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Integration of an Organic Rankine Cycle and a Photovoltaic Unit for Micro-Scale CHP Applications in the Residential Sector

J. Settino[a], P. Morrone[b]*, A. Algieri[b], T. Sant[a], C. Micallef[a], M. Farrugia[a], C. Spitieri-Staines[a], J. Licari[a], A. Micallef[a]

[a] *University of Malta, Msida MSD 2080, Malta*
[b] *University of Calabria, Via P. Bucci, 87036 Arcavacata di Rende (CS), Italy*

Abstract

The purpose of this work is to analyse the performance of a novel system for combined heat and power (CHP) generation in small-scale applications. The system is based on an Organic Rankine Cycle (ORC) fed with biomass and a photovoltaic (PV) unit. The ORC and PV sub-systems operate in parallel to produce the required electrical energy. A preliminary investigation is performed to define the proper size of the photovoltaic unit. Afterwards, the analysis is focused on the hybrid system and a comparison between the two configurations is carried out.
This work demonstrates the potential for integrating biomass and solar energy resources: during daylight, solar radiation is significant and the ORC system can be switched off or operated at partial load. Furthermore, the adoption of biomass makes it possible to overcome the intermittency of solar resource, increase the self-consumed electrical energy, and produce thermal energy, thereby saving natural gas for heating purposes.

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Keywords: Photovoltaic, Organic Rankine Cycle, Combined Heat and Power, Hybridisation

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1. Introduction

Nowadays, the combined heat and power (CHP) production is considered an efficient alternative to conventional

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* Corresponding author. Tel.: +39 0984 494162; fax: +0-000-000-0000
E-mail address: pietropaolo.morrone@unical.it

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Nomenclature

A	area (m^2)
G	solar irradiance (W/m^2)
I	current (A)
P_{el}	electric power (W)
$\dot{Q}_{th}$	thermal power (W)
V	voltage (V)
η	efficiency

systems with separate electric and thermal generation owing to the higher energy efficiency and saving capability and to the lower pollutant emissions [1]-[2]. In this context, the integration of biomass-fired Organic Rankine Cycles (ORCs) and photovoltaic systems (PVs) represent an interesting solution for small-scale CHP applications, capable to overcome the stochastic nature of the solar source. Specifically, ORC systems present different advantages compared to conventional installations due to their lower maintenance requirements, better partial load performance, faster start-up and stop procedures, higher flexibility and safety [3]-[4]. In this framework, energy systems hybridisation appears to be a very innovative and efficient solution, able to assess larger operation flexibility and lower costs [5]-[7]. In particular, there is significant potential for integrating solar and biomass resources: during daylight the solar radiation is high and the ORC system can be fuelled with a low amount of biomass. Furthermore, the adoption of biomass satisfies the energy demand also when the solar radiation is absent or insufficient.

Nevertheless, few investigations on this topic have been documented in literature and further studies are necessary [8]. The present work aims at analysing the energy performance of a hybrid ORC/PV system for domestic applications. The two sub-systems operate in parallel to produce electrical and thermal energy. The investigated concept may offer interesting opportunities to achieve the Nearly Zero Energy House (NZEH) target in the residential sector and to overcome the energy “trilemma” of affordability, supply security, and environmental protection.

2. Methodology

The work aims at analysing the performance of an innovative hybrid energy system for domestic micro-scale combined heat and power (CHP) generation. Figure 1 shows the simplified scheme of the proposed system that consists of a biomass-fired Organic Rankine Cycle (ORC) and a photovoltaic (PV) unit. Solar PV is the primary energy source while the ORC works when the solar radiation is not sufficient to satisfy the electric demand of domestic users. Furthermore, electrical energy can be exchanged with the grid and an auxiliary boiler is used to cover the thermal demand if the CHP output is low.

2.1. Biomass-fired ORC model

The Organic Rankine Cycle consists primarily of a pump system, an evaporator, an expander, and a condenser. The pump supplies the organic fluid to the evaporator, where the fluid is preheated and vaporised. The vapour flows into the expander where it is expanded to the condensing pressure and then, it is condensed to saturated liquid. A biomass boiler provides the energy input to the evaporator through a thermal oil circuit in order to avoid local overheating and to prevent organic fluids from becoming chemically unstable.

