The Qualification of Electricity Production in High Efficiency Cogeneration for the Access to the Support Scheme through Green Certificates

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Abstract. The promotion of high efficiency cogeneration is a priority of the European Union, given the potential benefits of cogeneration relating to primary energy savings, avoiding network losses and reducing emissions of greenhouse gases. The paper presents the manner of determining the amount of electricity generated in high efficiency cogeneration for access to the support scheme through green certificates. The support scheme for the promotion of cogeneration is based on useful heat demand and primary energy savings compared with separate production of electricity and heat. We examine a cogeneration heat and power plant with ORC technology and biomass fuel, which have the technical characteristics in the nominal conditions of 1.3 MWe (electrical power) and 5.4 MWth (thermal power). We also propose an algorithm for determining the useful heat, who takes into account the operational requirements of the analysed CHP unit.
Keywords: combined heat and power (CHP), organic Rankine cycle (ORC), support schemes, green certificates, high efficiency cogeneration, biomass, renewable energy sources (RES).

Calificarea producţiei de energie electrică în cogenerare de înaltă eficienţă pentru accesarea schemei de sprijin prin certificate verzi

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Rezumat. Promovarea cogenerării de înaltă eficienţă este o prioritate în Uniunea Europeană, având în vedere beneficiile potenţiale ale cogenerării din punct de vedere al economisirii energiei primare, al evitării pierderilor în reţele şi al reducerii emisiilor, în special a gazelor cu efect de seră. În lucrare se prezintă modalitatea de determinare a cantităţii de energie electrică produsă în cogenerare de înaltă eficienţă pentru accesarea schemei de sprijjin prin certificate verzi. Schema de sprijin pentru promovarea cogenerării se bazează pe cererea de energie termică utilă şi economia de energie primară în comparaţie cu producerea separată a energiei electrice şi a căldurii. Este analizată o instalaţie de cogenerare cu tehnologie ORC şi combustibil biomasă cu caracteristicile tehnice nominale 1,3 MW (putere electrică) şi 5,4 MW (putere termică). Se propune un algoritm de determinare a energiei termice utile ţinând cont de particularităţile instalaţiei de cogenerare analizate.
Cuvinte-cheie: centrale de cogenerare, ciclu Rankine organic, scheme de sprijin, certificate verzi, cogenerare de înaltă eficienţă, biomasă, surse regenerabile de energie.

Определение объема производства электроэнергии в системе высокоэффективной когенерации для доступа к схеме поддержки зеленых сертификатов

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Аннотация. Содействие высокоэффективной когенерации является приоритетом в Европейском Союзе, учитывая потенциальные выгоды от когенерации с точки зрения экономии первичной энергии, избежания потерь в сетях и сокращения выбросов, в частности парниковых газов. В документе описывается, как определить количество электроэнергии, производимой в высокоэффективной системе когенерации, для доступа к схеме поддержки зеленых сертификатов. Схема поддержки для содействия когенерации основана на спросе на полезную тепловую энергию и экономию первичной энергии по сравнению с отдельным производством электроэнергии и тепла. Проанализирована когенерационная установка с технологией Органического цикла Ренкина и топливом - биомассой с техническими характеристиками: 1,3 МВт (электрическая мощность) и 5,4 МВт (тепловая мощность). Предложен алгоритм определения полезной тепловой энергии с учетом особенностей анализируемой установки когенерации.
Ключевые слова: когенерационные установки, органический цикл Ренкина, схемы поддержки, зеленые сертификаты, высокоэффективная когенерация, биомасса, возобновляемые источники энергии.

Introduction

In most Member States of the European Union (EU) were adopted a series of measures to encourage investment in renewable energy sources (RES) and cogeneration heat and power plants [1-3]. The motivation to encourage investment in RES is represented by fulfilling the European target: 20% of the energy generated by the year 2020 in the EU must come from renewable energy sources [4].

Directive 2004/08/EC on the promotion of cogeneration and Directive 2012/27/EU on energy efficiency, established the political framework that allow the expansion of the cogeneration implementation in the Member States [5,6].

The support scheme for the promotion of high efficiency cogeneration has the following objective: each Member State must reach the targets for reducing emissions of greenhouse gases. The economic viability of cogeneration units depends largely on the technology used and the support schemes implemented in each EU country [7].

