Numerical investigation of the smart energy management of modular latent heat thermal storage on the performance of a micro-solar power plant

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Abstract:

Solar energy is widely considered as one of the most attractive renewable energy source to curb CO_2 emissions at residential level where micro-cogeneration has a very interesting potential. One promising application of solar energy is in combination with Organic Rankine Cycle (ORC) plants due to the ability to utilize low-medium temperature heat sources. However, because of the intermittent availability of solar energy, thermal energy storage (TES) systems are required to improve the performance of such systems and assure their prolonged operation. At medium temperatures, latent heat thermal energy storage (LHTES) systems allow to effectively store and release the collected thermal energy from the solar field. However, room for improvements exists to increase their efficiency when in operation. For this reason, in this work the authors have numerically investigated the performance of a 2 kW_e micro-solar ORC plant coupled with an innovative LHTES system that is going to be built and tested under the EU funded project Innova MicroSolar. The novel LHTES, developed and designed by some partners of the Consortium, is subdivided into six modules and consists of 3.8 tons of high-temperature phase change material. In this study the effect of the storage volume partialization on the performance of the integrated plant is evaluated using a fuzzy logic approach. Main aim of the storage management is to achieve a reduction of the thermal losses and improve the plant overall efficiency. Annual dynamic simulations are performed in order to determine the optimal storage volume needed in different operating conditions. Results clearly show a remarkable annual increase in electric and thermal energy production of 8 % and 6 % respectively, in comparison with the configuration without fuzzy logic control: this achievement was obtained decreasing the working LHTES modules in winter and conversely increasing them in summer.

Keywords:

Fuzzy logic, Micro combined heat and power plant, Micro-scale ORC system, Renewable energy systems, Concentrated solar power.

1. Introduction

The building sector accounts for about 40 % of the final energy consumption and 36 % of CO_2 emissions in Europe [1]. In order to curb the share of the sector on the final energy consumption and the related environmental impact, the European Union is pushing towards an improvement of the energy efficiency of buildings and an increase of renewable energy technologies penetration into the grid [2]. Among the different renewable energy technologies, Concentrated Solar Power (CSP) plants in combination with CHP systems [3] are foreseen as a valuable alternative to substitute thermal and electric power generation from fossil fuel. So far, a good contribution in this direction has been given by the introduction of concentrated evacuated tube collectors due to their optimal compromise between cost and conversion efficiency, all these advances have been promoted by recent progress in manufacturing [4]. To effectively convert the solar energy into power, Organic Rankine Cycle systems are usually adopted at small scale [3]. Thanks to their low maintenance and noise operation, as well as high reliability, ORC systems are receiving increasingly attention from academia [5][6][7] and industry [8][9].

However, in order to achieve higher conversion efficiencies and annual performance of ORC systems, solar technologies with higher concentration ratio than CPC are required. Recently, many researchers are focusing in this field. For example, Xu et al. [10] assessed the performance of a LFR-ORC system through a theoretical and simulation study. Results showed that supercritical ORC systems is better than the subcritical one independently from the considered working fluid.

At residential level micro-cogeneration has a very interesting potential [11] and thermal power output from ORC systems can be usefully recovered for Domestic Hot Water or Space Heating purposes [12].

Owing to the fact that energy production from solar technologies and user demand are not always simultaneous, thermal energy storage (TES) systems are required to decouple them and usefully extend the operation of solar plants. At present sensible heat TES are commonly adopted at low temperatures range [13] whilst at medium-high temperatures range latent heat thermal energy storage (LHTES) systems are preferred. For example, Manfrida et al. [14] mathematically investigated a LHTES in application to a solar power ORC over one week period. Authors found that the proposed plant was able to generate power for almost 80% of the simulated period with a weekly average overall solar-to-electricity efficiency of 3.9%. At the same time, they pointed out that appropriate control logics are required to improve the performance of the system over a more extended period.

