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# Investigation of Integrated Organic Rankine Cycles and Wind Turbines for Micro-Scale Applications

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## Abstract

The aim of this work is the investigation of the performance of an innovative biomass/wind energy integrated 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 wind turbine (WT). The ORC and WT sub-systems operate in parallel to produce the required electrical energy and an auxiliary boiler provides thermal energy if the CHP output is low. A preliminary investigation is performed to define the proper size of the wind turbine. Afterwards, the analysis is focused on the integrated system. In particular, the application to the Italian residential sector is analysed. Results illustrate that hybridisation improves the global conversion efficiency, by reducing the biomass consumption and overcoming the intermittency of the wind source. When the wind source is significant, the ORC system can be switched off or operated at partial load.

*Keywords:* Organic Rankine Cycle; Combined Heat and Power; Hybridisation; Biomass; Wind energy

## 1. Introduction

Combined heat and power (CHP) production allows higher energy efficiency, sustainability and lower pollutant emissions compared with conventional systems with separate electric and thermal generation [1]-[2]. Specifically,

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**Nomenclature**

| | | | |
|---|---|---|---|
| $\alpha$ | wind shear exponent (-) | $u_1$ | cut-in wind speed (m/s) |
| $P_{el}$ | electric power (kW) | $u_n$ | rated wind speed (m/s) |
| $\dot{Q}_{th}$ | thermal power (W) | $u_2$ | cut-off wind speed (m/s) |
| u | wind speed (m/s) | $P_n$ | nominal power (kW) |
| $\eta$ | efficiency (%) | z | height (m) |

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, multi-generation systems appear to be a very innovative and efficient solution, able to assess larger operation flexibility [5]-[7]. In particular, there is significant potential for integrating wind energy and biomass resources, overcoming the stochastic nature of the wind source: when the wind is low or insufficient, the ORC system can be fuelled with biomass. Nevertheless, few investigations on this topic have been documented in literature and further studies are necessary [8]-[9].

The present work aims at analysing the energy performance of an integrated ORC/wind turbine (WT) system for domestic applications. The two sub-systems operate in parallel to produce electrical and thermal energy. The investigated concept may offer opportunities to achieve the Nearly Zero Energy House (NZEH) target in the residential sector.

## 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 wind turbine (WT) unit. Wind is the primary energy source while the ORC works when the wind energy 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 [10]-[11]. To this purpose, 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.

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

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

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

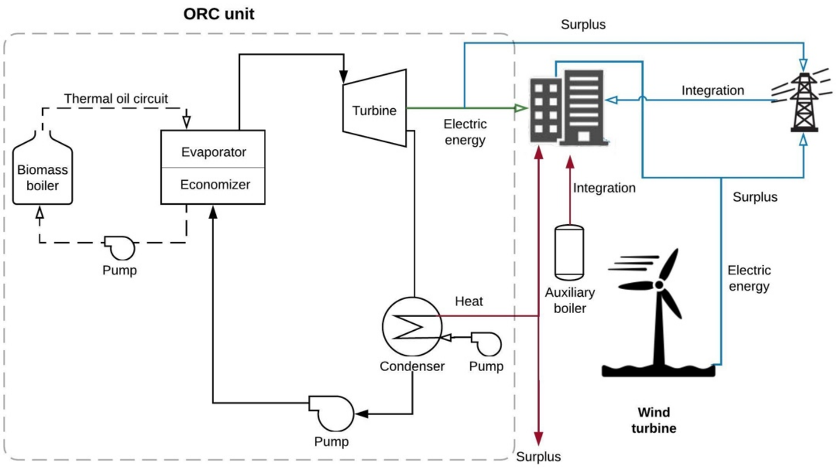


Fig. 1. Simplified scheme of the integrated ORC/WT system.

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;
$\eta_{cog}$ 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 [14].

