ARTICLE IN PRESS

Available online at www.sciencedirect.com

ScienceDirect

Energy Reports xxx (xxxx) xxx

www.elsevier.com/locate/egyr

6th International Conference on Energy and Environment Research, ICEER 2019, 22–25 July, University of Aveiro, Portugal

Analysis of multi-source energy system for small-scale domestic applications. Integration of biodiesel, solar and wind energy

A. Algieri*, P. Morrone, D. Perrone, S. Bova, T. Castiglione

Department of Mechanical, Energy and Management Engineering, University of Calabria, Via P. Bucci - Cubo 46C, 87036 Arcavacata di Rende (CS), Italy

Received 30 July 2019; accepted 16 September 2019
Available online xxxx

Abstract

The paper aims at analysing the energy performance of an innovative multi-source energy system for residential small-scale combined heat and power (CHP) applications. The integrated system is based on an Organic Rankine Cycle (ORC) fuelled by biodiesel, a wind turbine, and a photovoltaic unit. The application refers to the Italian residential sector. The ORC system operates in order to satisfy the thermal demand of domestic users while wind and solar based sub-systems work in parallel to increase the electric self-consumption rate. An auxiliary boiler provides thermal energy when the CHP thermal output is low. Furthermore, when the solar and/or wind sources are significant, the ORC can be switched-off or operated at partial load.

A preliminary investigation is performed to define the proper size of the ORC unit. Afterwards, the analysis is focused on a multi-variable optimisation of the integrated system. In particular, the nominal power of the wind turbine and photovoltaic units have been found in order to guarantee a proper trade-off between electric self-consumed and surplus energy.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: Biodiesel; Combined heat and power; Multi-source generation; Organic Rankine cycle; Solar; Wind

1. Introduction

Nowadays, multi-source energy systems for combined heat and power generation appear to be a very innovative and efficient solution, capable to increase operation flexibility of traditional systems in a smart-grid context [1,2] and reduce fuel consumptions and emissions [3,4].

In this framework, organic Rankine cycles (ORCs) 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 [5,6]. In particular, there is a significant potential for integrating wind energy, solar and biofuel resources, overcoming the intermittent nature of wind and solar energy. Nevertheless, few investigations on this topic have been documented in the literature and further studies are necessary [7].

* Corresponding author.
E-mail address: a.algieri@unical.it (A. Algieri).

https://doi.org/10.1016/j.egyr.2019.09.045

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Nomenclature

A_m	Module area
G	Global irradiance
N	Number of modules
P	Power
z	Height
α	Wind shear exponent
H_i	Lower heating value
η	Efficiency
u	Wind speed

Acronyms

CHP	Combined heat and power
PV	Photovoltaic
ORC	Organic Rankine cycle
WT	Wind turbine

Subscripts

el	Electric
th	Thermal
n	Nominal

The present work aims at analysing the energy performance and the optimal configuration of an integrated biofuel/wind/solar multi-source system for residential applications. The three sub-systems (ORC, wind turbine, and photovoltaic unit) operate in parallel to produce electric and thermal energy. The investigated concept may offer opportunities to achieve the Nearly Zero Energy House (NZEH) target in the domestic sector.

2. Methodology

The paper aims to analyse the energy performance of an innovative multi-source energy system for residential small-scale CHP applications. Fig. 1 shows the simplified scheme of the proposed system that consists of a biodiesel-fired organic Rankine cycle (ORC), a photovoltaic unit (PV), and a wind turbine (WT). ORC operates according to a thermal-driven operating strategy, whereas an auxiliary boiler is used to meet the thermal request when the energy output of the system is low. Solar and wind sub-units are integrated in order to achieve an increase in the electric self-consumption and the electric energy can be exchanged with the grid.

