Energetic and economic analysis of a solar assisted trigeneration system

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Abstract

The aim of this paper is to present the simulation activities carried out for the energy and economic assessment of a solar-assisted trigeneration system within the framework of EU FP7 BRICKER project. The system comprises a parabolic trough collectors field, an Organic Rankine Cycle unit and an adsorption chiller. It is installed in a hospital building in Aydin (Turkey). TRNSYS system simulations are used for the evaluation of the yearly performance.

This work shows that the economic feasibility of the trigeneration layout concept is limited by low energy tariffs and by the low electricity generation efficiency of the small-scale ORC unit. For the system and application here presented, the operation of the trigeneration system should be driven by heating and cooling working modes, having the priority on a pure electricity generation.

Keywords: Solar energy, Trigeneration, Heating and cooling; TRNSYS

1. Introduction

Today, cogeneration (also termed as Combined Heat and Power – CHP) has become an energy efficient, economically viable and mature technology and it is being addressed on a very large scale. According to 2016 REN21 Global Report (REN21, 2016), about 8% of world's electricity generating capacity is in CHP facilities, with a total installed capacity of 325 GW and an average overall efficiency of 75-90%. Trigeneration systems, also known as Combined Cooling, Heating, and Power (CCHP) systems, are a technical extension of CHP systems, which use thermally activated chilling technologies to produce cooling using the discarded thermal energy by the power generator. The concept of trigeneration has come up since a few decades, in the same time when CHP system began to be applied for residential consumers, usually involving large units with district heating. Typically, CCHP systems are considered in large-scale centralized power plants and industrial applications (Jradi and Riffat, 2014) as an energy efficiency measure to recover high-temperature heat losses.

In the last years, CCHP has attracted considerable interest for small-scale decentralized applications (< 1 MW_{el}) with the development of different options regarding cooling technologies and cogeneration units. Potential trigeneration users might be multi-residential dwellings and communities, large tertiary and commercial buildings. Small-scale CCHP systems could be effectively exploited within district heating and cooling networks (EU H2020 FLEXYNETS, 2015).

Different heat and power generating technologies have been considered in literature to serve as prime movers for CCHP applications. Some of these technologies are commercially mature with wide availability in the market (combustion engines and turbines), while others are still in a development stage such as Stirling, ORC and fuel cell based units.

The ORC modules with higher evaporator inlet temperatures result in better performances, producing more electricity and achieving better cycle efficiencies. Commercially available capacities of ORC range from 0.2-2 MW_{el}, which cost between 1000-4000 €/kW_{el} depending on capacity and manufacturer (Velez et al., 2012). Technical feasibility of ORCs as a prime movers in trigeneration systems applied to buildings has been actively researched (Buonomano et al., 2014) and possible combinations of ORC modules and renewable sources have been studied (Tchanche et al., 2011).

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Within this technological trend, the aim of the paper is to discuss energy and economic results of a novel solar-assisted trigeneration system where a small small-size Organic Rankine Cycle (ORC) unit is used as prime mover. The CCHP system is installed in the city hospital of Aydin (Turkey) and is part of the demonstration activities of EU FP7 BRICKER project (EU FP7 BRICKER, 2013). The goal of the project is to develop the layout of a small-scale CCHP system that can exploit solar heat to cover the heating and cooling loads of buildings while generating electricity. System performance is evaluated by means of TRNSYS numerical simulations (Klein S.A. et al., 2010).

2. Description of the energy system

In the proposed energy system, the ORC unit is assisted by a PTC field and a gas boiler. An operationally flexible system layout supporting different working mode configurations is proposed. Figure 1 shows the layout of the CCHP system. Energy generation units, namely the PTC field and the gas boiler, deliver high-temperature heat to the ORC unit or to the heat exchangers (HX1 and HX2). In this loop, Therminol SP is used as heat transfer medium. The ORC unit generates electricity and rejects heat to the secondary side of the CCHP system for covering heating loads or for trigeneration purposes in combination with an adsorption chiller (ADCH).

One of the advantages of this CCHP concept is the flexibility in covering thermal heating loads at high (radiators), medium (heating and ventilation coils) or low (radiant system) distribution temperatures. Beneath to these, a series of challenges should be mentioned:

- The integration of the new energy system into the existing one, not only from a mere electro-mechanical installation perspective but mainly in the control and regulation of systems operation priorities and strategies;
- The mismatch between energy consumption and generation through stochastic solar energy sources should be solved in order to maximize the renewable energy exploitation;
- The optimization of the thermal cascade exploitation in heating and cooling processes;
- The definition of cost-optimal scenarios in which final energy savings make the higher upfront costs as effective as state-of-the-art alternatives.