Saturated conditions have been considered at the expander inlet. Table 1 shows the critical temperature and pressure of toluene, 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 [15]. Minimum evaporation temperature has been set to 150 °C while the maximum value (300 °C) has been chosen to avoid the presence of liquid during the expansion phase [16]. Table 2 summarises the main assumptions used for the parametric analysis [15],[17]. The performance of the ORC section at full and partial loads in terms of electric and thermal efficiency and power have been evaluated as a function of the evaporation temperature. Results show the progressive increase in electrical and thermal performance with the maximum temperature [19]-[20]. Specifically, the nominal power (14.1 $kW_{el}$ and 70.5 $kW_{th}$) corresponds to the maximum thermal level (300 °C) while minimum ORC power is found at 150 °C (5.7 $kW_{el}$ and 55.6 $kW_{th}$). At 150 °C the corresponding electrical and cogeneration efficiencies are 8.4% and 81.0%, respectively, while the 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 |
| Inlet turbine temperature | [°C] | 300 |
| Nominal Pressure | [bar] | 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 | [MJ/kg] | 18 |
| Biomass Humidity | [%] | 10 |

### *2.2. Wind energy system*

The annual hourly wind data for Palermo (Southern Italy) according to System Advisor Model (SAM) [20] have been used in order to evaluate the energy production of wind turbines. The wind speed values have been corrected to the wind turbine hub height according to [18]:

$$u = u_0 \left(\frac{z}{z_0}\right)^{\alpha} \tag{5}$$

where $u_0$ is the speed at the reference height (10 m) and $\alpha$ is the wind shear exponent. The output wind turbine power depends on wind speed. Five commercial wind turbines have been considered in the present work. The design parameters (cut-in and cut-off velocity, rated velocity and power) are visible in Table 3.

Table 3: Climate conditions and wind turbine characteristics

| ***Climate conditions*** | | | | |
|---|---|---|---|---|
| Average ambient temperature | [°C] | 18.8 | | |
| Average wind velocity | [m/s] | 4.7 | | |
| Cubic average wind velocity | [m/s] | 7.3 | | |
| Wind Shear Exponent | [-] | 0.2 | | |
| Average ambient pressure | [mbar] | 1009.5 | | |
| ***Wind turbine characteristics*** | | | | |
| *Model* | **Pn** [kW] | $\mathbf{u_1}$ [m/s] | $\mathbf{u_n}$ [m/s] | $\mathbf{u_2}$ [m/s] |
| Windmel Jamaha | 16.5 | 3.5 | 8.0 | 25 |
| Espe FX Evo 21-50 | 25 | 2.5 | 8.5 | 25 |
| Fuhrlander FL 30 | 30 | 3.0 | 12 | 28 |
| Kaman 40 | 40 | 2.5 | 9.0 | 25 |
| Espe FX Evo 21-50 | 49.9 | 2.5 | 8.5 | 25 |

## 3. Results

The analysis is focused on a CHP system based on a wind turbine (WT) 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 WT unit whereas the ORC system works when the wind velocity is not able to satisfy the electric demand. The investigation was focused on a domestic application in Palermo (Southern Italy), considering a block of 40 dwellings. Hourly wind data have been estimated through SAM software [20]. In particular, the mean wind speed is 4.7 m/s (Table 3). The electric request 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 [22]. The annual electric and thermal requests for a single apartment are estimated to be equal to 2.7 $MWh_{el}$ and 9.1 $MWh_{th}$, respectively.

A first set of results concerns with the wind system alone. To this purpose, a parametric analysis has been carried out to evaluate the size of the unit (Figure 2). The plot highlights the percentage of electrical energy produced by the WT system and the share supplied from the grid with respect to the annual demand. In particular, the WT electric production consists of self-consumption and surplus electric energy that could be injected to the grid. As expected, the higher the WT nominal power, the higher the self-consumption, except for the 30 kW wind turbine due to its high cut-in and rated speed. However, it is worthy to notice that the increase rate of self-consumption with the size is not significant and ranges from 25.4% to 45.1% for the 16.5 kW and 49.9 kW wind turbines, respectively. Conversely, the surplus electricity is considerably high for the WTs with the highest power unit. As an example, the value ranges from 13.1% to 70.2% of the domestic electric demand. At the same time, the integration from the grid is always higher than 55% for all the investigated sizes. The equivalent hours of the wind turbines present similar values (2500 – 2600 hours/year), with the exception of the 30 kW unit (about 2000 hours/year).

