DESIGN OF ORC SYSTEMS UNDER VARIABLE INPUT PARAMETERS: A MULTI-SCENARIO APPROACH

Mario Petrollese[1]* and Daniele Cocco[2]

[1]University of Cagliari, Department of Mechanical, Chemical and Materials Engineering, Cagliari, Italy
petrollese@unica.it

[2]University of Cagliari, Department of Mechanical, Chemical and Materials Engineering, Cagliari, Italy
daniele.cocco@unica.it

* Corresponding Author

ABSTRACT

Organic Rankine cycle (ORC) powered by solar energy is a viable and effective option for a high efficiency conversion of solar thermal energy into electricity at a distributed scale. However, the fluctuations of the thermal energy produced by the solar collectors often force solar-based ORC systems to operate at part-load conditions. Consequently, the intrinsic uncertainty of solar irradiation requires the development of novel approaches able to give robustness to the design phase of power generation systems fed by solar energy. A novel methodology for the preliminary design of solar ORC systems, based on the minimization of the expected Levelized Cost of Energy (LCOE) under variable input conditions is therefore proposed and analyzed in this paper. The expected variations of the solar irradiation together with the fluctuation in the ambient temperature that affects the condenser pressure, are considered during the design phase by adopting a multi-scenario approach. The proposed methodology has been tested by referring to a medium-scale ORC unit and by considering different working fluids. As case studies, the direct coupling of the ORC unit with a solar field and the integration of a Thermal Energy Storage (TES) system have been investigated. In all the cases, the results obtained by using a multi-scenario approach have been compared with those obtained by a single-scenario approach, achieving a lower value of the actual LCOE. In fact, the ORC configuration obtained by adopting a multi-scenario approach is characterized by lower performance under design conditions, but it is less sensitive to the variation of the main inputs. This fact is particularly evident for the case with the direct coupling of the solar field, where important fluctuations in the heat source mass flow rate are expected, while it becomes more and more marginal with the rise in the TES storage capacity.

1. INTRODUCTION

Among the various advantages in using Organic Rankine Cycle (ORC) units for the thermal-to-electricity conversion of medium- and low-grade heat sources, the great flexibility at off-design conditions with limited efficiency drops makes this technology particularly suitable for the operation under variable conditions (Macchi and Astolfi, 2017). The determination of the working point of the ORC unit at part-load conditions can be intentional, for instance in case the turbogenerator operates in isolated grid for the supplying of variable loads, or accidental, when undesirable fluctuations in the heat source and heat sink characteristics occur. The variability in heat source characteristics arises both in terms of fluctuations in the mass flow rate and temperature and it is typical in the recovery of waste heat or in the exploitation of not-dispatchable renewable energy sources (Pethurajan et al., 2018). In particular, solar energy is a promising renewable heat source for ORC systems but the daily and annual fluctuations of the thermal energy produced by the solar collectors often force solar-based ORC systems to operate at part-load conditions. Regarding the heat sink characteristics, a variation in the cooling fluid inlet temperature is typical of condenser cooling systems based on dry air coolers or cooling towers, where a dependence on the ambient temperature occurs. The operability of ORC units under variable input parameters has been largely studied in literature with a particular focus on the development of reliable models for the evaluation of the ORC performance under off-design conditions. In this regard, Dickes et al. (2017) compared three modelling methods for the ORC off-design simulation, where experimental measurements gathered on two ORC facilities were used as reference for the models' calibration and evaluation. The effects of the ambient temperature variation on low- and medium-temperature ORC systems were analyzed by Usman et al. (2017), and both dry air coolers and cooling tower installed at different geographical locations were considered. The actual operability of a ORC unit integrated with a solar field was analyzed by He et al. (2012) through the development of a proper simulation model and the system performance were analyzed considering four typical days. The important variations in the ORC performance during the off-design conditions as well as their dependence on the design features of the main components was proved and highlighted by the previous studies. For this reason, the proper characterization of the heat source and heat sink, including their foreseen variation, could be beneficial even during the ORC design process, leading to more robust design solutions able to achieve better mean performance during the overall plant operation phase. Obviously, a robust design is obtainable if the uncertain input parameters can be characterized and their variability is predictable in a certain way. This is the case of solar energy, which is characterized by daily fluctuations, but its annual availability can be statistically forecasted. The robust optimization of ORC units under variable input parameters is quite elusive in the state of the art. Among the few studies available in literature, Hajabdollahi et al. (2015) proposed a thermo-economic optimization of a solar-based ORC plant where the main design parameters (evaporator and condenser pressures, working fluid mass flow rate and regenerator effectiveness) were optimized to maximize the relative annual benefit by considering the hourly system performance. Mavrou et al. (2015) proposed a systematic sensitivity procedure considering the impacts of working fluid and ORC design/operating decisions on the ability of the ORC unit to face operating conditions different from the nominal one. A robust optimization approach for the waste heat recovery of heavy duty engines was proposed by Bufi et al. (2017), where the fluctuations of exhaust gas mass-flow and temperature have been evaluated. A two-step optimization methodology for the design and off-design optimization of geothermal ORC units was proposed by Van Erdeweghe et al. (2019), where the off-design performance were calculated for the expected net present value.