Managing LHTES efficiently is a crucial point in optimizing the operation of solar energy based ORC systems. Indeed, an increase of the working fluid inlet temperature to the expander of the ORC unit entails higher electric conversion efficiency, but at the same time, it leads to higher thermal losses from the envelope to the ambient. Moreover, in case of LHTES the collected thermal energy can be efficiently recovered in the melting temperature range of the phase change material, thus it is convenient limiting its proper operation in this interval. For these reasons, under the framework of the H2020 Innova MicroSolar project [15] a consortium of three EU Universities and six EU companies coordinated by Northumbria University [16] have designed a novel 2 kWe concentrated solar ORC system coupled with a LHTES equipped with reversible heat pipes that is going to be tested in the city of Almatret, Spain. With reference to the LHTES it consists of 3.8 tons of Solar Salt, whose melting temperature is in the range 216 – 223 °C, subdivided into six modules. In this paper the authors according to a fuzzy logic approach investigate the effects of the storage partialization and its smart management on the performance of the overall plant. To the best of the authors' knowledge, some studies in literature addressed the influence of TES partialization [17][18], but none of them referred to LHTES. Therefore, the main novelties of the work rely on: (i) the development of a fuzzy logic approach to LHTES systems; and (ii) the assessment of the influence of the smart management of the LHTES on the performance of the small-scale integrated plant.

Hence, after the Introduction, Section 2 briefly reports the methodology of the work, Section 3.1 presents a description of the model of the plant while Section 3.2 the fuzzy logic control in detail. In Section 4 the effects of the LHTES smart management on the performance of the integrated system are reported and eventually in Section 5 the main conclusions drawn.

2. Methodology

A dynamic model of the Innova MicroSolar plant is developed in Matlab/Simulink and the performance of the integrated system assessed in terms of electric and thermal efficiency and energy production. The control logic implemented into the model aims at producing electricity at its maximum, whilst the thermal load is considered as a by-product which can be usefully collected by final users. In addition, a cascade fuzzy logic controller managing the operation of the subdivided LHTES system is designed with the final aim of improving the global performance of the plant. Indeed, by the results of previous simulations [19], during winter and mid seasons the main control system slowly charged the LHTES, but this energy was systematically lost due to the low enthalpy level. The smart cascade fuzzy logic control would have interesting potential on the overall annual performance of the plant because it acts predominantly in reducing such losses. Strasburg, France, is considered as location for the simulations, since it represents a temperate climate location in Europe with a medium level of solar radiation. Eventually, the obtained performances of the integrated system are compared with those of the plant operating at the same ambient conditions, but without a smart control management of the LHTES.

3. Simulation Models

3.1. The Innova MicroSolar Plant model

The Matlab/Simulink [20] plant model works under quasi-steady state conditions and the dynamic performance of the integrated system is carried out for a whole year. Meteonorm database available in the TRNSYS library has been used for weather data in terms of solar radiation and ambient temperature for the city of Strasburg, France.

