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Energy and economic analysis of a residential Solar Organic Rankine plant

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Abstract

To answer the actual energy, water, economic, social and environmental challenges, renewable, distributed power plants need to be developed. Among renewables, solar tri-generative power plants can be a solution where there is big low temperature heating/cooling demand and small electricity demand, like many residential and industrial utilities. In this case, solar thermal plants can produce thermal energy with low cost and high efficiency. The higher temperature heat not needed by the user can be exploited via Organic Rankine Cycle to produce electrical energy and desalinized water via reverse osmosis. The present paper analyses, via TRNSYS simulation, a system composed of 50 m^2 of CPC solar thermal collectors, 3 m^3 of thermal storage, a synthetic heat transfer fluid, 3 kW_e ORC, 8 kW_{th} absorber, 200 l/h direct reverse osmosis desalination device. The system is able to produce power, heating/cooling and fresh water needs for a residential house. Although system's components are well known technologies, the integration to a efficient and economic working system is still a challenge. Global energy and economic analyses have been performed. Low temperature heating/cooling terminals allow to increase not only the use of thermal energy but also the ORCand absorber efficiency. ORC-Absorber configuration and relative fluids and temperatures are central. Government support and/or cost reduction of 30% are necessary to have positive NPV and acceptable PBT and IRR.

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Keywords:Power plants; Renewable energy sources; Distributed generation; Solar Thermal; Organic Rankine Cycle; Absorber; Desalination

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1. Intoduction

To answer to the actual energy, water, economic, social and environmental challenges, smalllocal integrated solutions to low cost green energy demand and water scarcityneed to be developed[1,2]. Indeed, when the additional demand for electricity induced by water needs is not taken into account, electricity demand can be underestimated by nearly 40% [3]. A solution could be the combination ofsolar renewable energy source with an efficient desalination technology since a large part of the world's population is concentrated in sunny coastal areas [4].

The reverse osmosis (RO) is a pressure-driven process whereby a semi-permeable membrane rejects dissolved constituents in the feeding water but allows water to pass through, and it is the most energy efficient desalination process[5–7].

Where there is great demand of low temperature thermal energy and low demand of electricity, like many residential and industrial utilities, solar thermal plants can be conveniently applied. Solar thermal energy can be used to produce the low temperature thermal energy needed. Moreover the thermal power can be used to produce also cold, via absorber, and electricity by means of a thermodynamic power cycle, exploitingthe higher temperature heat not needed by the user[5,6]. ORC lowest efficiencies (e.g. 1-8%) are obtained with low temperatures (70-130 °C) and low pressures (1-20 bar), using R134a or R218 fluids, and a simple configuration (single cycle without regenerator) [4,5,7–9]. Average efficiencies (8-20%) are obtained with medium temperatures (100-200°C) and medium pressures (10-30 bar), using R245fa or Isopentene fluids[10–12]. The highest efficiencies (20-35%) are obtained with high temperatures (200-400°C) and high pressures (20-40 bar), using R601a or Toluene or Hexamethyldisiloxane fluids, and a complex configuration, but these systems are too complex and too expensive at the small size analysed here [5,9,13].

Solar thermal tri-generation systems can, thus, potentially improve environmental sustainability; but investment cost and encumbrance are still higher, meanwhile efficiency and reliability appear lower especially at small residential scale [14–17]. However, only a small number of research papers have been published on low temperature solar thermal desalination, and none of these is encompassing a small-scale unique solution to all the energy house needs (heating, cooling, electricity, and water demands), as the one envisaged in this paper.The house consumption, a 100 square meters house with two dwellers, the ORC model, and the global system model, in different configuration, have been already analysed in previously papers, respectively[18–20]. TRNSYS software has been used to analyse the energy performance meanwhile the economical trade-off conditions have been analysedvarying some selected system parameters,as in the papers [9,19,21–29].Concluding the authors, that studied several kind of renewable energy systems and processes [30–40], in this paper focus the attention on the annual energy and economic performance of a residential solar tri-generative system.

