Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2012, Article ID 124280, 10 pages
doi:10.1155/2012/124280

Research Article

Modeling Small Scale Solar Powered ORC Unit for Standalone Application

**Enrico Bocci,[1] Mauro Villarini,[2] Luca Bove,[2]
Stefano Esposto,[3] and Valerio Gasperini[3]**

[1] *Università degli Studi Guglielmo Marconi, Via Plinio 44, 00193 Roma, Italy*
[2] *Università degli Studi della Tuscia, Via S.M.in Gradi n.4, 01100 Viterbo, Italy*
[3] *Enertecna s.r.l., Via della Polveriera 14, 00184 Roma, Italy*

Correspondence should be addressed to Enrico Bocci, e.bocci@unimarconi.it

Received 17 October 2012; Accepted 15 November 2012

Academic Editor: Maurizio Carlini

When the electricity from the grid is not available, the generation of electricity in remote areas is an essential challenge to satisfy important needs. In many developing countries the power generation from Diesel engines is the applied technical solution. However the cost and supply of fuel make a strong dependency of the communities on the external support. Alternatives to fuel combustion can be found in photovoltaic generators, and, with suitable conditions, small wind turbines or microhydroplants. The aim of the paper is to simulate the power generation of a generating unit using the Rankine Cycle and using refrigerant R245fa as a working fluid. The generation unit has thermal solar panels as heat source and photovoltaic modules for the needs of the auxiliary items (pumps, electronics, etc.). The paper illustrates the modeling of the system using TRNSYS platform, highlighting standard and "ad hoc" developed components as well as the global system efficiency. In the future the results of the simulation will be compared with the data collected from the 3 kW prototype under construction in the Tuscia University in Italy.

1. Introduction

Solar energy is available everywhere and completely renewable. In remote locations, the conversion of solar energy in electricity could be an important option to enhance the development of rural communities. The low energy density and the fluctuations of the source availability are the main obstacles in the solar energy applications. The photovoltaic module is a commercial technology to convert solar energy directly in electricity, but the low efficiency conversion and above all the need of batteries for storage purpose limit the application in developing countries. As a matter of fact, storage of electricity with batteries requires skilled maintenance and it is not easily achievable in remote locations. The technological option analyzed in this paper is the conversion of solar energy through solar collectors and storage as hot water in an insulated tank. This tank is the hot source of an Organic Rankine Cycle system with electricity output. The appropriate design of all the components involved is important to achieve high efficiency and continuous electricity production. Thus, an efficient mathematical model that describes systems performances, environmental interaction, and development is needed [1]. The modeling with TRNSYS supports the analysis allowing the user to interact with the numerous parameters involved and obtaining different scenarios and results [2–4]. The aim of the present work is developing an important tool for guiding the assembling of a prototype of a solar energy/ORC compact electricity generator with 3 kW as power output.

The first important choice is individuating the working fluid in the ORC system [5, 6]. Among the liquids for the Organic Rankine Cycle R245fa is an interesting fluid. It is a nonchlorinated hydrofluorocarbon, non-Ozone depleting liquid with a low global warming potential [7]. In the mathematical model R245fa has been used, individuating all the necessary thermodynamic properties for the simulation of the Rankine Cycle. Data from the NIST Chemistry WebBook has been used in the simulation [8].

2. Mathematical Model of the Working Fluid

The working fluids that are suitable for low temperature ORCs are well known in the literature [5]. The choice of the fluid depends on the following main factors [9]:

(i) the critical point of the working fluid (in this case of small solar power plant the maximum temperature can be within 100 and 200°C);

(ii) the specific volume ratio over the expander must be low in order to reduce the size, and, thus, the cost (in general the higher the critical temperature, the higher the specific volume ratio over the expander);

(iii) the working fluid should have a null Ozone Depleting Potential (Montreal Protocol and, for EC, Regulation 2037/2000);

(iv) the fluid must fulfill other conditions such a toxicity, cost, and flammability;

(v) if scroll compressors is used for the expander the temperature must be below 150°C because refrigeration compressors are not designed for temperatures higher than 150°C.

We have chosen the fluid R245fa, because of the following:

(i) its critical temperature is greater than 150°C (temperature that can be reached in a boiler feed by vacuum solar panels);

(ii) it shows very advantageous swept volumes no toxicity and low cost;

(iii) it has a null Ozone Depleting Potential;

(iv) it is the fluid most often used in small ORC applications [10].

