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Solar Thermal-Based ORC Power Plant for Micro Cogeneration – Performance Analysis and Control Strategy

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Abstract

The paper deals with the performance assessment of a small scale cogeneration system for building applications, featuring an Organic Rankine Cycle-based plant bottoming a solar collector array for combined heat and electricity generation. A sliding vanes rotary expander and a water cooled condenser are employed in the recovery section. A comprehensive MATLAB® model accounts for the dynamic of each component, as both a stand-alone device and a plant-integrated unit: a parametric study is presented and an off-design analysis is performed to properly assess the performances of both the heat exchanger and the expander. Heat availability to the ORC heat exchanger is evaluated, based on solar availability, thermal losses in the pipes and plant requirements, in terms of operating temperature and pressures, having the collection area, the mass flowrate for the fluid in the solar collector branch and the fluid type in the recovery section as main variables. Due to the need for DHW production, a storage unit for hot water is present, upstream the recovery branch: dependently on the ability the fluid at the collector outlet has to meet the ORC requirements for proper operation (about 110°C), the ORC evaporator is fed and the recovery section enabled. Both continuous and unsteady operation underwent an in-depth analysis, as well as the benefits associated with different discharge times for the storage unit: dependently on whether the electrical output or the thermal one need to be maximized, a different control logic for the whole system comes out (e.g. either a flash or a progressive tank discharge). The virtual platform allowed the setting-up of a pilot plant, for direct performance assessment and model validation.

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1. Introduction

The transition towards a manageable and sustainable energy sector relies on both the development of new clean energy technologies and the comprehensive uptake of already available ones. The former option has its main limitations in the time-to-market and implementation costs. Consequently the latter is currently addressed as the only one able to better match the stringent time constraints the policy makers summarized in the 2 Degrees Scenario (2DS) pathway [1]. In light of present 411.6 ppm CO_2 atmospheric concentration [2], renewables and energy efficiency are expected to contribute to the biggest share (30% and 38%, respectively) of the cumulative 760 $GtCO_2$ emissions reduction needed by 2060 [3], particularly in the residential sector, responsible for up to 25% global energy-related CO_2 emissions at present [4]. Solar thermal collectors technology is on track to meet a sustainable energy transition and has been experiencing a continuous scale-up in deployment, mostly due to the drop of production costs. Nonetheless, the reaching of a 2DS-compliant cumulative capacity calls for further policy action to support its large-scale market penetration [5]. In light of a growing interest in combined heat/power generation on both the small and the big scale, current trends address the opportunity of its integration with newer technologies for electricity generation, such as Organic Rankine Cycle (ORC) based plants, as very promising, for it could assure a mutual benefit, in terms of speeding up the market diffusion and the reaching of the expected growth rate in decades to come. Despite the fact that solar collectors technology is well established, its potential remains still untapped, with main research areas in fluid type [6], optical properties [7] and heat transfer [8] enhancement. A comprehensive literature, gathering all analytical and simulation models for the storage unit [9], feeding either a bottom section for energy conversion [10] or a thermal load [11, 12] is available as well. Concentrating collectors seem to be very effective as the upper thermal source [13, 14], as they assure the reaching of higher temperatures per square meter of collecting surface than traditional solar collectors, with obvious space saving and higher expected performances for the bottoming ORC unit [12, 15]. Nonetheless, plant costs are higher than those for a non-concentrating collector, as well as the costs for O&M - and where of the case, tracking devices – so that the final price for the purchase, installation and maintenance, as well as for operation of the combined system falls short of large-scale market expectations [16]. Plus, in spite of the higher temperature at which the heat is available to the recovery section, concentrating collectors only process direct normal irradiance and assure a lower yield of solar energy than non-concentrating systems. As far as the ORC section is concerned, a proper selection of both the fluid [17, 18] and the expander and pump type [19] can bridge the performance gap with the configuration featuring concentrating devices: positive displacement machines are the best option, due to low cost, high reliability, suitability to low power outputs and applicability to both full and part load operation. Furthermore, the presence of a storage unit, providing a continuous heat availability to the ORC, allows at once an additional set of operating modes (i.e. direct ORC feeding by the collector, tank discharge - either fast or slow - onto the ORC unit, or a combination of the two) and a more uniform operation to the recovery section, crucial for a proper ORC energy response [20]. The paper goes deep inside the modeling of a unit for combined heat and electricity generation for residential applications, able to meet the above mentioned cost constraints and technological simplicity requirements, both keys to success for any technology for the residential market. Energy performances for the system are assessed on a daily and monthly basis.

