Experimental investigation of domestic micro-CHP based on the gas boiler fitted with ORC module

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Abstract The results of investigations conducted on the prototype of vapour driven micro-CHP unit integrated with a gas boiler are presented. The system enables cogeneration of heat and electric energy to cover the energy demand of a household. The idea of such system is to produce electricity for own demand or for selling it to the electric grid – in such situation the system user will became the prosumer. A typical commercial gas boiler, additionally equipped with an organic Rankine cycle (ORC) module based on environmentally acceptable working fluid can be regarded as future generation unit. In the paper the prototype of innovative domestic cogenerative ORC system, consisting of a conventional gas boiler and a small size axial vapour microturbines (in-house designed for ORC and the commercially available for Rankine cycle (RC)), evaporator and condenser were scrutinised. In the course of study the fluid working temperatures, rates of heat, electricity generation and efficiency of the whole system were obtained. The tested system could produce electricity in the amount of 1 kWe. Some preliminary tests were started with water as working fluid and the results for that case are also presented. The investigations showed that domestic gas boiler was able to provide the saturated/superheated ethanol vapour (in the ORC system) and steam (in the RC system) as working fluids.

Keywords: Micro-CHP; Organic Rankine cycle; Prototype domestic unit

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Nomenclature

$\dot{m}$	–	mass flux, g/s
N	–	electric power, kW
P	–	pressure, Pa
$\dot{Q}$	–	rate of heat, kW
t	–	temperature, °C
x	–	quality
CHP	–	combined heat and power
C-R	–	Clausius-Rankine cycle
kWe	–	kW of electric power
ORC	–	organic Rankine cycle
RC	–	Rankine cycle

Greek symbols

η	–	efficiency, %

Subscripts

b	–	exergy
C	–	Carnot
el	–	electric
et	–	ethanol
in	–	inlet
out	–	outlet
t	–	thermal
T	–	turbine
w	–	water

1   Introduction

In recent years there is observed a tendency to increase the importance of so called dispersed generation, based on the local energy sources and the working systems utilizing both the fossil fuels and the renewable energy resources. Generation of electricity on a small domestic scale together with production of heat can be obtained through employment of the technologies like gas engine units, gas microturbines, fuel cells with efficient electrolysis, Stirling engines or the organic Rankine cycle (ORC) systems. All of them are mentioned in the European Union directive 2012/27/EU [1] for cogenerative production of heat and electricity. It is worth noting that practical realization of the Rankine cycle (RC) or ORC technology in a microscale (the electrical power production below 10 kWe) is kind of technical challenge. Such unit must be equipped with small size turbine (expansion machine) and highly efficient and compact heat exchangers.

With an increase in demand for various energy carriers, there arises a noticeable trend in the search for new forms of electricity production. In recent years, energy production tends to the distributed energy based on local energy sources and technologies using fossil fuels and renewable energy sources. One way to improve the efficiency of these sources usage is an autonomous energy production in the form of electricity and heat in individual households. Such a solution could also increase energy security for households due to the generation of electricity at the point of consumption. The cogeneration ORC technology is promoted by the legislative bodies of the European Union what could be found in Directive [1], which is also consistent with the national strategy of sustainable development [2].

In general, the operation of system implementing ORC follows the fundamental principles of the classic Clausius-Rankine (C-R) cycle. The main difference between these two cycles is in the working fluid. In the case of ORC the working fluid is an organic compound instead of water which is used in the classical Rankine cycle. In combined heat and power (CHP) systems based on organic fluids, their operating temperatures and pressures are lower than in the case of conventional steam C-R systems. Therefore, from the thermal point of view, the ORC technology is more safe for users than C-R systems, especially in the light of households' applications. These systems will be also able to partially cover the residential buildings demand for electricity. Moreover, it will allow better utilization of the fuel, reduction of the emissions. Examples of microcogeneration solutions are a gas engine [3], gas microturbine [4], fuel cells with efficient electrolysis [5], Stirling engine [6], or a system with the use of ORC technology [7–11].

To meet the expectations posed by the energy future of small-scale applications, authors attempted to dedvelop a prototype unit for the cogeneration of electricity and heat to cover the needs of individual households. The idea of this system operation was based on the ORC (with ethanol as working fluid) cooperating with a gas boiler with a thermal power of 25 kW as an autonomous source of heat [12]. The experimental investigations of the precursory version of such unit with ethanol and HFE-7100 (methoxy-nonafluorobutane, $C_4F_9OCH_3$) as the working fluids were reported in [13].