A thermodynamic model has been developed to characterise the performance of the biomass ORC section. More details can be found in literature [9]-[11]. The REFPROP database [12] has been integrated with the energy model to define the thermodynamic properties of the organic fluid. For the analysis, a steady state condition has been assumed, while pressure drops and heat losses in the system components have been neglected.

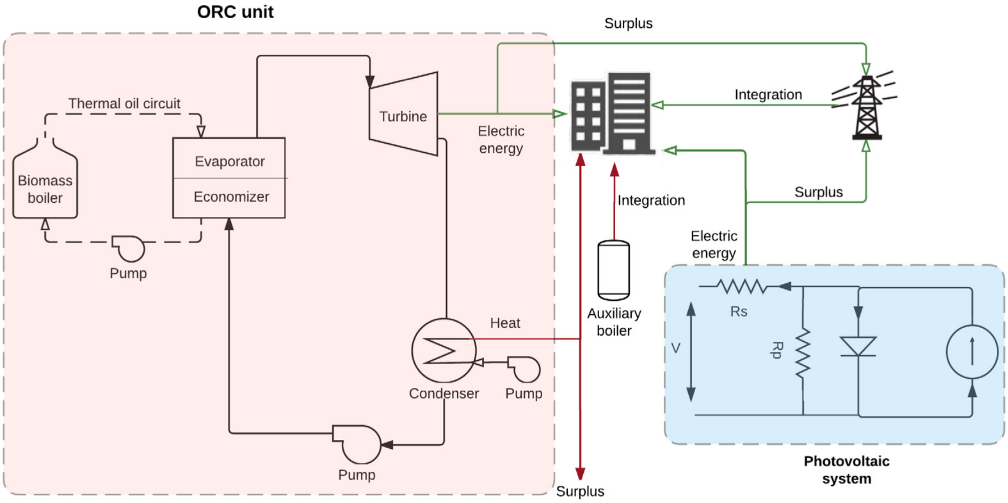


Fig. 1. Simplified scheme of the hybrid CHP system.

The ORC electrical and cogeneration efficiency have been evaluated as follows [13]-[15]:

$$\eta_{el} = \frac{P_{el}}{\dot{Q}_{th}} \tag{1}$$

$$\eta_{cog} = \frac{P_{el}}{\dot{Q}_{th} - \dfrac{\dot{Q}_{cog}}{\eta_{th,ref}}} \tag{2}$$

where P_{el} is the ORC electrical power output;
$\dot{Q}_{th}$ is the thermal input of the biomass boiler.
$\dot{Q}_{cog}$ is the thermal power from the condensation process used for cogeneration;
$\eta_{th,ref}$ is the reference efficiency of a conventional boiler that is used to produce $\dot{Q}_{cog}$ separately.
η_{cog} is the cogeneration efficiency

Toluene has been selected as working fluid for the ORC unit due to its high operating temperatures, consistent with the requirements of biomass systems [16]-[17].

The investigation has been carried out considering saturated conditions at the expander inlet. Table 1 shows the critical temperature and pressure of the selected organic fluid, and the operating conditions assumed in the investigation. In particular, the condensation temperature has been set to 80°C in order to satisfy the thermal request of domestic users [18]-[19]. Minimum evaporation temperature has been set to 150°C while the maximum value of 300°C has been chosen to avoid the presence of liquid during the expansion phase. This depends on the slope of the saturated vapour curve in the T-s diagram [20]. Table 2 summarises the main assumptions used for the parametric energy analysis. Specifically, the expander and pump efficiencies have been set to 0.70 and 0.60 respectively and the global efficiency of the heating process (from biomass to organic fluid through the thermal oil circuit) is 0.85, according to the literature [19],[21].

Figure 2 highlights the behaviour of the ORC section at full and partial loads in terms of electric and thermal efficiency and power, as a function of the evaporation temperature. Results show the progressive increase in performances with the maximum temperature [22]-[24]. In particular, the nominal power (14.1 kW_{el} and 70.5 kW_{th}) corresponds to the maximum thermal level (337 °C) while minimum ORC power is found at 150 °C (5.7 kW_{el} and 55.6 kW_{th}). At 150°C the electrical and cogeneration efficiencies are 8.4% and 81.1%, respectively, while the corresponding values reach 14.6% and 82.6% at the maximum evaporation temperature (300°C).

