeneration is only 32.82% (Figure 6). Solutions for increasing generated electricity are needed in high efficiency cogeneration.

The heat delivered to consumers is the main factor in the qualification of generated electricity in high efficiency cogeneration. Therefore, new consumers can be connected which to use the available thermal potential of the cogeneration unit. The particularities of the existing heating network shall be taken into account in terms of heat flow rate and temperatures which may be available without disturbing existing consumers.

The main role of integrating of thermal energy storage is the takeover of load variations and facilitating the connection of a new heat consumer which does not disturb the operating of existing consumers.

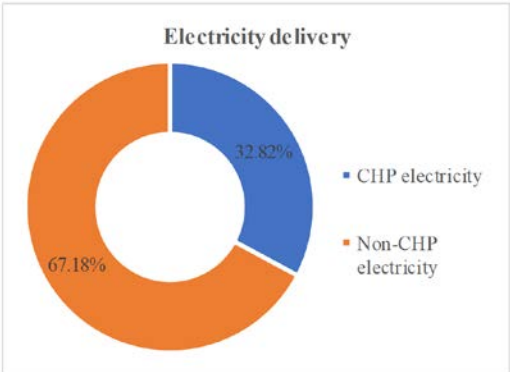


Fig. 6. Electricity qualified in high efficiency cogeneration.

In order to determine the optimal capacity of a heat storage unit, it is necessary to analyse the variation of the thermal load [7]. Figure 7 shows the variation in useful heat demand in the case of the analysed cogeneration unit for a typical operating period.

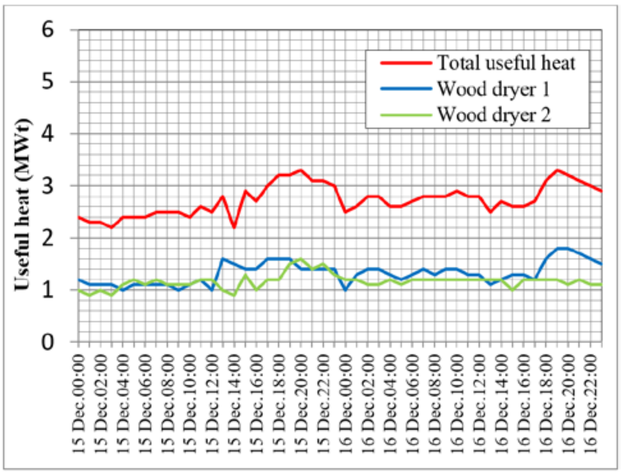
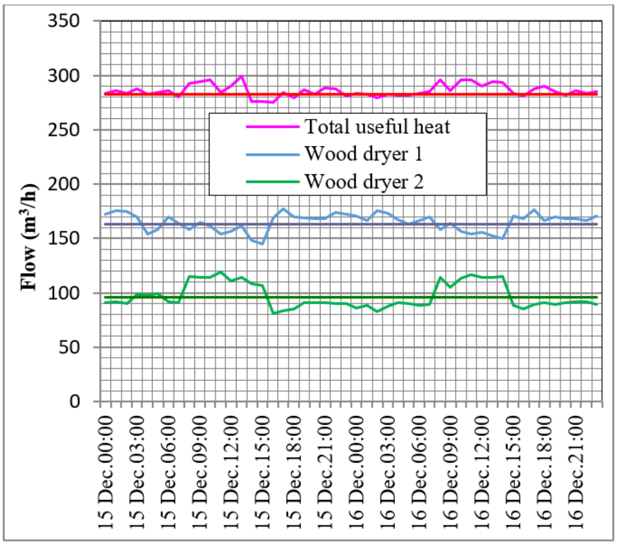


Fig. 7. The heat consumption variation of the cogeneration unit.

Figure 8 and 9 shows the flow and temperature variation in the heating network of the ORC unit.

The return temperature of the heating network is over the value of 80 ºC. The condenser of the ORC unit requires an inlet temperature of 70 ºC. For this reason, water cooling is required which returns from the heat consumers. Thus, an important amount of heat is lost to the cooling source (cooling tower).

The integration of heat accumulator in the heating network toward heat consumers will be able to ensure peak loads greater than 6 MWth compared to the placement before the heat exchanger. In order that the return pipe temperature to maintain around value of 70 ºC, in order to optimal operation of ORC cycle, connecting of the heat accumulator will be on the delivery pipe to the consumers.



Total useful heat:	Wood dryer 1:	Wood dryer 2:
Gmed. = 283 m³/h	Gmed. = 96 m³/h	Dmed. = 163 m³/h
Gmax. = 313 m³/h	Gmax. = 119 m³/h	Dmax. = 185 m³/h

Fig. 8. The flow variation in the heating network.

