FLEXIBLE PVT-ORC HYBRID SOLAR-BIOMASS COGENERATION SYSTEMS: THE CASE STUDY OF THE UNIVERSITY SPORTS CENTRE IN BARI, ITALY

Kai Wang[1]*, Antonio Marco Pantaleo[1,2], Oyeniyi A. Oyewunmi[1], Christos N. Markides[1]

[1] Clean Energy Processes (CEP) Laboratory, Imperial College London, London, United Kingdom
kai.wang@imperial.ac.uk

[2] University of Bari, Department of Agro-Environmental Sciences, Bari, Italy

* Corresponding Author

ABSTRACT

The thermoeconomic feasibility of a hybrid solar-biomass renewable cogeneration systems based on a wood-chip boiler, photovoltaic-thermal (PVT) collectors and an organic Rankine cycle (ORC) engine is investigated for combined heat and power (CHP) provision in a sports-centre application. The PVT-based CHP (PVT-CHP) subsystem, integrated with thermal energy storage, is designed to meet most of the energy demands of the facility at high solar-irradiance conditions, while the biomass ORC-based CHP (ORC-CHP) subsystem, driven by a wood-chip boiler, is used to compensate the intermittent solar energy and match the onsite energy demand. A technoeconomic model is proposed to optimise the hybrid cogeneration system design and operation. Annual energy simulations are conducted in a case study focused on the provision of electricity, space heating, swimming pool heating and hot-water supply to the University Sports Centre (USC) of Bari, Italy. The size of the ORC engine is found to be critical to the performance of the PVT-ORC cogeneration system. With an installation area of 4,000 m^2 for the PVT collectors and an ORC engine size of 40 kWe/310 kWt, the hybrid solar-biomass cogeneration system can provide 100% renewable energy supply to the USC with a payback time of 11.5 years, compared to 12.3 years for the solar-only PVT-CHP system. Although the biomass-only ORC-CHP system has much shorter payback time (5.0 years), the electricity output is insufficient to match the demand, accounting for only 27% of the electricity consumed onsite. This work shows that neither the solar-only nor biomass-only systems can provide full renewable energy supply to the USC, while their hybridisation makes this target attainable, with a moderate payback on investments.

1. INTRODUCTION

Cogeneration or combined heat and power (CHP) is the combined production of two forms of energy, i.e., electric or mechanical energy and useful thermal energy, in one technological process. Cogeneration can provide multi-vector energy supplies with much higher overall efficiency and better match to the energy demands than alternative standalone energy production processes, and thus has an excellent decarbonisation potential and economic benefits.

Renewable energy-based CHP is especially attractive as the consumption of fossil fuels can be significantly reduced. Solar and biomass are among the most widespread energy sources for cogeneration systems. Solar CHP systems are mainly based on the integration of solar-thermal collectors with heat-to-power conversion units (Chatzopoulou *et al*., 2019, Ramos *et al*., 2019), or integration of solar photovoltaic (PV) panels with power-to-heat conversion units (Ramos *et al*., 2017), or the combination of side-by-side solar-thermal and PV systems. Another emerging solar CHP technology, namely hybrid PV-thermal (PVT) collector, can generate both electricity and useful thermal energy from the same collector area, and therefore has higher overall efficiency if operated appropriately (Herrando *et al*., 2018, Guarracino *et al*., 2019, Herrando *et al.*, 2019). Previous studies have suggested that PVT-based cogeneration systems can cover a significant amount of the energy demand of end-users given access to reasonable installation areas with excellent decarbonisation potential (Guarracino *et al.*, 2016, Herrando and Markides, 2016, Wang *et al.*, 2019). Due to the inherent intermittence of solar energy and the constraints of available areas, it is often challenging to meet all the onsite energy demand with solar cogeneration systems, despite the use of thermal storage. Integrating biomass with solar energy is interesting as these renewable resources can complement each other: biomass can compensate the fluctuations of solar energy while solar energy can provide extra flexibility for the supply chain of biomass (Pantaleo *et al*., 2014, Pantaleo *et al*., 2017).