In this framework, the authors have recently proposed a novel methodology for the preliminary design of an ORC unit based on the minimization of the expected LCOE under variable input conditions (Petrollese and Cocco, 2019). In particular, a multi-scenarios approach is used to characterize the uncertainty of the input parameters, where a given number of scenarios with their corresponding probability is generated based on the annual expected fluctuations in the heat source and heat sink.

In this paper, the proposed methodology has been tested by referring to a medium-scale ORC unit and by considering different heat source and heat sink characteristics as well as different working fluids. As case study, the direct coupling of the ORC unit with a solar field has been investigated. Furthermore, the introduction of a thermal energy storage system, with the consequent reduction in fluctuations of the heat source mass flow rate, is also examined. In all the cases, the results obtained by using a multi-scenario approach have been compared with those obtained by a single-scenario approach.

2. METHODOLOGY

The proposed methodology used for the preliminary design of an ORC unit considering the expected heat source and heat sink variability is schematically shown in Figure 1. The first step is related to the choice of the working fluid (and the definition of the corresponding thermodynamics properties) and the proper characterization of the heat source (HTF mass flow rate) and heat sink (ambient temperature) by means of a scenarios generation. Starting from the expected variability of these inputs throughout a given reference period (one year in this study), a specified number of scenarios with a certain probability of occurrence is defined through the class discretization of the frequency distribution of the given parameter. Consequently, each scenario is represented by the mean value of the represented class range and a corresponding probability of occurrence. The latter is calculated as the ratio between the frequency (in hours) of the class and the overall operating hours of the ORC unit.

Subsequently, an optimization procedure is implemented for the identification of the ORC design achieving the minimum expected LCOE. Five independent design variables are optimized, namely, condensing temperature (T_{CD}, directly related to the minimum cycle pressure) evaporating temperature (T_{EV}, directly related to the maximum cycle pressure), degree of superheating (ΔT_{SH}, that is the difference between maximum cycle temperature and evaporating temperature), recuperator effectiveness (ε_{REC}) and working fluid mass flow rate ($\dot{m}_{WF}$). Because of the non-linearity of the mathematical problem, a genetic algorithm was used to find the optimum solution. For the case presented here, an initial population of 100 individuals was built inside the range of variability defined by the lower and upper bounds of each variable. It is noteworthy to observe that the algorithm stops if the average relative change in the best fitness function over the 50th generation is less than 0.1%. For each individual of the population (which represents a possible ORC configuration), the expected LCOE is calculated according to three steps. The first step corresponds to the design stage of the ORC unit, where the thermodynamic cycle under design conditions is defined according to the five independent variables and the preliminary design of the main components, (heat exchangers area and turbomachinery size) as well as an estimation of the investment and annual costs of the ORC unit is carried out. The second step regards the assessment of the ORC performance under off-design conditions. By considering the ORC unit designed in the previous step, its expected performance is calculated for each scenario considered and, accordingly, the annual energy produced by the ORC unit is evaluated starting from the corresponding probabilities of occurrence. Finally, the expected levelized cost of energy of the ORC unit, that is the objective function of the optimization problem, is estimated.