2.1. Organic Rankine cycle (ORC) unit

The ORC system consists of a pumping apparatus, an evaporator, an expander, and a condenser. The pump increases the pressure of the working fluid to the turbine inlet pressure. The evaporator preheats and vaporises the fluid that is expanded in the turbine until reaching the condensation pressure. Afterwards, the working fluid is condensed. A biodiesel boiler provides the thermal energy input to the ORC unit through a thermal oil circuit in order to avoid local overheating and to prevent organic fluids from becoming chemically unstable. Saturated conditions at turbine inlet have been considered, whereas toluene has been taken as working fluid for its high performance and thermal stability according to the literature [8].

A lumped thermodynamic model has been developed to characterise the performance of the ORC section. More details can be found in the literature [9–11]. Furthermore, REFPROP database [12] has been integrated to

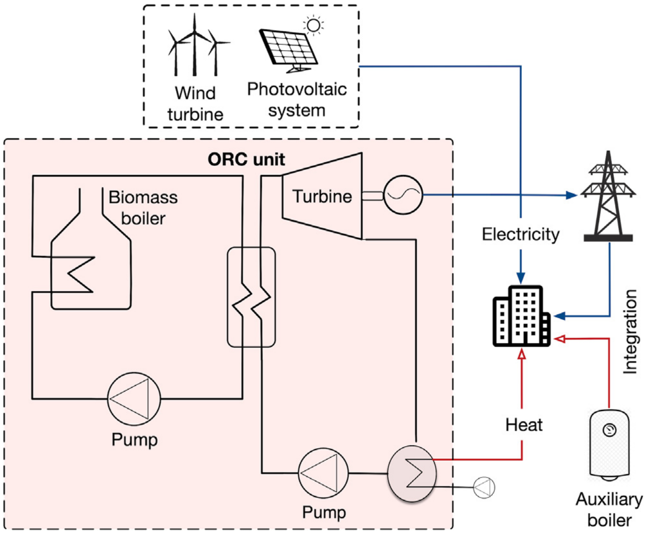

Fig. 1. Scheme of the CHP multi-source energy system.

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

characterise the properties of the organic fluid. As performance parameters, the ORC electric and thermal efficiencies have been evaluated as follows [13]:

$$\eta_{el} = \frac{P_{ORC,el}}{\dot{m}_b H_i} \tag{1}$$

$$\eta_{th} = \frac{P_{ORC,th}}{\dot{m}_b H_i} \tag{2}$$

where $P_{\mathrm{ORC,el}}$ and $P_{\mathrm{ORC,th}}$ are the ORC electric and thermal power output, respectively, $\dot{m}_b$ is the biodiesel mass flow rate and H_{i} is the biofuel lower heating value.

Table 1 shows the critical temperature and pressure of toluene, and the adopted operating conditions. Condensation temperature has been set to 80 °C in order to meet thermal request of the domestic users [14]. The energy performance of the CHP unit at full and partial loads in terms of electric and thermal efficiency and power have been evaluated as a function of the evaporation temperature. To this purpose, 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. Table 2 summarises the main assumptions used for the parametric analysis. The nominal electric and thermal efficiencies at 300 °C are 14.6% and 70.5%.

2.2. Photovoltaic (PV) sub-system

A mathematical model of the photovoltaic (PV) system has been developed and integrated to the ORC section. To this purpose, solar irradiance and ambient temperature have been obtained adopting the PV-Gis software [15] and the analysis has been performed on an hourly basis.

Please cite this article as: A. Algieri, P. Morrone, D. Perrone et al., Analysis of multi-source energy system for small-scale domestic applications. Integration of biodiesel, solar and wind energy. Energy Reports (2019), https://doi.org/10.1016/j.egyr.2019.09.045.