The integration of concentrated solar-thermal and biomass has been studied extensively in the context of power generation. Heat-to-power conversion technologies of interest mainly included the organic Rankine cycle (ORC) (Pantaleo *et al*., 2018), supercritical CO_2 (Wang *et al*., 2018), Stirling (Wang *et al*., 2016), thermofluidic (Oyewunmi *et al*., 2017) and combined cycles (Anvari *et al*., 2019). Various hybrid solar-biomass cogeneration/polygeneration systems have been proposed based on different technology integrations. Morrone *et al.* (2019) performed a thermodynamic modelling on a hybrid solar-biomass transcritical ORC system for combined heat and power generation for residential applications based on in-series parabolic trough collectors (PTCs) and biomass boilers. It was found that the hybridisation allows the reduction of biomass consumption, increasing maximum operating hours and improving the overall system efficiency while overcoming the intermittency of the solar source. Khalid *et al.* (2017) performed a thermoeconomic assessment of a solar multigeneration system with the outputs of electricity, space heating, cooling and hot water for a community application, based on the integration of a biomass boiler, PTCs, an ORC engine, a gas turbine and an absorption chiller. The results suggested that the hybrid system is more efficient and economic than individual renewable energy systems. Sahoo *et al.* (2018) proposed to use biomass boiler to upgrade the fluid temperature of the PTC field for generating electricity, cooling and clean water using an ORC engine, a vapor absorption refrigerator and a desalination unit. It was concluded that the polygeneration system is more cost-effective compared to solar thermal and hybrid solar-biomass power plants. A solar-biomass ORC powered cascaded vapor compression-absorption system was proposed by Patel *et al.* (2017), and parabolic dish, PTC and linear Fresnel reflector were considered as the solar technology. The thermoeconomic analyses indicated that the fully biomass powered system outperforms the solar-biomass powered alternative option in terms of the capital cost and payback time.

Almost all of existing work on hybrid solar-biomass CHP systems has focused on concentrated solar thermal collectors (usually PTCs), the application of which may have limitations in sectors such as residential or public buildings located in regions with dense populations. Here, we propose a hybrid solar-biomass CHP system targeted for full renewable energy supply, based on PVT collectors, a biomass boiler and an ORC engine. The ORC engine is coupled to the boiler for power generation and its rejected heat is used to supplement the fluctuating solar heat from the PVT collectors. The electrical outputs of the ORC engine and PVT collectors are used to cover the onsite electricity demand. A thermodynamic model is developed and the thermoeconomic potential of various system designs are then assessed and compared to alternative standalone solar and biomass CHP systems, with the University Sport Centre (USC) of Bari (Italy) selected as an application case.

2. METHODOLOGY

The proposed PVT-ORC hybrid solar-biomass CHP system is shown in Figure 1(a). It consists of a solar-driven PVT subsystem and a biomass-driven ORC subsystem. Part of the solar energy is directly converted into electricity by the PV cells and the rest is partially collected as low-temperature thermal energy through a heat transfer loop between the PVT collectors and the water tank. The ORC engine is driven by the heat from the biomass boiler via a thermal oil heat transfer loop, and its *T-s* diagram is shown in Figure 1(b). Wood chips are used for heating the thermal oil to a temperature of 310 °C. The high-temperature thermal oil pumped into the evaporator of the ORC engine is used to produce high-pressure refrigerant vapor (2−5), which is then expanded to a lower pressure producing electric power in the expander-generator assembly (5−6). The low-pressure vapor is then condensed to saturated liquid in the condenser (6−1) which is pumped back to the evaporator (1−2) for the next cycle.

Along with the electricity generation, the ORC engine is designed to provide useful thermal energy through the heat rejected during the condensation of the refrigerant, which is collected by a cooling water loop connected to the water tank. When the water temperature in the tank is lower than the desired value (70 °C) due to the insufficient heat supply from the PVT subsystem, the biomass-ORC subsystem is turned on to produce hot water until the water temperature reaches the upper-limit (80 °C). The solar intermittence problem is thus overcome by the biomass subsystem. The thermal energy stored in the water tank is used to cover the thermal demand of the USC of Bari for space heating (70 °C), swimming pool heating (55 °C) and hot water (55 °C). The electricity generated by the PVT collectors and the ORC engine is used to compensate the electricity consumption of the pumps and the rest to cover the electricity demand. Any surplus electricity is exported to the grid via net metering option. The USC has total annual demands of 1600 MWh and 810 MWh for thermal energy and electricity respectively, which are currently met by natural-gas boilers and electricity grid. The monthly breakups of the demands are shown in Figure 2. High thermal demand is required during cold seasons while electricity demand is relatively stable over the year.