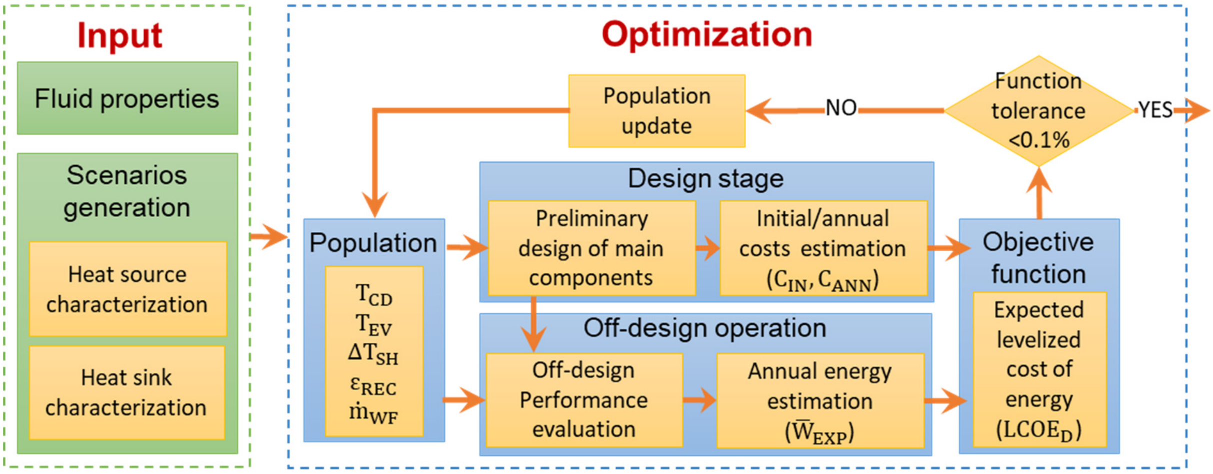

Figure 1 - Schematic procedure adopted for the preliminary design of a solar-based ORC unit

As formulated, the optimization problem requires the development of proper ORC models for the preliminary design of the main components and for the evaluation of the ORC performance during off-design conditions. The thermodynamic cycle under the design conditions is completely defined by the five variables to be optimized (a subcritical recuperative cycle is assumed). Limitations both in the minimum temperature difference inside the heat exchangers as well as in the heat source outlet temperatures are introduced as constraints. Since both the inlet and outlet temperatures of all the heat exchangers are known, the LMTD method is used for the evaluation of the overall heat transfer area of pre-heater, evaporator, condenser and, in case, recuperator. The turbine design isentropic efficiency, together with the number of stages, is calculated according to the correlations proposed by Astolfi and Macchi (2015), as a function of the size parameter and the volume ratio, while the specific speed was optimized for each case. The heat transfer area of preheater/evaporator (A_{EV}), recuperator (A_{REC}) and condenser (A_{CD}), together with the nominal power of both turbine ($\dot{W}_T$) and pump ($\dot{W}_P$) are used for the calculation of the overall investment cost. The latter is calculated as the sum of the bare module costs, that are the product of the purchased equipment cost (C_p^0) and the bare module factor (F_{BM}) of the five main ORC components, in accordance with the approach proposed by Turton et al. (2008), while the annual operating costs (C_{ANN}) are assumed equal to 2% of the overall investment cost.