In addition to legislative requirements, which usually refer to primary energy savings and reducing emissions of greenhouse gases, some papers suggest other criteria for a better assessment of cogeneration units [8].

There are various market instruments used by governments of EU Member States for support the production of electricity from renewable energy sources and combined heat and power plants. The support schemes can be divided into investment support (capital grants, exemptions or reductions in purchases of goods) and operating support (price subsidies, green certificates, auction schemes and tax exemptions or deductions).

The support scheme of electricity production from the renewable energy sources (RES-E) in Romania combines the mandatory quotas with the trading of green certificates (GC). The mandatory quota system is a mechanism for promoting the production of electricity from renewable energy sources through the acquisition by suppliers of mandatory quotas of electrical energy generated from these sources and sale to consumers. For every unit of electricity produced from renewable energy sources (1 MWh) that is delivered to the network, the producers get a number of green certificates, which depend on the technology used. These green certificates can be sold, separately from the electricity generated, on green certificates market. In their turn, the electricity suppliers are obliged to purchase annually a number of green certificates proportional to the amount of electricity sold to the final consumers. The number of green certificates purchased is proof of fulfilling those mandatory quotas.

Because of the analysis of overcompensation, compared to the initial system for granting the number of green certificates, during the implementation of the support scheme there have been changes concerning to deferment for a certain period or even reducing the number of green certificates (Table 1) [9].

TABLE I. THE PROMOTION SYSTEM OF RES-E IN ROMANIA

RES Type	Type of Power Plant/Group	Number of GC/MWh*	Currently (after the 2013 year)
1. Hydraulic energy – used in power plants with installed power ≤10 MW	New Refurbished Not upgraded	3 GC 2 GC 0.5 GC	reduction 0.7 GC - -
2. Wind energy	New	2 GC until 2017	reduction 0.5 GC until 2017
		1 GC as of 2018	reduction 0.25 GC as of 2018
3. Biomass, Biogas, Landfill gas, Bio-liquid, Geothermal	New	2 GC	-
	High efficiency cogeneration (additional to the 2 GC)	1 GC	-
4.Solar energy	New	6GC	reduction 0.7 GC

*Originally granted (in year 2008).

The market for green certificates is a competitive market distinct from the electricity market where are traded green certificates corresponding of electricity produced from renewable energy sources which benefit from the support scheme.

I. Use of the Organic Rankine Cycle for Cogeneration Applications

The simultaneous conversion into electricity and heat of energy from renewable sources or the waste heat from various processes is a solution to an efficient capitalization of some energy forms available in large quantities and underused.

If the primary energy source has a sufficiently high thermal potential, it is recommended to use the Rankine cycle classic with steam, as a possible solution for the conversion of heat into electricity.

If the primary energy source has a lower thermal potential, as in the case of renewable energy sources [10-13], the organic Rankine cycle (ORC) can be used for cogeneration of both useful forms of energy: electricity and heat.

Due to its modular construction, the ORC technology can be coupled to various primary energy resources (Figure 1): solar, geothermal, biomass, waste heat recovery. In addition, unlike the conventional Rankine cycle, it is possible to produce electricity and heat locally at medium and low power. The organic Rankine cycle is similar to a conventional Rankine cycle, but uses an organic fluid instead of water.

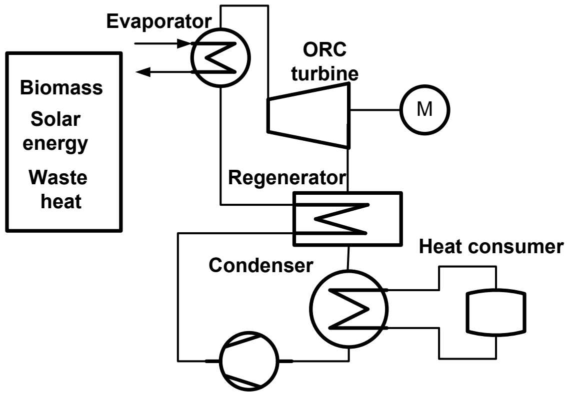


Figure.1. Cogeneration with Organic Rankine Cycle.

The working fluids from installations who work according to the Rankine cycle presents different thermodynamic properties which influence the operating conditions and the energy performances.