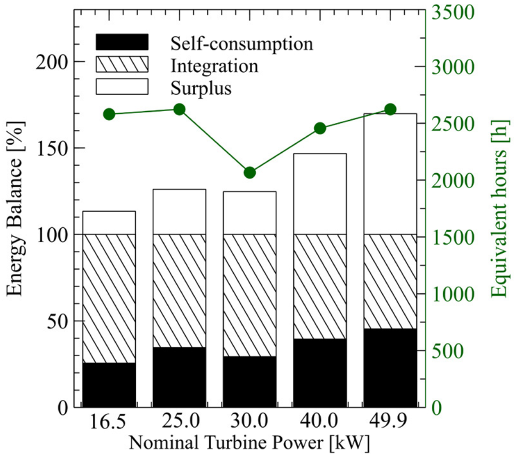


Figure 2. Energy balance in terms of self-consumed, surplus and integrated energy for wind systems

For this reason, the 16.5 kW and 25 kW have been taken into account for the analysis of the integrated system, also considering their lower surplus energy production (13% and 25%, respectively).

The analysis has been extended considering the coupling of the selected WT unit with a biomass-driven ORC system. Specifically, the size of the Organic Rankine Cycle has been defined through a parametric analysis in order to evaluate the energy balance (self-consumed, integrated and surplus energy production) of the hybrid system to satisfy the electrical energy demand. Furthermore, the ORC unit can operate at partial load as a function of the evaporation temperature. Figure 3 shows the electric and thermal energy balances for the integrated system with the 16.5 kW WT and also for the fully biomass-driven unit as a function of the ORC thermal input. The general criterion for sizing of the Organic Rankine Cycle is the equivalence of the integrated and the surplus electrical energy. Figure 3.a shows that the thermal input for the fully biomass unit is equal to 135 $kW_{th}$, corresponding to a nominal electric power equal to 19 $kW_{el}$. The integration with wind energy reduces the nominal power of the ORC sub-system to 14.6 $kW_{el}$ (the thermal power input decreases to 100 $kW_{th}$). The electric self-consumption of both systems is close to 80%, allowing a significant increase with respect to the self-consumed share of the WT alone (25%).

In order to better understand the operation of the integrated unit, Figure 4 shows the electric and thermal energy balances on a daily basis for three typical days in winter, summer, and intermediate season. The hourly wind energy production, the electric and thermal loads, self-consumption, integration and surplus energy shares have been plotted. The hybrid CHP system always provides an electric energy surplus that could be injected to the grid, while the electric integration is necessary especially during summer (Figure 4.c from 15:00 to 16:00 p.m.). The surplus and energy integration are significantly reduced due to the wind energy production.

The yearly electrical and thermal balance in terms of percentage self-consumed, surplus, and integrated energy with respect to the energy demand is visible on Figure 7. Data refer to two integrated systems with 16.5 $kW_{el}$ and 25 $kW_{el}$ wind turbines, a biomass ORC system (19.8 $kW_{el}$), and a single source wind turbine (16.5 $kW_{el}$). Table 4 summarises the four investigated configurations. The nominal power of the ORC unit for the integration with the 25 kW wind turbine has been found with the same criterion adopted in Figure 5. The yearly self-consumed electric energy is close to 80 % for the investigated systems whereas the surplus ranges from 13% for the fully biomass unit to 30% for the “Hyb 2” configuration. A noticeable increase with respect to the corresponding value of WT system is visible for both biomass and hybrid arrangements. Furthermore, the hybrid unit is able to provide from 32% to 48% of the annual thermal energy demand of domestic users for heating and hot water purposes.

The thermal surplus of the integrated units are significantly lower with respect to a fully biomass system. As a consequence, the proposed hybrid CHP systems ~~guarantees~~ a significant biomass saving compared to a full-driven biomass system (from 281 t/year to 125 t/hear for the “Hyb 2” configuration). The equivalent full load running hours of the ORC system is close to 4500 hours/year for both hybrid systems. Results illustrate that the proposed hybrid system allows to overcome the intermittency of the wind source and to increase the self-consumed electric amount.

