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Application of concentrating solar technologies in the dairy sector for the combined production of heat and power

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Abstract

The use of concentrating solar technologies for supplying the heat and power demand of a typical dairy factory is investigated in this paper. A yearly-based performance analysis is carried out considering different values of solar field collecting area and thermal energy storage capacity with reference to a typical meteorological data set of a Sardinian location. Specific simulation models are developed for each section of the plant. Moreover, a novel energy management strategy is developed for the determination of the priority order between thermal and electrical demand.

The results demonstrate that concentrating solar technologies could be a promising option if power and heat are both required. In particular, the presence of the energy storage section provides important flexibility features to the plant and by suitably setting the control variable, the energy management strategy allows to give priority to the heat or to the electrical demand of the dairy.

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Keywords: Solar energy; CSP; Linear Fresnel reflector; ORC; energy management strategy

1. Introduction

Nowadays, together with photovoltaic (PV) systems, Concentrating Solar Power (CSP) plants are the most effective solution for power generation from solar energy. As it is known, CSP plants use concentrating solar collectors to produce high temperature thermal energy, which is subsequently used by the power generation section. To offset the intermittence of solar energy, CSP plants are usually coupled with a Thermal Energy Storage (TES)

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section. Up to now, the thermal energy produced by the solar field has been mainly used for electricity production. However it can also be used to produce useful heat or power and heat in a combined manner. In the literature, some researchers have highlighted the potential of solar power plant for the heat and power production in industrial process [1,2] both in terms of high exploitation of solar energy and reduction of fossil fuel consumption.

Energy is a key factor for ensuring the competitiveness of dairy factories, since thermal and electrical demand significantly affect the total production costs. The use of solar energy to partially cover the dairy energy demand can be a cost-effective solution, especially for locations characterized by a high solar radiation, such as Southern Italy.

In particular, combined heat and power generation through concentrating solar collectors can be a very interesting option for users with a medium-temperature heat demand like diary factories. Because of the power and heat demand of dairy factories is usually in the range of few MW, the configuration of CSP plants significantly differs from that of large-size CSP plants. In particular, Organic Rankine Cycle (ORC) units are preferred to steam power plants [3] for small-size power blocks. The inlet temperature required by such ORC units (250-300°C) makes thermal oil the most suitable option as Heat Transfer Fluid (HTF). Moreover, with such temperature levels, linear concentrating collectors appear to be the most suitable option and Linear Fresnel Collectors (LFC), may be a viable alternative to Parabolic Trough Collectors (PTC), especially if the land requirement is a key feature [4,5]. Finally, the most suitable option for the TES section is a two-tank direct system using thermal oil as storage medium [6].

This paper reports a preliminary performance analysis of a concentrating solar plant designed for supplying heat and power to a typical dairy factory, based on linear Fresnel collectors integrated with a two-tank TES system, an ORC power plant and a solar steam generator. The study has been carried out on a yearly base by considering different values of solar field collecting area and thermal storage capacity and with reference to the typical meteorological conditions of a South Sardinia site. Moreover, the energy management strategy proposed in this study uses the state-of-charge of TES system for determining the most appropriate use of the available thermal energy and the level of integration between the heat and power generation.

2. Description of the system

Figure 1 shows the schematic diagram of the concentrating solar system considered in this paper, which includes four main sections: solar field, TES system, solar steam generator and power block. The solar field is based on linear Fresnel collectors using thermal oil as HTF. The TES section includes the hot tank, which directly stores the high temperature thermal oil produced by the solar field, and the cold tank, which feeds the solar field and collects the cold oil coming from the power block and the solar steam generator. The thermal energy produced by the solar field and stored in the TES section is used to produce low-pressure steam by means of the solar steam generator and electricity through the power block, which is based on an Organic Rankine Cycle (ORC) unit.