The off-design simulation model is developed for the calculation of the actual net power produced in each scenario considered. The ε-NTU method is adopted for the assessment of the heat exchanger performance. According to Gabbrielli (2012), the turbine operates in a sliding pressure mode, with a fixed nozzle area and the Stodola's ellipse approach is used as calculation of the turbine inlet pressure. The complete evaporation of the working fluid is imposed in the evaporator to avoid liquid formation inside the turbine, while the partial evaporation of the pressurized liquid inside the recuperator is not permitted. Finally, a constant temperature difference of the condenser cooling water is assumed, independently from the chosen scenario and a suitable cooling water mass flow rate is determined for assuring the complete condensation of the working fluid stream. Therefore, the expected yearly ORC net energy production ($\overline{W}_{EXP}$) is computed as the product of the expected annual operating time (t_{OP}) and the weighted mean value of the net ORC power estimated in each scenario, being the weights the probabilities of occurrences (p_s) of the various scenarios:

$$\overline{W}_{EXP} = t_{OP} \cdot \sum_{s=1}^{n_S} p_s \cdot \dot{W}_{NET}(s) \tag{1}$$

The estimation of the LCOE during the preliminary design of the ORC unit (called design LCOE - $LCOE_D$) is therefore computed by using the following correlation:

$$LCOE_D = \frac{C_{IN} + \sum_{n=1}^{N} \frac{C_{ANN}}{(1+i)^n}}{\sum_{n=1}^{N} \frac{\overline{W}_{EXP}}{(1+i)^n}} \tag{2}$$

where i is the discount rate (set equal to 7%) and N is the expected plant lifetime (assumed equal to 20 years. It is worth noting that the overall costs for the calculation of the expected LCOE directly depend on the design cycle, while the expected net energy production depends on the behavior of the system during off-design operation.

2.1 Operating phase

Once the preliminary design of the ORC unit is completed and the system configuration is optimized according to the scenarios considered, the actual performance of each ORC configuration are computed by simulating the yearly operation of the ORC unit, by taking into account the hourly fluctuations of the HTF mass flow rate and ambient temperature. In this way, the effective yearly ORC net energy production ($\overline{W}_{EFF}$) can be calculated as:

$$\overline{W}_{EFF} = \sum_{t=1}^{8760} \dot{W}_{NET}(t) \cdot \Delta t \tag{3}$$

where Δt is the time step, imposed equal to 1 hour. Consequently, the effective LCOE occurring during the operating phase of the ORC unit (called operating LCOE – $LCOE_{OP}$) can be calculated by substituting in eq. (2) the expected yearly energy production, $\overline{W}_{EXP}$, with the effective yearly energy production, $\overline{W}_{EFF}$.

3. CASE STUDY

A typical configuration of a medium-size solar ORC plant was chosen for the application of the proposed design methodology. The solar field used as heat source of the ORC unit refers to the existent solar field of the Ottana solar facility (Petrollese et al., 2018). This solar field is based on six linear Fresnel collectors and it is characterized by an overall net collecting area of about 8500 m^2, which corresponds to a solar multiple of about 1.5. The Heat Transfer Fluid (HTF) is a thermal oil (Therminol SP-I) with an inlet and outlet temperature of 165 °C and 275 °C. These temperatures also correspond to the minimum heat source outlet temperature and the heat source inlet temperature imposed in the optimization problem, respectively. The nominal HTF mass flow rate ($\dot{m}_{HTF}$) for the ORC unit is imposed equal to 12 kg/s but a maximum HTF mass flow rate of 18 kg/s circulating in the solar field is considered. Starting from the meteorological data set obtained from the Meteonorm software for the location of Ottana, the expected solar field performance during a typical year have been calculated in terms of HTF mass flow rate. In a first case study, the direct coupling of the ORC unit with the aforementioned solar field is investigated, without any thermal energy storage (TES) system. Consequently, the ORC unit is frequently fed by HTF mass flow rates far from the nominal one (12 kg/s) due to the large variability of the solar radiation. On the other hand, to minimize these fluctuations and to reduce the operating time at off-design conditions, the case with the inclusion of a TES system is also analyzed. In particular, two different storage capacities (h_{TES}), namely, 2.5 and 5 equivalent hours of ORC operation under nominal conditions, are considered.