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
Biodiesel lower heating value	[MJ/kg]	37.5
ORC electric efficiency	[%]	14.6
ORC thermal efficiency	[%]	70.5

The PV power at the generic time has been evaluated as:

$$P_{PV} = \eta_{tot}\, G\ N\ A_m = \eta_m\, \eta_T\, \eta_R\, \eta_o\, G\ N\ A_m \quad (3)$$

where η_{tot} is the total efficiency of the photovoltaic system, N is the number of modules, G is the global irradiance and A_m is the module area. Specifically, the total efficiency is a function of the module efficiency η_m, the reflectance efficiency η_R, the efficiency of other components η_o (e.g., inverters, cables, etc.), and temperature efficiency η_T that is evaluated according to [16]:

$$\eta_T = 1 + k_T \cdot [T_a + (T_{NOCT} - 20) \cdot G/800 - T_{NOCT}] \quad (4)$$

where k_T is the temperature coefficient, T_{NOCT} represents the nominal operating module temperature and T_a is the ambient temperature. Table 3 summarises the PV module characteristics [17] and the main assumptions used in the work.

2.3. Wind turbine (WT) sub-system

A zero-dimensional model of the wind turbine (WT) has been developed in order to estimate the hourly electric production of the wind source. The annual hourly wind data for Palermo have been considered according to System Advisor Model — SAM [18]. The wind speed values have been corrected to the wind turbine hub height according to the well-known wind shear velocity equation [19]:

$$u = u_0 \cdot (z/z_0)^{\alpha} \quad (5)$$

where u_0 is the speed at the reference height (10 m) and α is the wind shear exponent. Four production wind turbines have been compared [20,21]. The design parameters (cut-in and cut-off velocity, rated velocity and power) are visible in Table 3.

3. Results

The investigation has been focused on an innovative biodiesel/wind/photovoltaic energy system for small-scale combined heat and power (CHP) applications. The integrated apparatus is based on a wind turbine (WT), a photovoltaic unit (PV), and a biodiesel-fired organic Rankine cycle (ORC).

The ORC, WT, and PV sub-systems operate in parallel to satisfy the energy request while a backup boiler provides the thermal energy when the ORC contribute is insufficient.

The analysis has been performed considering a block of 40 dwellings in Southern Italy (Palermo). The annual thermal and electric requests are equal to 360.8 MWh_{th} and 108.1 MWh_{el}, respectively, and are based on space heating, hot water demand, lighting system and appliances, including air conditioners. More details are provided in the literature [1]. Hourly solar and wind data have been estimated through PV-GIS and SAM software, respectively.

First, the organic Rankine cycle system has been sized in order to satisfy the thermal request of domestic users on an hourly basis. To this purpose, a parametric analysis has been performed to evaluate the influence of the ORC nominal power on the thermal energy balance. Specifically, Fig. 2 shows the annual thermal self-consumption, integration, and surplus as a function of the ORC characteristics (electric and thermal nominal power).

As expected, the higher the ORC power, the higher the self-consumption. However, it is worthy to notice that 90% of the thermal request is satisfied when the ORC thermal power ($P_{ORC,th}$) is equal to 106 kW_{th} and a negligible effect

Table 3. Climate conditions, photovoltaic and wind turbines characteristics.

Climate conditions					
Average ambient temperature	[°C]	18.8			
Yearly global irradiance	[kWh/m^2]	2060			
Average wind velocity	[m/s]	4.7			
Wind Shear Exponent	[−]	0.2			
Photovoltaic system characteristics					
Module nominal power at STC	[W$_p$]	315			
Module efficiency	[%]	19.3			
Temperature coefficient	[%/°C]	−0.38			
Nominal operating cell temperature	[°C]	45			
Module area	[m^2]	1.631			
Number of modules	[-]	1–200			
Module slope	[°]	30			
Wind turbine characteristics		WT_1	WT_2	WT_3	WT_4
Nominal power	[kW]	5.0	10.0	16.5	20.0
Cut-in wind velocity	[m/s]	3.0	2.5	3.5	2.0
Rated wind velocity	[m/s]	10	10	8	10
Cut-off wind velocity	[m/s]	45.0	59.5	25.0	50.0
Rotor blade diameter	[m]	6.4	8.0	15.0	10.0