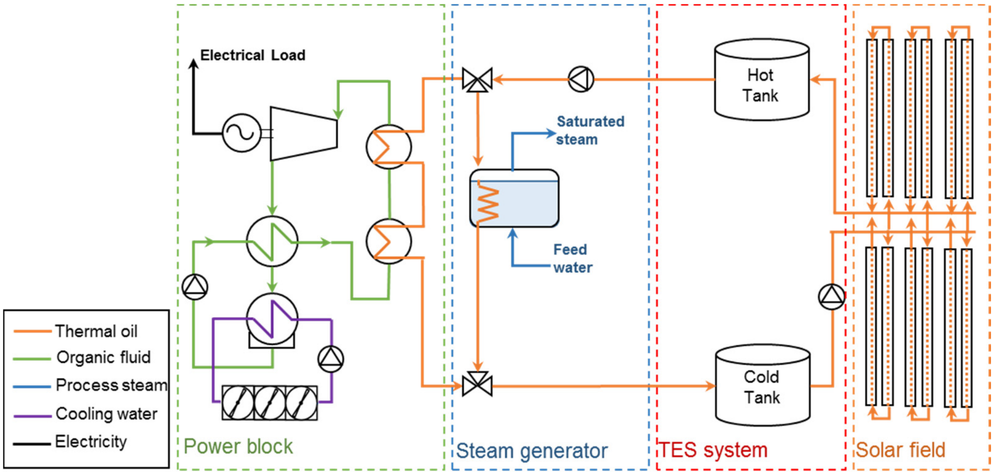

Figure 1 – Schematic diagram of the Concentrating Solar Combined Heat and Power Plant.

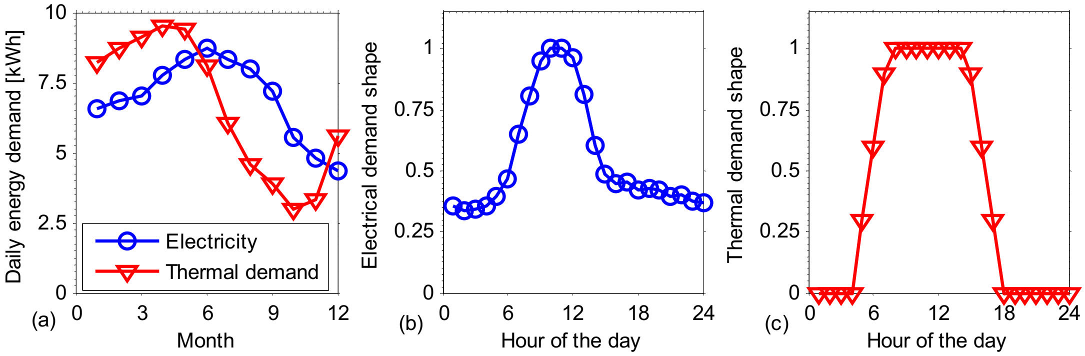

Figure 2 – (a) Monthly variation of daily electrical and thermal demand of the dairy factory and (b) electrical and (c) thermal demand curves.

The three-ways valve downstream of the hot tank is used to distribute the thermal oil to the steam generator and/or to the ORC system according to the adopted energy management strategy. The dairy considered in the present analysis is representative of a medium size factory devoted to the production of different types of sheep cheese and processes about 9-10 million liters of milk annually. The typical electrical and heat load curves have been evaluated by means of a specific energy audit [7] and the monthly and daily electrical and thermal demand are shown in Figure 2. A strong daily and seasonally dependence of electrical and thermal demand was observed during the energy audit. In fact, the thermal energy strongly depends on the amount of processed milk. During periods of milk production (winter, spring and summer) the dairy works 12 hours per day and 7 days per week and high thermal requests occurs. Instead, the cheese production stops during the autumn and heat demand reaches its minimum value. Unlike the heat requests, a not negligible electrical demand occurs during nights and autumn due to the electrical requests for the cool storage warehouses, cheese packaging and cleaning systems. The highest electrical requirements occurs during summer due to the refrigeration equipments. Overall, the ratio between thermal and electrical yearly demand is about one.

3. System modeling and assumptions

The expected annual performance of the concentrating solar plant has been assessed through a simulation model developed under Matlab® environment. Specific simulation models have been developed to evaluate the performance of the four main sections (solar field, TES system, steam generator and ORC power block) by assuming the main design parameters reported in Table 1. A dataset obtained from the Meteonorm® software is used for characterizing a typical meteorological year of the South Sardinia site. Figure 3 shows the monthly values of the average daily DNI, ambient temperature and mean wind speed.