Nomenclature

SC	Solar compound parabolic Concentrator field (heat pipe evacuated tube plus parabolic concentrator)		
HTT	High Temperature heat storage Tank	RO	Reverse Osmosis device
LTT	Low Temperature heat storage Tank	AB	Absorption chiller (Absorber)

2. Power plant description

As shown in Fig.1, the SC feeds the HTT, establishing the first plant fluid loop. The HTT feeds the ORC, establishing the second plant fluid loop. The ORC evaporator heat exchanger hydraulically separates SC-HTT-ORC loopsfrom the ORC loop.The ORC feeds, electrically and not mechanically as usual, the reverse osmosis device, and the electrical house needs. The heat released by the ORC is sent to the LTT, which feeds the house heating and cooling (via absorber) loads. Therminol 62, a synthetic heat transfer fluid, was chosen as the thermal vector fluid of the high temperature primary (SC-HTT) and secondary (HTT-ORC) loops owing to its thermal stability up to 325 °C and low vapour pressure [41–43]. As in [19,20]R245fa fluid was chosen as ORC fluid[44–47].

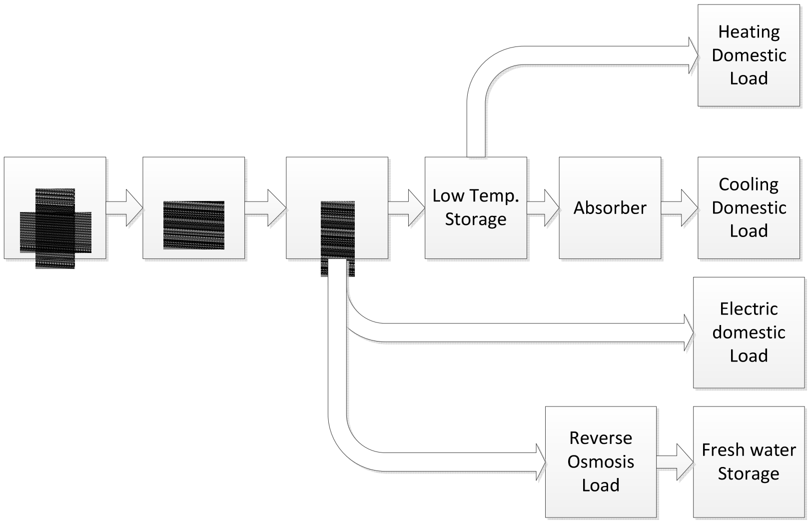

Fig. 1. Block diagram of the system.

The difference with the previously published paper [20] are not only the addition of the reverse osmosis consumption, absent in the previous paper, but also bigger stratified tanks (3 instead of 1 m^3) and a bigger flow of the first and secondary loop (7000 versus 5000 kg/h). The HTT and LTT have been increased, because even if they are more bulky and expensive,they reduce thermal losses per liter andincrease the SC efficiency (owing to a higher volume at low temperature) and the ORC time functioning regardless the instantaneous solar radiation availability. The flow has been increasedeven if it requires more expansive pumps, because higher flows givelower temperature differences from one point to the other of the loop and lower times to transfer the thermal energy, increasing the global efficiency (owing to the higher functioning time at higher temperature difference of the ORC and absorber devices). Table 1 below summarizes the main power plant component parameters. The pipeline is copper tube with nominal diameter 40 mm.

Table 1.Main power plant components and parameters.

Component	**Producer (Model)**	**Parameter**	**Value**
Solar collectors	Kloben (CPC heat pipe)	Square meters	50 m^2
Pumps	Wilo (TOP-S 40/10 EM)	Flow - Maximum head	30-120 l/min – 10 m
HTT and LTT Storage	Kloben (without heat exchanger)	Volume – Heat loss coefficient	3 m^3 – 4 W/K
ORC	Newcomen (Piglet)	Nominal Electric Power	3 kW
Absorber	Sortech (ACS 08)	Nominal Cooling Power	8 kW
Terminals	Kloben (Klimaboden)	Heating – Cooling temperature	30 °C – 15 °C
Reverse Osmosis device	Linntech (C200)	Fresh water production	200 l/h