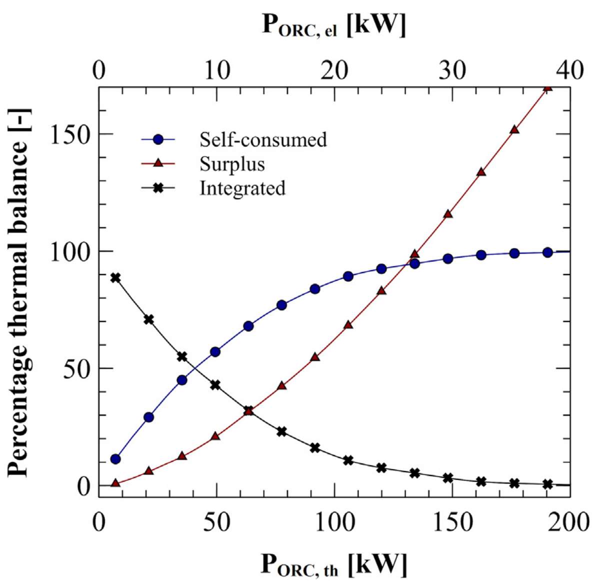

Fig. 2. Energy balance of ORC system in terms of thermal self-consumed, surplus and integrated energy.

on the thermal self-consumption is evident for larger units. Conversely, the heat surplus increases noticeably moving from 68% to 200% when $P_{ORC,th}$ passes from 106 to 200 kW$_{th}$, respectively. For this reason, the organic Rankine cycle has been selected in order to guarantee the equivalence of the integrated and the surplus thermal energy, according to the literature [21]. In particular, the nominal electric and thermal power corresponds to 12.7 kW$_{el}$ and 63.5 kW$_{th}$, respectively. In this condition, the thermal self-consumption is equal to 68% while the integration and surplus reach 32%. Furthermore, the selected system assures 41.1% of the electric demand whereas the surplus electricity to be injected to the grid is equal to 8.8%.

In order to improve the electric performance of the CHP system, the selected organic Rankine cycle has been integrated with production photovoltaic units and wind turbines, as highlighted in Fig. 1. Specifically, four wind turbines have been considered (P_{WT} = 5–20 kW$_{el}$) while the photovoltaic peak power (P_{PV}) ranges from 0.31 to 63 kW$_{el}$ (1 to 200 modules).

Please cite this article as: A. Algieri, P. Morrone, D. Perrone et al., Analysis of multi-source energy system for small-scale domestic applications. Integration of biodiesel, solar and wind energy. Energy Reports (2019), https://doi.org/10.1016/j.egyr.2019.09.045.

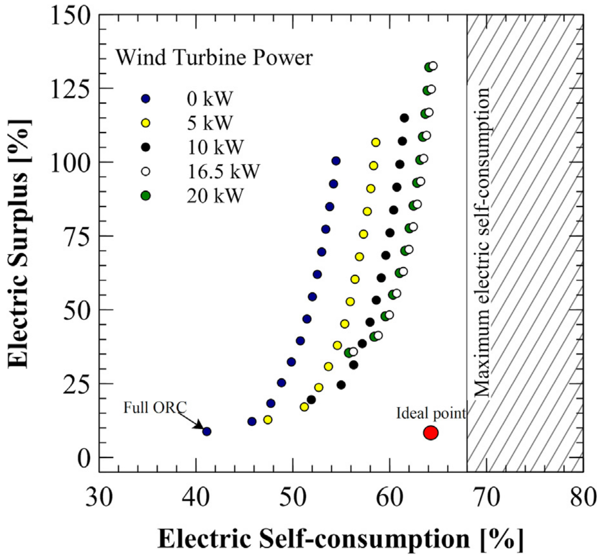

Fig. 3. Performance of integrated multi-source energy systems in terms of electric surplus and self-consumption.