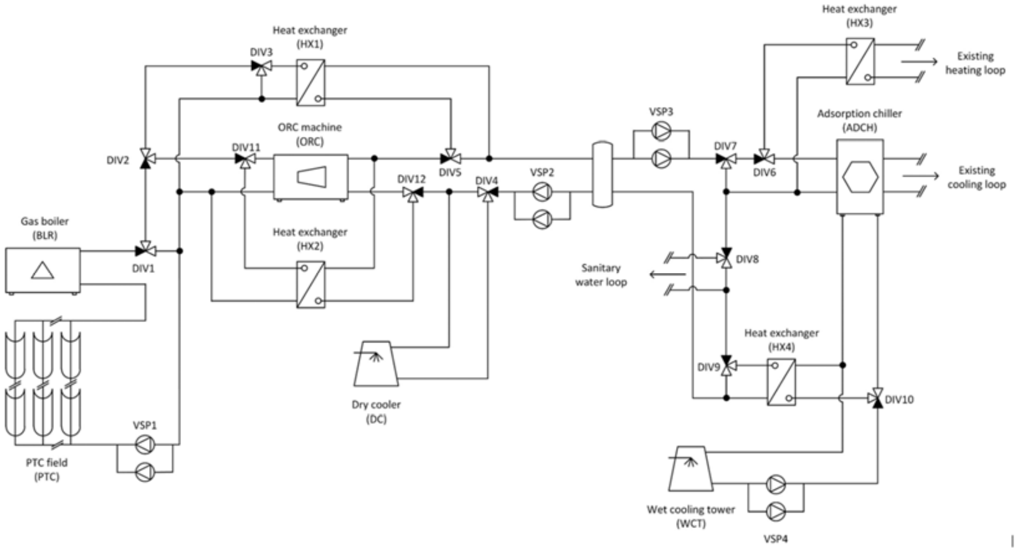

Fig. 1: Layout of the CCHP system developed within BRICKER project.

2.1. Building description and system integration into the existing energy system

The CCHP is installed in the hospital building of the Adnan Menderes University in the province of Aydın (Turkey). The hospital has three building blocks with an overall conditioned are of about 43200 m^2. Most of the building blocks areas are used with a 7/24 schedule. The indoor air temperature is kept to 24°C during the heating season whereas to 25°C during the cooling season. The technical staff performs manually the switch from heating to cooling working mode. For the sake of simplicity, the heating season schedule is defined from 1st of November, to 15th of March, whereas the cooling season is complementary.

The hot water for heating purposes is generated by two natural gas boilers (6500 kW each, model: Buderus SB825). The set point temperature of the boilers is manually imposed by the operator and is usually kept at 70 °C during typical winter days, but it might be increased up to 80 °C during extraordinarily cold days and down to 60°C when mild heating is required. The cooling water is produced through a centralized system composed of three centrifugal chillers (2x 4650 kW each and 1x 2326 kW, model: Carrier 19XR). As condensing unit, a dedicated open cycle wet cooling tower is installed for each chiller. Heating and cooling thermal energy is provided to the air-conditioned spaces in the hospital through wall-mounted fan coil units. The HVAC system of the building includes 19 air-handling units, which operate with 100% fresh air without any heat recovery system.

Mass flow rates, temperature set points and performance characteristics of existing HVAC system components are fragmented or missing. On-site measurements were not feasible as the interruption of building's services (heating, cooling or hot water delivery) would have been required. For these reasons, the development of a detail numerical model of the existing energy system was not possible.

The installation of the new CCHP system aims to drastically improve the environmental performance of the existing heating and cooling system. The approach used in the evaluation of the BRICKER system is typical of an energy potential analysis. In other words, constant return temperatures from heating and cooling distribution loops (50°C and 15°C, respectively) are imposed as boundary temperatures to the CCHP system. Since heating, cooling and electricity loads of the hospital are much greater than the installed capacity of the CCHP system, it is assumed that 100% of energy outputs (heating, cooling and electricity production) are consumed in the building.

2.2. Description of main system component

The solar technology employed in the CCHP system consists of a field of parabolic trough collectors (1632 m^2 of net collecting area) with an automatic controlled sun-tracking motion that allows the continuously adjusts the position of the mirrors to concentrate the solar beams onto the receiver tube. Performance and dimensional parameters are based on the data provided by the manufacturer of the PTC (Soltigua, model "PTMx-36"). The installation includes 20 concentrating collectors arranged in five rows of four collectors each for a total estimated thermal power of overall estimated thermal power of the PTC field is about 950 kW.

The gas boiler (Babcock Wanson, model "TPC-H400) has a capacity of 465 kW and uses thermal oil. It is a horizontal thermal oil boiler with an average thermal efficiency of about 86 %. The gas boiler modulates between 10% and 100% of its capacity in order to reach a set point outlet temperature of 225 °C.