As in the previous paper[20], owing to the residential application (limited space for the solar field and limited thermal loads), the solar collector field size is 35 kW_{th}, in order to guarantee the production of the thermal energy required by the house and the ORC nominal heat power required. The Kloben Compound Parabolic Concentrator, CPC, heat pipe solar collectors (absorptance 0.92, emittance 0.065) were chosen in order to have a relatively high (150°C) storage temperature but not to excessively increase the system cost[20]. At present, the research group is reckoning to apply an optimization system [48] developed for solar system in order to further improve collector performances.The ORCis mainly composed of an evaporator, an alternative engine (three radial cylinders expander) directly coupled with a permanent magnet generator, a condenser, a pump and a regenerator.Themathematical model of the fluid and the ORC isdescribed in [19]. The ORC pump nominal flow rate is set at 500 kg/h, begins working as soon as HTT temperature reaches 150 °C and stops as soon as it goes down to 100 °C. The absorber COP is 0.6. The absorber drive temperature isfixed at the minimum allowable (55 °C) in order to increase ORC efficiency. The terminals are radiant floor in order to have the lowest heating temperature (set at 30 °C) and the highest cooling temperature (set at 15 °C).

Considering a per-capita consumption of 80 l/d [49] and the two dwellers, the production have to be of 160 l/d. However, not every day the thermal storage reaches 150°C in order to start the ORC. Estimating that in average the thermal storage reaches 150°C in 3 days (from the simulation the average time between two starts of the ORC is about 3 days), a production of 480 l has been evaluated.Thus a tank of 500 litres has been chosen. The RO device consume 0.55 kW of electric power to produce 200 l/h. Thus 2.75 kWh/m^{3}a bit higher than the State of Art of 1-2.5 kWh/m^3[16]. The consumption every 3 days for 480 l is 1.320 kWh, in a year the consumption is about 160 kWh. The power consumption of RO shouldbe analysed with the power load and the power generated by the ORC, in order to better match production and load. Anyway, considering that this affects only the day-by-day production and that the paper's objective is to assess the global annual performance, this analysis is out to the paper scope.

3. Model and simulation

Fig. 2 shows the TRNSYS model.Type109 has been set with Rome radiation data. The pump (Type3b) is activated via the type2b, when the difference between the solar collector output and the HTT average temperature is higher than 10°C and it is stopped when this difference is lower than 2°C. The pump (Type3b-2) of the secondary HTT-ORC loop is activated when the higher storage temperature fluid is greater than 150°C and it is stopped when the higher storage temperature fluid is lower than 100°C. The system decides to direct the ORC thermal power to the absorber or to the thermal load on the grounds of load demand (cooling or heating) through the three-way valves (Type11f and Type 11f-2). The absorber waste is re-cooled via the evaporative tower (Type51a).

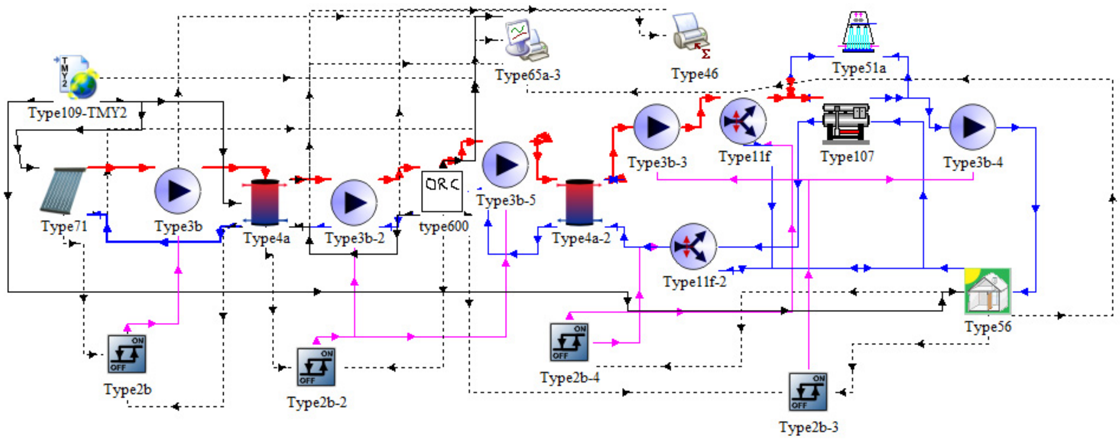

Fig. 2. TRNSYS model layout.