2. Plant layout and model definition

The plant layout under investigation features a flat plate 3 cover solar thermal collector, providing heat to water stored in a 250 l volume tank, in line with technological standards for market solar domestic hot water (DHW) applications. A circulation pump allows a water/Glycol (40%) mixture to flow on the back of the solar collector and no mixing with the water for domestic uses occurs within the tank (active indirect configuration). Preliminarily to the modeling, an analysis was performed on various flow configurations, to assess each one's potential in a heat recovery-oriented system, featuring a DHW solar thermal collector and a bottoming ORC based cycle: a low flow set-up turns out to be the best fit, with a water/Glycol specific mass flowrate in the 2-8 g/s per square meter collector area. A double advantage over the high flow configuration is appreciated, in terms of (i) a higher temperature increase for the water/Glycol mixture, for any given collection area (i.e. higher thermal availability at the tank, in spite of slightly higher thermal losses in the pipes) and (ii) lower pumping requirements and lower friction losses. Furthermore, it is worth observing that space constraints apply in building applications and a compromise between minimum collection area and maximum gain on heat recovery is of the essence. No thermal draw-offs are considered, so that the heat at the tank is entirely available for electricity generation. An ORC based plant bottoms the solar collector/tank system, according to the layout in Figure 1: plant components are reported along with functional connections and main parameters the MATLAB® lumped parameters model monitors.

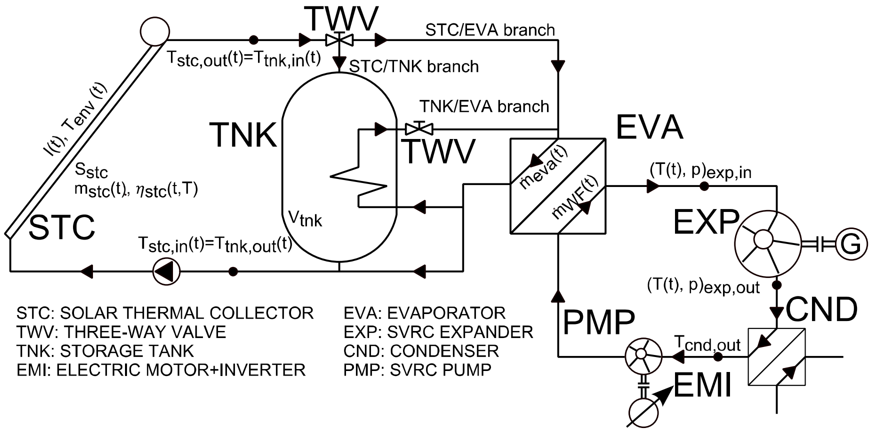

Figure 1. Solar collector/DHW tank/ORC-based plant set-up

An average 65% daily collector efficiency applies: such a value is retrieved from datasheets of market solar thermal collectors, as well as coefficients for the performance sensitivity to the operating temperature. The temperature at the collector outlet results from the energy balance, involving main power fluxes at the collection section, i.e. the radiative and convective loss to environment, the heat removal by the cooling fluid and the heat storage within the collector, associated with the temperature increase during operation, as in Equation (1):

$$S_{stc} \times F_R \times [I - U \times (T_{stc,in} - T_{env})] = \dot{m}_{stc} \times c_{p,w+glycol} \times (T_{stc,out} - T_{stc,in}) + m_{stc} \times c_{p,stc} \times \frac{dT_{stc}}{dt} \quad (1)$$