Starting from meteorological conditions, in particular solar radiation and position, the hourly-based performance of the LFC are calculated considering their main geometrical and technical characteristics and the thermodynamic properties of the thermal oil. The thermal energy collected by the solar field (Q_{SF}) mainly depends on the available solar energy, optical losses (Q_{OPT}), thermal losses in the receiver and in the piping ($Q_{L,SF}$). Optical losses due to mirror reflectivity and absorptivity of the selective coating of the receiver tube are evaluated by means of a reference optical efficiency (η_{OPT}), corrected by the Incidence Angle Modifier (IAM), an end-loss optical efficiency (η_{END}) and a cleanliness factor (η_{CLN}). Thermal losses in the receiver tube and in the piping ($Q_{L,SF}$) are evaluated as a function of the difference between the average oil temperature inside the tube and the ambient temperature. The hourly thermal energy output is therefore evaluated as:

$$Q_{SF} = A_{SF} DNI - Q_{OPT} - Q_{L,SF} = A_{SF} \left(DNI\, \eta_{OPT}\, IAM\, \eta_{END}\, \eta_{CLN} - q_{L,SF} \right) \quad (1)$$

where A_{SF} is the collecting area of the solar field and $q_{L,SF}$ are the thermal losses per unit area. The collecting area is the main design parameter that determines the annual thermal energy produced by the solar field.

Table 1. Main design parameters of the Concentrating Solar Combined Heat and Power Plant.

Fresnel collector (Solar field)		***Thermal storage***		***Steam generator***	
Collector length	100 m	Oil density	840 kg/m^3	Process pressure	3 bar
Collector width	9 m	Specific heat capacity	2.417 kJ/kgK	Inlet water temperature	60°C
Line distance	4 m	Minimum SOC_{TES}	5%	ΔT Pinch Point	10°C
Reference optical efficiency	62%	Maximum SOC_{TES}	95%	***ORC power block***	
Cleanliness efficiency	98%	Initial SOC_{TES}	50%	Nominal power output	600 kW
Oil inlet / outlet temp	150/260°C	Average heat losses	2%	Nominal efficiency	20%

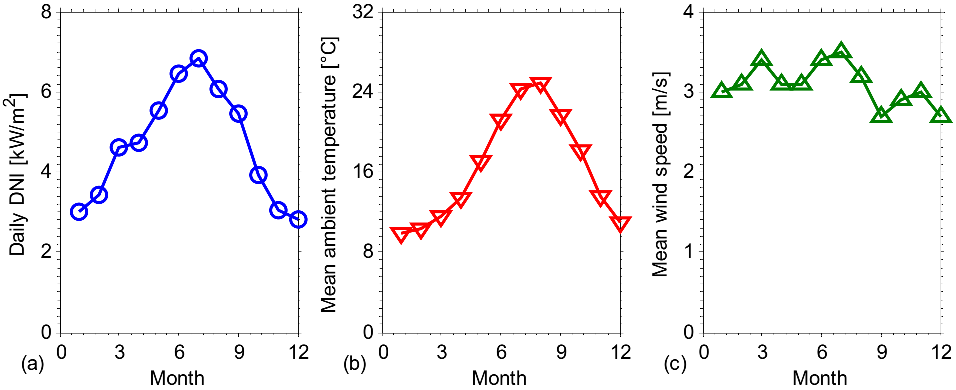

Figure 3 - Average daily values of (a) DNI, (b) ambient temperature and (c) wind speed as a function of the month.

The TES section is used to mitigate the DNI variation and to separate the production from the utilization phases. The evaluation of the available energy content of the TES section is based on its energy balance by considering the energy produced by the solar field (Q_{SF}), the energy required by both the power block (Q_{ORC}) and the steam generator (Q_{SG}), and the heat losses ($Q_{L,TES}$). According to [8], the energy balance of each tank can be expressed as:

$$m_{OIL} c_{P,OIL} \frac{dT_{OIL}}{dt} = Q_{SF} - Q_{SG} - Q_{ORC} - Q_{L,TES} \tag{2}$$