Water is used as a working fluid for applications at high temperatures but it has its limitations that become more significant during operation with lower temperature at the entrance of the cycle. The main difference between organic fluids and water is represented by their behaviour when expanding from a saturated or superheated state through a turbine with moderate temperatures at the beginning of the cycle (200-400°C). This behaviour is observed by examining the fluid expansion through turbine in this temperature regime [14-17].

A high content of moisture at the output of the turbine is unacceptable because it can lead to the final blades damage and worsening of the turbine efficiency.

The organic fluids have a much different behaviour from that observed in water, after expansion the working fluid remains in the region of superheated vapor with favourable effects on the operation of the turbine. In contrast, in a steam cycle, the steam is superheated to avoid formation of moisture in the final stages of the turbine.

In the case of the cogeneration unit with ORC, the condensation of the working fluid takes place at a temperature level which allows the recovered heat to be used by heat consumers (hot water feed temperature about 80 to 100°C).

In order to obtain a high electric efficiency of the ORC cogeneration unit, it is necessary to keep the back-pressure of the turbine as low as possible. This can be achieved by the operation and control optimization of the district heating network and cooling source.

The studies of economic feasibility are decisive in choosing of cogeneration solutions with ORC technology, and therefore a growing number of publications includes estimating of the investment and operating cost for the ORC systems [18-20].

II. Mathematical Model Used for Calculating the Amount of Electricity from Cogeneration

The comparison between combined production and separate production of heat and electricity is based on the principle of comparing the same types of fuel [21, 22]. As a general rule, each cogeneration unit shall be compared with the best available and economically justifiable technology for separate production of heat and electricity on the market in the year of construction of the cogeneration unit.

Determining the quantities of electricity who benefit from the support scheme is based on the quality factor of the cogeneration unit. The quality factor (QF) is an indicator of energy efficiency and environmental performance for cogeneration unit, compared with separate production by alternative technologies, under similar conditions for the same amounts of useful heat and electricity. The quality factor of cogeneration unit is calculated by the relation [23].

$$QF = X \cdot \eta_{e,CHP} + Y \cdot \eta_{h,CHP} \quad (1)$$

where, X is the coefficient of definition for cogeneration unit which considers the alternative options for separate production of electricity; Y is the coefficient of definition for cogeneration unit which considers the alternative options for separate production of heat; $\eta_{e,CHP}$ is the electrical efficiency of the cogeneration production; $\eta_{h,CHP}$ is the heat efficiency of the cogeneration production.

The coefficient of definition X that considers the alternative options for separate production of electricity, is calculated by the equation:

$$X = \frac{100}{\eta_{e,Ref} \cdot p_{loss}} \quad (2)$$

where:

p_{loss} is the correction factor for avoided grid losses (Table 2) [24];

$\eta_{e,Ref}$ is the efficiency reference value for separate production of electricity (Table 3) [24].

The coefficient of definition Y which considers the alternative options for separate production of heat, is calculated by the equation:

$$Y = \frac{100}{\eta_{h,Ref}} \quad (3)$$

where $\eta_{h,Ref}$ is the efficiency reference value for separate production of heat (Table 4) [24].

The overall efficiency of a cogeneration unit is:

$$\eta_{gl,CHP} = \eta_{e,CHP} + \eta_{h,CHP} \quad (4)$$

TABLE II. VALUES OF THE CORRECTION FACTOR FOR AVOIDED GRID LOSSES.

Connection Voltage Level	**Correction Factor (Off-site)**	**Correction Factor (On-site)**
> 345 kV	1	0.976
200-345 kV	0.972	0.963
100-200 kV	0.963	0.951
50-100 kV	0.952	0.936
12-50 kV	0.935	0.914
0.45-12 kV	0.918	0.891
< 0.45 kV	0.888	0.851

TABLE III. THE EFFICIENCY REFERENCE VALUES FOR SEPARATE PRODUCTION OF ELECTRICITY.

Type of Fuel	**Year of Construction**		
	Before 2012	***2012-2015***	***From 2016***
Hard coal	44.2	44.2	44.2
Lignite	41.8	41.8	41.8
Fuel oil (diesel oil), bioliquids	44.2	44.2	44.2
Natural gas	52.5	52.5	53.0
Biogaz	42.0	42.0	42.0
Biomass	33.0	33.0	37.0
Municipal/biodegradable waste	25.0	25.0	25.0

TABLE IV. THE EFFICIENCY REFERENCE VALUES FOR SEPARATE PRODUCTION OF HEAT.