The energy availability from the sun is a function of the collection surface S (m^2), irradiance I (W/m^2), temperature T (K) for both the fluid at the collector inlet and the environment and contributes partly to fluid heating – dependently on the mass flowrate $\dot{m}$ (kg/s), temperature increase at the collector and fluid thermal capacity c_p (J/kgK) – partly to the collector temperature rise dT/dt, dependently on the equivalent mass m (kg) and thermal capacity for the collector [21]. The overall heat transfer coefficient U (W/m^{2}K) dependence on number of covers (N), tilt angle (β) mean plate and environment temperature T_{pm} and T_{env} (K), Fanning friction factor f, wind heat transfer coefficient h_w (W/m^{2}K), Stefan-Boltzmann constant σ (W/m^{2}K^4) and plate and glass emittance ε_p and ε_g is in Equation (2):

$$U = \left[\frac{N}{\frac{520 \times (1 - 0.00005 \times \beta^2)}{T_{pm}} \left[\frac{T_{pm} - T_{env}}{N + f} \right]^{0.43 \times \left(1 - \frac{1}{T_{pm}}\right)}} + \frac{1}{h_w} \right]^{-1} + \frac{\sigma \times (T_{pm} + T_{env}) \times ({T_{pm}}^2 + {T_{env}}^2)}{(\varepsilon_p + 0.00591 \times N \times h_w)^{-1} + \frac{2 \times N + f - 1 + 0.133 \times \varepsilon_p}{\varepsilon_g} - N} \quad (2)$$

The Fanning factor (f) and the heat removal factor (F_R) are in Equation (3) and (4), respectively:

$$f = \left(1 + 0.089 \times h_w - 0.116 \times h_w \times \varepsilon_p\right) \times (1 + 0.07866 \times N) \tag{3}$$

$$F_R = F' \times \frac{\dot{m} \times c_p}{S_{stc} \times U \times F'} \times \left(1 - \left(0.43 \times \left(1 - \frac{100}{T_{pm}}\right)\right)^{-\frac{1}{m_{stc}}}\right) \tag{4}$$

where F' is the collector efficiency factor [21]. With a 750 W/m^2 irradiance, 27 m^2 collection area, 2 g/s/m^2 specific mass flowrate maximizes the temperature at the collector outlet: the mass flowrate increase from 2 g/s/m^2 to 8 g/s/m^2 results in a 25°C lower temperature at the collector outlet, meaning less applicability in a combined set-up. The increase in the water/Glycol mass flowrate further limits the achievable temperature at the collector outlet due to the lower collector/fluid heat exchange efficiency: a 1.5%-2% reduction occurs every 5°C drop in the plate mean temperature, i.e. every 2 g/s/m^2 mass flowrate increase. A lower number of covers would mitigate such a loss term, but the gain on the heat removal efficiency would be negligible with respect to the loss on the solar irradiance collection. Furthermore, the heat transfer to water/Glycol would only slightly benefit from the lower heat loss to the environment, due to the lower mean plate temperature: F_R in Equation (4) increases from 81% to 98%, for 2-to-20 g/s/m^2 flowrate increase, with a mean plate temperature varying between 94.2°C and 77.6 °C. The collection area is slightly oversized, to account for a 20% reduction in the solar irradiance. In order to establish whether the ORC section is enabled or not, a control on the temperature at the tank is needed: a target 110°C temperature needs to be achieved and a controller actuates on the three-way valve to open either the STC/EVA branch, for direct ORC feeding, or the STC/TNK branch, till the temperature threshold is not achieved. The 110°C threshold temperature at the storage unit represents the best compromise between the system efficiency maximization, possible by increasing the ORC upper temperature, and the need to limit the thermal losses to the environment in pipes: as a matter of fact, little variations around this value are possible, but 110°C can be safely assumed as the reference for calculations. The model accounts for the possibility to feed the ORC from the tank, by opening a TNK/EVA branch as soon as the temperature within the tank exceeds the 110°C threshold, as a result of poor draw-offs to the thermal uses and continuous heat additions from the solar collector. The ORC section features a R245fa working fluid, whose flowrate depends on the cycle coordinates. Based on current trend in small-scale ORC-plants technology, sliding vane rotary machines can be conveniently employed as expander and pump. A first guess is on the expander size: a 500 W mechanical power expander is considered, with a 90°C inlet temperature and a 10°C overheating. The saturation temperature at the condenser is 28°C, to allow direct cooling in environment, with no additional expense for a cooling medium at the condenser. Maximum and minimum cycle pressures are 7.98 bar and 1.67 bar, respectively. A 36 g/s R245fa mass flowrate is needed resulting in a 9.69 kW thermal power at evaporator. As the expander size varies, the mass flowrate in the ORC section varies accordingly, so that the heat removal at the evaporator is maximized. This calls for an increased power absorption at the pump: as the expander size moves from 300 W to 1000 W, the pump power increases, but never exceeds 70 W. Hence, the pump power absorption is negligible and does not represent a major limit for the combined plant.