where m_{OIL} is the oil mass stored in the tank, $c_{P,OIL}$ is the oil specific heat, T_{OIL} is the oil temperature inside the tank. The storage capacity is the main design parameter of this section and depends on the on its geometrical volume. Moreover, the available energy content of the TES is evaluated by means of its state-of charge (SOC_{TES}). Because of the the oil temperature variation due to the TES heat losses is negligible (lower than 1-2 °C), the SOC_{TES} is defined as the ratio between the actual oil mass inside the hot tank and the maximum thermal oil mass. If the hot tank is completely charged (SOC_{TES}= SOC_{MAX}) and the solar field delivers more thermal power than that required by the steam generator and/or the ORC unit, the solar field is suitably defocused and the reduction of the solar field thermal power output is responsible for the so-called defocusing energy losses ($Q_{L,DEF}$). Consequently, the latter are strongly dependent from the TES storage capacity. On the other hand, if the stored oil mass reaches its minimum value (SOC_{TES}= SOC_{MIN}) the solar plant is unable to supply a share of the load demand.

The low-pressure steam required by the dairy is produced by using the stored oil in the solar steam generator. With reference to the design heat demand (900 kW_{th}), the mass flow rate and the output temperature of the oil are evaluated by imposing the minimum pinch point temperature difference and the water inlet temperature. The LMTD (Logarithmic Mean Temperature Difference) method [9] is used to evaluate the performance of the steam generator during off-design operation. The ORC power block is designed to satisfy the maximum power request by the dairy (600 kW). Starting from the ORC design efficiency (20%), the actual efficiency of the ORC unit is evaluated by considering the effect of both part load operation and air temperature.

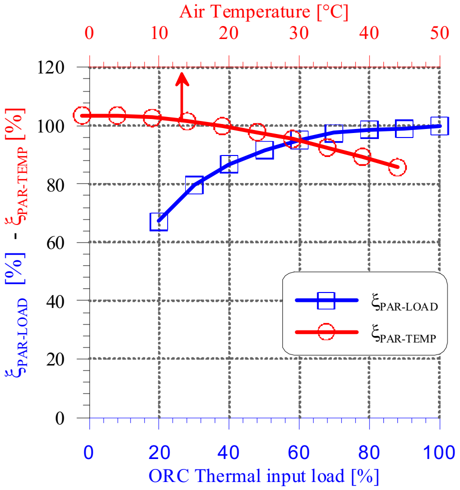

Figure 4 - Partial load effect and air temperature effect.

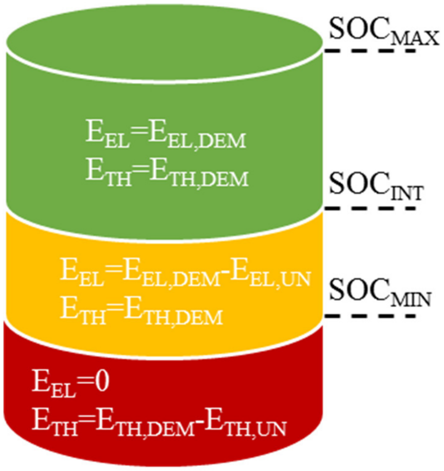

Figure 5 – SOC_{TES} values for the energy management strategy with heat demand as primary request.

Figure 4 allows to evaluate the ratio of the actual efficiency with respect to the nominal one (called $\xi_{PAR-LOAD}$) in function of the ORC thermal input. Finally, since the condensing heat is removed by using dry coolers, Figure 4 reports also the ratio between the actual efficiency and the nominal one in function of the air temperature ($\xi_{PAR-TEMP}$). The simulation model of the ORC module also computes thermal losses related to daily start-up. The start-up was considered to require 20% of the nominal thermal power for 30 min before being able to produce electrical energy.