The CCHP is built around the ORC unit, a prototype developed by RANK with R245a as working fluid. The rated electrical generation capacity ranges between 99.2 kW and 70.8 kW according to evaporator/condenser inlet temperature respectively, whereas the thermal power extracted from the oil loop ranges from 562.9 kW to 455.7 kW.

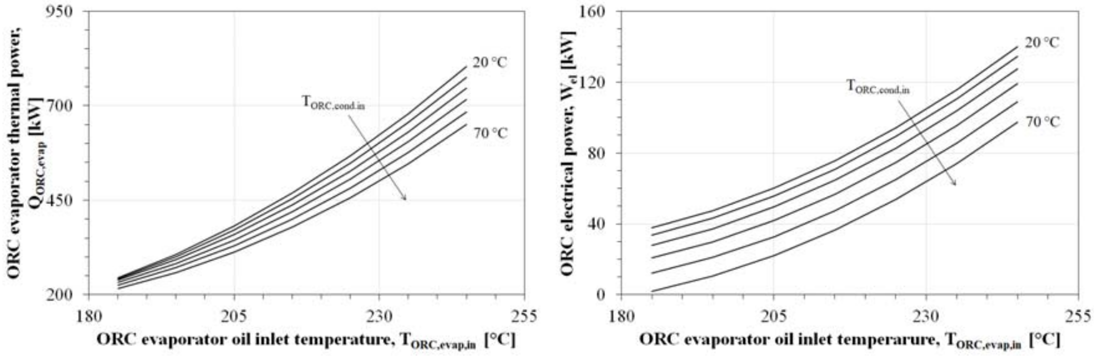

Fig. 2: Dependency of the evaporator thermal power (left side) and of the electrical power (right side) of the ORC unit from the inlet oil temperature (evaporator side) and the inlet water temperature (condenser side).

The ADCH model "ECO-MAX D-75" manufactured by PPI is considered for installation. It includes two beds of silica gel and water as refrigerant fluid. Its rated capacity and COP_{th} are 267 kW and 0.55, respectively. However, these performance values are achieved in different operating condition than the BRICKER system nominal condition, with the main difference represented by the nominal source mass flow, which is reduced by a half in the BRICKER system. Subsequently, the ADCH will work in off-design condition to match the real inlet condition. Figure 3 shows the dependency of COP_{th} and cooling capacity to hot water and chilled water inlet temperatures for the selected model.

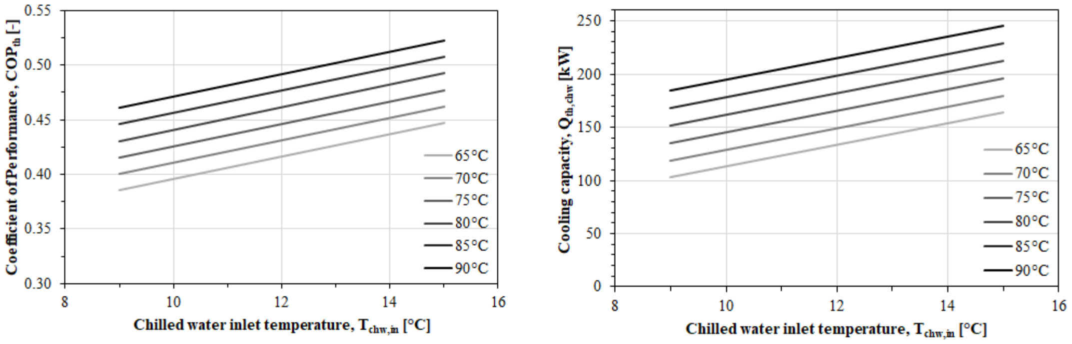

Fig. 3: Dependency of the COP_{th} (left side) and of the cooling capacity (right side) of the ADCH unit from the chilled water inlet temperature for a cooling water inlet temperature of 30 °C.

2.3. Operation strategies

The ORC unit is activated through high-temperature heat (in the operative range of 185-245 °C) generated by the PTC field and the gas boiler. The PTC field is activated when the Direct Normal Irradiation (DNI) on the collector surface exceeds the threshold of 250 W/m^2. When the DNI ranges between 250-300 W/m^2, the solar pump recirculates the oil into the solar loop performing a pre-heating of the circuit. This working scheme is necessary since the ORC evaporator requests at least 500 kW and the gas boiler has a limited capacity of 465 kW. Under these circumstances, the gas boiler is shut off. The flow rate in the thermal oil loop is set at such constant value (21 m^3/h), avoiding overheating of the transfer fluid. When the DNI on the collector surface rises above 300 W/m^2, the solar harvesting mode starts and heat is delivered for ORC activation. Such threshold was derived from a preliminary set of simulations that aimed to assess which conditions must be maintained to avoid overheating in the high-temperature loop for the specific demo installation. The PTC operational limits have a crucial influence on the design of the entire oil loop. The flow rate in the PTC field is modulated between a minimum (13 m^3/h) and a maximum (26 m^3/h) value. The lower limit is due to the necessity of keeping an uniform flow inside the receiver pipe, avoiding localized increases of temperature that can lead to a degradation of the oil. The upper limit is set in order to limit fluid pressure losses while flowing in the solar collector absorber.