3. Layout assessment and model results

A first assessment is performed on the plant, with the STC/EVA branch closed. The only heat availability to the ORC comes from the tank directly, through the TNK/EVA branch. Since each draw-off to the evaporator is a heat subtraction to potential thermal uses, a condition on the temperature of the water within the tank is needed to make such a layout feasible in actual applications: the mass flowrate to the evaporator assures that the minimum temperature at the tank never drops below 60°C. As a consequence, under the assumption of an instantaneous discharge to the ORC section, a profile is derived as the one in Figure 2: data refer to July, 21, as the day with the maximum irradiance for the location at hand (L'Aquila, central Italy), but analogous considerations apply to all situations of interest. With a 20°C temperature in the tank, prior to any contribution from the solar collector, four ORC activations are possible, similarly to what happens in absence of thermal uses for the tank water; in actual plants, any draw-off would reduce the tank temperature and result in a delayed ORC activation and consequently, a lower amount of discharges possible. A positive effect comes from the availability of a higher kick-off temperature for the tank, which would help in having an earlier ORC activation (ORC-ON). Figure 3 reports the effect of a higher tank temperature on the time of first ORC-ON: as the temperature within the tank varies between 25°C and 70°C, the ORC-ON advance ranges between 120 and 840 seconds. The tank temperature control for ORC-ON is a further area of possible intervention: the lower the ORC trigger temperature, the higher the amount of ORC activation possible. A 3% global efficiency for the ORC plant is considered, in general agreement with experimental data on ORC in the same size-range and for unsteady applications, such as WHR on the lubricant from air compressors [22], on-board recovery of exhaust thermal power in vehicles [23] and heat recovery from hybrid photovoltaic modules for building applications [24]. Under this assumption, the electric power generated never exceeds 1.83 kWh, with 110°C and 60°C upper and lower tank temperatures, respectively; 2.1 kWh electric energy is available, when the upper temperature is reduced to 100°C. Hence, even if no DHW demand has to be satisfied and the tank thermal energy is entirely destined to ORC feeding, the electricity generation associated with the TNK/EVA connection does not justify the plant cost and complexity. Plus, operation uniformity and conditions close to the design ones, hard to achieve in a set-up like the one being investigated, are crucial to keep the global efficiency at levels suitable for normal operation. The benefit in terms of electricity generation, associated with a lower size tank would be in the shorter time-to-target temperature for ORC-ON and would unable a higher number of discharges. Main concern of such an option, though, is the ability to satisfy DHW and ORC demand at once.