3.1. Energy Management Strategy (EMS)

The presence of the TES section allows the concentrating solar plant to supply the electrical and thermal energy demand at different times and without a mutual dependence. The main benefit of this configuration is therefore its ability to follow only the electrical or the thermal demand or both the energy requests. The energy management strategy proposed in this paper uses as control variable the SOC_{TES}, which is directly related to the oil mass content of the hot tank. Other than the minimum and maximum SOC_{TES} values, an intermediate SOC value (SOC_{INT}) has been introduced in order to decide the most appropriate use of the available thermal energy and therefore the priority order between thermal and electrical demand. In particular, if the SOC level is higher than SOC_{INT}, both the electrical ($E_{EL,DEM}$) and thermal demand ($E_{TH,DEM}$) are completely satisfied. For SOC values lower than SOC_{INT}, the control system gives priority to the so-called primary demand (thermal or electrical, depending on user's choise), which is completely supplied, while the other is only partially satisfied or completely unmet. Finally, for SOC values lower than SOC_{MIN} the energy content of the hot tank is used to cover only the primary demand without guaranteeing its complete satisfaction. Figure 5 shows the TES use scheme considering heat demand as primary request. It is worth noting that the SOC_{INT} is a variable that largely affects the energy flows of the plant. A high value of SOC_{INT} enhances the ability of the plant to satisfy the primary energy demand but reduces the duration of the integrated heat and power generation and rises the unmet fraction for the secondary energy demand. The assumption of a SOC_{INT} level equal to SOC_{MAX} gives the maximum priority level to the primary energy demand and the secondary one can be supplied only after the complete charge of the TES and just to avoid the defocusing losses. Vice versa, if SOC_{INT} is equal to SOC_{MIN} , the same priority order is given to both heat and electrical demands.

4. Results and discussion

In this section, the results obtained for an annual simulation of the concentrating solar plant are presented. A first performance assessment has been carried out by varying the solar field collecting area and the storage capacity of the TES section, which is the volume of each of the two tanks. Obviously, the increase of the collecting area results in an almost linear increase of the thermal energy produced by the solar field. However, in order to effectively use this thermal energy, the increase of the collecting area should be joined with an increase of the storage capacity.

Figure 6a and 6b show the percentage of the electrical and thermal dairy demand supplied by the concentrating solar plant by imposing a SOC_{INT} equal to the minimum value (5%). Figure 6a and 6b demonstrate that the plant is unable to completely fulfill the electrical and thermal dairy demands. Since the system is only powered by solar energy, which is a non-programmable and seasonally dependent source, the complete supply of the annual energy demand could lead to an oversized and uneconomical plant design. For this reason, the system is planned to accept that a share of electrical and thermal load is unserved. Although the ratio between electrical and thermal annual consumption of the dairy is about one, the percentage of thermal demand satisfied by using solar energy is higher than the electrical one. As can be observed, the proposed plant is able to cover the thermal demand by about 55-75% and the electrical one by about 20-65%. The thermal demand occurs during the dairy operating hours and therefore during periods of high solar energy availability. The direct exploitation of the energy produced by the solar field decreases the need of energy time-shifting and consequently the need of a high TES capacity. On the other hand, the electrical consumption occurs even during the night, despite the presence of a peak demand during the midday. Accordingly, the use of stored oil is unavoidable to provide the night electrical demand. However, depending on the daily energy production and request, the final SOC values is often unable to meet the night electrical requests. Moreover, unlike the steam generator, a limit to the lowest power output of the ORC unit is imposed by the manufacturer (20% of the nominal power). Therefore, if the electrical request is lower than this limit value, the ORC is unable to satisfy the electrical dairy demand. Figure 6c shows the TES effectiveness, which is defined as the ratio of thermal energy actually stored in the TES system and the surplus energy produced by the solar field and not directly used by the ORC or by the steam generator. Figure 6c demonstrates that for tank volumes exceeding 300 m^3 (which allows to supply the heat and power nominal demand for about 5 hours) the TES section is always able to store over 90% of the available thermal energy and leads to a minimum use of the solar field defocusing.