The simulation step has been always 10 minutes. Owing to the difficulty to show all the annual results, here it follows a synthesisof the data, meanwhile the first 20 days simulations are quoted in the figures below.

The total (direct and diffuse) solar radiation on solar panel surface, on average varies from 0 to about 3,700 kJ/m^2 during summer and from 0 to about 3,100 kJ/m^2 during winter. The total annual radiation value is about 90,000 kWh.TheSC temperature, varies, on average, between 5°C, during winter, or 15°C, during summer, and about 150°C (with little peaks that reach also 250°C). The total annual energy stored is about 40,000 kWh, with a global SC efficiency of about 45%.The tank thermal losses are about 4,000 kWh, thus about 36,000 kWh has been annually sent to the ORC. The decrease in efficiency respect to the standard test efficiency (Wuzburg test 71%) is due to the high temperatures fixed (150-100°C) of the activation and deactivation of the HTT-ORC pump flow. The ORC powervaries from 0 to 3,000 W (with peaks that reach also 4000 W during summer). The total annual energy produced from the ORC is about 5,000 kWh. This meaning, considering the solar radiation energy, an annual ORC efficiency of 6%. This values are similar to the ORC efficiency values quoted in literature for small scale similar systems, 4%–12% [17,20,44,46,50–53]. The annual thermal energy discharged by the ORC is about 32,800 kWh (10% of ORC thermal losses). From this energy is produced about 17,000 kWh of heating effect and 3,600 kWh of cooling effect (average 60% absorber COP). The high thermal energy effect relies on use of low temperature heating terminals (radiant floor). The low temperature terminals allow also to increase the efficiency of the ORC, owing to the lower condenser temperature, and of the absorber, owing to the higher cooling temperature.

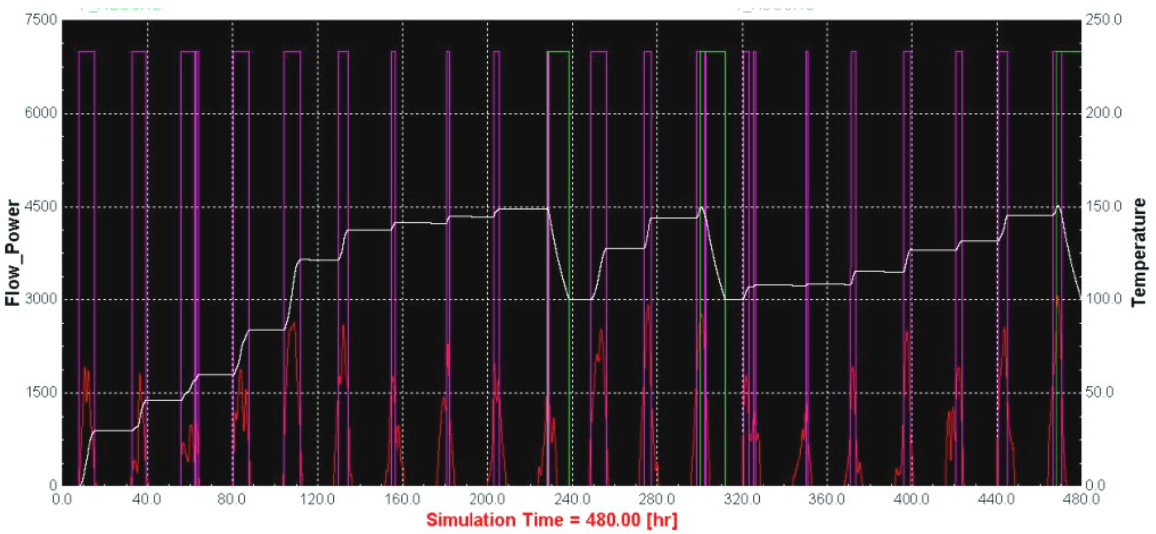

Fig. 3. First 20 days of SC and HTT temperature on right, Pump Flow and Solar Radiation on left.