This paper provides a summary of the construction and commissioning of the demonstration prototype of micro-CHP. In the authors opinion the prototype bears the signs of innovation due to the compactness of the unit, its mobility and dedicated solutions of heat exchangers such as evaporator and condenser. Additionally, the authors attempted to modify the micro-

CHP that it can operate as a low-temperature Rankine cycle. In this paper some preliminary results are also presented.

2   Prototype domestic CHP

For the prototype of domestic CHP, the ORC system is a kind of the add-on module for a gas boiler DTG X 23 N [12], which in the commercial version is offered by De Dietrich company to the domestic market. This kind of boiler has been modified by the authors to operate with thermal oil as heat carrier and subsequently tested at the high temperatures [12]. The schematic of a laboratory facility is shown in Fig. 1. Axonometric view of the micro demonstration ORC installation with the gas boiler is shown in Fig. 2a. The overall view of the facility is presented in the photograph in Fig. 2b.
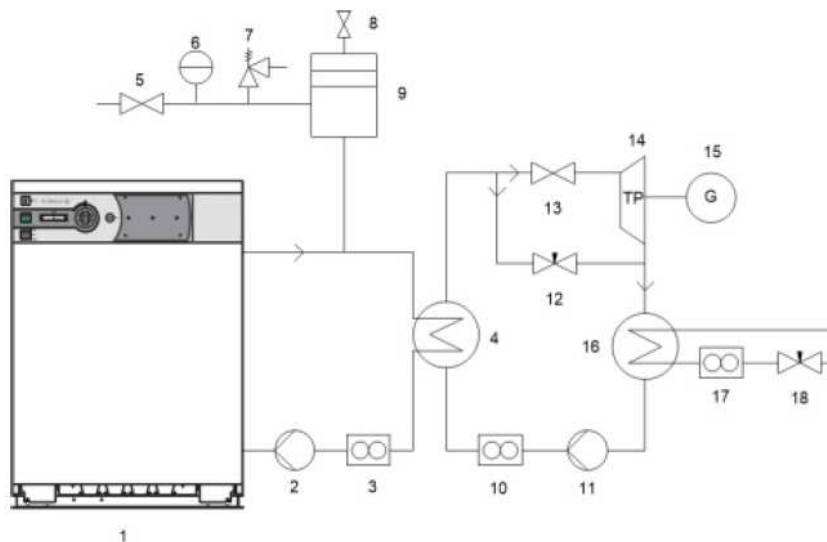

Figure 1: Schematic of the laboratory installation: 1 – gas boiler, 2 – oil circulation pump, 3 – oil flow meter, 4 – evaporator, 5,8,13,18 – ball valve, 6 – manometer, 7 – safety valve, 9 – compensation vessel, 10 – mass flow meter, 11 – pump of working fluid, 12 – throttle valve, 14 – expander, 15 – alternator, 16 – condenser, 17 – water flow meter.