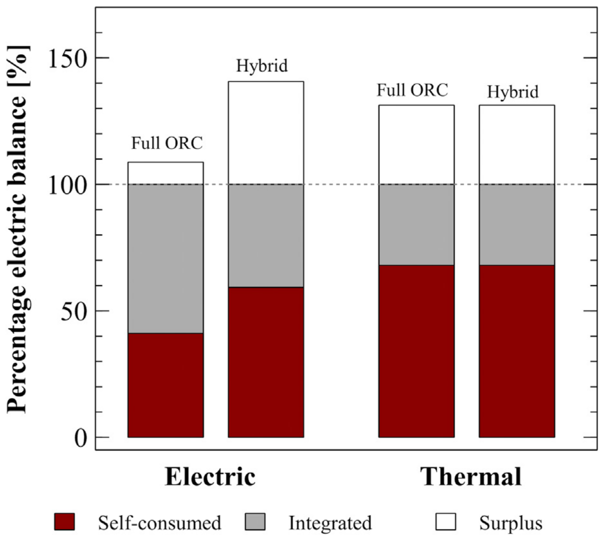

Fig. 4. Energy balance of the multi-source energy system and comparison with full ORC unit.

The configuration of the hybrid system has been found through a multi-variable optimisation, considering the annual electric balance. Fig. 3 shows the Pareto front for the investigated systems in terms of self-consumption and surplus. The ideal point corresponds to the maximum self-consumption ($S_{\%} = 64.5\%$) and the minimum surplus ($s_{\%} = 8.8\%$). The analysis demonstrates that the full biodiesel ORC unit assures the minimum self-consumed electricity ($S_{\%} = 41.1\%$) and surplus ($s_{\%} = 8.8\%$). On the other hand, hybridisation guarantees a significant increase in the electric request satisfaction, with values always higher than 47.4% when at least a wind turbine is adopted.

The maximum rate reaches 64.5% when $P_{WT} = 16.5$ kW and $P_{PV} = 63$ kW. It is worthy to notice that the higher the self-consumption, the higher the electricity excess. For this reason, a trade-off should be found and the integrated CHP system that minimises the distance with respect to the ideal point has been used as optimisation criterion. In particular, the investigation suggests integrating the selected ORC unit ($P_{ORC,el} = 12.7$ kW_{el} and $P_{ORC,th} = 63.5$ kW_{th}) with 16.5 kW_{el} wind turbine and 6.3 kW_{el} photovoltaic system.

The multi-source energy apparatus produces 102.8 MWh_{el} per year and it is able to satisfy 59.3% of the electric load of the domestic users while the electricity injected to the grid corresponds to 43.5% (Fig. 4). Specifically, the percentage contribution of wind and solar sub-systems to the overall electric energy production are 41.0% and 10.5%, respectively. The comparison with single-source units highlights that the adoption of integrated hybrid systems represents a very attractive solution for smart-grid communities increasing the self-consumed electric energy and overcoming the intermittency of solar and wind sources. The economic analysis is beyond the aim of this paper and a future work will investigate the economic viability of the proposed integrated CHP unit.

4. Conclusions

A multi-source energy system for combined heat and power (CHP) generation has been analysed. The apparatus is based on a biodiesel-fuelled organic Rankine cycle, a wind turbine, and a photovoltaic unit. The ORC has been dimensioned in order to satisfy the thermal request of a block of 40 apartments in Southern Italy adopting a thermal-driven strategy. The ORC thermal and electric power are equal to 63.5 kW_{th} and 12.7 kW_{el}, respectively, and permit to satisfy 68.0% of the thermal request and 41.1% of the electric load.

The integration with four production wind turbines (5–20 kW_{el}) and photovoltaic systems (0.31–63 kW_{el}) has been analysed. The hybrid system configuration has been defined through a multi-variable optimisation in order to guarantee the best trade-off between electric self-consumed and surplus energy. To this purpose, an hourly energy analysis has been performed and a 16.5 kW wind turbine and 6.3 kW photovoltaic unit have been selected. The multi-source energy system guarantees 102.8 MWh_{el} per year and satisfies 59.3% of the electric load of the domestic users while the electricity injected to the grid corresponds to 43.5%.

The investigation reveals that integrated multi-generation CHP systems are an interesting technical solution for smart-cities increasing the primary energy saving and the energy self-consumption with respect to the corresponding single-source systems, and overcoming the intermittency of the wind and solar source.