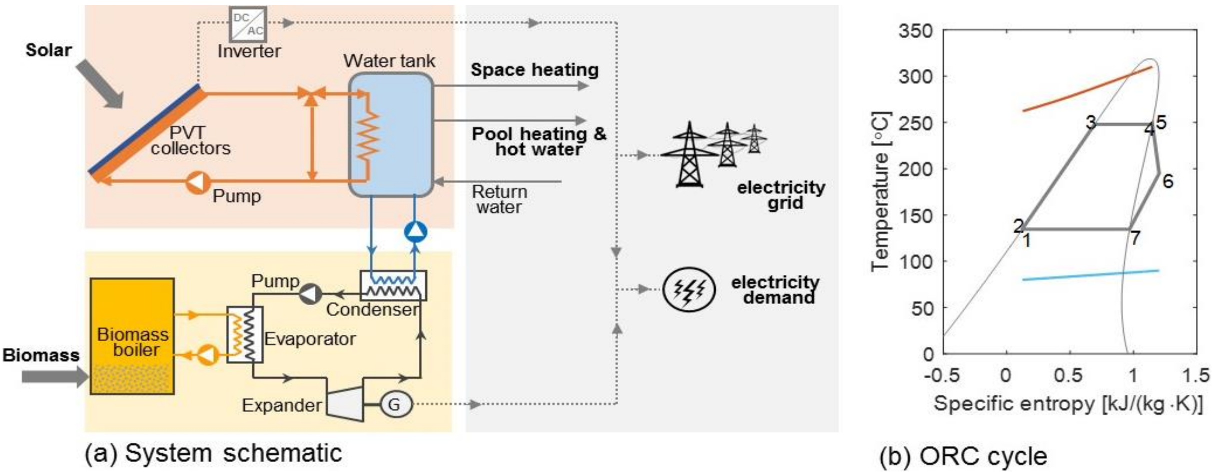

Figure 1: (a) Schematic of the PVT-ORC CHP system. (b) *T-s* diagram of the investigated ORC system.

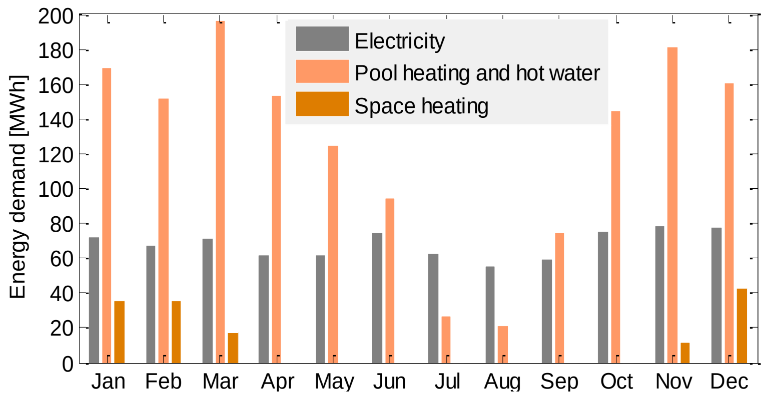

Figure 2: Energy demands for the University Sport Centre (USC) of Bari, Italy.

2.1 Solar-PVT subsystem model

A transient thermodynamic model has been built for the PVT subsystem, which accounts for the key heat transfer mechanisms that determines its thermal and electrical performance. Single-glazed PVT-water collectors with sheet-and-tube thermal absorbers are used in the work. The main control equations of the glass covers, PV cells and water in the water tank are:

$$M_{\mathrm{g}}c_{\mathrm{g}}\frac{\mathrm{d}T_{\mathrm{g}}}{\mathrm{d}t} = Q_{\mathrm{s,g}} + Q_{\mathrm{r,pv-g}} + Q_{\mathrm{c,pv-g}} - Q_{\mathrm{r,g-sky}} - Q_{\mathrm{c,g-a}} \tag{1}$$

$$M_{\mathrm{pv}}c_{\mathrm{pv}}\frac{\mathrm{d}T_{\mathrm{pv}}}{\mathrm{d}t} = Q_{\mathrm{s,pv}} - Q_{\mathrm{r,pv-g}} - Q_{\mathrm{c,pv-g}} - Q_{\mathrm{c,pv-w}} \tag{2}$$

$$M_{\mathrm{wt}}c_{\mathrm{wt}}\frac{\mathrm{d}T_{\mathrm{wt}}}{\mathrm{d}t} = Q_{\mathrm{ORCcond}} + Q_{\mathrm{w-wt}} - Q_{\mathrm{wt,loss}} - Q_{\mathrm{dem}} \tag{3}$$

where *M*, *c*, *T* and *Q* denote mass, specific heat capacity, temperature and heat transfer rate, respectively, and subscripts ‘g’, ‘s’, ‘r’, ‘pv’, ‘c’, ‘sky’, ‘a’, ‘w’, ‘wt’, ‘ORCcond’, ‘loss’ and ‘dem’ refer to the glass cover, solar energy, radiation, PV cells, convection, sky, ambient, water, water tank, ORC condenser, heat losses and thermal demand, respectively. The detailed equations for these heat transfer mechanisms can be found in Herrando *et al*. (2014) and Guarracino *et al*. (2016). The thermal and electrical efficiencies (η_{t}, η_{e}) of the PVT collectors obtained by the model under standard condition are given in Equations (4) and (5):

$$\eta_{\mathrm{t}} = 0.664 - 5.41 \cdot T_{\mathrm{r}} - 0.0209 \cdot G \cdot T_{\mathrm{r}} \tag{4}$$

$$\eta_{\mathrm{e}} = 0.15 \cdot [1 - 0.0045 \cdot (T_{\mathrm{pv}} - 25)] \tag{5}$$

where T_{r}, G and T_{pv} denote the reduced temperature, solar irradiance and PV cell temperature.