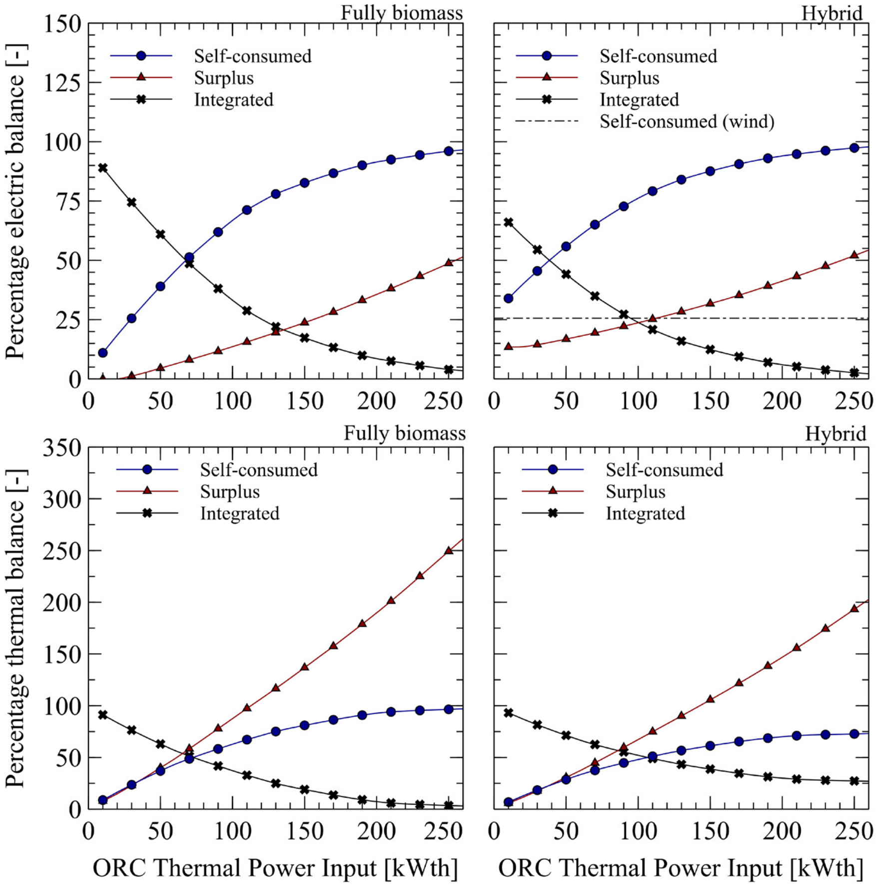
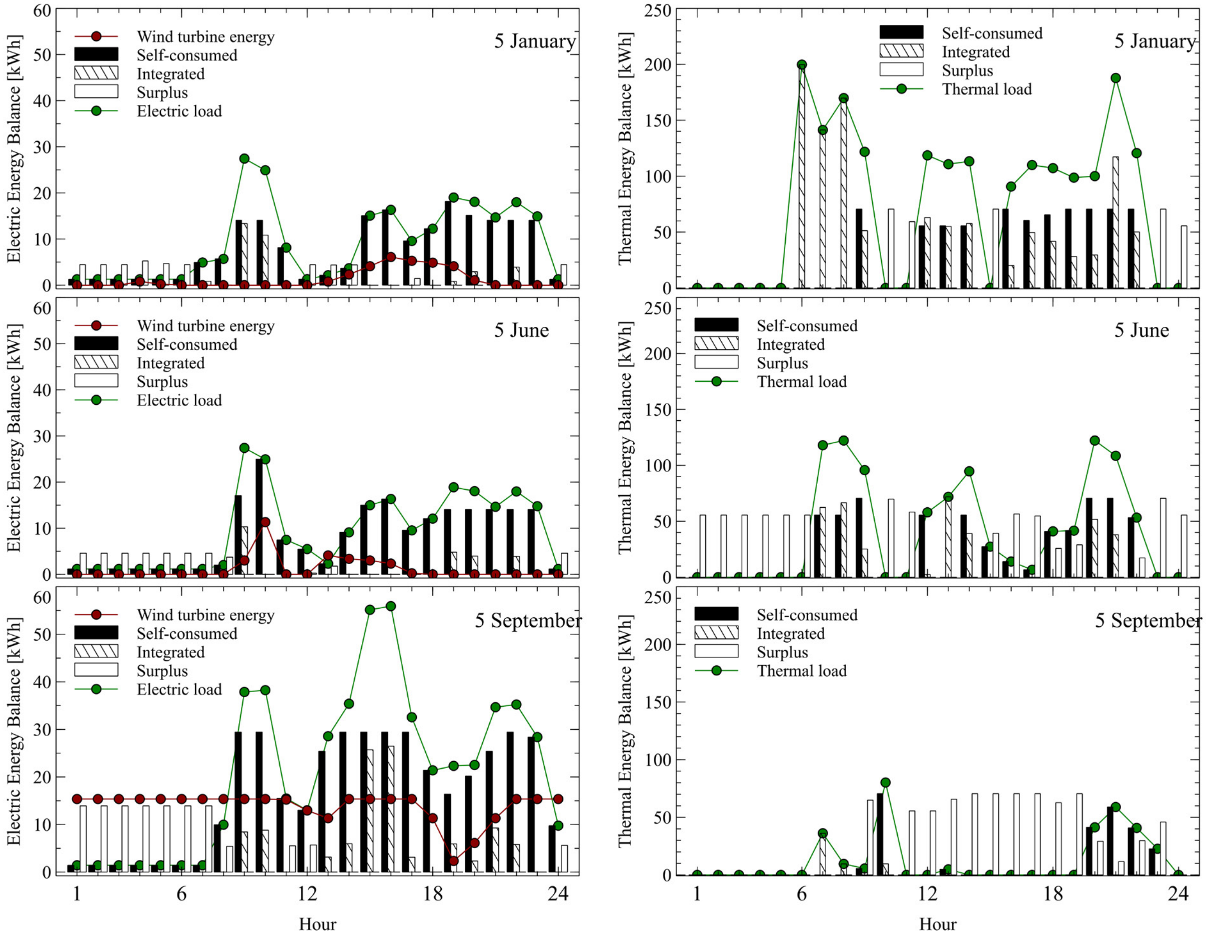