Following, a brief description of the facility operational principles are presented – notation used in the description corresponds to the indicators marked in Fig. 1. As previously mentioned, an autonomous source of heat
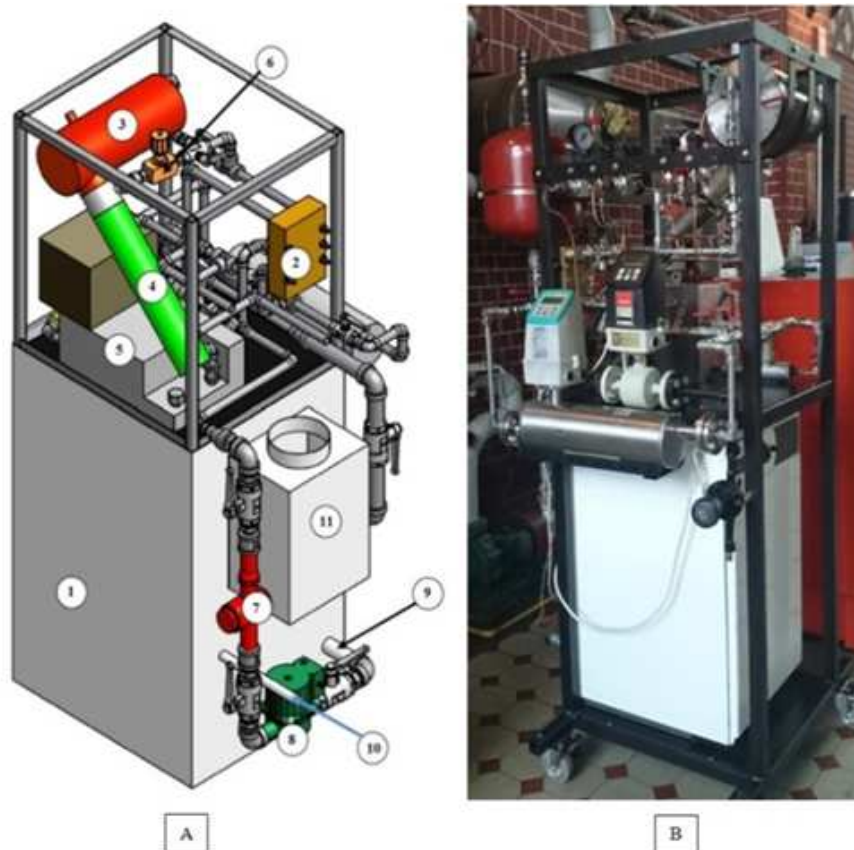
Figure 2: (A) Micro-CHP – axonometric view: 1- gas boiler, 2 – evaporator, 3 – turbogenerator, 4 – condenser, 5 – tank with ethanol, 6 – throttle valve, 7 – oil flow meter, 8 – oil circulating pump, 9 – inlet oil, 10 – gas connector, 11 – exhaust; (B) overview of micro-CHP with gas boiler.

for the ORC was the domestic gas boiler (1) in which the chemical energy of the fuel (natural gas) was converted into thermal energy received by thermal oil. Oil is an intermediate heat transfer medium circulating in a closed loop between the boiler and evaporator (2) of vapour cycle with working fluid (ethanol-ORC, H_2O-RC). Oil circulation in the loop was ensured by the circulation pump (8) with a maximum capacity of 3.5 m^3/h and a maximum head of 6 m. Vane flow meter (7) was used to measure the volumetric flow of oil. Circulation of ethyl alcohol/H_2O in a closed loop of ORC/RC module was provided by a hermetic gear pump with magnetic

coupling of a nominal capacity of 0.4 m^3/h at a differential pressure of 1.03 MPa. The adjustment of the pump's efficiency was possible by changing the frequency, or by using a manually operated throttle valve - installed in the form of 'by-pass'. Coriolis mass flow meter with signal converter was used to measure the flow of ethanol/H$_2$O. Working fluid passing through the evaporator received heat energy from the thermal oil and evaporated to reach the state of superheated vapour with applied appropriate heat flux. Saturated/superheated vapour was ultimately directed to the turbine (3), where it expanded and then flowed to the condenser (4). During the facility start-up phase the turbine was bypassed by the throttling valve (6) to obtain required vapour parameters. After that the valve was closed. The condenser was cooled by tap water. After the condensation process, the condensate was turned back to the reservoir (5).

De Dietrich gas boiler DTG X 23 N featured the open combustion chamber, electronic ignition with ionisation flame control, atmospheric burner able to burn all kinds of natural gas and liquefied petroleum gas. In addition to the main burner, boiler was also equipped with an ignition burner, which enabled 'soft' (inexplosive) start of the main burner. The boiler's body was made of thermally shocked and corrosion-resistant eutectic cast iron.

During the test stage of assembled facility, function of the evaporator was performed by the in-house design and manufacture of the shell and tube heat exchanger, with circular minitubes [14]. The function of condenser was also performed by the shell and tube heat exchanger with minitubes – the mirror structure of the evaporator.

ORC turbine was connected with the condenser by means of a flexible compensator providing the damping in the system. The vapour microturbine equipped with the alternator was designed and constructed for the needs of prototype micro-CHP, with ethanol as the working fluid. The electric generator was mounted on the turbine shaft, directly behind its low pressure part. The turbine and generator had then the common casing, Fig. 3. The rotor disk is shown in Fig. 4.