The gas boiler is activated only in solar harvesting mode and if the inlet temperature is lower than the inlet set point temperature of ORC (225 °C). When the oil temperature is higher than 225 °C, cogeneration/trigeneration is fed only by the PTC field.

The ORC unit is designed as the core of the trigeneration system. It produces simultaneously thermal and electrical energy, and the relative energetic output and system efficiency are dependent to its optimal working conditions. The activation of the ORC is restricted to the following conditions: (1) evaporator inlet oil temperature between 185-245 °C; (2) consender inlet water temperature between 20-70 °C; (3) presence of heating/cooling demands from the building. The operation in cogeneration / trigeneration modes is prioritized against electricity generation mode.

Working schemes for both heating and cooling are activated only when there is a solar output from the high-temperature oil loop. If the outlet temperature from the gas boiler is compatible with the operation of the ORC unit, the simultaneous generation of thermal energy and electricity is possible. Being the nominal oil volumetric flow rate of the ORC equal to 13 m^3/h, ORC and HX1 are operated together when the solar pump is modulated up to 26 m^3/h. An alternative heating scheme is used when inlet oil and water temperature restrictions are not met. Under these conditions, the ORC operation is not possible and HX1 and HX2 are considered.

Preheating of the ORC's condenser water loop during the cooling season is required in order to achieve the minimum source temperature for the ADCH's operation, set at 65 °C. As long as the inlet source temperature to the chiller is below the minimum threshold value, the hot water flow is recirculated and cooling and chilled water circuit pumps are not activated. Those conditions lead to a rather quick pre-heating of the loop, as no thermal load is being covered. During this operation, the ORC unit produces electricity with a variable efficiency, depending on the temperature of the condensing water.

The main cooling scheme is activated when the minimum required temperature for sorption chilling is achieved and the ORC is working in cogeneration mode. The adsorption chiller generator is then fed with the water exiting the condenser of the ORC unit, which can be also further heated up by HX1, depending on availability of solar radiation. Similarly to the main heating scheme, also the main cooling working scheme allows the generation of electrical power. If ORC inlet condensing temperature is greater than 70 °C (maximum allowed value for ORC operation), a dry cooler rejects the excess of heat.

The alternative cooling scheme is used during summer season when the ORC is in out of operation conditions. In this case, HX2 performs the heat transfer usually done by ORC working fluid condensation, in conjunction with HX1. Similarly to the alternative heating working scheme, no electricity is generated under this scheme. In this case, the amount of cold water produced by the adsorption chiller and delivered to the existing cooling system is slightly higher than in the case of cooling through ORC wasted heat, since no heat rejection is required.

Whenever the return temperature from the CCHP heating/cooling units is greater than 60 °C, there is the possibility to reject part of the heat for the production of domestic hot water. This additional operating scheme allows to reach constantly the nominal inlet water temperature to either the ORC condenser or to HX2 load side. This operation scheme permits to optimize the thermal cascade of the system, replacing the operation of the dry cooler in the ORC condensing loop.

3. System performance by means of transient simulation

3.1. Definition of KPIs and energy tariffs

The performance analysis of any energy system starts with the definition of appropriate system boundaries. With respect to the installation at the demo building, system boundary Σ_2 is considered (see Figure 4). At this boundary, it is possible to identify:

- energy inputs: useful energy provided by the solar field (P1) and the gas boiler (P2) , electricity inputs for water and oil pumps and ORC operation;
- energy outputs: heating (P18) and cooling (P12) production supplied to the building and electricity generated by the ORC unit;
- thermal losses from hydraulic components like pipes, buffers, storages and hydraulic junctions.