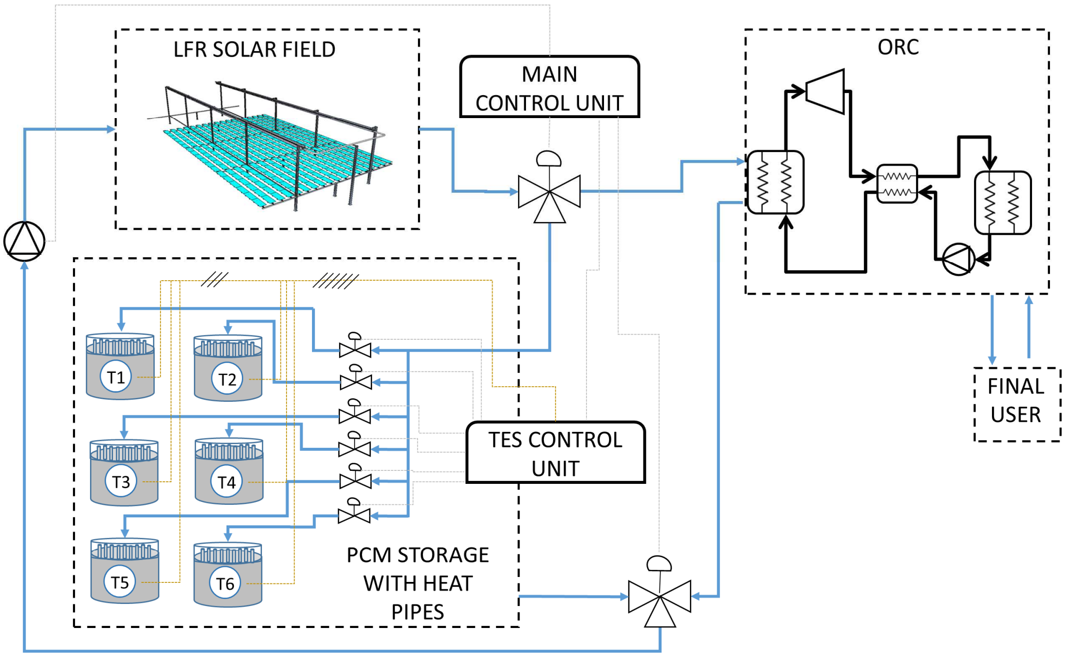

Figure 1 Schematic of the integrated system under analysis.

The following main components have been included into the model: (i) the LFR solar field; (ii) the micro ORC plant; and (iii) the PCM thermal energy storage tanks equipped with reversible heat pipes.

Specific subroutines for the LFR solar field and the PCM storage tanks equipped with heat pipes have been developed by the authors in Matlab in addition to the ORC unit. Details of the ad hoc subroutines have been reported in a previous work by some of the authors [19].

Depending on the solar radiation and the state of charge of the LHTES the integrated plant works according to different operation modes. Indeed, the diathermic oil from the solar field flows to the LHTES and/or directly to the ORC, depending on its temperature and on the amount of power collected at the receiver. On the contrary, when the power produced by the solar field is low or zero and the average TES temperature is within a given operating range ($T_{ORC,on}$ = 217 °C and $T_{ORC,off}$ = 215 °C), the thermal energy of the TES can be used to run the ORC unit and assure its operation for a maximum of 4 hours with no sun. *Table 1* reports set-points and threshold values of each operation mode.

Table 1 Operating conditions for the different operation modes of Plant

Operation Mode	Description	Operating conditions
OM1	LFR supplies ORC	T_{oil} = 210 °C
OM2	System off	-
OM3	LFR supplies TES	$T_{oil} = T_{TES,av}$+10 °C
OM4	LFR supplies TES and ORC	T_{oil} = 210°C if $T_{TES,av} < 200$ °C or $T_{TES,av} > 280$ °C otherwise $T_{oil} = T_{TES,av}$ + 10 °C if $T_{TES,av} > 200$ °C
OM5	TES supplies ORC	oil flow rate 0.22 kg/s
OM6	TES and LFR supply ORC	T_{oil} = 210 °C and oil flow rate 0.22 kg/s

In this work, the model of the LHTES is subdivided into six modules, each of them having a distinct operation and temperature range. Accordingly, the TES control unit monitors their state of charge and sends signals to the main control system to choose which one works. Further details are provided in the following section.

3.2. The fuzzy logic controller

The fuzzy logic controller has been implemented on the basis of the following assumptions. First of all, to ensure an effective LHTES charging, LFR must supply oil with a temperature greater than the storage (10°C is the temperature difference assumed). Due to the different temperature of each module, the LFR shall check the maximum temperature of the current connected LHTES module and shall supply all the connected modules with a temperature higher than that. Secondly, during the discharging phase, corresponding to OM5 and OM6 (*Table 1*), the connected LHTESS must have a temperature suitable for the ORC supply, thereby the control system of the storage allows the connection only to the modules with a temperature higher than the temperature of the ORC inlet oil. Third, the oil flow rate is split equally among the LHTES both in charging and discharging.

The fuzzy logic controller has been designed according to a cascade approach to accomplish the following tasks: (i) select the number of modules to be connected with the plant; and (ii) manage each module based on a priority scale set out by the previous decision.