The data from the NIST Chemistry WebBook indicates the thermodynamic properties of the fluid chosen, R245fa, varying according to the different working conditions. Thus it is necessary to develop a mathematical model of the fluid in order to have the thermodynamic properties of the fluid inside the global power plant simulation. The model developed is based on the following assumptions.

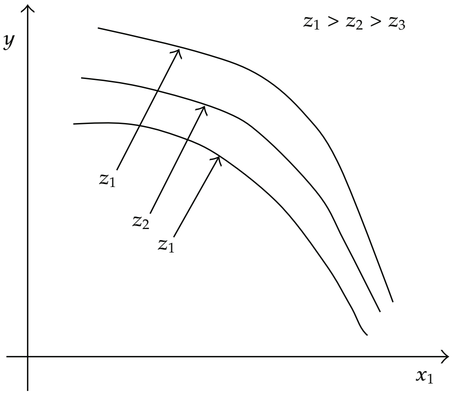

Figure 1: The function $y(x)$ considering z as parameter.

Assuming that a single thermodynamic property is individuated by the values of two other properties:

$$y = f(x, z) \tag{2.1}$$

and considering z as parameter, it is possible to show the function y in an x, y Cartesian graph, as shown in Figure 1.

Having the different values of x, y of the two properties for each z (the source is the NIST Chemistry WebBook), we can interpolate using software like Matlab and obtaining polynomials (the following example is a second grade polynomial):

$$y = c_1 x^2 + b_1 x + a_1 \quad (z = z_1). \tag{2.2}$$

The same can be done for the other values of the parameter z:

$$\begin{aligned} y &= c_2 x^2 + b_2 x + a_2 \quad (z = z_2), \\ y &= c_3 x^2 + b_3 x + a_3 \quad (z = z_3). \end{aligned} \tag{2.3}$$

The constants $a, b,$ and c can be also interpolated related to the different values of the parameter z:

$$\begin{aligned} a_n &= A_o + A_1 z + A_2 z^2, \\ b_n &= B_o + B_1 z + B_2 z^2, \\ c_n &= C_o + C_1 z + C_2 z^2. \end{aligned} \tag{2.4}$$

Equation (2.1) is therefore

$$y = \left(A_o + A_1 z + A_2 z^2\right) + \left(B_o + B_1 z + B_2 z^2\right) x + \left(C_o + C_1 z + C_2 z^2\right) x^2. \tag{2.5}$$

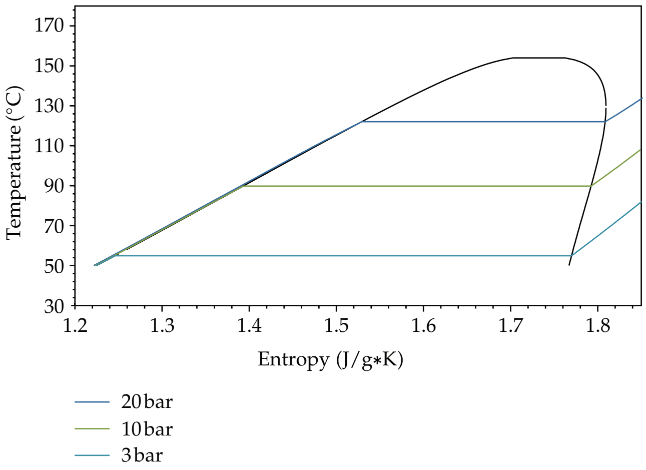

Figure 2: *T-S* diagram of the working fluid.

In the mathematical model, the pressure of the fluid is the parameter and the other properties are interpolated using the NIST database. Figure 2 shows different cycles of the working fluid R245fa in the *T-S* diagram.

3. TRNSYS 16 Simulation

TRNSYS 16 is a powerful software using Fortran subroutines and able to simulate energy patterns with time dependent inputs. Therefore it is possible to include the fluctuant and variable sun irradiation as input and to monitor the energy fluxes linked to it. Each Fortran subroutine, linked together in the TRNSYS environment, represents a component of the system, and a mathematical model simulates his functions having inputs, outputs, variable with time, and parameters, constant for all the duration of the simulation. The TRNSYS library has a wide set of already tested subroutines "type" for the simulation of solar collectors, thermal storage, and piping. The subroutine for the simulation of the Organic Rankine Cycle has been developed to include this component in the simulation.

The graphic environment of Studio has been used to run the TRNSYS simulation. The system simulated is composed by the following components.