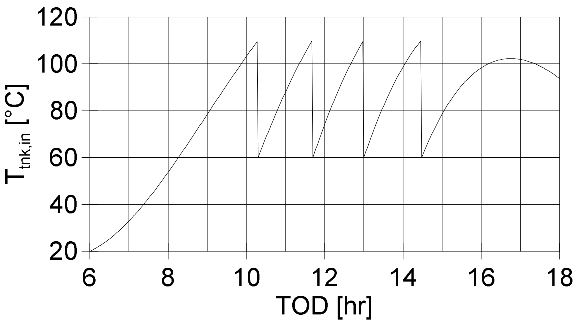

Figure 2. TNK/EVA branch opened – Temperature profile

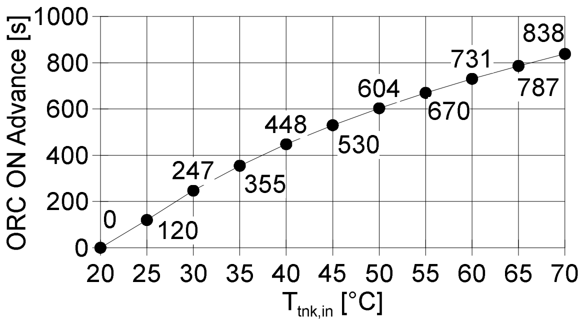

Figure 3. TNK/EVA branch opened – ORC ON advance

Moreover, the energy gain associated with a 150 l tank volume reduction never exceeds 200 Wh (Figure 4) for specific mass flowrates beyond 4 g/s/m^2, whilst for the case at hand (2 g/s/m^2) the difference is negligible. Dependently on the water/Glycol mass flowrate, the plant electric production depends on a combination of the STC/EVA and TNK/EVA contributions: in presence of a 2 g/s/m^2 mass flowrate, the temperature for direct STC/EVA feeding is reached before any contribution from the tank takes place, which is why points corresponding to different tank capacities collapse in a single point in Figure 4. Higher flowrates are associated with higher electricity outputs but, as the flowrate increases, the reaching of the temperature for direct STC/EVA feeding takes more time, during which the tank is filled: as a consequence, the STC/ORC direct feeding is delayed, but a TNK/EVA contribution is available. Generally speaking, the bigger the flowrate, the more delayed the STC/ORC direct interaction, but at the same time the faster the reaching of the ORC-ON temperature at the storage unit: these two effects compensate each other, so that, for a fixed tank volume and from 4 g/s/m^2 on, the electric generation is only slightly affected by the flowrate (Figure 4). For a given mass flowrate, the TNK/EVA feeding is delayed, as the tank volume increases, resulting in a lower electricity generation at the ORC section. The idea of employing lower size tanks is usually associated with the idea of employing a parallel tank-combination, allowing a more uniform ORC operation, achievable by discharging one tank at the time, while the other/s are reaching the discharge conditions. The additional plant and piping complexity, the more complex control strategy and the need for system balance, along with the additional space requirement to lodge more tanks, advises from adopting such a layout in building applications. Moreover, in spite of all possible interventions, a major limit for the layout at hand is in its thermodynamic merit, in terms of the heat sink at the condenser. The model swept a set of variable expander sizes:

when the expander power shifts from 300 to 1000 W, the condenser loss increases from 4.8 kW to 16.4 kW, corresponding to 90% to 95% the thermal power the R245fa is fed with at the evaporator. Great room for improvement is offered by the implementation of a control logic accounting for a STC/EVA branch as in Figure 1. As a matter of fact, two options are possible, since the ORC can be directly fed by the solar thermal collector, in addition to the direct interaction with the tank on the TNK/EVA branch.