In general, the performance of the plant can benefit from the partialization of the LHTES. However, the management is strictly related to the ambient and operating conditions of the whole plant and to its peculiarities. For example, based on the operation of the plant extensively discussed in [19], when the solar radiation is high and the LHTES is not fully charged, connecting a high number of modules allows to mitigate the temperature overheating of the LFR solar field, thus avoiding the inefficient defocusing of some mirrors. On the contrary, when the solar radiation is low (OM3), it is convenient to connect and charge as less modules as possible. Therefore, a close relationship exists between the outlet temperature of the diathermic oil from the LFR solar field and the number of modules to be connected. For this reason, a logarithmic function, shown in *Figure 2*, has been chosen to correlate the diathermic oil outlet temperature from the solar field with the number of modules that have to work. The LFR outlet oil temperature ranges between 210°C, corresponding to operation mode OM1, and 305°C, i.e. the maximum allowed temperature before defocusing. The logarithmic function has been preferred since it leads to a low number of modules to be connected at low temperatures, whilst at high temperatures it increases quickly to prevent the risk of defocusing.

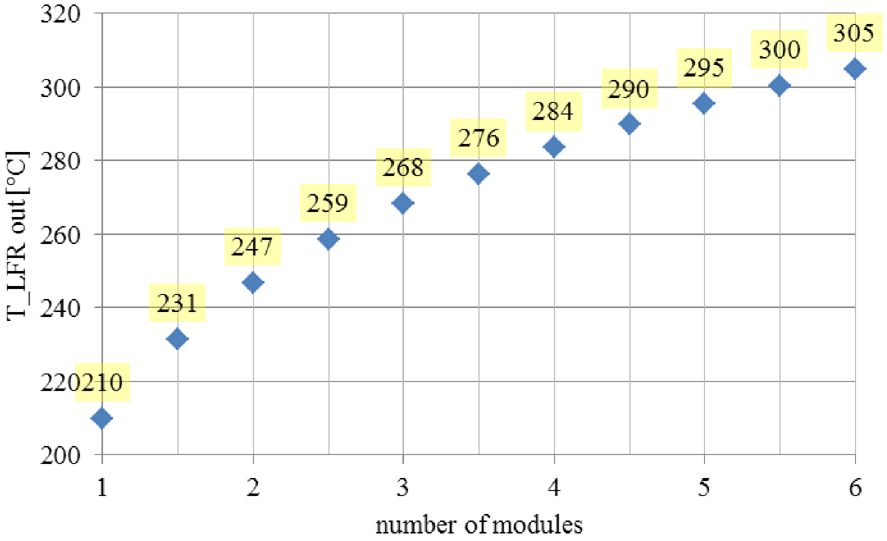

Figure 2 Logarithmic correlation between number of modules and LFR output temperature.

The fuzzy logic decision criteria is based on the above-mentioned logarithmic function, used to defined the membership functions (related in this case with the number of modules) as presented in *Figure 3*: it provides as output a not integer value correlated with the final number of modules by varying the oil temperature.