Figure 2(a-b) shows the frequency distributions of the HTF mass flow rate feeding the ORC unit during one year by considering three and five scenarios, respectively, and for the three TES capacities (0, 2.5 and 5 hours). With reference to the three scenarios case (Figure 2(a)), the introduction of a storage system leads to an important increase of the ORC operating hours at nominal HTF mass flow rate, reaching almost 90% of occurrence for the case h_{TES}=5 h. On the contrary, the ORC operates at part load conditions for almost half of the operating time in case of direct coupling with the solar field. The introduction of five scenarios (Figure 2(b)), with a consequent decrease of the class range, results in a more detailed frequency distribution.

Together with the variation in the heat source mass flow rate, the change in the ambient temperature determines some effects on the ORC performance if dry air coolers or, to a lesser extent, cooling towers, are used in the cooling water circuit. This is due to the influence of this parameter on the ORC condenser temperature, and thus to the cycle performance. Although this effect is of minor importance compared to that of the heat source mass flow rate variation, the expected variation of the ambient temperature during the ORC operation could be introduced through the definition of proper scenarios. In particular, Figure 2(c) shows the frequency distribution of the ambient temperature during the operating hours of the aforementioned Ottana ORC unit, by considering 3 scenarios. Starting from the ambient temperature, the cooling water inlet temperature was calculated by assuming an approach temperature of 10 °C in the dry air cooler.

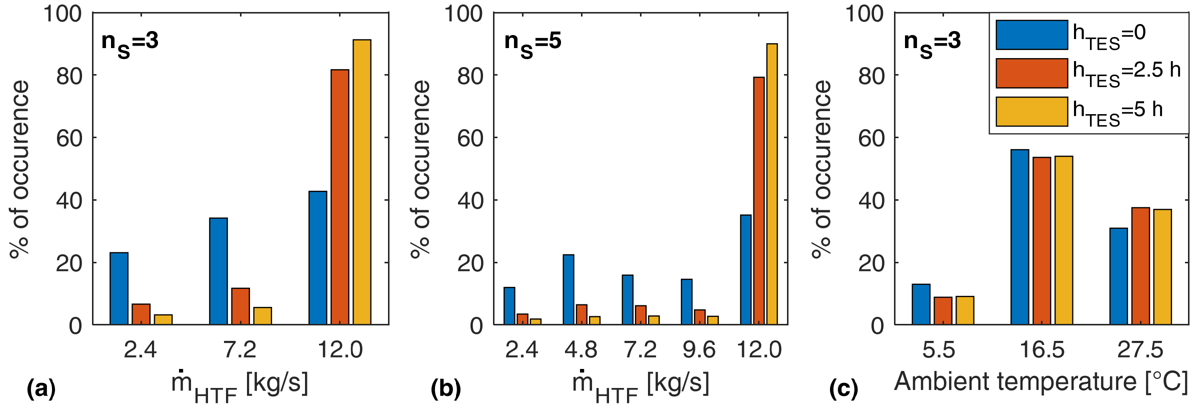

Figure 2 – (a) Yearly percentage of occurrence of the HTF mass flow rate feeding the ORC unit by assuming 3 scenarios or (b) 5 scenarios and (c) yearly percentage of occurrence of ambient temperature during the ORC operating time capacity by assuming 3 scenarios as a function of the TES storage capacity

4. RESULTS AND DISCUSSION

Starting from the characteristics of the solar field and the TES section discussed in the previous section, the results obtained in terms of preliminary design of an ORC unit based on a multi-scenarios approach are compared to those obtained by the single-scenario case (i.e. without considering the HTF mass flow and the ambient temperature variations during the design step). In particular, the cases with 3, 5 (by considering the sole HTF mass flow rate variations) and 9 scenarios (which includes also the ambient temperature variations) are analyzed. Five different organic fluids (benzene, cyclopentane, MM, octane and toluene) are chosen as possible working fluid candidates since they are characterized by suitable values of critical temperature and pressure and suitable molecular complexity for guaranteeing a dry expansion. Coolprop database was used for the fluid properties evaluation.