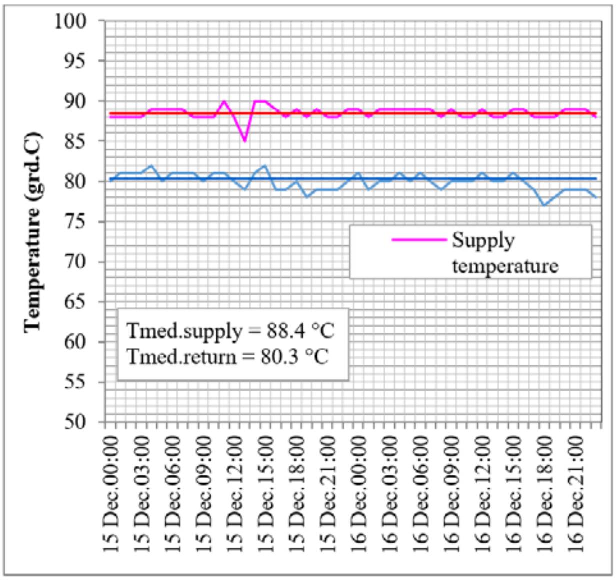


Fig. 9. The temperature variation in the heating network.

The thermal energy storage will allow the system to capture thermal energy when not in use and then deliver it when the process requires more heat than the cogeneration unit can offer. Therefore, the cogeneration system can work more profitably and for longer periods of time.

V. Technical and Economic Analysis of Heat Storage Integration in the CHP Systems of Medium and Small Power

The storage of thermal energy can be done in one of three known forms: sensible heat storage, latent heat storage and thermo-chemical storage [8-10].

The storage of sensible heat is based on changing the temperature of storage medium. Sensible heat can be stored in solid or liquid materials. Less commonly used are gas media because they are more voluminous. The most used storage media are: water, oil, sand, molten salts, rocks. Each material has its own advantages and disadvantages. Choosing storage media is made according to its heat capacity and the space available for storage.

The storage of latent heat is achieved by the storage of energy in phase change materials (PCM). The solid-liquid phase change is achieved by melting and solidifying a material. Initially, the phase change materials it behaves like sensible heat storage and the materials temperature is increased. After the transition temperature is reached the material will continue to absorb heat at a constant temperature while it changes state. The reaction being exothermic and the phase change materials gives heat. The phase change materials used can be organic and inorganic materials. Organic materials include paraffins and non-paraffins such as fatty acids, while inorganic materials comprise salt hydrates, saline composites and metallic alloys.

The thermochemical storage using chemical reactions to store and release thermal energy. A reversible chemical reaction which absorbs heat is used to absorb the thermal energy that is to be stored. Subsequent, the reaction can then be reversed to release the stored heat. The chemical reaction most used for the heat storage is the hydration of salts.

The main features of the heat storage systems are shown in Table II [11]. Storage capacity, storage period and cost price are important criteria in choosing of the storage technology.

TABLE II.
THE MAIN FEATURES OF THE HEAT STORAGE SYSTEMS [11]

TES system	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage period	Cost (Euro/kWh)
Sensible (hot water)	10-50	0.001-10	50-90	day/month	0.1-10
Phase change materials	50-150	0.001-1	75-90	hour/month	10-50
Chemical reactions	120-250	0.01-1	75-100	hour/day	8-100

By comparison, the storage of heat using the phase change materials and chemical reactions is more expensive than the sensible heat storage. Also, these storage systems are much more complex. The storage of heat using water is a mature technology from a commercial point of view. The main advantage is the lower costs for storing heat up to 100 ºC compared to other storage media. The cylindrical vertical tanks of hot water as a storage medium are the most widespread in practice. Due the stratification there is the possibility that higher temperatures be sent to consumers and the smallest temperatures to the heat source. Thus, reducing the mixture and therefore the destruction of exergy is improving the overall performance of the plant.

The main purpose of integrating storage of thermal energy in the cogeneration unit with existing ORC technology is to allow increased consumption of useful heat by connecting a new consumer over existing consumers. The increase in useful heat consumption delivered from the cogeneration unit will allow the qualification of a larger amount of electricity in high efficiency cogeneration. The storage system must be sized to ensure storage capacity at least equal to 8 hours of maximum load. To get maximum storage capacity the temperature difference between the top and bottom of the tank must be as large as possible. This can be achieved by achieving a lower temperature on the return of heating network and a mixture as low as possible in the storage tank. A low grid return temperature can be obtained by choosing the right heat consumers in the heating network.