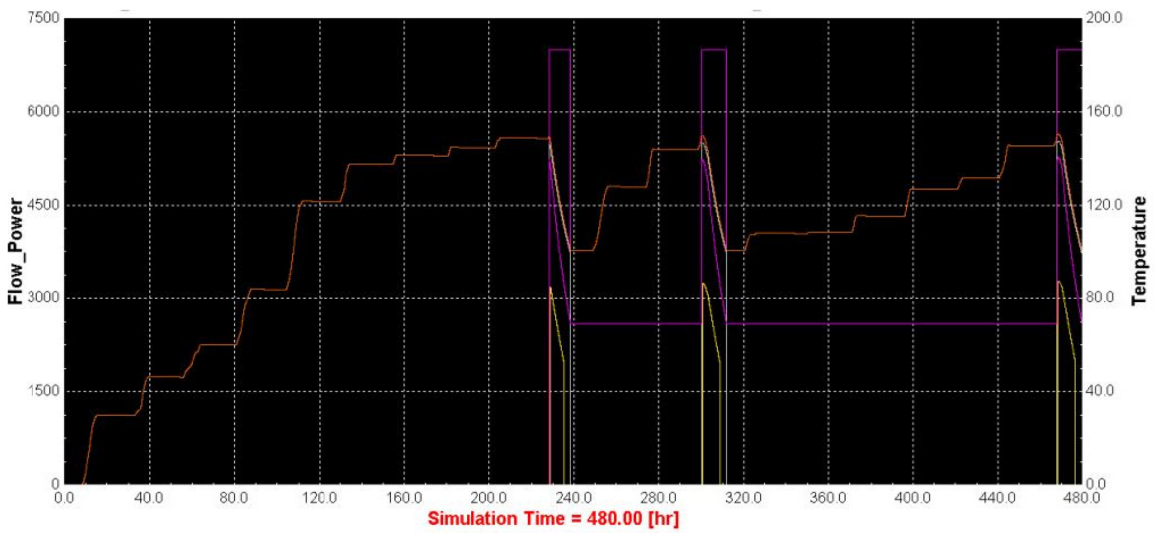

Fig. 4. First 20 days of HTT and Evaporator temperature on right, Pump Flow and Electricity on left.

Figure 3 shows the variation of the SC temperature, in orange, corresponding to the variation of the total solar radiation, in red, and thus the relative activation (the flow, in violet, fixed at 7,000 kg/h) of the SC-HTT pump. The HTT-ORC pump flow is in green. It is possible to see that, starting from 15 °C, temperature starting point of the simulation, after ten days of solar radiation the HTT average temperature, in white, reaches the fixed ORC starting temperature (150 °C), this temperature, and thus the HTT-ORC pump activation, is reached again after 2.5 days (at 300 h) and again after 6.7 days (at 460 h). The annual simulation shows that 150°C is reached every1-7 day in winter and every 0-2 day during summer. These data show that, the choice of set high HTT temperatures (150-100 °C) allows to have higher ORC pressureat the expander thus higher ORC efficiency (ORC efficiency of about 13% on thermal energy sent to the ORC); but the high temperatures not allows to recover all possible solar radiation energy (collector efficiency of about 45%). This happens in every solar-ORC power plants: the choice of the temperatures values that feed the ORC are a compromise between the solar collector efficiency and the ORC efficiency. Therefore, it could be convenient to decrease the temperature of the HTT, at least in winter, to increase the collector efficiency. This imply a bypass of the ORC, switching from series (ORC top, thermal loads bottom) to parallel (directly thermal loads) configuration during the days of low solar radiation; or a change in the ORC fluid (e.g. from 245fa to 134a) to have "same" pressure at lower temperature. Also an opposite series configuration can be evaluated, sending during summer the absorber waste heat to the ORC and not the opposite, but ORC and absorber fluid have to be changed, in order to have "same" performance with different temperatures. Anyway the evaluation of the different configurations and different ORC and absorber fluids,is out of the paper scope. Figures 3 and 4quoted below show the results of the simulation regarding the solar, and the ORC respectively during the first 20 days (thus January 1-20). Figure 4 shows that the evaporator temperature varies from 140°C to 70°C, and that the electric power produced varies from 3 to 1.8 kW.