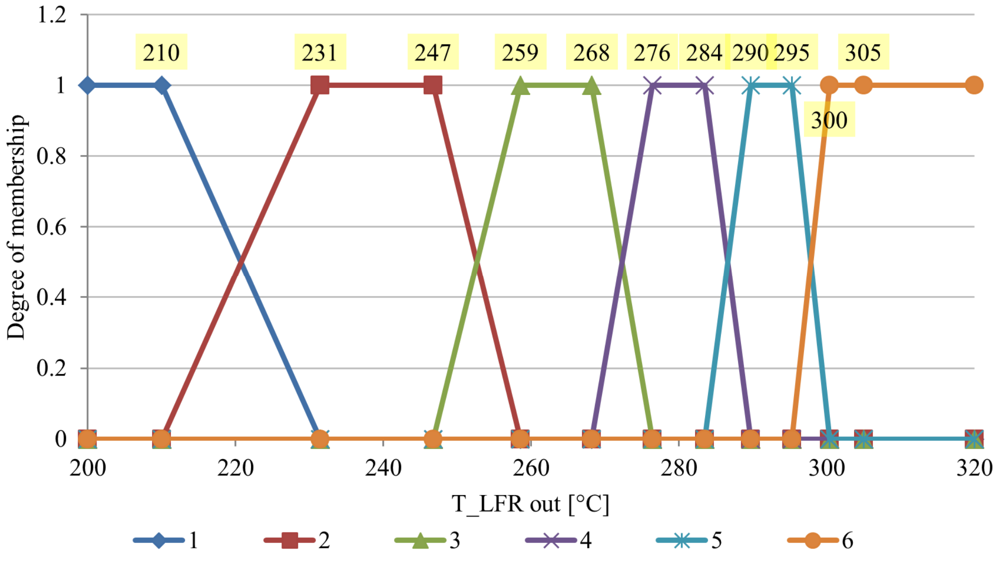

Figure 3 number of working modules by varying the solar field output temperature

Furthermore, in order to take into account more accurately the changes in the diathermic oil temperature, a second parameter, i.e. its derivative with time, is included in the fuzzy logic. Therefore, the relative membership function of the controller adds a module if the derivative is positive (T_LFR derivative greater than 0.1 °C/min) or keeps the same number of modules if the derivative is zero, and finally it reduces the number of modules in case it is negative according to *Figure 4*.

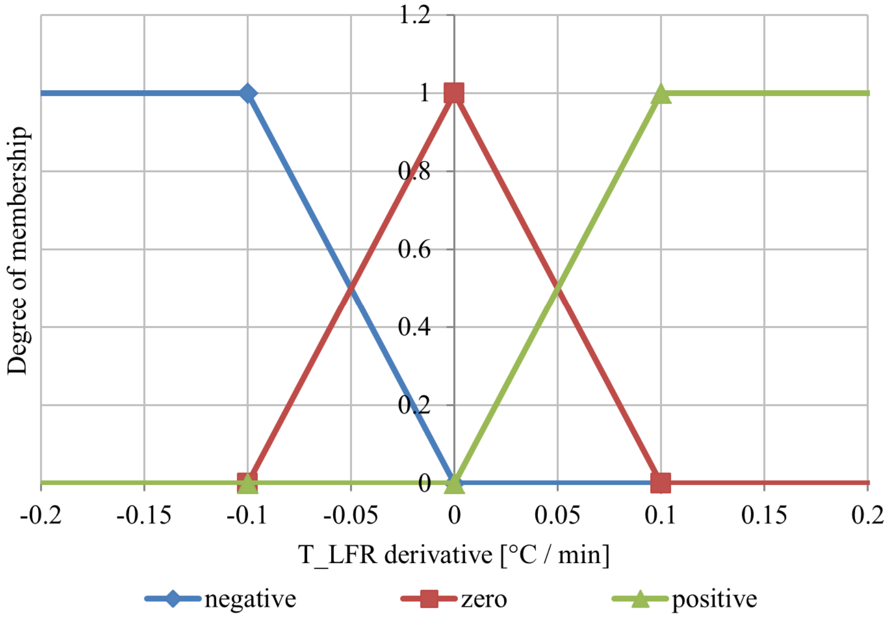

Figure 4 derivative component of the first fuzzy logic controller

Once the number of modules to be connected with the plant is assessed by the first fuzzy logic controller, a second fuzzy logic controller in cascade is applied in order to establish the working priority on the basis of the storage state of charge. The priority of charging has been chosen on the basis of the melting temperature range of the selected PCM, but also on the ORC turn on/off set points (OM5) and on the ability of oil-heat pipes-LHTES "chain" to exchange the heat efficiently among each other. The criteria for priority are as follows: (i) it is not convenient charging a thermal storage at low temperature, though the corresponding thermal losses are negligible, and at the same time the high difference in temperature between the PCM and the LFR outlet temperature facilitates the thermal exchange (preventing the defocusing). Indeed, rarely the received energy increases to the point that LHTES temperature is suitable for the ORC supply, it is often lost, and thus, it has been chosen a low priority. The low priority also occurs when the LHTES is at high temperature, since the thermal losses are high, whilst the ORC unit does not benefit of this increase in temperature. Moreover, the LHTES is less prone to receive thermal energy at high temperatures, because of the low temperature difference between the PCM and the oil and, therefore, a serious risk of LFR defocusing exists. (ii) The highest priority occurs whenever the LHTES module has a temperature close to the melting temperature range of the PCM. In this case, indeed, the thermal energy input can be exploited to run the ORC unit in OM5 and OM6. (iii) When the LHTES is at mid-high temperature, although the storage is in melting phase with good thermal exchange properties, thermal losses are significant and the temperature difference between the PCM and the outlet temperature of the diathermic oil from the LFR is quite low, it is not very convenient to charge the LHTES, therefore a mid priority is assigned. The membership functions of the second fuzzy logic controller are established and the charging of the LHTES modules occurs with the priority shown in *Figure 5*.