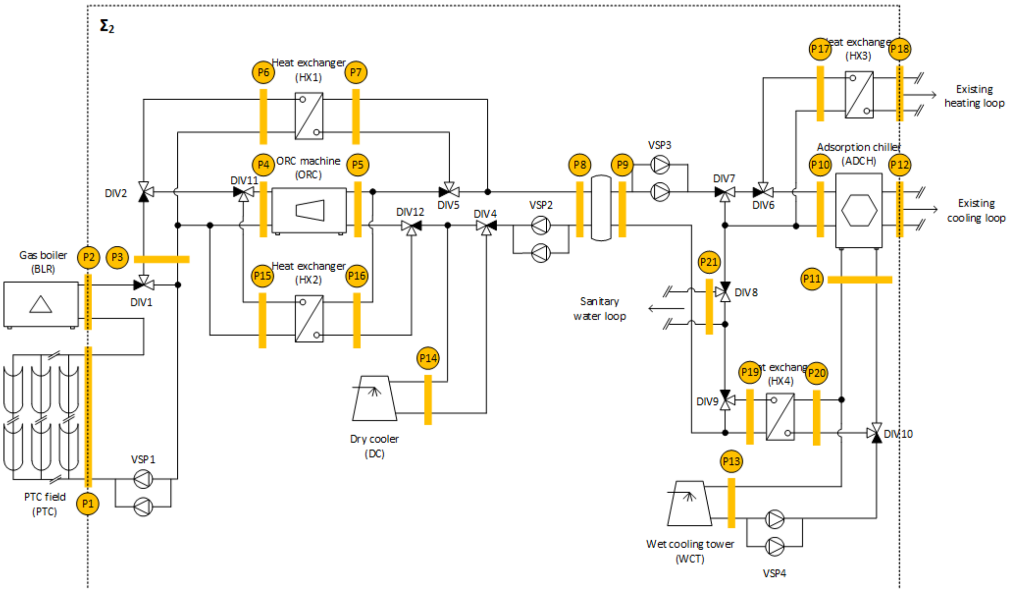

Fig. 4: CCHP system layout showing system boundaries in yellow.

Since the performance characteristics of the existing energy system are not available, it assumed that gas boilers have an average thermal efficiency of 90% and that the compression chillers have a SEER of 3.5. With respect to this system (also defined reference system), the energy savings in terms of lower electricity and gas consumptions are calculated from the amount of heating and cooling energy delivered by the CCHP.

3.2. Simulation results

The yearly amount of heating energy provided by the CCHP system amounts to 541 MWh, while the overall cooling energy generation amounts is 318 MWh. The gas final energy consumption amounts to 247 MWh/year equivalent to about 22570 Sm^3 of gas, whereas electricity final energy consumption is 570 MWh/year. The electricity generated by the system during an annual operation period is 194 MWh.

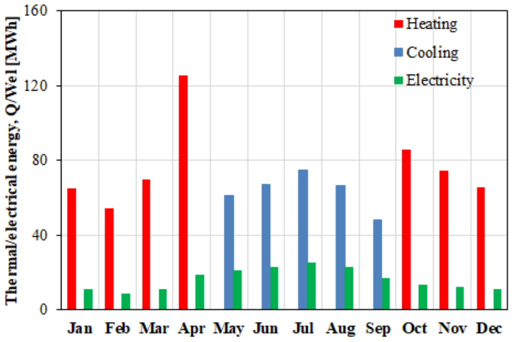

Fig. 5: Monthly thermal and electrical energy production.

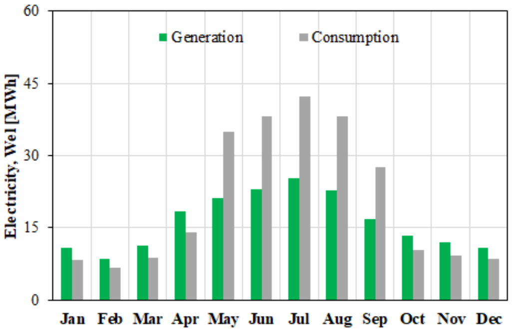

Fig. 6: Monthly electricity generation and consumption.

The yearly DNI available on the collectors surface is about 1696 kWh/(m^{2}y). The average thermal efficiency of the solar field is about 41% on yearly basis, whereas the Gross Solar Yield amounts to 687 kWh/(m^{2}y). As mentioned before, the gas boilers compensate the solar field output in order to achieve a constant oil temperature at the evaporator of the ORC unit. Defining Solar Fraction (SF) as the relative share of the solar yield on the total heat provided by the high-temperature oil loop (gas + solar), this figure varies from winter to summer from 54% and 79%, respectively.

The working hours of the CCHP system are calculated as follows:

- Winter season: 1201 hours (all working days, according to sun radiation), with an average value of 5 hours and 40 minutes per day;
- Summer season: 1691 hours (all working days, according to sun radiation), with an average value of 11 hour per day.
- Year: 3030 hours, including the preheating scheme of the solar loop, with an average of 8 hours and 20 minutes per day.

3.3. Economic analysis

For the economic analysis, average electricity and gas costs of 0.0845 €/kWh and 0.0253 €/kWh, respectively, are retrieved from demo owner tariffs. Electricity prices for consumed and generated electricity are considered equal, since electrical energy is completely self-consumed by either the CCHP system or the users of the hospital. Net energy costs are computed as the net electricity and gas consumptions multiplied by the respective specific energy costs. The calculation of the specific costs for heating and cooling leads to 11.7 €/MWh and 39.6 €/MWh, respectively, whereas the specific energy costs of the reference system (gas boilers + electrically driven chillers) for heating and cooling amount to 28.1 €/MWh and 24.1 €/MWh, respectively.