4. Economic analysis

As Fig. 5 shows, Tuscia University is building the system at the office of the dry port of Orte (VT, Italy). Therefore, it has been possible to assess the real capital system cost. About 20,000 € is the cost of: solar thermal collectors (12 panel of about 4 meters of gross area), two tanks, three expansion vessel, sixpumps (HTT-ORC, ORC-LTT, LTT-AC/Terminals, AC-Evaporative tower, AB-Terminals), fourflow meters (SC-HTT, HTT-ORC, ORC-LTT, HT/LT), about 200 meters pipeline and temperatures and pressure sensors. The ORC costis about 10,000 €. Indeed, the Newcomen price for the Piglet model is 15.000 euro but they realize 2-3 prototype per year, so a cost of 10.000 euro is more realistic considering an industrial production. The absorber and evaporative tower cost isabout 20,000 €. The RO unit cost is 3,000 €. Including control and installation costs, estimated at 7.000 €, a total amount of € 60,000 is totted up. Indeed, the real project, control and installation cost has been more than70.000 euro. Nevertheless, considering a standardization, the cost of the project (more than 20.000 €) can be avoided, and the control and installation cost can be lowered to 1/7 (e.g. avoiding the pumps flow control via inverter, data logger, etc.).

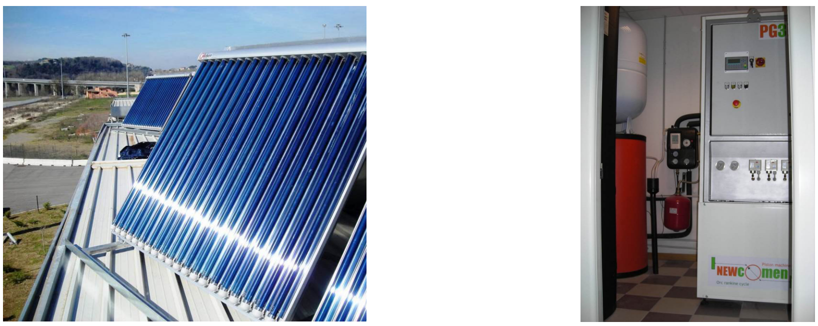

Fig. 5. Power plant under construction.

Revenue consists of electricity feed in tariff (5,000 kWh of electricity at0.36 €/kWh), thermal energy savings (17,000 kWh of heating assessed by virtue of 0.70 €/m^3 natural gas cost) and electricity savings (at 0.21 €/kWh, average 2013 residential electricity price)due to refrigeration(3,600 kWh cooling produced via a heat pump with a COP of 2). 25 years feed-in-tariff is an invariable revenue.The annual energy cost growth is always equal to 2%.

The cumulated cash flows trend is slowly positive. The total amount of income during the 25-year period is about 115,000 € and the yearly gain, after the payback time, amounts to a value between € 4,495 and € 5,295.The PBT, Pay Back Time,mainlydepends on annual rate of energy cost growth and overall system costs. In case of feed-in-tariff incentive and 5,000 electric kWh produced, the cost reduction is more efficacious than the energy growth cost, making the PBT vary of 4 or 5 units, from the baseline value of 60,000 € to the possible target value of 40,000 € while the energy growth rate gives small advantages making the PBT vary of maximum 2 units.

Table 2. Payback time sensitivity depending on electric kWh produced (columns) and overall system costs (rows).

	4.000	**4.500**	**5.000**	**5.500**	**6.000**	**6.500**
-40.000	11	10	10	9	9	8
-45.000	12	11	11	10	10	9
-50.000	14	13	12	11	11	10
-55.000	15	14	13	12	12	11
-60.000	16	15	14	13	13	12

Table 2 shows as, reached a system cost of 40,000 or 45,000 €, the rise of energy production allows to reach reasonable results, in terms of payback time(eight years). The same sensitivity analysis, in case of lack of feed-in-tariff incentive shows the need to reduce systems costs of 30%.The lack of such a support, would obviously increase the payback time (19 years in case of an overall cost of 60,000 €). The solar multigenerator system would compare unfavorably with the present market, if unprovided with government support. After the initial investment, in case of lack of feed-in-tariff incentive, with a system cost of € 40,000 and an electricity production of 6,500 kWh the PBT would be of 12 years. The other relevant parameters calculated are NPV, the net present value of a time series of cash flows, and IRR, the internal rate of return. In the basic configuration, the first one is positive (a bit more than € 4,000) and the second one is equal to 5.7%. The tables 3 and 4 shows the sensitivity, in case of feed in tarif.