Irradiation (Solar Energy Source)

A standard type 109 has been chosen to give the necessary irradiation values. The simulation reads the weather data from the chosen geographic location. In this case Orte is the location where the prototype will be assembled and installed. Because TRNSYS dataset does not have the Orte data, the Rome data has been chosen. Rome is near to Orte so solar irradiation is similar. Moreover the authors are inserting Orte data in TRNSYS dataset and this will be used in the future publication which compares the simulation with the experimental data available from the prototype under construction in Orte.

Solar Collector and Storage Tank

The vacuum solar collectors type with CPC technology to enhance the diffuse radiation absorption has been chosen, in particular the SKY 21 CPC 58 made by Kloben. Thus the type 71 and the Kloben data of the SKY 21 collector have been used in the simulation. In particular the SKY 21 has an efficiency of 0.718, a first order coefficient of $0.974\,\mathrm{W/m^2\,K}$, a second order coefficient of $0.005\,\mathrm{W/m^2\,K^2}$, and a collector area of $3.75\,\mathrm{m^2}$. A collector slope of 45° has been chosen in order to maximize the winter power, like usually in Italy [11, 12]. We use only one collector in order to test the simulation with the minimum module of collector. The water heated by the solar collector is pumped to a storage tank only if the temperature of the tank is lower than the outlet solar collector temperature, avoiding heat losses during night or cloudy days.

Storage Tank and ORC Unit

A suitable heat storage system is required to maximize the productivity of the solar plant and to provide solar heat at the desired rate regardless the instantaneous solar radiation availability and the thermal needs [13–15]. The overall aim of this basic component is the same for the high temperature concentrated solar power systems and for the small scale solar system with the difference that the second one has to directly face the user energy needs. The storage tank is simulated with the type 4a, a standard stratified tank, with loss coefficient of $0.0833\,\mathrm{W/m^2\,K}$. The ORC unit, being not in standard TRNSYS components, has been developed like a user type with the mathematical model showed in the next paragraph. The hot fluid from the upper part of the storage tank is pumped to the evaporator of the ORC unit only if the temperature is higher than the working ORC fluid evaporation temperature. The working fluid (R245fa) is then cooled down by a cold source.

Photovoltaic Modules

The photovoltaic modules are part of the simulation to supply energy to the ORC unit in the start-up phase. A standard PV type, the 194b, has been chosen with standard PV values (panel slope 30°) [16].

Figure 3 shows the global power plant scheme in the TRNSYS environment.

4. The ORC Type: Mathematical Model

The Fortran subroutine simulating the Organic Rankine Cycle unit has been developed using the R245fa as working fluid in the equation of state present in the algorithm. Using Matlab, it was possible to interpolate the NIST Chemistry data to obtain second/third grade polynomial equations among the thermodynamic properties [5].

The expander type has not been specified, thus an efficiency η has been generally indicated to calculate the work. The outlet enthalpy after the expander is calculated using the following equation:

$$h_2 = h_1 - \eta(h_1 - h_{2s}). \tag{4.1}$$

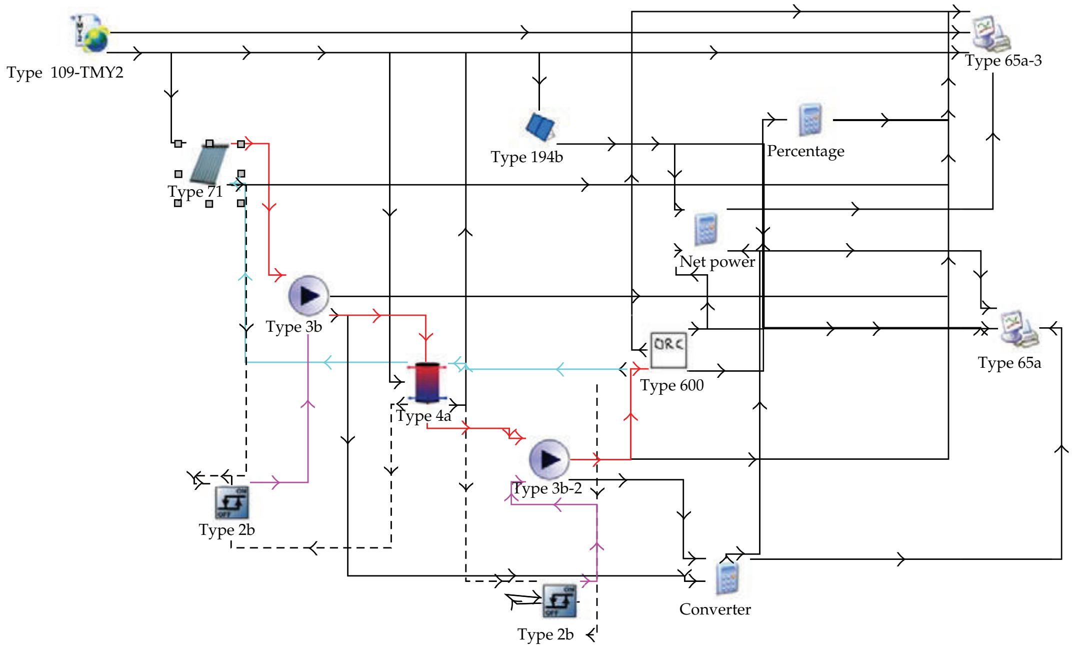

Figure 3: Global power plant scheme.

The evaporator and the condenser have been modeled using the NTU efficiency method. One has

$$\varepsilon = \frac{1 - e^{-\mathrm{NTU}(1-C_r)}}{1 - C_r e^{-\mathrm{NTU}(1-C_r)}}. \tag{4.2}$$

NTU is the Number of Transfer Unit and C_r is the ratio between the lower and higher capacity of the two fluids participating in the heat transfer, in our case water and R245fa.

5. Results

Following are the main assumptions for the simulation:

(i) working fluid: R245fa,
(ii) expander efficiency: 0.7,
(iii) evaporation pressure: 20 bar,
(iv) evaporation temperature: 150°C,
(v) condensation pressure: 3 bar,
(vi) pump efficiency: 0.5,
(vii) storage tank volume: 0.1 m^3.

The results show efficiency for the ORC in the range 4.6%–5.3%, according to the existing references for similar systems [9, 17]. Indeed Quoilin et al. [9] have shown that, with real expander efficiency curves, an overall electrical efficiency between 6.9% and 7.9% can be reached. These efficiencies are higher than the ones calculated here because the greater expansion considered. In this paper the minimum expander temperature was limited to about 100°C (condensation pressure of 3 bar versus 1 bar of [9]) in order to have residual heat at temperature as high as the inlet temperature of different machines (e.g., absorbers for cold generation). Moreover Quoilin et al. [9] efficiency is a steady-state efficiency at a nominal working point, while the calculated efficiency of the TRNSYS simulation is linked to a dynamic model.

In more detail Quoilin et al. [9] argue that only three working fluids, R245fa, Solkatherm (SES36), and n-pentane, are suitable for ORCs at evaporation temperature of about 150°C. But if the Solkatherm is the fluid showing the highest efficiency of 7.9%, it is also the one requiring the biggest expander, while n-Pentane requires recuperator area very high due to the low density and the very high pressure drops in the low-pressure vapor [9]. Thus the best working fluid for Quoilin et al. [9] is the R245fa also if it shows an overall efficiency of 6.9%.

In general the global efficiency depends on the efficiency of the solar collector and the ORC systems. The evacuated tube collectors solar systems have higher efficiency than the plate technology systems (normally 70% versus 55%) and higher collection temperatures. The higher collection temperatures give higher ORC efficiency (normally the ORC efficiency is about 10% for a maximum temperature cycle of 100°C, [5, 18]). Thus the global system is efficient if the solar collectors have high efficiency and are able to generate high boiler temperature values (i.e., 150°C) and if the expander efficiency is high (from at least 60 to 80%) and the consumptions (pumps, funs, etc.) are low. As a consequence, analyzing, for example, the heat transfer fluid flow rate, it must be not so high in order to avoid very high fluid pumping consumption but not so low in order to avoid low heat transfer coefficient in the collector (e.g., optimum heat transfer fluid flow rate of 1.2 kg/s corresponding to a temperature glide of 15 K [9]). Finally the part-load conditions, necessary to increase the annual production, have to be reduced to the minimum in order to avoid high global efficiency loss.

Figure 4 shows the behavior of the outlet solar collector temperature (solar irradiation, measured in W on the right) and of the power output (power, measured in W on the left) during about ten days during the summer (when there is the maximum solar irradiation in Italy). The figure shows how the power output from the ORC is linked to the solar energy availability; when there is sufficient solar energy (e.g., the storage reaches the evaporation temperature of the working fluid) the power is generated; the power is generated also after the solar energy availability, that is, until the temperature of the storage is over the evaporation temperature of the working fluid.