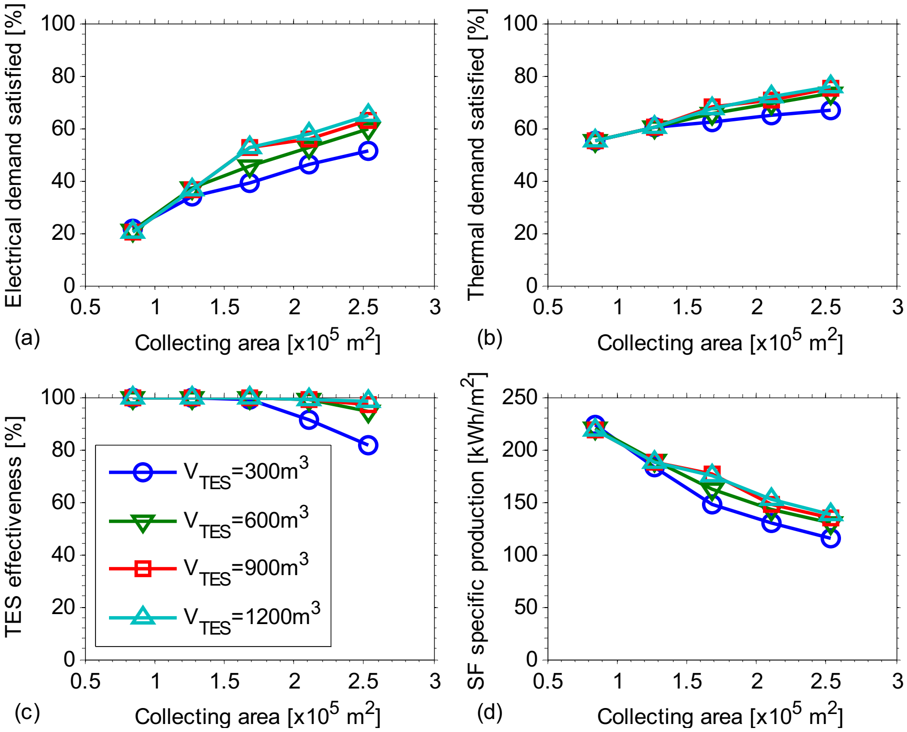

Figure 6 – CS-CHP performance as a function of collecting area and TES volume.

Instead, a storage volume of 300 m^3 (or less) results in a significant increase of defocusing losses and, at the same time, in an increase of the unmet load. Finally, Figure 6d shows the solar field specific production, which is defined as the ratio of useful thermal energy (that is the thermal energy annually used by the steam generator and by the ORC unit) and the overall solar field area. This performance parameter is a worthwhile indicator of the effective land use. Obviously, an increase of the collecting area leads to a rise in the thermal energy production of the solar field but, without a suitable storage capacity, a large amount of defocusing losses may occur with a less effective use of the land area. Therefore, this performance parameter is representative of the effective benefit resulting from the rise of the collecting area. As previously explained, the implemented control strategy uses the TES state-of-charge to give priority supply to one of the two energy requests. Figure 7 shows the effect of the SOC_{INT} parameter on the main performance of the concentrating solar plant based on a collecting area of $1.25 \cdot 10^5$ m^2 and a tank volume of 600 m^3. In particular, if the energy management strategy gives priority to the heat demand (blue line), the electrical production occurs only if significant amounts of thermal oil are stored. Consequently, the thermal energy available for the power generation is usually low and the ORC unit often operates at part-load conditions. Vice versa, if the energy management strategy favors the electrical demand (green line), the heat demand is fulfilled only for SOC_{TES} higher than SOC_{INT} whit a consequent decrease of the annual steam production. As shown in Figure 7, the variation of the SOC_{INT} largely influences the performance of the system and the share of heat and power demand covered by solar energy. Referring to the heat priority case, a remarkable rise in the solar contribution to the heat request occurs by increasing the SOC_{INT} from 5% (about 60% of heat demand covered by solar energy) to 25% (more than 85% of solar energy share). However, with higher SOC_{INT} values the increase of solar contribution becomes more and more marginal and even with a SOC_{INT} =75%, namely, by using almost all the available energy for heat production, the concentrating solar plant is unable to completely fulfill the dairy heat demand. Obviously, with the rise of SOC_{INT}, the ORC electricity production decreases. Overall, the solar contribution to the dairy electrical consumption linearly reduces from 38% to 23% by varying the SOC_{INT} from 5% to 75%. The electrical priority case shows an opposite trend: by increasing SOC_{INT} from 5% to 75%, solar contribution to the electrical demand only rises from 45% to 50% while that to heat demand drops from 36% to 0%. This result is strictly related to the presence of a significant electrical demand even during periods of low solar energy availability (nights and winter). Overall, Figure 7 demonstrates that with the adoption of a suitable energy management strategy the concentrating solar plant is able to cover almost all the annual heat demand but only about 50% of the electrical consumption. Finally, Figure 7c shows the effect of the EMS and SOC_{INT} level on the main energy losses of the solar field and TES sections. In particular, the energy losses are reported as a percentage of the available solar energy input minus the optical losses of the solar concentrator. As shown by Figure 7c, the energy losses of the solar field $Q_{L,SF}$ (thermal losses of receiver tube and piping) accounts for about 13-15% of its potential production. Moreover, these losses are almost constant for the electricity priority case while decrease by increasing the SOC_{INT} level for the heat priority case. In fact, by favoring the use of the steam generator, its lower outlet temperature with respect to the ORC unit leads to a lower receiver inlet temperature and therefore lower thermal losses.