2.2 Biomass-ORC subsystem model

Biomass-ORC engines are typically operated at relatively high temperatures, and thus a high critical temperature is required for the working fluid. Toluene (Pantaleo *et al*., 2018), octamethyltrisiloxane (MDM) (Prando *et al*., 2015) and hexamethyldisiloxane (MM) (Uris *et al*., 2017) have been used for biomass-ORC engines. In this work, Toluene is chosen as the working fluid considering its better performance, good environmental and safety properties. A sub-critical, non-regenerative ORC is considered, as shown in the *T-s* diagram in Figure 1. The performance of the thermodynamic cycle is calculated by using an in-house ORC model (Oyewunmi and Markides, 2016). The heat extracted from the condenser, Q_{ORCcond}, is collected via a water circulation loop and is coupled to the energy balance equation of the water tank in the model, as given in Equation (3).

The heat exchangers are modelled as counter-flow, double-pipe heat exchangers. For single-phase heat transfer in the heat exchangers, the Nusselt number correlation presented by Dittus-Bölter (Lecompte *et al*., 2013) is used. For two-phase heat transfer in the condenser, the correlation proposed by Shah (1979) is used, while that by Chen-Zuber correlation (Chen, 1966) is used for two-phase boiling in the evaporator. The thermodynamic cycle of the ORC engine is optimised using the *fmincon* algorithm in MATLAB® to maximise its thermal efficiency while considering the constraints of the pinch point (≥10 °C), pressure drop (≤100 kPa), etc., to ensure reasonable operating conditions and designs. The main parameters of the designed ORC engine are given in Table 1. The overall efficiency from biomass energy to thermal energy transferred to the evaporator is assumed as 85% (Morrone *et al*., 2019). The control equations of the solar-PVT and biomass-ORC subsystems are implemented in MATLAB® and solved iteratively with a time step of an hour over the whole year.

Table 1: Designed operational condition and main parameters of the ORC engine.

Parameter	Value
ORC working fluid	Toluene
Thermal oil inlet temperature	310 °C
Water inlet temperature	80 °C (maximum)
Water outlet temperature	90 °C
Evaporating temperature/pressure	248 °C/1.6 MPa
Condensing temperature/pressure	135 °C/0.19 MPa
Pump isentropic efficiency	60%
Expander isentropic efficiency	70%

2.3 Economic models

The economic performance of the system is assessed in terms of payback time based on the capital costs, operational and maintenance costs and revenues due to displaced natural gas and grid electricity consumption as well as the exported electricity. The annual cost saving, C_{s}, is calculated by,

$$C_{\mathrm{s}} = E_{\mathrm{cov}} \cdot c_{\mathrm{e}} + E_{\mathrm{exp}} \cdot s_{\mathrm{e}} + \frac{Q_{\mathrm{cov}}}{\eta_{\mathrm{boil}}} c_{\mathrm{ng}} - \frac{Q_{\mathrm{ORCevap}}}{\eta_{\mathrm{bio}}} c_{\mathrm{bio}} - C_{\mathrm{O\&M}}\ , \tag{6}$$

where E_{cov} and Q_{cov} denote the electrical and thermal demands covered, E_{exp} is the electricity exported to the grid, Q_{ORCevap} represents the heat added to the evaporation of the ORC engine, η_{boil} and η_{bio} are the natural-gas boiler efficiency (80%) and the overall efficiency from biomass to thermal energy added to the ORC condenser (85%), respectively. c_{e}, c_{ng} and c_{bio} are the prices of electricity (0.205 €/kWh), natural gas (0.056 €/kWh) and wood chips (0.018 €/kWh), respectively, s_{e} is the electricity price for the net metering option (0.103 €/kWh), and $C_{\mathrm{O\&M}}$ is the operation and maintenance costs. The cost models of the PVT and ORC subsystems can be found in Wang *et al*. (2019) and Oyewunmi and Markides (2016), respectively. The payback time is calculated by,

$$PBT = \frac{\ln\left[\frac{C_0(i_{\mathrm{F}}-d)}{C_{\mathrm{S}}}+1\right]}{\ln\left(\frac{1+i_{\mathrm{F}}}{1+d}\right)}, \tag{7}$$

where d is the discount rate (2.8%) and i_{F} is the inflation rate (1.2%).