6. Conclusions

Small-scale solar Organic Cycles are well adapted for remote off-grid areas. Compared to the main competitive technology, the PV collector, Solar ORCs have an advantage of being manufacturable locally. They are also more flexible and allow the production of hot water as a by-product [9]. With little commercial experience to draw on, realistic costs estimates for solar thermal power plants are extremely difficult to make; however, it is expected that cost reduction will result from technical and commercial progress. At the moment the overall plant costs for a 3 kW production (and thus 30–60 kW of solar thermal with a useful heat

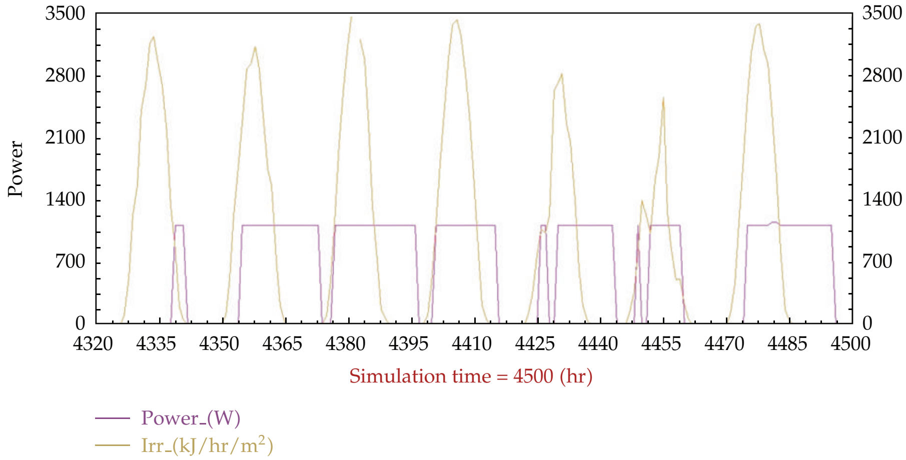

Figure 4: Solar energy and power output.

power of 15–30 kW) are about 40.000 euro; thus the investment is not profitable. This is common for new power plants like other small scale power plants analyzed by the authors [19–21]. But the system can be economically feasible with higher size of the plant, higher degree of storage, and low cost of land or with, as expected, a reduced components cost because of an industrial production of the components and the advance of the technologies involved. Indeed, as the size of the solar thermal plant increases and the number of daily operating hours increases (i.e., from kW to MW and from 1500 to 5000 operating hours), the investment becomes more attractive [22]. Furthermore, one of the most important reasons of the remarkable difference of costs between small scale solar thermodynamic and photovoltaic lies in the lack of incentives for the first application. In fact, up to now the incentives apparatus have almost uniquely accompanied the large scale solar power systems [23].

This work focused on the simulation of the power generation of a solar thermal ORC using refrigerant R245fa as a working fluid. An efficiency of about 5%, even with residual heat at temperature of about 100°C and the use of a dynamic model, was calculated. Further studies will include analysis of different size of solar collector plant and storage tank in a 1-year simulation and a comparison of the simulation results with the first experimental data of the plant under construction in Orte (Italy).

Conflict of Interests

The authors certify that there is no conflicts of interest with any financial organization regarding the material discussed in the paper. The company ENERTECNA is partner of CIRDER (Tuscia University Department), coordinator of the National project STS. In particular S. Esposto and V. Gasperini have started this collaboration for the project purpose in July 2011.

Acknowledgment

The authors acknowledge the financial support of Italian Contract SEC-DEC-2011-0000564 (regarding the research project STS, Solar Trigeneration System) by the Italian Ministry for the Environment, Land and Sea (Ministero dell'Ambiente e della Tutela del Territorio e del Mare).

References

[1] C. Cattani, S. Chen, and G. Aldashev, "Information and modeling in complexity," *Mathematical Problems in Engineering, AID*, vol. 2012, Article ID 868413, 4 pages, 2012.

[2] M. Carlini, S. Castellucci, M. Guerrieri, and T. Honorati, "Stability and control for energy production parametric dependence," *Mathematical Problems in Engineering*, vol. 2010, Article ID 842380, 21 pages, 2010.

[3] M. Carlini and S. Castellucci, "Modelling and simulation for energy production parametric dependence in greenhouses," *Mathematical Problems in Engineering*, vol. 2010, Article ID 590943, 28 pages, 2010.