Type of Fuel	**Year of Construction**			
	Before 2016		***From 2016***	
	Hot water	***Steam***	***Hot water***	***Steam***
Hard coal	88	83	88	83
Lignite	86	81	86	81
Fuel oil (diesel oil), bioliquids	89	84	85	80
Natural gas	90	85	92	87
Biogaz	70	65	80	75
Biomass	86	81	86	81
Municipal/biodegradable waste	80	75	80	75

The electrical efficiency of the cogeneration production is:

$$\eta_{e,CHP} = \frac{E}{F} \qquad (5)$$

The heat efficiency of the cogeneration production is:

$$\eta_{h,CHP} = \frac{H + H_{own}}{F}\ , \qquad (6)$$

where:

E is the electricity output from cogeneration unit;

H is the useful heat output from cogeneration unit;

H_{own} is the consumption of internal thermal services for fuel heating;

F is fuel input in cogeneration unit.

The primary energy saving (PES) is calculated by the equation:

$$PES = \left(1 - \frac{1}{\dfrac{\eta_{h,CHP}}{\eta_{h,Ref}} + \dfrac{\eta_{e,CHP}}{\eta_{e,Ref} \cdot p_{loss}}} \right) \cdot 100(\%) \qquad (7)$$

If the quality factor fulfills the minimum value, the whole production of electricity of cogeneration unit is considered high efficiency, respectively:

$$E_{CHP} = E\ , \qquad (8)$$

where, E_{CHP} is the electricity of high efficiency cogeneration.

The amount of electricity that benefit from the support scheme E_{SS} is calculated as:

$$E_{SS} = min\left(E_{delivered}, E_{CHP}\right) \qquad (9)$$

where, $E_{delivered}$ represent the electricity delivered to the public network.

The electricity of a cogeneration unit is considered as being produced in high efficiency cogeneration, if the quality factor fulfills the minimum condition.

The minimum values for the quality factor are:

- $QF_{min} = 100.001$ for small scale and micro-cogeneration units;
- $QF_{min} = 111.112$ for all other cogeneration units.

The small-scale cogeneration unit is a unit with an installed capacity below 1 MWe. The micro-cogeneration unit is a unit with a maximum capacity below 50 kWe.

If the quality factor determined by the equation 1 is lower than the minimum value, we recalculate the amount of electricity, which can benefit from the support scheme according to the technology used.

For cases in which the cogeneration unit does not operate in full cogeneration mode under normal conditions of use, it is necessary to identify the electricity and heat not produced under cogeneration mode, and to distinguish it from the CHP production [25].

A. The cogeneration unit does not have district heating outlet

It is recalculated the value of the thermal efficiency for achieving the QF_{min}:

$$\eta_{h,cogE} = \frac{QF_{\min} - X \cdot \eta_e}{Y} \tag{10}$$

It is considered:

$$\eta_{e,cogE} = \eta_e \tag{11}$$

The fuel consumption for the production of electricity and heat in cogeneration:

$$F_{cogE} = \frac{H + H_{own}}{\eta_{h,cogE}}. \tag{12}$$

It is calculated the value of the power to heat equivalent ratio C_{ech}:

$$C_{ech} = \frac{\eta_{e,cogE}}{\eta_{h,cogE}}. \tag{13}$$

The high efficiency electricity of the cogeneration unit:

$$E_{CHP} = \left(H + H_{own}\right) \cdot C_{ech}. \tag{14}$$

B. The cogeneration unit have district heating outlet

It is recalculated the value of the thermal efficiency for achieving the $QF_{\min}$:

$$\eta_{h,cogE} = \frac{QF_{\min} - QF}{\left(Y - X \cdot \beta\right) + \eta_h}. \tag{15}$$

It is recalculated the value of the electrical efficiency for achieving the $QF_{\min}$:

$$\eta_{e,cogE} = \eta_e - \frac{QF_{\min} - QF}{\left(Y - X \cdot \beta\right) \cdot \beta}, \tag{16}$$

where β is the reduction factor of power for cogeneration unit with district heating outlet.