Table 1. ORC operating conditions

Critical conditions		
Critical temperature	[°C]	318.6
Critical pressure	[bar]	41.26
Operating conditions		
Condensation temperature	[°C]	80
Condensation pressure	[bar]	0.39
Evaporation temperature	[°C]	150 ÷ 300
Evaporation pressure	[bar]	2.75 ÷ 32.76

Table 2. Main assumptions for the energetic analysis.

Expander isentropic efficiency	[%]	70
Pump isentropic efficiency	[%]	60
Boiler and thermal oil circuit efficiency	[%]	85
Electro-mechanical efficiency	[%]	90
Thermal reference efficiency	[%]	86
Biomass lower heating value (dry basis)	[MJ/kg]	18
Biomass humidity	[%]	10

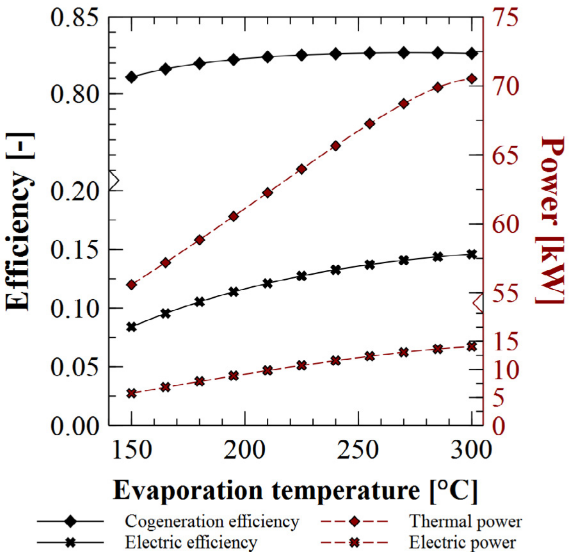


Fig. 2. Influence of the evaporation temperature on the ORC electric and thermal performances.

2.2. PV model

A mathematical model of the photovoltaic panels has been implemented and integrated to the ORC section. The PV model used allows for the evaluation of the conversion efficiency of the system and estimate the produced electrical energy, based on the cell temperature and incident radiation. A single diode model with a parallel (R_P) and a series (R_S) resistance has been implemented. According to the equivalent electric circuit, reported in Figure 1, the output current can be determined through eq. 3:

$$I = I_L - I_0\left(\exp\frac{V + IR_s}{aV_T} - 1\right) - \left(\frac{V + IR_s}{R_p}\right) \tag{3}$$

where $_{VT}$ is the thermal voltage, which is a function of the number of cells in series, I_0 the reverse saturation current and I_L the current produced by the incident solar radiation. These currents can be determined, from eq. 4 and eq. 5 respectively, as described by Ishaque et al. [25], considering PV module characteristics and efficiency at standard conditions provided by the manufacturer (Table 3).

$$I_0 = \frac{I_{sc,STC} + K_i\Delta T}{\exp\frac{V_{oc,STC} + IR_s}{aV_T} - 1} \tag{4}$$

$$I_L = \left(I_{sc,STC} + K_i \Delta T\right)\frac{G}{G_{STC}} \tag{5}$$

To estimate the value of R_S and R_P, the approach illustrated by Ishaque et al. [25] has been followed and eq. 3 has been solved iteratively with the Newton-Raphson method until the maximum power value at standard conditions measured by the manufacturer is matched. The resulting values of R_S and R_P are then used to obtain the characteristic curve V-I under different operating conditions. The electric power is obtained by the product of voltage and current, assuming that the maximum power point (MPP) unit ensures the tracking of the maximum power conditions. The conversion efficiency is defined, as the ratio between the electric power output and the global incident solar radiation, which takes into account beam, diffuse and reflected radiation [26]:

$$\eta = \frac{P_{el}}{G \cdot A} \tag{6}$$

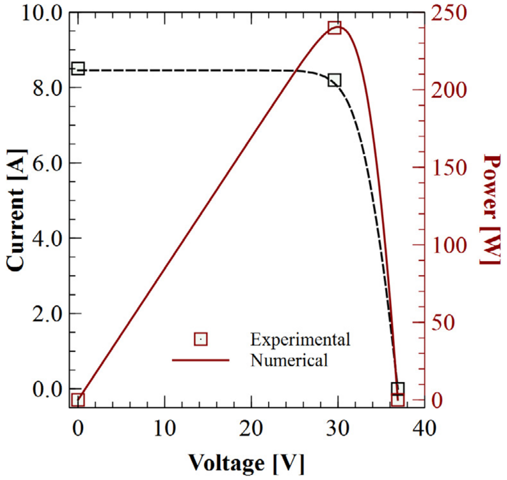


Fig. 3. Characteristic curves of a PV module at standard conditions (G = 1000 W/m^2 and T =25°C).

Table 3. Poly-Si PV Module: data provided by the manufacturer

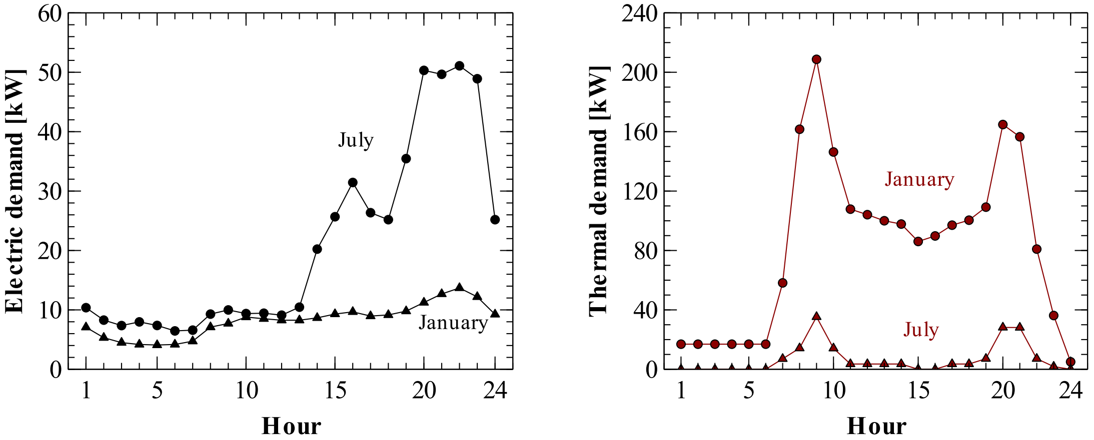
I_{SC} Short Circuit Current	8.46 A
V_{OC} Open Circuit Voltage	36.9 V
I_{mp} Current at MPP	8.11 A
V_{mp} Voltage at MPP	29.6 V
K_v Voltage/Temperature Coefficient	-0.31 %/°C
K_i Current/Temperature Coefficient	0.051 %/°C
PV module efficiency (STC)	14.75 %

3. Results

A novel combined heat and power generation system for small-scale applications has been analysed. The CHP system is based on a photovoltaic (PV) unit coupled with a biomass-fired Organic Rankine Cycle (ORC). The two systems operate in parallel to produce electrical and thermal energy: priority is given to PV unit whereas the ORC system works when the photovoltaic panels are not able to satisfy the electric demand. Solar data have been estimated on hourly basis through SAM software [27].

The investigation was focused on a hypothetical domestic application in Venice (Northern Italy), considering a block of 40 dwellings. The electric demand considers the consumption of domestic lighting system and appliances, including air conditioners during the hot season, whereas the thermal demand takes into account the typical space heating and hot water request [28]-[29]. Figure 4 shows the daily electric (a) and thermal (b) demand during January and July that present the minimum and maximum monthly loads, while the annual electric and thermal requests are estimated to be equal to 85.0 MWh_{el} and 282.2 MWh_{th}, respectively.

A preliminary analysis has been carried out considering the photovoltaic system alone. To this purpose, a parametric investigation has been performed in order to evaluate the proper size of the unit (Figure 5). The plot highlights the percentage of electrical energy produced by the PV system and that supplied from the grid with respect to the annual demand. In particular, the PV electric production consists of self-consumption and surplus electric energy that could be injected to the grid.



a) b)

Fig. 4. Hourly electric (a) and thermal (b) energy request of a block of 40 apartments in Venice (Italy) during January and July.