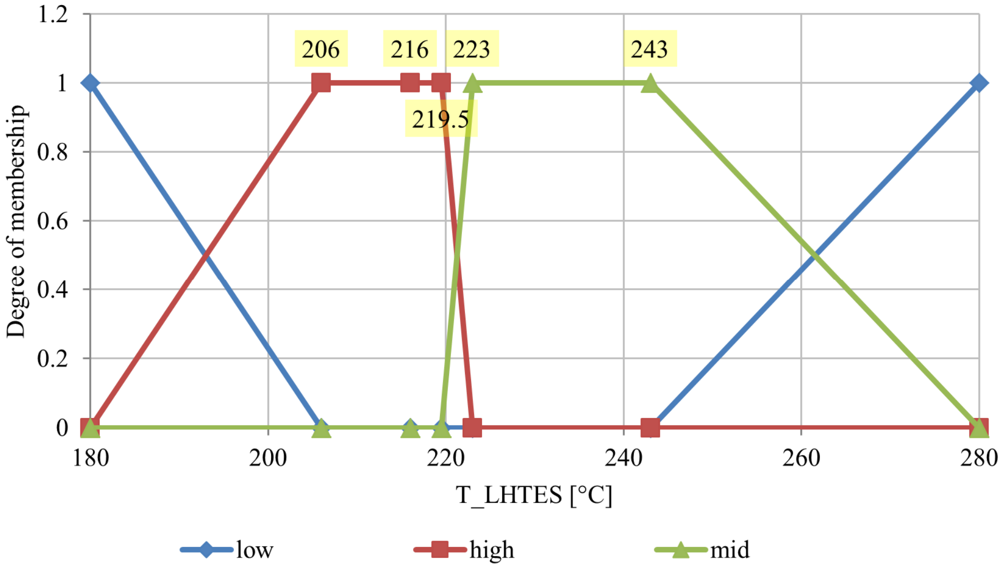

Figure 5 LHTES charging priorities

Therefore, according to the two cascade fuzzy logic controllers described above, a matrix of identification of the modules to be connected with the plant and their priority is defined. All the identification codes are managed by an ad-hoc routine, which sorts the six outputs coming from the respective fuzzy logic controllers and acts on the oil flow rate by directing it into the selected modules of the LHTES.

4. Results and discussion

In order to better appreciate the influence of the developed cascade fuzzy logic control, the performance of the plant is investigated for a whole year with an hourly time step. *Table 2* compares the yearly performance of the plant with and without smart management.

Considering the system with fuzzy logic controller, the thermal losses (tube loss) due to the piping and to the thermal storage (TES loss) account for 22 % and 12 % of the total energy available, respectively. In *Table 2* it is evident that the operation of the plant benefits from the smart management of the LHTES. While the thermal losses of the tubes are higher in case of smart management of the LHTES, the thermal losses of the LHTES are almost 8 % lower. Moreover the higher thermal production of the solar field (LFR_{out}) is reflected in more ORC operative hours ($ORC_{time,on}$) and higher mean inlet temperature, consequently it results in greater electric energy generated (EE_{out} ORC) and higher average ORC electric efficiency (ORC eff). Operation hours of the plant in OM5 and OM6 increase of 9.5 % and 7.2 % compared to the standard control. The proposed smart management allows indeed raising the temperature of the single modules, thus achieving the melting temperature range and the consequent use of the stored energy.