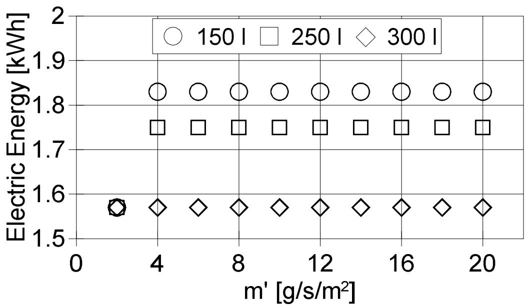

Figure 4. TNK/EVA branch opened – Tank size influence

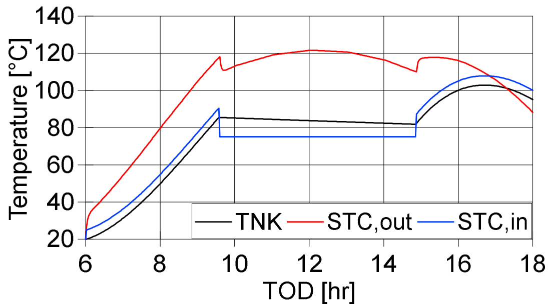

Figure 5. STC/EVA branch opened – Temperature profile

Figure 5 refers to the plant layout featuring the STC/EVA branch, and allows the cycle characterization and performance assessment, having a 110°C temperature at the collector outlet and a 75°C temperature at the collector inlet, for July 21 as the reference day: the model the Authors developed integrates a control on both the temperature at the collector outlet and the solar irradiance, to make sure that the ORC ON condition only occurs when a continuous operation can be supported. This is particularly evident in the absence of ripples as the ORC unit kicks in and in the fact that the draw-off to the ORC section takes place continuously (six hours) and no chatter is detected. This does not only induce better operating conditions for the ORC unit, but also allows a greater electricity generation: the electric energy generation tops 2.6 kWh, i.e. 800 Wh surplus with respect to the direct ORC feeding by the tank. A further advantage of a uniform operation with respect to any early ORC activation situation, is the fact that in presence of a mediated interaction between the ORC unit and the solar collector, additional degrees of freedom are gained on the control strategy for the whole system: the possibility to temporarily stock thermal energy within the tank, makes the progressive tank discharge on the ORC unit an option as effective as the one accounting for a flash tank discharge. A plant more capable of adapting to actual draw-off profiles, both thermal and electrical, comes out and ORC operation at design points is easier to achieve, with obvious direct gain on the plant performance. Figure 6 reports the results of the analysis, performed on March, in terms of specific surface – defined as the ratio between collection area and electric energy generated - as a function of the expander size. Same analysis accounted for all other months, i.e. for different situations in terms of solar irradiance at the collector: due to the variable thermal availability at the evaporator, in order to keep the mechanical power to a constant value, a different expander size is needed. The temperature at the tank inlet and outlet is 110°C and 75 °C, respectively. A minimum for the specific surface corresponds to an optimum operating condition, i.e. to the maximum electricity gain for a given collection surface. As a matter of fact, the indication on the specific surface mirrors the one on the plant cost, with the minimum corresponding to a 700 W expander: hence, 700 W is assumed as the reference size for the expander in the analysis. Figure 7 reports the minimum values of specific surface by month. An 11.3 m^2/kWh is appreciated and corresponds to 4 kWh electricity generation, i.e. up to 2.2 times the electric power associated with the direct ORC feeding by the tank. As previously stated, the model at this preliminary stage does not consider any thermal DHW draw-off, whereas they will be present in actual operation, in addition to those for ORC feeding. Simulations performed on a 250 l tank proved that, dependently on the irradiance level and environmental conditions, a high variability must be expected on the conditions the water for DHW purposes is available: in presence of a 25°C mean day temperature, the water within the tank after ORC-ON/OFF switch is available at 95°C, in line with the values for standard solar thermal applications. With a mean 10°C day temperature, the tank water temperature after draw-off to ORC section is 60°C.