3. RESULTS AND DISCUSSION

The design target of the PVT-ORC hybrid solar-biomass cogeneration system is to provide full renewable energy supply without any need for backup fossil fuel solutions for the USC, i.e., net-zero energy balance. The operation characteristics and thermodynamic performance of the solar-only PVT and biomass-only ORC systems are first examined. For the PVT-CHP case (i.e., no ORC integrated), an installation area of 4,000 m^2 is considered for the PVT collectors, which corresponds to the maximum roof area available in the USC and a total installed electrical power of 600 kW$_{\mathrm{p}}$. The size of the water tank is fixed for all cases considering the amount of the thermal demand and the water temperature constraints. The annual water temperature variation of the water tank of the PVT-CHP system is shown in Figure 3(a). It is observed that the water temperature is typically between 40 °C and 50 °C in winter, which is significantly lower than the required delivery temperature (70 °C) for space heating. As the solar resource becomes better and the thermal demand drops (see Figure 2) in summer, the water temperature is remarkably higher, reaching above 90 °C in July and August. The thermodynamic results show that the thermal demand coverage fractions are 13%, 49% and 75% respectively for the space heating, pool heating and hot water, corresponding to a total coverage fraction of 52% of the total thermal demand. The total electricity output of the PVT-CHP system accounts for 82% of the electricity demand, and the onsite coverage fraction is 38% due to the fluctuation feature of solar energy. The results show that the solar-only PVT-CHP system without any biomass integration is not able to fulfil the demand of the USC due to the constraints of the installation area and the unavoidable fluctuations of solar energy.

An equivalent biomass-only ORC-CHP system (i.e., without PVT integrated) is also investigated. The ORC engine is sized to meet all the thermal demand of the USC. To achieve this target, the minimum size is found as 60 kWe/490 kWt for the electrical and thermal outputs. The temperature variation in the water tank is shown in Figure 3(e). In winter period when space heating is required, the temperature to trigger the ORC engine is set as 2 °C higher than the required delivery temperature (70 °C), while in the other periods it is set at 57 °C. The temperature variation shows that the ORC-CHP system can effectively ensure that the water is above the needed temperature; therefore 100% of the thermal demand is covered. All of the electricity generated by the ORC-CHP system is directly used and accounts for 27% of the electricity demand, which indicates that the system has a baseload supply capability. This provides a good potential to compensate the fluctuations of solar energy. Although the biomass-only ORC-CHP system with an appropriate size can meet all the thermal demands, the amount of electricity production is still well below the target for full renewable energy supply. In order to avoid intermittent operation of the biomass boiler, a thermal storage buffer could also be integrated between the boiler and the ORC evaporator (Pantaleo *et al.*, 2018), which is not considered in this work.

Comparing the results of the PVT and ORC systems, it is found that they can complement each other in terms of the energy production and dynamic response, i.e., more electricity demand can be covered by the PVT system while the ORC system has better capability for covering the thermal demand with faster responses. Results of the hybrid ORC-CHP system with different sizes of the ORC engine are shown in Figures 3(b), (c) and (d). In order to meet the full renewable energy supply target, the area of the PVT collectors is kept as the maximum available area (4,000 m^2). It shows that the size of the ORC engine affects the tank temperature significantly. With a smaller size, the annual temperature profile is less affected by the ORC system, as the thermal power provided by the ORC engine is insufficient to cover the demand, as shown in Figure 3(b). Increasing the ORC size can effectively stabilize the water temperature within the required range. As the thermal demand in summer is low and can be fully fulfilled by solar energy, the ORC engine is therefore turned off for most of the time, leading to the similar shapes of the temperature variations in these scenarios.