The fuel consumption for the production of electricity and heat in cogeneration:

$$F_{cogE} = \frac{H + H_{own}}{\eta_{h,cogE}} \tag{17}$$

It is calculated the value of the power to heat equivalent ratio C_{ech}:

$$C_{ech} = \frac{\eta_{e,cogE}}{\eta_{h,cogE}}. \tag{18}$$

The high efficiency electricity of the cogeneration unit:

$$E_{CHP} = \left(H + H_{own}\right) \cdot C_{ech}. \tag{19}$$

III. Application for a Cogeneration Unit with ORC Technology and Biomass Fuel

The analyzed cogeneration plant is based on the organic Rankine cycle. The CHP unit became operational in the year 2015.

The cogeneration plant only consumes biomass fuel. The biomass comes from forestry and related industries (the primary wood industrialization): wood chips, bark, and sawdust.

The delivered heat by the CHP unit is mainly used for industrial purposes (dryers for wood) and a small part for heating of the administrative and production buildings.

The principle thermal scheme is shown in Figure 2. The fuel consumption and electricity production in the year 2016 is shown in Figure 3. The load duration curve of heat demand in the year 2016 is shown in Figure 4.

In order to determine the amount of useful heat delivered from the cogeneration plant, in Figure 5 are presented the main flows of energy resulting from the process of cogeneration.

On the basis of the operating conditions, we present the proposed algorithm for determining the amount of useful heat supplied from the cogeneration unit. For this, we used the groups of metering shown in Figure 5:

a) HM_1 is heat metering generated from the ORC cogeneration unit;
b) HM_2 is heat metering transferred to the cooling source (cooling source);
c) HM_3 is heat metering supplied to consumers.

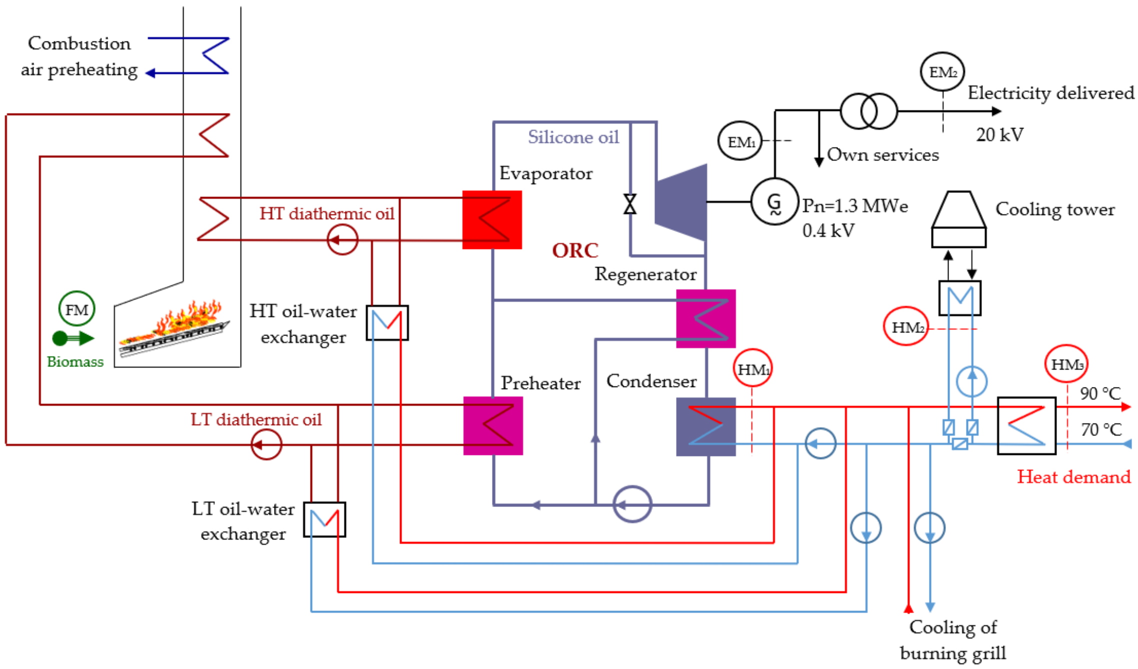
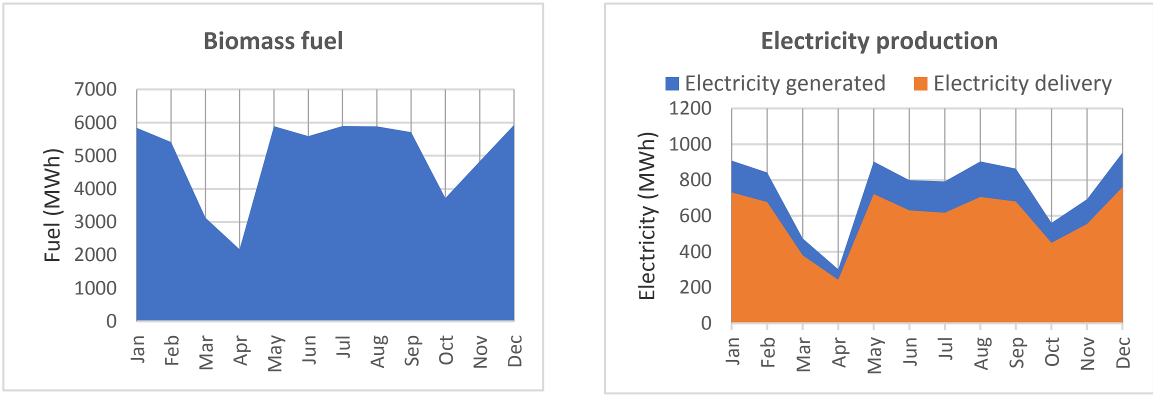