Described micro-turbogenerator had following features:

- electrical power output 1.8–1.9 kW,
- rotational speed of rotor $n \approx 36000$ rpm,
- mass flow rate of ethanol 24 g/s,
- vapour pressure at the turbine inlet, 0.7 MPa,
- the Mach number at the blade cascade output, Ma ≈ 2.4,

- oil-free technology for the bearing system design.

Figure 3: View of vapour ORC microturbine.

Figure 4: Turbine rotor disk with generator rotor.

In the next step of studies the authors challenged to create the domestic CHP cooperated with the classical steam cycle (Rankine Cycle) with water as the working fluid. This required the replacement of the turbogenerator. A unit available on the market, dedicated to a steam at low temperature was used. The turbine with generator is presented in Fig. 5. Applied steam turbine had two stages with separate generators. The nozzle disk of microturbine 1st stage is shown in Fig. 6. Nominal operating parameters of turbine were [15]:

- inlet steam pressure: 0.052 MPa,
- inlet steam temperature: 200 °C,
- outlet steam pressure: 0.01 MPa,
- nominal power: 1.2 kW,
- steam consumption: 5 g/s,

- design rotational speed: 30 000 rpm.

Figure 5: View of microturbine in RC application.

Figure 6: Nozzle disc of microturbine 1st stage.

3   Experimental analysis

3.1   Ethanol system

On the basis of theoretical analysis and previous experimental studies the
dehydrated ethyl alcohol was selected as a working fluid for the ORC mod-
ule [16]. Its physical properties necessary for the thermal calculations, were
taken from REFPROP 9.0 [17].

In the first stage of experimental analysis the cooperation of a gas boiler with the ORC module, supporting the start-up of the demonstrative station was verified. It was followed by the studies of installed in the ORC module heat exchangers (evaporator and condenser) performance. In this case, the expansion valve was simulating the action of the expander. The results of this stage investigations were reported by authors in [18]. For better transparency they are also recalled below. Thus the results of measurements and calculations for the evaporator in Tab. 1 and results for the condenser are summarized in Tab. 2. In addition to the list of mass flow rate, temperature and pressure, in the tables are also presented the heat exchanger performance and quality of ethanol, x, at the outlet of the evaporator (Tab. 1) and at the inlet to the condenser, i.e., after the throttle valve (Tab. 2).

Table 1: Micro-ORC evaporator energy balance.

No.	Thermal oil				Ethanol				
Parameter	$\dot{m}_{oil}$	t_{in}	t_{out}	$\dot{Q}_{oil}$	$\dot{m}_{et}$	t_{in}	t_{out}	P	x
Units	g/s	°C	°C	kW	g/s	°C	°C	MPa	–
1	297	167.0	142.0	17.66	20	42.4	119.0	0.415	0.858
2	267	164.5	138.5	16.41	20	38.1	116.4	0.380	0.835
3	369	159.0	139.0	17.43	20	49.8	116.1	0.386	0.847
4	352	159.0	138.6	16.97	16	53.3	115.1	0.370	0.998
5	287	162.0	137.7	16.47	17	51.7	114.8	0.359	0.974
6	258	165.5	138.2	16.66	18	49.8	115.0	0.365	0.910
7	201	173.5	139.1	16.45	18	50.4	115.0	0.370	0.921
8	171	178.5	140.3	15.81	18	51.3	115.2	0.372	0.884
9	151	183.8	140.9	15.50	18	51.4	114.8	0.363	0.894
10	146	187.4	145.1	14.95	15	50.2	120.6	0.440	0.997
11	141	193.5	149.5	15.14	15	46.6	126.1	0.511	0.998

At this stage of study it was demonstrated that the adapted boiler could produce saturated vapour of ethyl alcohol with a dryness factor (quality) close to unity, when the mass flow was in the range from 15 to 20 g/s and a pressure in the range 0.36–0.51 MPa, which corresponded to the saturation temperature in the range 115–126 °C. These results served as the basis for the experiment second stage – system operation with microturbine

Table 2: Micro-ORC condenser energy balance.