Fig. 3. Annual electrical energy balance in terms of percentage self-consumed, surplus, and integrated energy with respect to the energy demand. Influence of input ORC thermal power

## 4. Conclusions

An integrated Organic Rankine cycle with a wind turbine for combined heat and power (CHP) generation has been analysed. The sub-systems work in parallel to satisfy the electric demand of 40 apartments. Two wind turbines have been selected (16.5 $kW_{el}$ and 25.0 $kW_{el}$) taking into account the operating equivalent hours and a trade-off between surplus and self-consumed energy. The size of the organic Rankine cycle unit has been selected in order to limit the surplus electrical energy to a value not higher than the integrated energy production. A traditional boiler has been adopted for the thermal energy integration. Four different configurations have been compared: a full biomass, a full wind, and two hybrid arrangements with different wind turbines and ORC units.

Results show that the ORC system can overcome the intermittency issues of the wind resource, increasing the self-consumed electric energy and producing thermal energy, saving biomass with respect to a biomass alone configuration. When the wind power is significant, the ORC system can be switched off or it can be operated at partial load. Integrated units provide the 69% and 79% of the yearly electric energy demand. The same result is obtained with the single source biomass system. However, the hybrid systems allow a significant biomass saving, up to 50%, and a significant reduction of electric energy surplus for both the hybrid configurations (from 40% to 70% with respect to fully biomass system). On the other hand, the fully biomass arrangement reaches the highest thermal energy self-consumption share.



a) b)

Fig. 4. Daily electric (a) and thermal energy balance.

Table 4: Investigated single-source and multi-generation systems

| Name | Technologies | Electric Power [$kW_{el}$] | | | Thermal Power [$kW_{th}$] |
|---|---|---|---|---|---|
| | | *ORC* | *Wind* | *Total* | |
| Hyb 1 | ORC + WT | 14.6 | 16.5 | 31.1 | 70.5 |
| Hyb 2 | ORC + WT | 9.9 | 25.0 | 34.9 | 49.3 |
| Wind | WT | - | 16.5 | 16.5 | - |
| Bio | ORC | 19.8 | - | 19.8 | 96.00 |

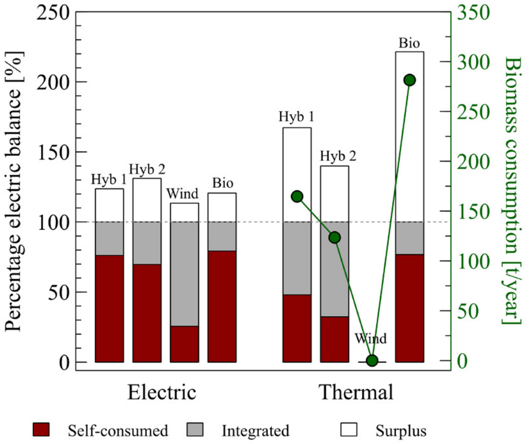


Fig. 5. Annual biomass consumption, electric and thermal balance.