By referring to the case study without the presence of the TES section, Table 1 reports the optimized five variables achieved after the optimization process procedure, together with the corresponding "design" LCOE (that is the value of the objective function calculated during the design phase). Moreover, for comparative purposes, Table 1 also reports the "operating" LCOE, which is here assumed as representative of the effective LCOE achieved during the operating phase of the ORC unit. The main differences between the ORC design optimized with multi-scenarios approach instead of a single-scenario one and common to all the working fluids examined is the increase of the maximum cycle temperature and, in particular, the superheating section size. In fact, thanks to the higher degree of superheating, the proposed ORC design leads to a lower decrease in the evaporating pressure with the reduction of the HTF mass flow rate, resulting in a lower power drop during part-load operation. To confirm this, Figure 3 shows the variation of the ORC net power production as a function of the HTF mass flow rate by using Toluene as working fluid for the case with 3 scenarios, compared to that obtained for the single scenario case. As can be observed, although a difference in the net power production less than 10 kW occurs at nominal conditions ($\dot{m}_{HTF}$=12 kg/s), during part-load operations the ORC unit designed with the multi-scenario approach is able to produce up to 15% more power than that obtained with the single scenario approach.
Regardless the approach used, the minimization of the condensing temperature is always pursued. In particular, a slight decrease of the condenser temperature observed for the multi-scenario approach occurs thanks to the decrease in the working fluid mass flow rate. This fact leads to a higher turbine enthalpy drop and consequently toward higher specific net work. In case of a regenerative cycle (used for MM and Octane), a small reduction of the recuperator effectiveness is also found by using the multi-scenarios approach. Obviously, the design LCOE achieves the minimum value for the single scenario approach, since in this case it is assumed that the ORC unit operates always under design conditions and therefore the expected yearly energy production reaches its maximum value. On the other hand, a reduced HTF mass flow rate is involved in the calculation of $\overline{W}_{EXP}$ in the multi-scenario approach with the consequent increase of the calculated $LCOE_D$ during the preliminary design.

Table 1 - Optimal ORC preliminary design for five different working fluids by adopting the single and the multi-scenarios design methodology.

Working Fluid	Number of scenarios	T_{CD} [°C]	T_{EV} [°C]	ΔT_{SH} [°C]	ε_{REC} [-]	$\dot{m}_{WF}$ [kg/s]	Design LCOE [€/MWh]	Operating LCOE [€/MWh]
Benzene	1	48.8	220.4	1.0	-	5.6	90.9	134.4
	3	47.9	216.5	15.3	-	5.3	126.7	134.3
	5	47.7	209.2	25.3	-	5.2	124.9	133.1
	9	48.3	212.0	19.4	-	5.3	129.7	131.5
Cyclopentane	1	47.8	202.7	10.7	-	5.7	97.9	144.0
	3	46.5	201.0	27.8	-	5.3	137.8	141.0
	5	45.8	221.2	28.9	-	5.1	131.4	139.7
	9	45.7	220.1	30.0	-	5.1	135.8	138.9
MM	1	47.2	210.4	24.1	0.78	9.8	104.8	149.1
	3	46.0	219.7	30.0	0.68	8.9	145.1	147.8
	5	45.8	216.8	29.9	0.65	8.8	143.7	147.8
	9	45.9	218.0	29.9	0.67	8.8	149.1	147.8
Octane	1	49.7	225.1	3.6	0.67	6.3	98.6	145.4
	3	47.3	216.8	20.4	0.62	5.9	137.7	143.1
	5	47.0	216.6	20.6	0.62	5.9	136.8	143.1
	9	44.6	226.1	17.6	-	4.6	138.4	142.7
Toluene	1	49.4	201.1	6.4	-	5.6	91.1	134.7
	3	47.4	207.0	28.1	-	5.2	126.4	131.7
	5	47.4	207.0	27.6	-	5.2	124.5	131.4
	9	46.4	213.8	12.2	-	5.3	129.0	131.3