Table 3. IRR sensitivity depending on electric kWh produced (columns) and overall system costs (rows).

	4.000	**4.500**	**5.000**	**5.500**	**6.000**	**6.500**
-€ 40.000,00	**8,9%**	**9,7%**	**10,5%**	**11,3%**	**12,2%**	**13,0%**
-€ 45.000,00	**7,5%**	**8,2%**	**9,0%**	**9,7%**	**10,5%**	**11,2%**
-€ 50.000,00	**6,3%**	**7,0%**	**7,7%**	**8,4%**	**9,1%**	**9,7%**
-€ 55.000,00	**5,3%**	**6,0%**	**6,6%**	**7,3%**	**7,9%**	**8,5%**
-€ 60.000,00	**4,5%**	**5,1%**	**5,7%**	**6,3%**	**6,9%**	**7,5%**

The IRR reaches satisfactory values from 50,000 to 40,000 € of system costs and 5,000 kWh production.

Table 4. NPV sensitivity depending on electric kWh produced columns) and overall system costs (rows).

	4.000	**4.500**	**5.000**	**5.500**	**6.000**	**6.500**
-€ 40.000,00	**16.046**	**19.633**	**23.219**	**26.805**	**30.392**	**33.978**
-€ 45.000,00	**11.284**	**14.871**	**18.457**	**22.044**	**25.630**	**29.216**
-€ 50.000,00	**6.522**	**10.109**	**13.695**	**17.282**	**20.868**	**24.454**
-€ 55.000,00	**1.760**	**5.347**	**8.933**	**12.520**	**16.106**	**19.693**
-€ 60.000,00	**-3.001**	**585**	**4.171**	**7.758**	**11.344**	**14.931**

NPV is always positive with the exception of 4,000 kWh and € 60,000 costs. It reaches satisfactory values at the target cost of 40,000 €.

Without incentives, the baseline case of 60,000 € system costs brings a negative NPV and a very low IRR (2,6% in case of 5,000 kWh). IRR reaches 6.4% and NPV reaches 5,883€ in case of 40,000 € system costs and 5,000 kWh electric production. In the best configuration, (€ 40,000 system costs and 6,500 kWh), without incentives IRR reaches 7.7% and NPV reaches 11,441 €.

The market competitiveness, conceived as system cheapness, can be obtained as a consequence of the learning curve pertinent to the energy system. The photovoltaic experience has showed the efficaciousness of learning curve by the escalation of economical profit in connection with electricity rise. The same efficaciousness is expected for small size ORC generator and absorption chillers costs.

4. Conclusion

A solar residential tri-generative power plant, including also the consumption for fresh water production, has been described. Although system's components are well known technologies, the integration into a efficient and economic working system is still a challenge. Global energy and economic analyses have been performed. The energy analysis shows that low temperature heating/cooling terminals allow to increase not only the use of thermal energy but also the ORCand absorber efficiency. In general, ORC-Absorber configurations and relative fluids and temperatures are crucial for the efficiency of the system, e.g., the choice of the temperatures values that feed the ORC are a compromise between the solar collector efficiency and the ORC efficiency.Therefore, the management of the energy flows, along with a reduction of system costs seems to be the most challenge issues. Indeed, in order to reach the grid parity conditions an investment cost reduction is indispensable and it is a long winding way. The mentioned cost reduction involves more specifically solar collectors and fluids, ORC and absorption unit. Currently, the ORC generator requires about 4,000 € /kW expenditure which is far from an affordable investment as showed by authors for other new technology small scale power plants [18,54–57]. Costs could benefit from enlargement of these components production scale, harnessing bigger size plants whose attraction is much more effective from the point of view of the investment [58–60].

Finally, the advantages of the system are not only addressed to the user of the system but also to the national energy distribution system and the national energy bill. This system does not impact on the grid as it is happening owing to a myriad of territory distributed photovoltaic and wind energy installations. Indeed, in virtue of system controllability, the energy received by aleatory solar irradiation can be used with a delay in comparison with time of collection [37]. Finally, owing to the use of renewable energies and the production of electric and thermal energy and water where they are needed, a reduction of fossil fuel and primary energy consumptions are other advantages of this system.

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