Acknowledgement

The work has been developed within the framework of the Miur Project "Community Energy Storage: Gestione Aggregata di Sistemi d'Accumulo dell'Energia in Power Cloud (ComESto)".

References

[1] Morrone P, Algieri A, Castiglione T. Hybridisation of biomass and concentrated solar power systems in transcritical organic Rankine cycles: A micro combined heat and power application. Energy Convers Manage 2019;180:757–68.
[2] Soares J, Oliveira AC. Numerical simulation of a hybrid concentrated solar power/biomass mini power plant. Appl Therm Eng 2017;111:1378–86.
[3] Emmi G, Zarrella M. A heat pump coupled with photovoltaic thermal hybrid solar collectors: A case study of a multi-source energy system. Energy Convers Manage 2017;151:386–99.
[4] Morrone P, Algieri A. Numerical investigation on the energetic performances of conventional and pellet aftertreatment systems in flow-through and reverse-flow designs. Thermal Sci 2011;15:1049–64.
[5] Liu H, Shao Y, Li J. A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC) - Thermodynamic modelling studies. Biomass Bioenergy 2011;35:3985–94.
[6] Preißinger M, Heberle F, Brüggemann D. Thermodynamic analysis of double-stage biomass fired Organic Rankine Cycle for microcogeneration. Int J Energy Res 2012;36:944–52.
[7] Zheng Y, Jenkins BM, Kornbluth K, Træholt C. Optimization under uncertainty of a biomass-integrated renewable energy microgrid with energy storage. Renew Energy 2018;123:204–17.
[8] Settino J, Morrone P, Algieri A, Sant T, Micallef C, Farrugia M, Spitieri-Staines C, Licari J, Micallef A. Integration of an organic rankine cycle and a photovoltaic unit for micro-scale CHP applications in the residential sector. Energy Procedia 2017;126:597–604.
[9] Algieri A, Morrone P. Comparative energetic analysis of high-temperature subcritical and transcritical Organic Rankine Cycle (ORC). A biomass application in the Sibari district. Appl Therm Eng 2012;36:236–44.
[10] 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. Appl Therm Eng 2014;71:751–9.
[11] Algieri A, Morrone P. Energy analysis of organic Rankine cycles for biomass applications. Thermal Sci 2015;19:193–205.
[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. Appl Therm Eng 2008;28:1177–88.
[14] Drescher U, Bruggemann D. Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants. Appl Therm Eng 2007;27:223–8.

Please cite this article as: A. Algieri, P. Morrone, D. Perrone et al., Analysis of multi-source energy system for small-scale domestic applications. Integration of biodiesel, solar and wind energy. Energy Reports (2019), https://doi.org/10.1016/j.egyr.2019.09.045.

[15] JRC European Commission. PVGIS. http://re.jrc.ec.europa.eu/pvgis. [Accessed 1 March 2019].
[16] Jakubiec JA, Reinhart FA. A method for predicting city-wide electricity gains from photovoltaic panels based on lidar and GIS data combined with hourly Daysim simulations. Sol Energy 2013;93:127–43.
[17] Sunpower. https://us.sunpower.com/. [Accessed 1 March 2019].
[18] NREL. System Advisor Model (SAM). https://sam.nrel.gov. [Accessed 1 March 2019].
[19] Letcher T. Wind energy engineering, a handbook for onshore and offshore wind turbines. Elsevier, Academic Press; 2017.
[20] Aeolos. http://www.windturbinestar.com/. [Accessed 1 March 2019].
[21] Morrone P, Algieri A, Castiglione T, Perrone D, Bova S. Investigation of integrated organic rankine cycles and wind turbines for micro-scale applications. Energy Procedia 2018;148:986–93.

Please cite this article as: A. Algieri, P. Morrone, D. Perrone et al., Analysis of multi-source energy system for small-scale domestic applications. Integration of biodiesel, solar and wind energy. Energy Reports (2019), https://doi.org/10.1016/j.egyr.2019.09.045.