The overall investment costs of the CCHP system (purchase of technologies, without installation) for this specific layout and application is of about 1.42 M€. The unitary specific cost of the ORC is about 1500 €/kW$_{el}$, which is actually a low value for small-scale ORC units, but still high if compared to other prime mover technologies (internal combustion engines: 340-1600 €/kW$_{el}$; micro gas turbines: 900-1500 €/kW$_{el}$). The unitary specific cost for PTC is 381 €/m^2, which together with the ORC represent 58% of the total capital costs.

With respect to the reference system, yearly total savings are quantified in 3960 €. With such conditions and in order to achieve a Return of Investment (ROI) of 20 years, the overall investment costs of the system should be 79.2 k€.

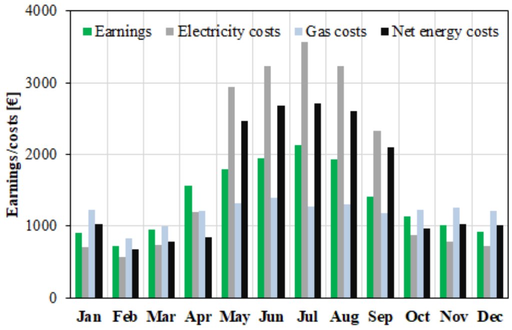

Fig. 7: Monthly earning and energy costs.

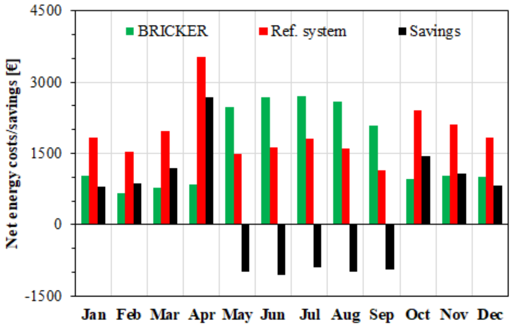

Fig. 8: Monthly energy savings of the CCHP system compared with a reference system.

3.4. Parametric analysis

A parametric analysis is carried out to investigate the dependency of system performance to a variation of some key parameters. For the sake of brevity, only a selection of the evaluated cases are here presented.

The first analysis focuses on the PTC field. The number of collector in each row is varied in order to understand the impact of the solar energy input on the yearly system performance. In the initial layout, 4 strings with 5 collectors each are considered. Here, the cases with 3 (15 collectors) and 5 (25 collectors) strings of 5 collectors each is further evaluated. In terms of yearly outputs, increasing the overall number of PTCs leads to a higher heating production in winter, whereas cooling production and electricity generation remain nearly the same (Figure 9). Consequently, energy provided by gas reduces 36.7 kWh/m$^2_{PTC}$. The solar fraction goes from a minimum of 62% to a maximum of 76%. Final and primary energy savings are proportional to gas savings. The impact in terms of net energy costs is a consequence of gas savings but in specific terms is almost negligible and estimated in 1.0 €/m$^2_{PTC}$.

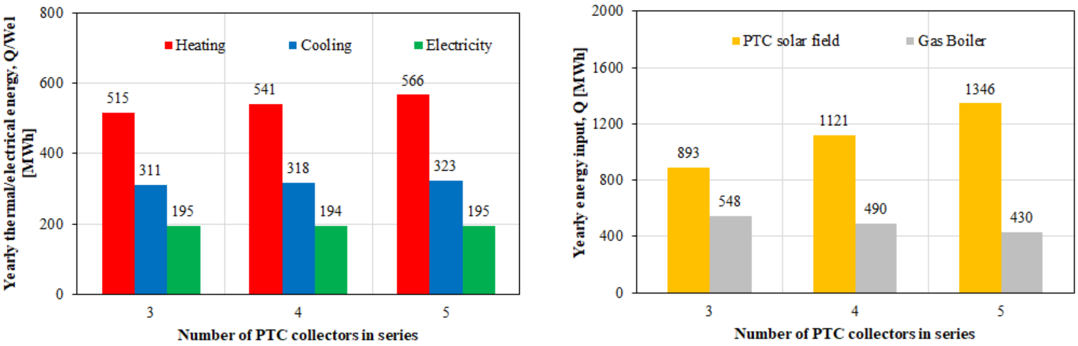

Fig. 9: Yearly thermal and electrical energy output and inputs for different solar field sizes.

In a second place, the set point temperature is varied from a value of 205°C to the maximum inlet oil temperature for the selected ORC unit (245°C). Herein, the goal is to study the trade-off between higher set point values and consequent higher heating, cooling and electricity productions, and the higher fuel consumption. This effect is shown in Figure 10. In general, higher oil set point temperatures lead to a proportional increase in heating, cooling and electricity production, but conversely increase the gas consumption at a similar raising rate. The energy delivery from gas boiler is in average 160 MWh for a variation of 10 K in the set point oil temperature, whereas the variation on solar energy input is null. Looking at the balance on electricity consumption, it can be seen from Figure 11 that higher oil set point temperatures lead to a conditions where the energy production is about twice the consumption in winter, while a complete self-consumption is almost achieved during summer.