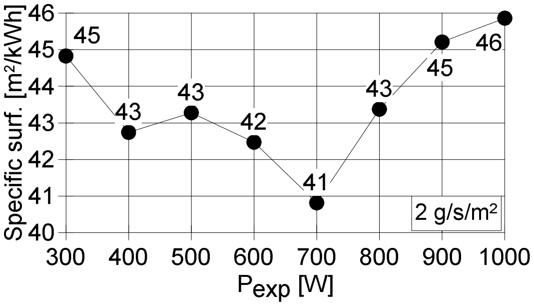

Figure 6. STC/EVA branch opened - Specific surface

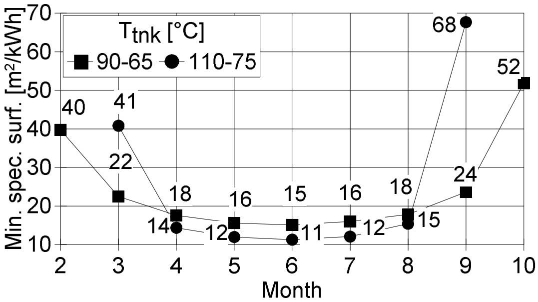

Figure 7. Minimum specific surface – Expander size influence

These figures clearly show that the ORC/STC integration is feasible, with no damage or applicability limitation for neither of them. In fact, the possibility to operate the plant in presence of a storage tank upstream the ORC unit allows to properly tune the electric and thermal part with mutual benefit for both. A monthly-based analysis of the thermal availability at the tank, once the ORC unit is shut down, in presence of 30 m^2 collection area and a 700 W expander gives evidence of a thermal power in the range 12 kWh to 22 kWh, dependently on the season being considered. A 700 W expander calls for a 13.2 kW thermal power of which up to 11.2 kW are lost to the condenser, i.e. 80.6% the heat made available to the R245fa at the evaporator is lost to the environment and does not contribute to the electricity generation in the ORC section. Even though the heat sink at the condenser in presence of a direct STC/EVA connection is lower if compared to the layout with a TNK/EVA connection alone, the loss entity still does not justify any further investigation on such a plant set-up: in the attempt to harvest as much thermal energy as possible, high collection surfaces are needed, with obvious cost increase and yet up to 80% the thermal energy available at the evaporator is lost at the condenser, even with little pinch point differences.

4. Conclusions and future developments

The paper discusses a thorough modeling activity performed on a solar thermal collector-based micro cogeneration unit for building applications. The set-up being investigated features an ORC unit bottoming the standard solar collector/tank for DHW applications. The model accounts for a direct tank/evaporator connection at first: different combinations of thermodynamic parameters for both the solar thermal collector and ORC circuits were swept, with reference to different sets of environmental conditions and irradiance values. Major limitations for such a plant configuration are in the low electricity generation at the ORC section and the unsteady operation for the ORC unit. Shifting to a plant layout where the evaporator is fed by the solar collector directly, through a dedicated branch that only opens when target temperature and irradiance are reached, allows a more steady plant operation, smoothing out the ORC operation regime and extending the timespan over which the electricity generation takes place. With reference to the combined heat/electricity set-up at hand, the model points out to small-scale expanders: both the domestic demand for electricity and the need to reduce plant and O&M costs (e.g. positive displacement machines, heat exchanger surfaces, oil) advice from selecting expander sizes beyond 1.0 kW. At the same time, the reaching of a proper temperature for ORC activation depends on the solar collection capability and ultimately on the surface extension, which also defines the amount of thermal power gathered and made available to the ORC working fluid at the evaporator. The model proves that even in presence of minimum temperature differences at the pinch point, such a plant configuration is characterized by high thermal losses at the condenser, since only a little share of the thermal power available to the fluid is converted by the expander. The daily electricity generation never exceeds 2 kWh, and up to 90% the thermal power gathered at the collector is lost to the environment (about 20 kWh). An interesting option would consist in switching the position of the tank and the ORC evaporator: the residual enthalpy at the expander discharge could be stored as thermal energy for DHW needs, rather than sunk to the environment. Nonetheless, the need to restore R245fa conditions at the evaporator inlet and to avoid further ORC efficiency penalties, along with the pinch point constraint call for a strict temperature control at the condenser: such a requirement is hard to fulfill when the heat exchange is controlled by a variable draw-off profile, as the one associated with a domestic application. Hence, the possibility of multiple condensing loops can't be ruled out: it could eventually lead to increased technological complexity and cost for the plant and needs to be addressed at both a model and experimental level. In order to decouple the thermal demand for DHW and ORC, the implementation of an additional low-temperature tank downstream the condenser should be considered: it would be in charge for direct coverage of DHW needs, whereas the mid-temperature tank, downstream the collector, would continue assisting the ORC section. Apart from its energy merit, the low-grade heat recovery downstream the condenser is particularly cost effective, since the temperature levels at hand allow the use of low-cost standard materials. Based on the model, an experimental campaign can be designed, to sweep a variety of operating conditions for an actual mini-ORC plant, featuring solar thermal collectors as upper thermal source and the heat sink controlled by typical heat draw-off profiles.

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