The following financial analysis tools were used for economic evaluation: the cash flow, the payback period (PBP), the net present value (NPV) and the internal rate of return (IRR). The PBP, NPV and the IRR indices are defined by the following equations:

$$PBP = \frac{C_0}{C_t} \tag{1}$$

$$NVP = \sum_{t=1}^{N} \frac{C_t}{(1+i)^t} - C_0 \tag{2}$$

$$C_0 - \sum_{t=1}^{N} \frac{C_t}{(1+i)^t} = 0 \tag{3}$$

where:

C_0 is the initial investment cost (Euro);
N is the lifetime of the investment (years);
i is the Weighted Average Cost of Capital (WACC);
C_t is the yearly revenue (Euro/year).

The PBP and the IRR for different storage capacities and for different values of the specific investment in the case of the CHP under consideration is shown in Figures 10 and 11.

The yearly revenue taken into account to recover the investment is due to the capitalization of green certificates as a result of the electricity amount increase in high efficiency cogeneration. The trading price of green certificates is between 29-58 Euro/GC. The value taken into account for the yearly revenue estimate is the minimum value that is currently registered in the green certificates market, respective 29 Euro/GC. The analysis highlights as a larger storage capacity to the same specific investment can be recovered in less time period. A larger storage capacity increases the flexibility of the cogeneration plant.

Figure 12 shows the influence of heat storage on the CHP efficiency.

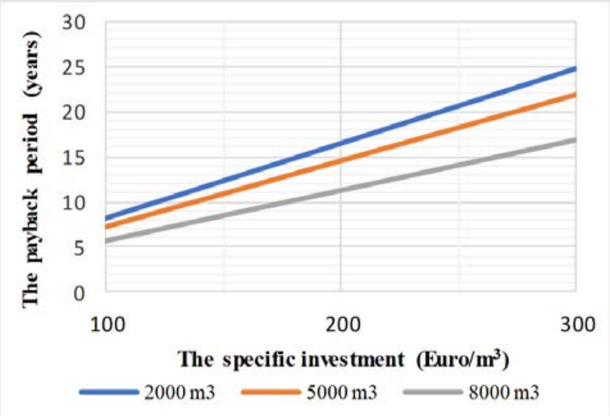


Fig. 10. The PBP for different storage capacities.

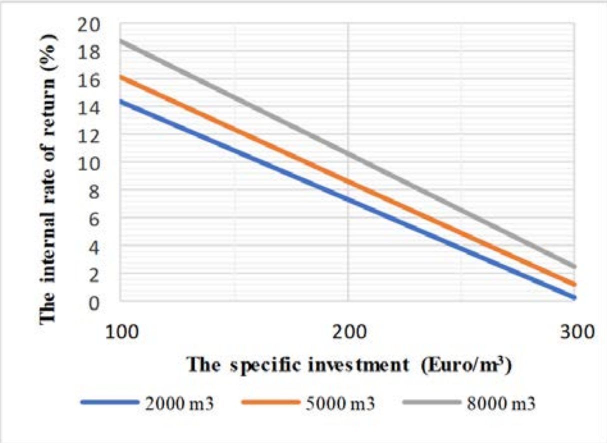


Fig. 11. The IRR for different storage capacities.

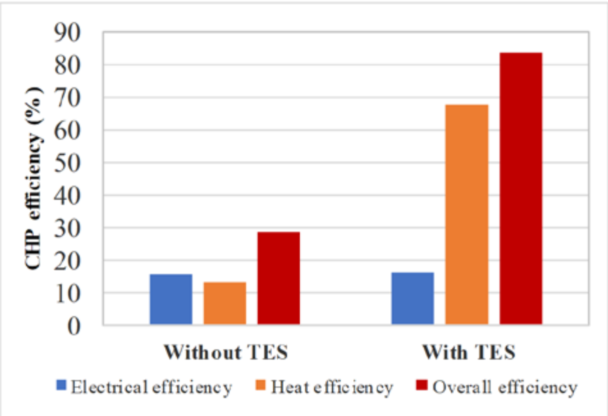


Fig. 12. The CHP efficiency, with and without TES.

The integration of thermal energy storage in the heating network allow connection of new consumers and implicitly increasing the consumption of useful heat.

VI. CONCLUSIONS

In case of medium and low power cogeneration units a heat storage system can be useful for the optimal operation of the plant. Where there is space available, water is a good storage medium and at lower costs compared to other fluids.

The demand for useful heat in the case of the analysed cogeneration plant is less than the available heat delivered of the ORC unit. Therefore, we can connect new heat consumers to consume the available heat.

The integration of thermal energy storage in the heating network of the ORC unit may allow connection of new consumers without disrupting the operation of current consumers. The particularities of existing consumers and the variability of the heat load should be considered in this case.

The increased heat consumption delivered of the cogeneration unit will allows qualifying for a larger amount of electricity in high efficiency cogeneration.

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Contribution of authors:

First author – 40%

First coauthor – 15%

Second coauthor – 15%

Third coauthor – 15%

Fourth coauthor – 15%

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