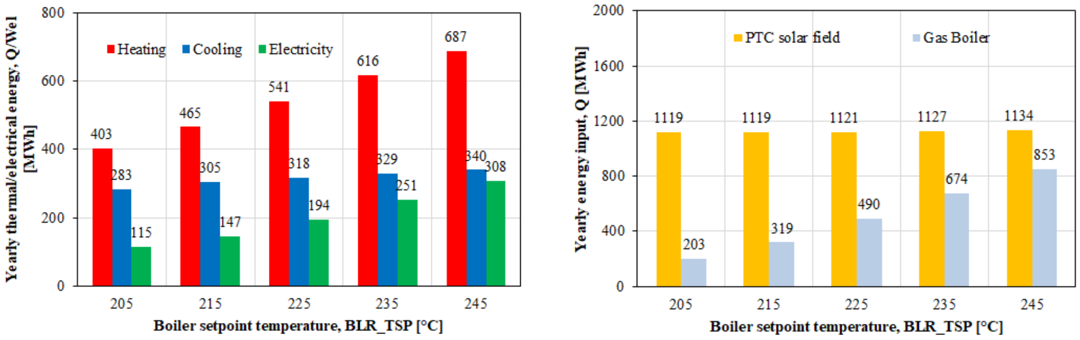

Fig. 10: Yearly thermal / electrical energy outputs and inputs for different setpoint temperature of the gas boiler.

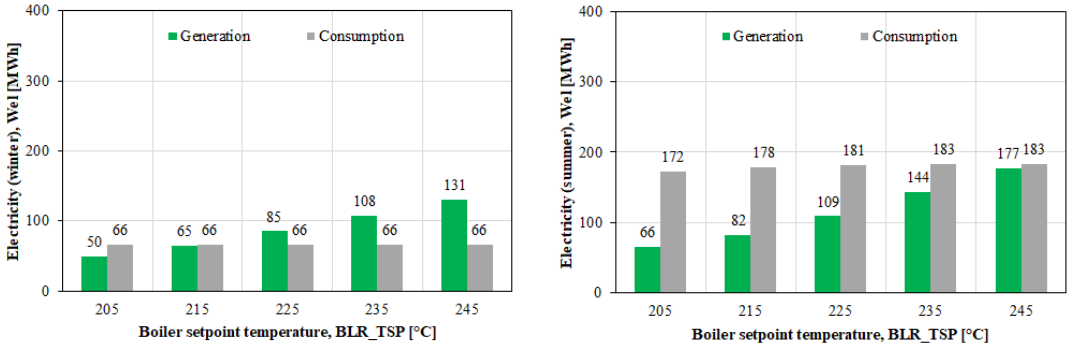

Fig. 11: Seasonal (winter – left, summer – right) electricity balance for different set point temperature of the gas boiler.

Finally, it is interesting to evaluate the performance of the system with and without the operation of the ORC unit. Without the ORC unit, the heating production is reduced by 7%, while the cooling production results increased (+19%) thanks to the higher COP_{th} achieved in the adsorption chiller. The impact in terms of earnings and energy costs is shown below. Although the lack of the ORC allows to reduce the electricity cost of about 19%, the gas consumption is increased of only 5%. In global terms, the lack of earnings from electricity generation increases the energy costs of 62% with respect to the case with ORC.

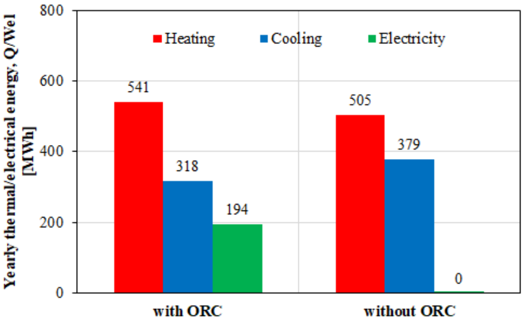

Fig. 12: Yearly energy outputs (heating, cooling and electricity) of the system with and without the ORC unit.

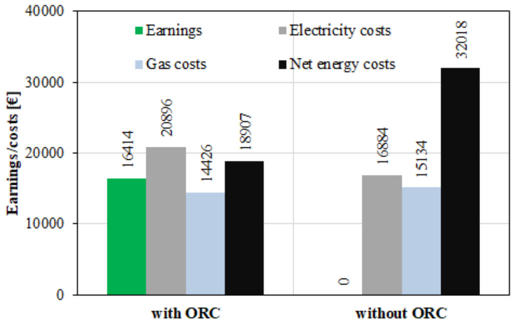

Fig. 13: Yearly earning and energy costs of the system with and without the ORC unit.