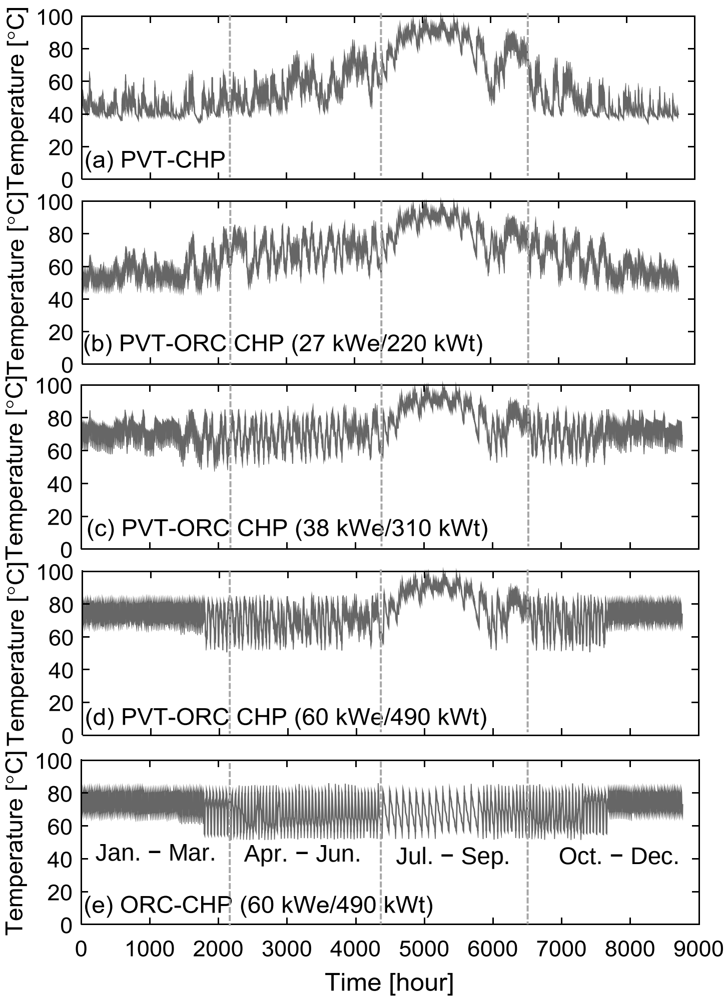

Figure 3: Annual results of the water temperature in the water tank of: (a) PVT-CHP system, (b) PVT-ORC CHP system with the ORC size of 27 kWe/220 kWt, (c) PVT-ORC CHP system with the ORC size of 40 kWe/310 kWt, (d) PVT-ORC CHP system with the ORC size of 60 kWe/490 kWt, and (e) ORC-CHP system with the size of 60 kWe/490 kWt. The installation area of the PVT collectors is 4,000 m^2 for all cases.

Figure 4 shows the changes of the electricity demand, coverage and generation by the PVT and ORC engine in the PVT-ORC CHP system with the ORC size of 60 kWe/490 kWt in two representative periods of the year, i.e., 5 days in January and in June. It is observed that the electrical power generated from the PVT system is highly fluctuating and can fulfil all the daytime demand with some excess exported to the grid at good solar conditions. During the periods in January when the water temperature of the water tank drops below the trigger point, the ORC engine is started to heat up the water and electricity is hereby generated, as shown by the blue dash line in Figure 4(a). Along with the solar electricity, the ORC engine provides a relatively stable baseload electricity supply for the USC. During the summer period, however, due to the adequate solar energy to sustain the required water temperature, the ORC engine is turned off and thus no electricity is generated from the biomass. As the solar radiation in summer is high, the electricity generated from the PVT collectors is sufficient to fulfil all the daytime demand with a significant amount of excess electricity.

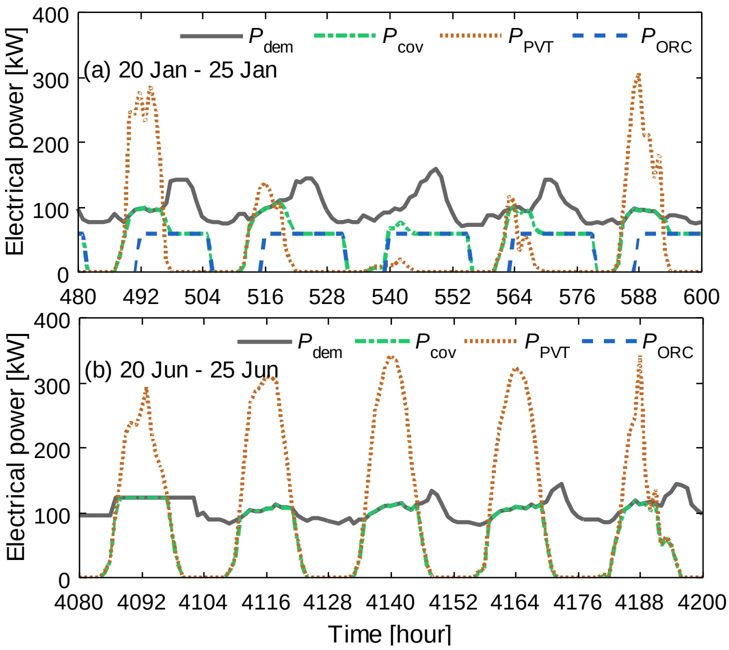

Figure 4: Transient electricity demand (P_{dem}), coverage (P_{cov}), generation by the PVT (P_{PVT}) and ORC (P_{ORC}) of the PVT-ORC CHP system (ORC size: 60 kWe/490 kWt) during the period: (a) 20 to 25 January, and (b) 20 to 25 June.

Figure 5 presents the thermodynamic and economic performance metrics based on the annual simulation results for the PVT-ORC system with different sizes of the ORC engine. As analysed above, the size of the ORC engine influences the performance of the hybrid solar-biomass cogeneration system. Integrating the ORC engine with an appropriate size can effectively increase the energy outputs and reduce the payback time. The optimal performance is found when the ORC engine is sized as 40 kWe/310 kWt. In this case, all the thermal demand can be fulfilled, and the total electricity generation accounts for nearly 100% of the demand, indicating that the target of near-zero energy dependency on fossil fuels is achievable with the proposed system. The shortest payback time is 11.5 years for the PVT-ORC cogeneration system, which is about 1 year shorter than the standalone PVT-CHP system. As a comparison, the standalone ORC-CHP system is the most cost competitive solution in terms of the payback time (5.0 years), but its electricity output is limited, accounting for only 27% of the electricity demand.