However, because of the intrinsic operation of the plant in case of smart management, a higher loss at the LFR solar field due to defocusing occurs also. Instead, a positive effect of the smart management is demonstrated by the augmentation of the working hours in operation mode OM5 and OM6, consequence of the best thermal management of the LHTES, which can store energy in a little quantity of PCM, thus causing a higher increase of its temperature over the exploitable threshold fixed as 215 °C (just under the melting phase).

Table 2 annual energy balance and performance of the plant with and without the smart fuzzy logic controller.

LHTESS	Single TES no fuzzy logic	TES divided in 6 modules with fuzzy logic	Variation, %
LFR $_{out}$, kJ	1.64E+08	1.74E+08	6.22
ORC $_{in}$, kJ	1.12E+08	1.18E+08	5.36
TES loss, kJ	2.00E+07	1.84E+07	-7.90
ORC time on, s	4.03E+06	4.26E+06	5.66
P $_{LFR}$ loss, kJ	7.80E+06	9.88E+06	26.73
tube loss, kJ	3.58E+07	3.97E+07	10.92
P $_{cond}$ ORC, kJ	7.20E+07	7.65E+07	6.20
EE $_{out}$ ORC, kJ	6.76E+06	7.29E+06	7.86
ORC eff, %	5.86	6.73	14.76
OM5, h	92	101	9.51
OM6, h	36	38	7.26

The analyses based on the yearly averaged values do not clearly show the exact influence of the developed fuzzy control logic on the whole performance of the plant. Therefore, the trend of the main performance parameters is shown in *Figure 6* and *Figure 7* on an average monthly basis.

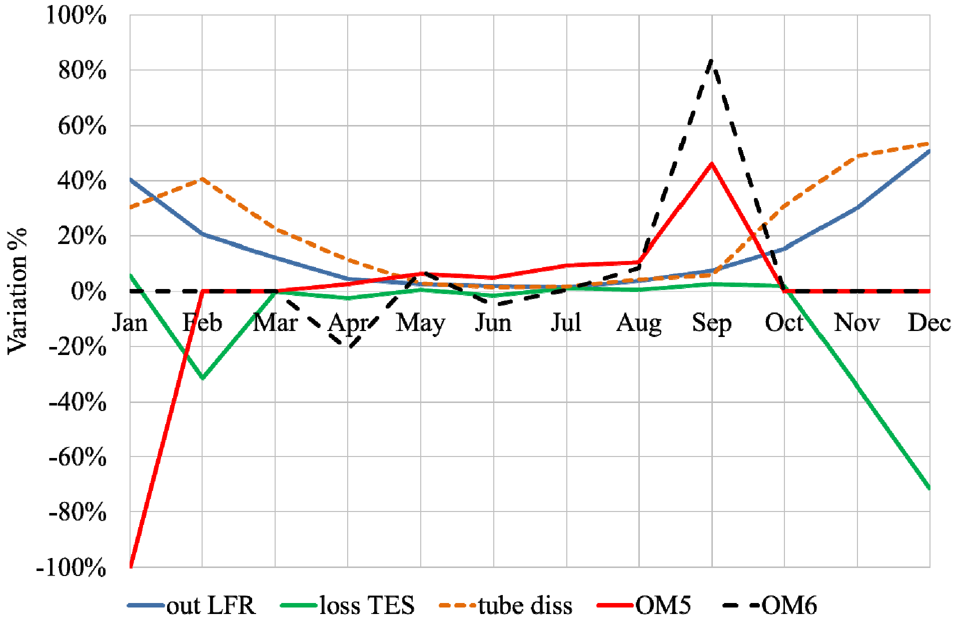

Figure 6 relative trends of performance parameters between the configuration with and without fuzzy logic.