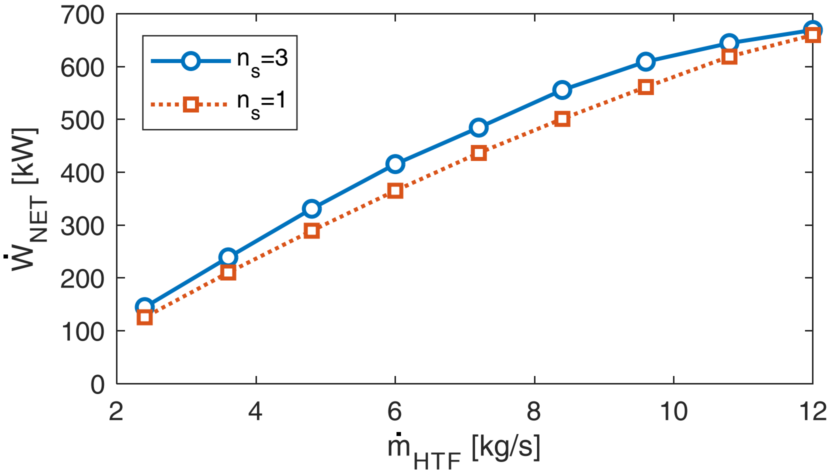

Figure 3 – Variation of the ORC power with the HTF mass flow rate using Toluene

Instead, Table 1 shows that the operating LCOE, which is calculated by considering the actual operating conditions of the ORC unit throughout one year, is higher than the design LCOE. However, the adoption of the multi-scenarios approach results in a design solution able to achieve lower values of the $LCOE_{OP}$ as well as lower differences between the $LCOE_D$ and the $LCOE_{OP}$ in comparison with the single scenario approach. This fact is observed for all the working fluids analyzed, with a general reduction of the LCOE in the order of 3-5%. The increase of the number of scenarios involved always leads to a reduction of the operating LCOE, although the marginal increment becomes more and more negligible. A higher number of scenarios also leads to a lower difference between the design and the operating LCOE, highlighting the better approximation of the design phase with the actual ORC operation. Moreover, regardless the working fluid, the design solutions proposed by the multi-scenarios approach are characterized by a design LCOE higher than that proposed by the single scenario if only design conditions are considered but less sensitive to the variation of the main inputs. This fact is shown in Figure 4, where starting from the design LCOE obtained if the ORC would operate always at nominal conditions (blue bars), the negative effects due to reduced mass flow rate (orange bars) and ambient temperature fluctuations (yellow bars) are introduced to determine the operating LCOE. As shown by Figure 4, an increase in the LCOE by considering only nominal conditions (blue bars) is observed with the rise in the number of scenarios even if a lower performance drop is obtained during the ORC part-load operation, with a consequent increase of the annual energy produced by the unit and a corresponding lower final LCOE.