As expected, the higher the PV nominal power, the higher the electric production. However, it is worthy to notice that the increase rate of self-consumption progressively reduces with the size and a negligible effect is obtained for installed power higher than 60 kW$_{el}$. Conversely, the surplus electricity is considerably more when the PV power is higher than 30 kW$_{el}$. As an example, the value ranges from 21% to 65% of the domestic electric demand when the nominal power moves from 30 kW$_{el}$ to 60 kW$_{el}$. At the same time, the integration from the grid is always higher than 60% for all the investigated sizes.

The PV nominal power has been set to 37.3 kW$_{el}$ in order to limit the energy surplus to 50% of the total production, taking into account that a significant integration from the grid is always necessary, as already observed. The performance of the selected PV system (P$_{el}$ =37.3 kW$_{el}$) are shown in Figure 6 in terms of monthly energy balance. It is evident that the photovoltaic unit is not able to satisfy the global electrical load hence a connection to the grid is necessary. In particular, the largest values are found during June, July and August, when the energy integration is higher than 8.7 MWh$_{el}$. At the same time, surplus energy generated by the PV system is larger than 2.2 MWh$_{el}$ for all the months with the exception of December, when the minimum solar radiation is registered.

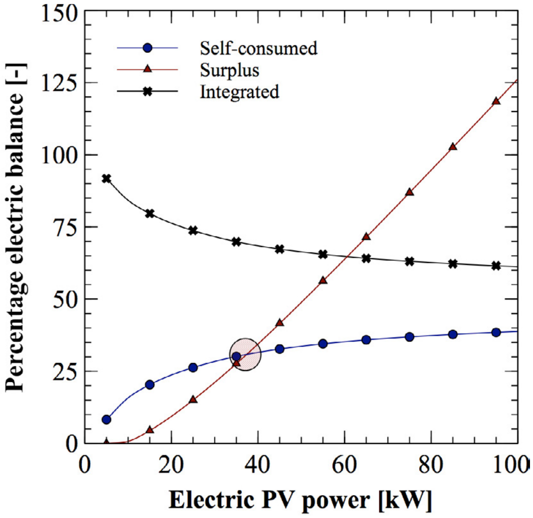


Fig. 5. Annual electrical balance in terms of percentage self-consumed, surplus, and integrated energy with respect to the energy demand. Influence of PV nominal power.

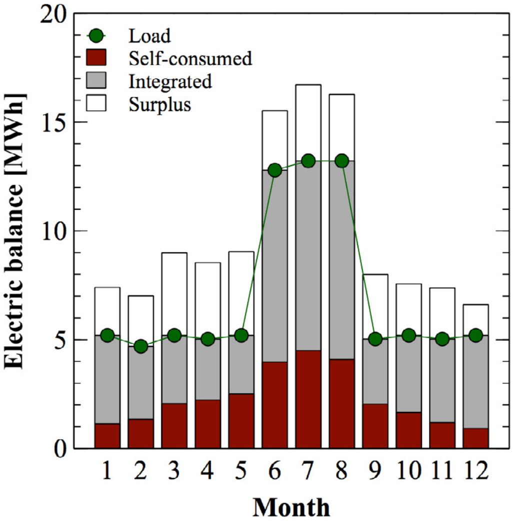


Fig. 6. Monthly electrical balance for the selected PV system.

The analysis has been extended considering the coupling of the selected photovoltaic unit with a biomass-driven ORC system. Specifically, the size of the Organic Rankine Cycle has been defined to satisfy the winter electrical energy demand that presents the maximum value (13.7 kW$_{el}$) at 10:00 pm when the contribution of the PV is absent. Furthermore, the ORC unit can operate at partial load, with a minimum electrical power equal to 5.4 kW$_{el}$.