Figure.2. Schematic thermal diagram of CHP (the technical characteristics in the nominal conditions: 1.3 MWe and 5.4 MWth).



(a) (b)

Figure.3. Fuel consumption and electricity production in the year 2016: (a) fuel consumption; (b) electricity production.

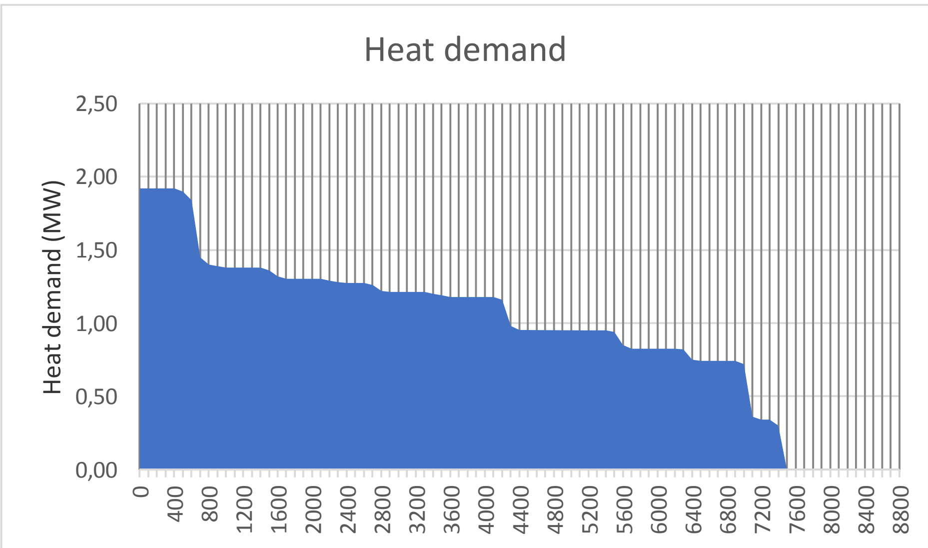


Figure.4. Load duration curve of heat demand in the year 2016.

A significant feature in the operation of the cogeneration unit is represented by heat gains in the cooling water circuit of the condenser and which are not produced in cogeneration mode:

1. The recovered heat from the cooling system of the biomass boiler (cooling of burning grill);
2. The heat from high temperature diathermic oil-water exchanger (HT) and low temperature diathermic oil-water exchanger (LT).

The cogeneration unit operation in this mode is necessary for a safe operation of the plant.

Both heat exchangers are kept warm for safety reasons. They provide evacuation of the main flow of heat from the biomass boiler if the electric generator is stopped. In addition, it can provide heat supply to consumers in case of failure of the cogeneration unit for a longer period of time.

The HT and LT heat exchangers are maintained in warm standing by the automation system of cogeneration unit by periodic starts of pumps from the secondary circuit, in order to cool the exchangers. In transitional situations (ORC turbine-generator unit stopped), the bypass connection of turbine for silicone oil recirculation in the ORC circuit is opened, and the evacuation of the main flow of heat from the biomass boiler is achieved by coupling the HT and LT heat exchangers. For such situations and for cases where consumers are supplied directly from the biomass boiler via the HT and LT exchangers, amounts of heat associated with operating modes that record null values of generated electricity are excluded. These amounts of heat are excluded from the monthly amounts recorded by all three groups of heat metering.