## References

[1] Dong L, Liu H, Riffat S. “Development of small-scale and micro-scale biomass-fuelled CHP systems - A literature review”. *Applied Thermal Engineering* 29 (2009): 2119-2126.

[2] Ren H, Gao W, Ruan Y. “Optimal sizing for residential CHP system”. *Applied Thermal Engineering* 28 (2008): 514-523.

[3] Liu H, Shao Y, Li J. “A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) - Thermodynamic modelling studies”. *Biomass and Bioenergy* 35 (2011): 3985-3994.

[4] Preißinger M, Heberle F, Brüggemann D. “Thermodynamic analysis of double-stage biomass fired Organic Rankine Cycle for micro-cogeneration”. *International Journal of Energy Research* 36 (2012): 944-952.

[5] Soares J, Oliveira A C. “Numerical simulation of a hybrid concentrated solar power/biomass mini power plant”. *Applied Thermal Engineering*, 111 (2017): 1378-1386.

[6] Heydari A, Askarzadeh A. “Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept”. *Applied Energy* 165 (2016): 601–611.

[7] J. Settino, P. Morrone, A. Algieri, T. Sant, C. Micallef, M. Farrugia, C. Spitieri-Staines, J. Licari, A. Micallef, Integration of an Organic Rankine Cycle and a Photovoltaic Unit for Micro-Scale CHP Applications in the Residential Sector, Energy Procedia. 126 (2017) 597–604. doi:10.1016/j.egypro.2017.08.223.

[8] Srinivas T, Reddy B V. “Hybrid solar-biomass power plant without energy storage”. *Case Studies in Thermal Engineering* (2014) 75–81.

[9] Y. Zheng, B.M. Jenkins, K. Kornbluth, C. Træholt, Optimization under uncertainty of a biomass-integrated renewable energy microgrid with energy storage, Renewable Energy. 123 (2018) 204–217. doi:10.1016/j.renene.2018.01.120.

[10] Algieri A, Morrone P. “Comparative energetic analysis of high-temperature subcritical and transcritical Organic Rankine Cycle (ORC). A biomass application in the Sibari district”. *Applied Thermal Engineering* 36 (2012): 236-244.

[11] Algieri A, Morrone P. “Energetic analysis of biomass-fired ORC systems for micro-scale combined heat and power (CHP) generation. A possible application to the Italian residential sector”. *Applied Thermal Engineering* 71 (2014): 751-759.

[12] Lemmon EW, Huber ML, McLinden MO. REFPROP Reference Fluid Thermodynamic and Transport. NIST Online Databases, 2008.

[13] Sanaye S, Meybodi MA, Shokrollahi S. “Selecting the prime movers and nominal powers in combined heat and power systems”. *Applied Thermal Engineering* 2008; 28:1177-1188.

[14] Wiśniewski S, Borsukiewicz-Gozdur A. “The influence of vapor superheating on the level of heat regeneration in a subcritical ORC coupled with gas power plant”. *Archives of Thermodynamics* 2010; 31:185-199.

[15] Drescher U, Bruggemann D. “Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants”. *Applied Thermal Engineering* 27 (2007): 223-228.

[16] Rayegan R, Tao YX. “A procedure to select working fluids for Solar Organic Rankine Cycles (ORCs)”. *Renewable Energy* 36 (2010): 659-670.

[17] Turboden. “Organic Rankine cycle (ORC) in biomass plants: an overview on different applications”. Available from: http://www.turboden.eu.

[18] Pallabazzer, R., Sistemi Di Conversione Eolica – Hoepli, 2011.

[19] Shengjun Z, Huaixin W, Tao G. “Performance comparison and parametric optimization of subcritical Organic Rankine Cycle (ORC) and transcritical power cycle system for low-temperature geothermal power generation”. *Applied Energy* 88 (2011): 2740-2754.

[20] Morrone P, Algieri A. “Biomass Exploitation in Efficient ORC Systems”. *Applied Mechanics and Materials* 260-261 (2013): 77-82.

[21] System Advisor Model (SAM). Available at: https://sam.nrel.gov/.

[22] Mongibello L, Bianco N, Caliano M, Graditi G. “Influence of heat dumping on the operation of residential micro-CHP systems”, *Applied Energy* 160 (2015): 206–220.