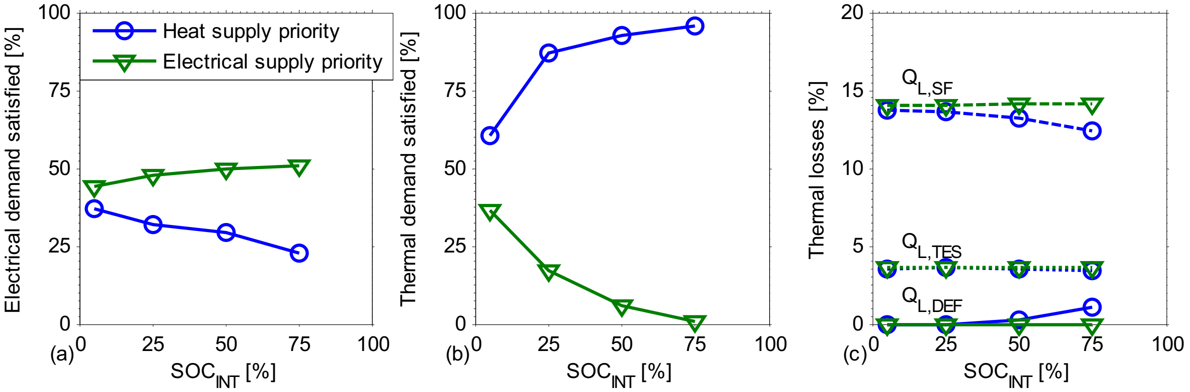

Figure 7– Plant performances as a function of the energy supply priority and the SOC_{INT} level.

The TES thermal losses $Q_{L,TES}$ are almost independent from energy management strategy and account for 3.5% of the solar field energy production. Finally, defocusing losses $Q_{L,DEF}$ are observed only for the heat priority case and increase with SOC_{INT}. Defocusing losses occurs especially during clear days of autumn, when the dairy heat demand is very low, the solar energy availability is high and the hot tank is completely charged. Overall, the sum of the above mentioned energy losses is almost constant and equal to about 16-17%. Moreover, since the optical losses (not reported in Figure 7c and equal to about 53-54% of the energy production) do not depend on the energy management strategy, less than 30% of the available solar energy is actually available for the use in the ORC power block and/or in the steam generator, independently from the adopted energy management strategy.

5. Conclusions

The study presented in this paper is the first step of a more wide research project aimed to evaluate the capabilities of concentrating solar technologies designed for supplying heat and power. In particular, with reference to a typical dairy factory located in Sardinia, the study investigated the influence of the most important design parameters (solar field collecting area and TES storage capacity) and the adopted energy management strategy on annual energy performance of the plant. The results demonstrated that the presence of a TES section provides important flexibility features to the plant and that by using the state-of-charge as control variable, the energy management strategy allows to give priority to the heat or to the electrical demand of the dairy.

As expected, the study proved that solar energy contribution to the heat and electrical annual consumption of the dairy raises by increasing both the collecting area of the solar field and the storage capacity of the TES section. However, these two design parameters must be suitably adapted in order to avoid excessive defocusing losses with the consequent uneffective use of the land area. In fact, the latter issue can be a key feature in the design of a solar plant for existing factories with a noticeable energy consumption. For the case study considered in this paper, the results demonstrated that unless the adoption of very high and uneconomical values of both solar field collecting area and TES capacity, the concentrating solar plant is unable to completely fulfill the energy demand of the dairy. If no priority is given to the heat or to the electrical demand, the plant is more suitable to supply heat rather electrical energy. However, by setting a suitable value for the TES control variable, the energy management strategy allows to give priority to the heat or to the electrical demand, thus increasing the corresponding solar contribution share. On the contrary, the energy management strategy causes only negligible effects on the overall energy losses of the solar field and TES systems. Future developments of this preliminary study must be directed towards the assessment of the economic performance of this kind of concentrating solar plant.

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