[4] M. Carlini, M. Villarini, S. Esposto, and M. Bernardi, "Performance analysis of greenhouses with integrated photovoltaic modules," *Lecture Notes in Computer Science*, vol. 6017, no. 2, pp. 206–214, 2010.

[5] B. Saleh, G. Koglbauer, M. Wendland, and J. Fischer, "Working fluids for low-temperature organic Rankine cycles," *Energy*, vol. 32, no. 7, pp. 1210–1221, 2007.

[6] U. Drescher and D. Brüggemann, "Fluid selection for the Organic Rankine Cycle (ORC) in biomass power and heat plants," *Applied Thermal Engineering*, vol. 27, no. 1, pp. 223–228, 2007.

[7] A. Boretti, "Recovery of exhaust and coolant heat with R245fa organic Rankine cycles in a hybrid passenger car with a naturally aspirated gasoline engine," *Applied Thermal Engineering*, vol. 36, pp. 73–77, 2012.

[8] http://webbook.nist.gov/chemistry/fluid/.

[9] S. Quoilin, M. Orosz, H. Hemond, and V. Lemort, "Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation," *Solar Energy*, vol. 85, no. 5, pp. 955–966, 2011.

[10] A. M. Delgado-Torres and L. García-Rodríguez, "Analysis and optimization of the low-temperature solar organic Rankine cycle (ORC)," *Energy Conversion and Management*, vol. 51, no. 12, pp. 2846–2856, 2010.

[11] M. Villarini, D. Germanò, F. Fontana, and M. Limiti, *I Sistemi SoLari Termici Per La Climatizzazione (SoLar Thermal Cooling and Heating pLants Design)*, Maggioli Editore, 2010.

[12] M. Gasparro, D. Germanò, and M. Villarini, *Principi Di Progettazione Degli Impianti Solari Termici (Solar Thermal Plants Design)*, Maggioli Editore, Rimini, Italy, 2011.

[13] V. Piemonte, M. De Falco, P. Tarquini, and A. Giaconia, "Life cycle assessment of a high temperature molten salt concentrated solar power plant," *Computer Aided Chemical Engineering*, vol. 28, pp. 1063–1068, 2010.

[14] C. J. Winter, R. L. Sizmann, and L. L. Vant-Hull, *Solar Power Plants*, Springer, New York, NY, USA, 1991.

[15] M. Carlini, S Castellucci, E. Allegrini, and A. Tucci, "Down-hole heat exchangers: modelling of a low-enthalpy geothermal system for district heating," *Mathematical Problems in Engineering*, vol. 2012, Article ID 845192, 11 pages, 2012.

[16] M. Carlini, T. Honorati, and S. Castellucci, "Photovoltaic greenhouses: comparison of optical and thermal behaviour for energy savings," *Mathematical Problems in Engineering*, vol. 2012, Article ID 743764, 10 pages, 2012.

[17] J. P. Roy, M. K. Mishra, and A. Misra, "Performance analysis of an Organic Rankine Cycle with superheating under different heat source temperature conditions," *Applied Energy*, vol. 88, no. 9, pp. 2995–3004, 2011.

[18] E. Bocci, A. Di Carlo, and D. Marcelo, "Power plant perspectives for sugarcane mills," *Energy*, vol. 34, no. 5, pp. 689–698, 2009.

[19] F. Orecchini, E. Bocci, and A. Di Carlo, "Process simulation of a neutral emission plant using chestnut's coppice gasification and molten carbonate fuel cells," *Journal of Fuel Cell Science and Technology*, vol. 5, no. 2, Article ID 021015, 9 pages, 2008.

[20] E. Bocci, F. Zuccari, and A. Dell'Era, "Renewable and hydrogen energy integrated house," *International Journal of Hydrogen Energy*, vol. 36, no. 13, pp. 7963–7968, 2011.

[21] A. Di Carlo, E. Bocci, and V. Naso, "Process simulation of a SOFC and double bubbling fluidized bed gasifier power plant, International," *Journal of Hydrogen Energy*. In press.

[22] A. Poullikkas, “Economic analysis of power generation from parabolic trough solar thermal plants for the Mediterranean region-A case study for the island of Cyprus,” *Renewable and Sustainable Energy Reviews*, vol. 13, pp. 2474–2484, 2009.

[23] M. Villarini, M. Limiti, and R. Impero Abenavoli, “Overview and comparison of global concentrating solar power incentives schemes by means of computational models,” *Computational Science and Its Applications*, vol. 6785, pp. 258–269, 2011.