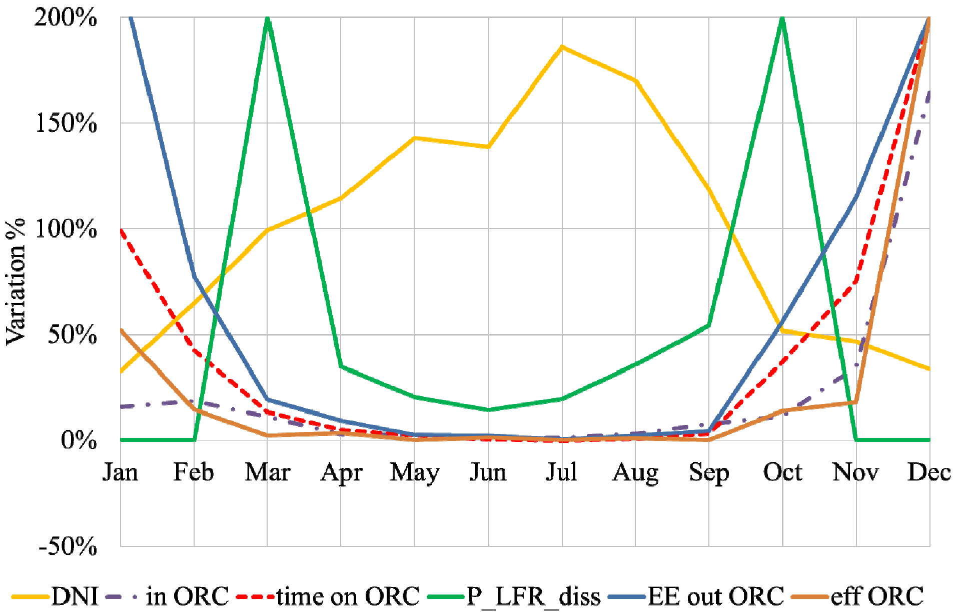

Figure 7 relative trends of performance parameters between the configuration with and without fuzzy logic.

Both Figures show the variation in percentage of the performance parameters in case of smart management compared to standard control without fuzzy logic. Although the annual results foster the fuzzy version, there are some adverse conditions that reduce its effect. In *Figure 8* the defocusing effect is empathized in the mid-season (P_LFR_diss), due to the LHTESS temperature just below the melting temperature. Such condition is more frequent during this period of the year, because in summer all the LHTES may be considered totally melted and then this behavior is attenuated. Partialization significantly reduces the storage losses (TES loss) in winter, as shown in *Figure 7* , while a secondary effect is the increase of the oil temperature in the piping highlighted by the “tube diss” variable. As result, the ORC electric efficiency and energy generated rise likewise. For sake of clarity, the monthly DNI during the year is also represented in *Figure* ***7*** in order to show the load of the plant over the year.

5. Conclusions

This paper aims at evaluating the annual performance of an innovative micro-solar CHP plant used in residential applications in case of smart management of the LHTES. In the proposed configuration the LHTES is divided into six modules and its operation is managed according to a cascade fuzzy control logic. While the main control system of the plant is designed to maximize the annual electric energy production, this further control aims at managing the LHTES system only, but, as a consequence, it affects the thermal and electric energy production of the whole plant over the year. Hence, the performances of the integrated plant are then evaluated on a monthly basis and compared to those of the plant with the LHTES without subdivision into modules and smart management. The main findings of the comparison highlight that the proposed smart management of the LHTES contributes to:

- a significant increase in the electric and thermal energy production of about 8 % and 6 % respectively over the year;
- a 6% higher thermal energy output from the LFR solar field;
- thermal losses of the LHTES system lower than 8% ;
- an electric efficiency of the ORC unit 15% higher ;
- a prolonged operation of the plant when the TES supplies the ORC (OM5 and OM6);
- 26% higher thermal losses of the LFR solar field due to its defocusing, occurring especially in mid-season.

Concluding, the adoption of a smart control management of the LHTES allows increasing the performance of an integrated micro-CHP unit powered by solar energy. Nevertheless, a further investigation is required to better estimate the exact potential of the proposed approach and a validation of the model is desirable during the forthcoming experimental tests campaign.

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