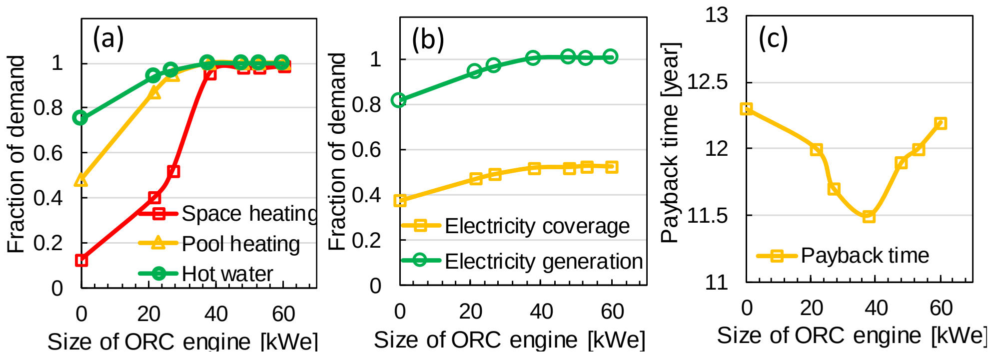

Figure 5: Thermoeconomic performance of different coupling scenarios of the CHP systems: (a) thermal demand coverage, (b) electricity demand coverage and electricity generation, and (c) payback time. The installation area of the PVT collectors is 4,000 m^2 for all cases.

4. CONCLUSIONS

A technoeconomic analysis has been conducted of a hybrid solar-biomass cogeneration system based on PVT collectors and an ORC engine, providing electricity, space heating, swimming pool heating and hot water to the USC of Bari, Italy. A transient model has been developed for the PVT-ORC CHP system by coupling a heat transfer model of the PVT collectors with a thermodynamic model of the ORC engine.

Standalone PVT and ORC systems have also been investigated for comparison purposes. The results from the annual simulations show that, given the maximum installation area of 4,000 m^2, a standalone PVT-CHP system without biomass integration can cover 52% of the total thermal demand along with an electricity generation amounting to 82% of the site's demand, while a standalone ORC-CHP system can fulfil all the thermal demand (with a faster response) but the generated electricity can only cover 27% of the demand. Integration of the solar and biomass system can provide better energy production capability and dynamic response to the demand, arising from the complementary effect of this hybridisation. Sensitivity analyses on the size of the ORC engine indicate that it has a significant effect on the system thermodynamic and economic performance. Based on a PVT-collector area of 4,000 m^2 and an ORC engine of size 40 kWe/310 kWt, the PVT-ORC system can provide full renewable energy supply to the USC with a payback time of 11.5 years, which is about 1 year shorter than a standalone (solar-only) PVT-CHP system.

REFERENCES

Chatzopoulou, M. A., Simpson, M., Sapin, P., Markides, C. N., 2019, Off-design optimisation of organic Rankine cycle (ORC) engines with piston expanders for medium-scale combined heat and power applications, *Appl. Energy*, vol. 238: p. 1211-1236.

Ramos, A., Chatzopoulou, M. A., Freeman, J., Markides, C. N., 2018, Optimisation of a high-efficiency solar-driven organic Rankine cycle for applications in the built environment, *Appl. Energy*, vol. 228: p. 755-765.

Ramos, A., Chatzopoulou, M. A., Guarracino, I., Freeman, J., Markides, C. N., 2017, Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment, *Energy Conver. Manag.*, vo. 150: p. 838-850.

Herrando, M., Ramos, A., Freeman, J., Zabalza I., Markides, C. N., 2018, Technoeconomic modelling and optimisation of solar combined heat and power systems based on flat-box PVT collectors for domestic applications, *Energy Conver. Manag.*, vol. 175: p. 67-85.

Guarracino, I., Freeman, J., Ramos, A., Kalogirou, S. A., Ekins-Daukes, N. J., Markides, C. N., 2019, Systematic testing of hybrid PV-thermal (PVT) solar collectors in steady-state and dynamic outdoor conditions, *Appl. Energy*, vol. 240: p. 1014-1030.

Herrando, M., Pantaleo, A. M., Wang, K., Markides, C. N., 2019, Solar combined cooling, heating and power systems based on hybrid PVT, PV or solar-thermal collectors for building applications, *Renew. Energy*, vol. 143: p. 637-647.

Guarracino, I., Mellor, A., Ekins-Daukes, N. J., Markides, C. N., 2016, Dynamic coupled thermal-and-electrical modelling of sheet-and-tube hybrid photovoltaic/thermal (PVT) collectors, *Appl. Therm. Eng.*, vol. 101: p. 778-795.

Herrando, M., Markides, C. N., 2016, Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations, *Appl. Energy*, vol. 161: p. 512-532.

Wang, K., Herrando, M., Pantaleo, A. M., Markides, C. N., 2019, Thermoeconomic assessment of a PV/T combined heating and power system for University Sport Centre of Bari, *Energy Procedia*, vol. 158: p. 1229-1234.