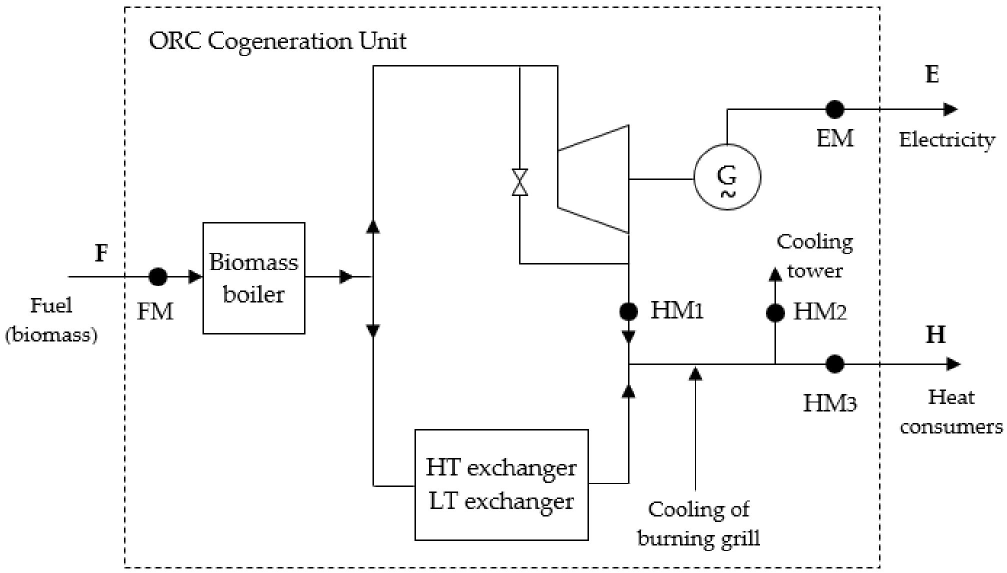


Figure.5. **Energy flows in ORC-CHP.**

For normal operation (electric generator coupled to the network), the following notations are used:

a) $HM_{1\_reg.CHP}$ is heat metering generated from the ORC cogeneration unit in cogeneration mode:

b)

$$HM_{1\_reg.CHP} = HM_1 + HM_{1\_bypass} \quad (20)$$

c) $HM_{2\_reg.CHP}$ is heat metering transferred to the cooling source (chiller) in cogeneration mode:

$$HM_{2\_reg.CHP} = HM_2 + HM_{2\_bypass}, \quad (21)$$

d) $HM_{3\_reg.CHP}$ is heat metering supplied to consumers in cogeneration mode:

$$HM_{3\_reg.CHP} = HM_3 + HM_{3\_bypass}, \quad (22)$$

where, HM_{1_bypass}, HM_{2_bypass} and HM_{3_bypass} its are recorded quantities by the three groups of metering if the electric generator is disconnected from the network (electricity from the generator terminals is zero).

The total thermal energy generated by the cogeneration unit is the amount of useful heat and dissipated heat registered by the HM_2 and HM_2 metering groups:

$$H_{total} = HM_2 + HM_3 . \quad (23)$$

The amount of heat generated in non-cogeneration mode resulting from the equation of energy balance:

$$H_{nonCHP} = HM_2 + HM_3 - HM_1 . \quad (24)$$

Therefore, each of the HM_2 and HM_3 metering groups, in normal operating conditions (electric generator coupled to the network), will record an amount of heat produced in cogeneration mode and an amount of heat produced in non-cogeneration mode:

$$H_{2\_reg.CHP} = HM_{2\_CHP} + HM_{2\_nonCHP} , \quad (25)$$

and:

$$H_{3\_reg.CHP} = HM_{3\_CHP} + HM_{3\_nonCHP} . \quad (26)$$

From the equations (24) and (26) it results:

$$HM_{3\_CHP} = HM_{1\_reg.CHP} \cdot k_{CHP} , \quad (27)$$

where k_{CHP} is the correction factor for the heat produced by the ORC unit and delivered to heat consumers.

$$k_{CHP} = \frac{HM_{3\_reg.CHP}}{HM_{2\_reg.CHP} + HM_{3\_reg.CHP}} \quad (28)$$

In conclusion, the useful heat delivered from the cogeneration unit is:

$$H = HM_{3\_CHP} \quad (29)$$

In order to determine the amount of useful heat delivered from the cogeneration unit, two reports that contain the records of the metering groups (a report with hourly records and a report records per minute) are used.