The results of this parametric analysis have contributed in defining an optimized system layout, characterized by a larger PTC solar field area with an improved control strategy for pump modulation and a set point inlet temperature into ORC's evaporator of 245°C. The heating production increases of 23%, while the cooling production achieves an improvement of only 5%. The electrical efficiency of the ORC unit largely improves and the electricity generation is increased of about 61%. These figures have a positive impact on the net energy costs, with an overall reduction of about 36% with respect to the initial layout. The net energy savings increase from about 4000 €/year to 14700 €/year.

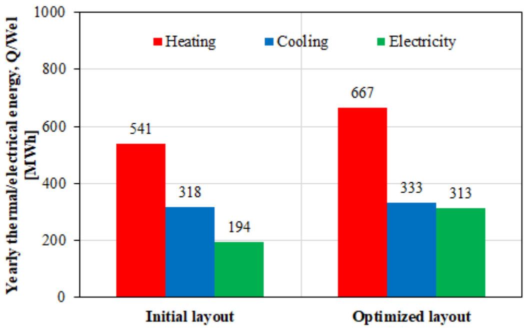

Fig. 14: Comparison of yearly energy outputs (heating, cooling and electricity) between initial and optimized layouts.

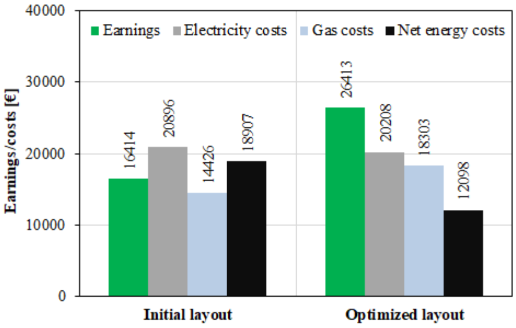

Fig. 15: Comparison of yearly earning and energy costs between initial and optimized layouts.

4. Conclusions

This paper has presented simulation results and economic analysis on the profitability of a small-scale CCHP system installed in the hospital of Aydin (Turkey). The CCHP system is built around a 51 kW_{el} ORC unit assisted by a 1632 m^2 PTC solar field. The priority of the system is directed on the production of heating and cooling throughout the year, whereas electricity generation has a secondary relevance. The work has been conducted within the framework of the EU FP7 BRICKER project that aimed to develop new solutions for the renovation of public-owned residential buildings.

The trigeneration system covers only a fraction of the energy demand of the hospital building, since its limited capacity is not able to cover neither the heating demand in winter, nor the cooling demand in summer. The electrical output is completely self-consumed by either the CCHP system or the existing system.

The yearly amount of heating provided by the trigeneration systems per kW of installed solar thermal capacity is 0.54 MWh/kW_{sol}, while the total cooling energy generation amounts to 0.32 MWh/kW_{sol}. The electric energy generated by the system during an annual operation period is 0.19 MWh/kW_{sol}, while final electricity and gas energies are 0.25 MWh/kW_{sol} and 0.57 MWh/kW_{sol}, respectively.

Since the gas boiler is in series to the PTC field and no thermal energy storage is included, the working hours of the CCHP system are strictly dependent on weather condition and cannot fulfil any variable energy demand. Because of this, such CCHP system is particularly suitable for applications where the energy demand is much larger than the trigeneration system capacity, such as large tertiary and commercial buildings or District Heating and Cooling networks preferably working at low or neutral temperatures.

Actual Turkish gas and electricity tariffs are used to calculate the net energy cost related to system operation. This calculation results in a specific space heating cost of 11.7 €/MWh and a cooling specific cost of 39.6 €/MWh. The total initial investment cost is estimated around 1.42 M€, while yearly energy savings obtained by cogenerating energy through this small-scale system with respect to a reference system are limited to approximately 4000 €. An optimized design of the CCHP is derived from the parametric analysis on key system parameters. Although the energy savings increase to 14700 €/year, the attractiveness of the system is still limited.

From a technological perspective, the replication of the system has to deal with a deep standardization of the CCHP layout. The efficiency of the ORC is limited by the small-scale of the unit. Compared to the ORC units available on the market with sizes in the order of 1 MW_{el}, the efficiency in electricity generation mode of the prototype here considered is half.

Looking at economic conditions, speculative approaches prioritizing electricity generation in place of thermal energy outputs, should be carefully considered. From a simplified analysis, a preliminary conclusion is that they can be only partly justified (1) through solar energy resource exploitation, (2) for larger capacity installations and (3) for high electricity and gas tariffs. Future works will investigate closer such aspects in quantitative terms.

5. Acknowledgement

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