No.	Ethanol					Water			
Parameter	$\dot{m}_{et}$	t_{in}	P	x	t_{out}	$\dot{m}_w$	t_{in}	t_{out}	$\dot{Q}_w$
Units	g/s	°C	MPa	–	°C	g/s	°C	°C	kW
1	20	86.2	0.135	0.846	38.7	100	12.4	52.8	16.98
2	20	85.4	0.133	0.804	39.4	91	12.4	55.0	16.22
3	20	88.6	0.151	0.811	50.4	70	12.8	68.7	16.35
4	16	88.6	0.149	0.985	45.0	70	13.1	66.9	15.80
5	17	88.2	0.149	0.943	44.3	71	13.2	66.2	15.63
6	18	88.2	0.149	0.871	45.9	70	13.5	66.1	15.39
7	18	88.5	0.149	0.899	46.8	70	13.6	67.5	15.76
8	18	88.6	0.151	0.876	46.5	70	13.7	66.7	15.44
9	18	88.4	0.149	0.868	45.5	70	13.7	66.2	15.36
10	15	87.6	0.144	0.981	39.9	70	13.7	63.3	14.58
11	15	87.0	0.142	0.976	40.1	70	13.7	62.5	14.34

instead of the expansion valve. All components of the system remaining in high-temperature area were covered with thermal insulation to reduce heat losses.

Measurements of physical quantities done during the ORC module working, allowed the calculations of following parameters: rate of heat received by the working medium (ethanol) in the evaporator, $\dot{Q}_{in}$, rate of heat in the cooling water in the condenser, $\dot{Q}_{out}$, generation of electric power, N_{el}, internal efficiency of the turbine, η_{iT}, theoretical efficiency of implemented thermodynamic cycle, η_t, maximum efficiency, i.e., Carnot cycle efficiency in the min/max working temperature, η_C, and exergy efficiency, η_b. The results of measurements and calculations are summarized in Tab. 3. The table additionally features: the mass flow rates of ethanol, temperature and pressure, the quality of ethyl alcohol vapour, x_{T_exit}, at the turbine's outlet.

3.2   Steam system

For the modified micro-CHP adapted to work with steam as the working fluid it was demonstrated that the gas boiler could produce superheated steam within the temperature range of 165–200 °C in the pressure range

Table 3: Measurements and calculations results of ORC module.

$\dot{Q}_{in}$	$\dot{Q}_{out}$	N_{el}	$\dot{m}_{et}$	P_{T_in}	t_{T_in}	P_{T_exit}	x_{T_exit}	η_{iT}	η_t	η_c	η_b
kW	kW	kW	g/s	MPa	°C	MPa	–	%	%	%	%
21.26	19.63	0.66	20	0.573	130.4	1.59	0.98	86.0	6,65	22.53	29,52
21.29	19.19	0.71	20	0.529	129.6	1.53	0.99	82.3	6,10	20.66	29,51
21.48	18.84	0.76	19	0.604	143.2	1.56	– *	81.8	6.40	23.54	27.21

* superheated vapour ($\Delta t_{superheat}$= 4.7 K)

0.45–0.57 MPa, when the mass flow was in the range 4.4–5.8 g/s. For the preliminary test of RC module the following parameters were determined: rate of heat received by steam in the evaporator ($\dot{Q}_{in}$), rate of heat transferred to the cooling water in the condenser ($\dot{Q}_{out}$), generated electric power (N_{el}), internal efficiency of the turbine (η_{iT}), theoretical efficiency of implemented thermodynamic cycle (η_t), maximum efficiency (η_C), and exergy efficiency (η_b). The results of measurements and calculations are summarized in Tab. 4. In that table there are also included: the mass flow rates of steam, the temperature and pressure before/behind the turbine, the quality of steam at the turbine's outlet.

Table 4: Measurements and calculations results of RC module.

$\dot{Q}_{in}$	$\dot{Q}_{out}$	N_{el}	$\dot{m}_{et}$	P_{T_in}	t_{T_in}	P_{T_exit}	x_{T_exit}	η_{iT}	η_t	η_c	η_b
kW	kW	kW	g/s	MPa	°C	MPa	–	%	%	%	%
14.58	12.39	0.92	5.31	0.520	180.6	0.036	0.96	61.9	9.66	36.34	26.59
13.43	10.89	0.84	4.85	0.489	190.4	0.035	0.97	62.1	9.59	37.62	25.49
11.93	10.05	0.78	4.40	0.450	166.4	0.027	0.95	62.2	10.04	33.85	29.67
12.39	10.55	0.88	4.52	0.456	179.3	0.021	0.96	59.8	10.88	35.81	30.38
14.92	12.90	1.00	5.40	0.535	190.8	0.022	0.97	56.2	10.30	37.50	27.47
15.53	13.23	1.04	5.60	0.540	195.4	0.023	0.98	53.4	10.31	38.14	27.04
15.97	14.07	1.08	5.75	0.570	198.4	0.023	0.98	53.4	10.42	38.53	27.05