By analysing these records, both categories of operating modes can be easily identified: one having the electric generator coupled to the network and the other having electric generator disconnected from the network. Both reports with records of the metering groups are taken from the SCADA system (supervisory control and data acquisition) of the cogeneration unit.

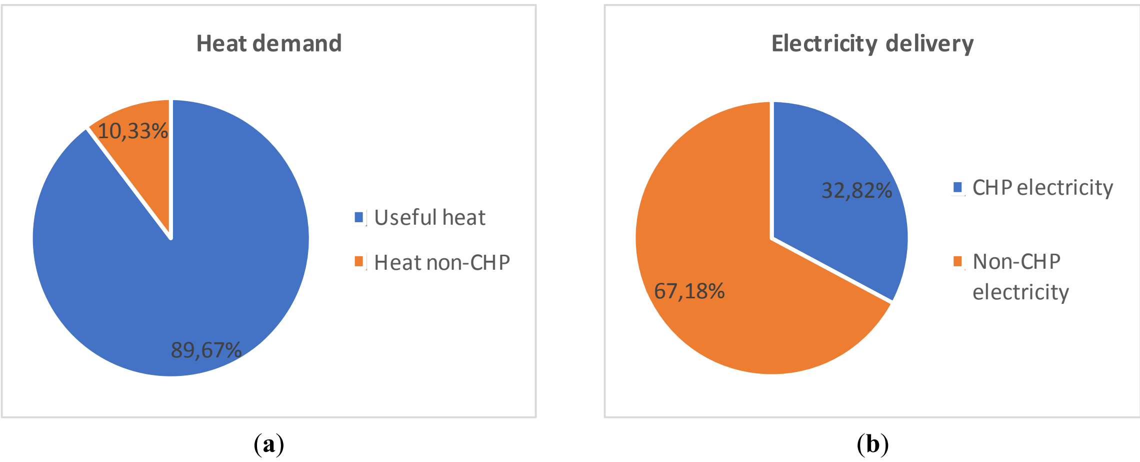


Figure.6. The useful heat delivered and electricity qualified in high-efficiency cogeneration in the year 2016: (a) heat demand; (b) electricity delivery.

Figure 6 shows the delivered useful heat and the electricity qualified in high-efficiency cogeneration, calculated by the presented mathematical model.

The heat demand of consumers in the year 2016 has been 9207 MWh/year, of which 89.67% is useful heat produced in cogeneration mode and 10.33% is useful heat produced in non-cogeneration mode. The delivered electricity has been 7154 MWh/year of which only 32.82% can be qualified as being produced in high efficiency cogeneration.

IV. CONCLUSIONS

High efficiency cogeneration is defined by the primary energy savings compared with separate production by alternative technologies of heat and electricity. Higher values of 10% for the primary energy savings justifies the use of the expression "high efficiency cogeneration".

The demand for heat represents the decisive aspect in justifying efficiency of cogeneration solution, it is the basic element for both the sizing of the cogeneration unit and for the qualification of the electricity in high efficiency cogeneration.

In order to maximize the primary energy savings, a detailed analysis of the specific operating conditions of the combined heat and power plants is required. This way, the opportunity to qualify a large amount of electricity as being produced in high efficiency cogeneration is not lost.

The mathematical model proposed for determining the useful heat resulted from the specific operating conditions of the combined heat and power plant with ORC technology. The algorithm helps to identify the electricity and heat, which are not produced in cogeneration mode, and highlights the electricity produced in high efficiency cogeneration.

The choice of the cogeneration technology and type of primary energy source have a decisive influence in the qualification of electricity generation in high efficiency cogeneration, both by the reference values of efficiency separate production of heat and electricity as well as by the power to heat ratio.

The combined heat and power plants that use renewable energy sources, even if have the higher investment costs, are attractive on the energy market because of the lower operating costs in comparison with conventional technologies. The investment effort, still high for these technologies may be diminished if there are taken into consideration the social and environmental benefits that come with the implementation of cogeneration plants.

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