Pantaleo, A. M., Camporeale, S., Shah, N., 2014, Natural gas-biomass dual fuelled microturbines: Comparison of operating strategies in the Italian residential sector, *Appl. Therm. Eng.* vol. 71 no. 2: p. 686-696.

Pantaleo, A. M., Camporeale, S. M., Miliozzi, A., Russo, V., Shah, N., Markides, C. N., 2017, Novel hybrid CSP-biomass CHP for flexible generation: Thermo-economic analysis and profitability assessment, *Appl. Energy*, vol. 204: p. 994-1006.

Pantaleo, A. M., Camporeale, S. M., Sorrentino, A., Miliozzi, A., Shah, N., Markides, C. N., 2018, Hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage: Techno-economic feasibility in selected Mediterranean areas, *Renew. Energy* [In press]

Wang, X. H., Liu, Q. B., Bai, Z., Lei, J., Jin, H. G., 2018, Thermodynamic investigations of the supercritical CO2 system with solar energy and biomass, *Appl. Energy*, vol. 227: p. 108-118.

Wang, K., Sanders, S., Dubey, S., Choo, F. H., Duan, F., Stirling cycle engines for recovering low and moderate temperature heat: A review, *Renew. Sustain. Energy Rev.*, vol. 62: p. 89-108.

Oyewunmi, O. A., Kirmse, C. J. W., Haslam, A. J., Müller, E. A., Markides, C. N., 2017, Working-fluid selection and performance investigation of a two-phase single-reciprocating-piston heat-conversion engine, *Appl. Energy*, vol. 186: p. 376-395.

Anvari, S., Khalilarya, S., Zare, V., 2019, Power generation enhancement in a biomass-based combined cycle using solar energy: Thermodynamic and environmental analysis, *Appl. Therm. Eng.*, vol. 153: p. 128-141.

Morrone, P., Algieri A., Castiglione T., 2019, Hybridisation of biomass and concentrated solar power systems in transcritical organic Rankine cycles: A micro combined heat and power application, *Energy Conver. Manag*., vol. 180: p. 757-768.
Khalid, F., Dincer, I., Rosen, M. A., 2017, Thermoeconomic analysis of a solar-biomass integrated multigeneration system for a community, *Appl. Therm. Eng.*, vol. 120: p. 645-653.
Sahoo, U., Kumar, R., Singh, S. K., Tripathi, A. K., 2018, Energy, exergy, economic analysis and optimization of polygeneration hybrid solar-biomass system, *Appl. Therm. Eng*., vol. 145: p. 685-692.
Patel, B., Desai, N. B., Kachhwaha, S. S., 2017, Thermo-economic analysis of solar-biomass organic Rankine cycle powered cascaded vapor compression-absorption system, *Sol. Energy*, vol. 157: p. 920-933.
Herrando, M., Markides, C. N., Hellgardt, K., 2014, A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance, *Appl. Energy*, vol. 122: p. 288-309.
Prando, D., Renzi, M., Gasparella, A., Baratieri, M., 2015, Monitoring of the energy performance of a district heating CHP plant based on biomass boiler and ORC generator, *Appl. Therm. Eng*., vol. 79: p. 98-107.
Uris, M., Linares, J. I., Arenas, E., 2017, Feasibility assessment of an organic Rankine cycle (ORC) cogeneration plant (CHP/CCHP) fueled by biomass for a district network in mainland Spain, *Energy*, vol. 133: p. 969-985.
Oyewunmi, O. A., Markides C. N., 2016, Thermo-economic and heat transfer optimization of working-fluid mixtures in a low-temperature organic Rankine cycle system, *Energies*, vol. 9, no. 6: p. 448.
Lecompte, S., Huisseune, H., van den Broek, M., De Schampheleire, S., De Paepe, M., 2013, Part load based thermo-economic optimization of the organic Rankine cycle (ORC) applied to a combined heat and power (CHP) system, *Appl. Energy*, vol. 111: p. 871-881.
Shah, M. M., 1979, A general correlation for heat transfer during film condensation inside pipes, *Int. J. Heat Mass Tran*., vol. 22, no. 4: p. 547-556.
Chen, J. C., 1966, Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow, *Ind. Eng. Chem. Proc. DD.*, vol. 5, no. 3: p. 322-329.
Wang, K., Pantaleo, A. M., Mugnozza, G. S., Markides, C. N., 2019, Technoeconomic assessment of solar combined heat and power systems based on hybrid PVT collectors in greenhouse applications, In: *10th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings.* Bari, Italy.
Pantaleo, A. M., Fordham, J., Oyewunmi, O. A., De Palma, P., Markides, C. N., 2018, Integrating cogeneration and intermittent waste-heat recovery in food processing: Microturbines vs. ORC systems in the coffee roasting industry, *Appl. Energy*, vol. 225: p. 782-796.

ACKNOWLEDGEMENT

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/M025012/1]. The authors would also like to thank UK company Solar Flow (www.solar-flow.co.uk). Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.