The hybrid CHP system always provides an energy surplus that could be injected to the grid, while the electric integration is necessary only during June, July and August (Figure 7a). During these months, electric request from the grid is lower than 4.4 MWh$_{el}$ that is about 50% of the corresponding value of the PV system, as shown in Figure 5. The yearly self-consumed electric energy reaches 84.9% of global electrical load when the hybrid configuration is adopted, with a noticeable increase with respect to the corresponding value of PV system (32.5 %). Furthermore, the hybrid unit is able to provide the 54.9% of the annual thermal energy demand of domestic users for heating and hot water purposes. As a consequence, the proposed CHP system guarantees a significant saving (17,260 m^3) of natural gas with respect to the separated heat production in the auxiliary boiler. In particular, the maximum percentage decrease in natural gas consumption is registered in October (70.3%) and the minimum in February (46.1%). A thermal surplus is always present, with the highest amount from May to September (Figure 7b). The equivalent full load running hours of the ORC system is 4072 hours per year whereas the annual biomass consumption for the hybrid system is 156.0 tons.

Results illustrate that the proposed hybrid system allows to overcome the intermittency of the solar source and to increase the self-consumed electric amount. Furthermore, the natural gas consumption reduces from 31,443 to 14,181 m^3.

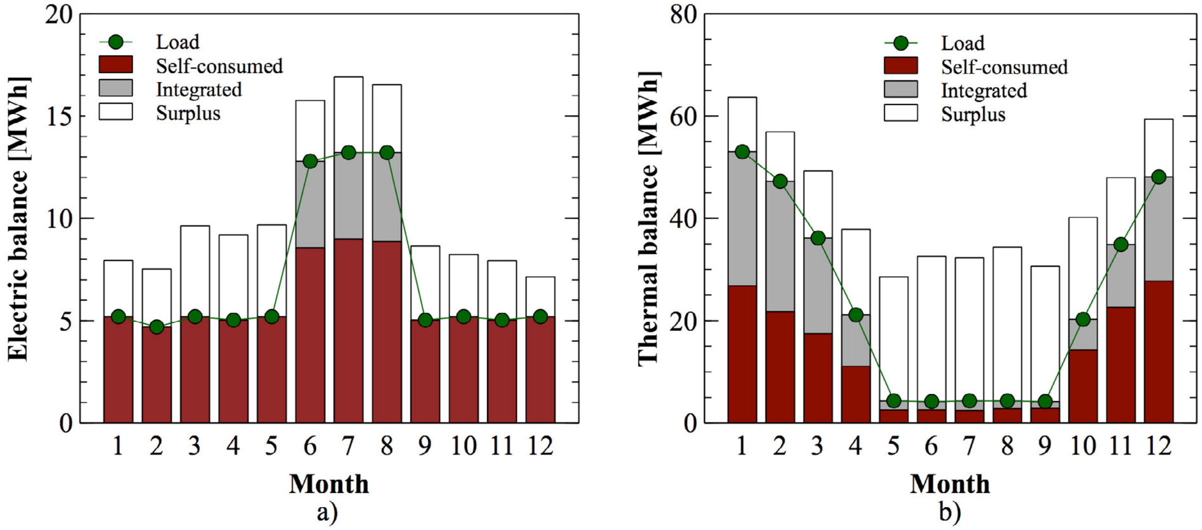


Fig. 7. Monthly electrical (a) and thermal (b) balance for the hybrid CHP system.

4. Conclusions

An ORC/PV hybrid system for combined heat and power (CHP) generation has been proposed. The ORC and PV sub-systems work in parallel to satisfy the electric demand of a 40 dwellings block. The size of the PV (37.3 kW$_{el}$) unit has been selected in order to limit the surplus electrical energy to a value not higher than the self-consumed energy production while the nominal power of the Organic Rankine Cycle has been defined to satisfy the maximum winter electric demand (14.07 kW$_{el}$). A traditional boiler has been adopted to satisfy the whole thermal demand of the domestic users when the sole PV system works and to provide the integrated heat that the CHP hybrid system cannot produce.

The energy balances of the hybrid and the PV system have been compared. Results show that the ORC system can overcome the intermittency issues of the solar resource, increasing the self-consumed electrical energy and producing thermal energy, saving natural gas for thermal purposes. At the same time, when the solar radiation is significant, the ORC system can be switched off or it can be operated at partial load.

The hybrid unit provides the 84.9% and 54.9% of the annual electric and thermal energy demand of domestic users, respectively, with a significant natural gas saving (17,260 m^3) with respect to the separated heat production. Specifically, the maximum percentage natural gas saving is registered in October (70.3%) and the minimum in February (46.1%). An electric and thermal surplus is always present, with the highest amount from May to September.

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