During the test of RC module the power characteristics of two generators with constant load resistance were determined. The characteristic of attained power versus 1st generator's rotational speed for the applied load resistance of 60 Ω is shown in Fig. 7. The 2nd generator's with load resis-

tance of 131 Ω corresponding characteristic is presented in Fig. 8.
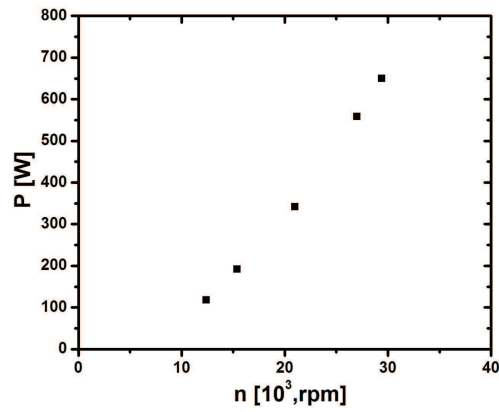

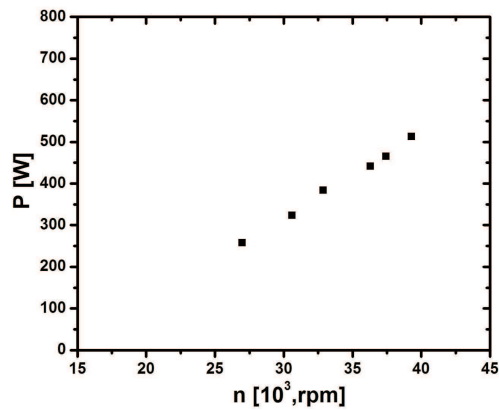Figure 7: Power characteristics of turbogenerator 1st stage with load resistance of 60 Ω.

Figure 8: Power characteristics of turbogenerator 2nd stage with load resistance of 131 Ω.

4   Conclusions

This paper presents the prototype of a domestic ORC micropower plant with a gas boiler as an autonomous source of heat. It allows the cogenerative production of thermal energy and electricity in terms of covering the needs for the individual household. The design is innovative due to the

compactness, mobility and original solutions of the evaporator and condenser.

In the course of studies it was demonstrated that the De Dietrich gas boiler allowed generation of ethyl alcohol saturated/superheated vapour of a mass flow rate at the level of 20 g/s at the pressure of 0.6 MPa. Obtained thermal parameters of vapour allowed to run a prototype microturbine and the generation of 760 W electric power.

In addition, the preliminary test proved that the RC module in cooperation with gas boiler was able to produce superheated steam of 5 g/s mass flow rate at the pressure of 0.5 MPa with temperature of about $200\,^\circ$C. These parameters were sufficient to generate about 1 kW of electric power by the steam turbine. In the authors opinion the commonly available gas boiler is suitable for ORC or RC modules in terms of cogeneration.

Due to the absence of ORC/RC modules casing in micro-CHP unit, the noise analysis was not yet conducted during the turbogenerators operation. This issue will be undertaken, when the prototypes are equipped with soundproof casing. The results will be then compared with European Union directives, dedicated to an evaluation of the heating devices energy efficiency class [19,20].

Proposed solution of combining commercial heat source, which is a gas boiler, with the ORC or RC module can be an interesting alternative for small households. This solution enables simultaneous production of electricity and heat. It should be noted that the production of electricity in the presented installation is only possible if there is demand for thermal energy. The expected period of operation for the installation is mainly the heating season, i.e., the period in which water is prepared for the central heating and for utility purposes. During summer, when the household's demand for heat is reduced, it is possible to apply different renewable energy technologies, such as photovoltaic for the support of ORC module in power generation [21]. Alternatively, in the summer period the ORC system can supply heat to the adsorption refrigeration system, extending in such way the alternativeness of the installation.

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