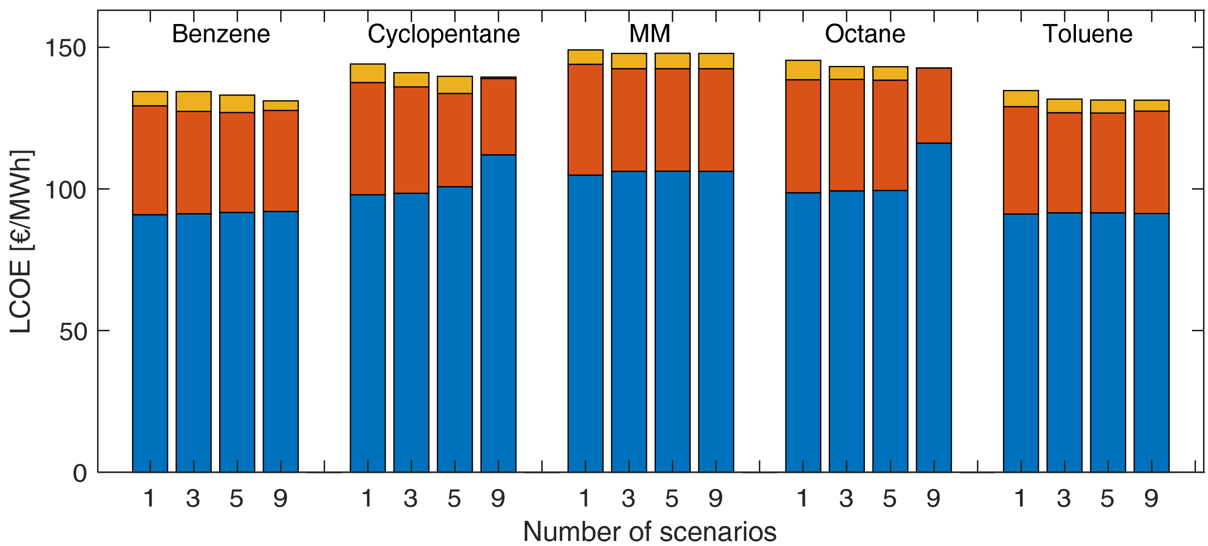

Figure 4 – Levelized cost of energy obtained for the five working fluids**.**

The Cyclopentane case well explains this behavior: the solution proposed by the multi-scenarios approach with n_s=9 is characterized by an LCOE at nominal conditions 15% higher than that obtained by the single scenario approach. However, this design solution is less sensitive to the HTF mass flow rate variation and its performance are not influenced by the temperature variation. Accordingly, the operating LCOE is 5% lower than that with n_s=1. Finally, it is worth noting that the best solution achieving the minimum value of the operating LCOE is obtained using Toluene as working fluid, unlike the case of the single-scenario approach, in which Benzene reaches the minimum design LCOE.

4.1 Solar-field + TES case

As observed in the previous section, the inclusion of a TES section reduces the HTF mass flow rate fluctuations and leads to an increase of the ORC operating hours at nominal conditions. Therefore, an improvement of the ORC performance is obtained with a consequent increase of both the average conversion efficiency and the annual energy production, with a corresponding decrease of the levelized cost of energy. The presence of the TES section, with the corresponding lower HTF mass flow variation, mitigates the benefits in using a multi-scenarios approach. In order to analyze the effect of the TES capacity on the optimal preliminary design, a TES capacity of 2.5 and 5 equivalent hours is considered by using Toluene as working fluid (that is the organic fluid with the lowest LCOE in the previous section). Table 2 reports the optimal design solution found for the two cases as a function of the number of scenarios considered during the optimization process. As observed, a decrease of the degree of superheating and a simultaneous increase of the evaporator pressure are proposed as optimal design solutions by the multi-scenario approach in comparison with the solution found in the no-TES case.

Table 2 - Optimal ORC preliminary design as a function of TES capacity by adopting the single and the multi-scenarios design methodology (working fluid: Toluene).

TES capacity	Number of scenarios	T_{CD} [°C]	T_{EV} [°C]	ΔT_{SH} [°C]	ε_{REC} [-]	$\dot{m}_{WF}$ [kg/s]	Design LCOE [€/MWh]	Operating LCOE [€/MWh]
2.5 h	1	49.4	201.1	6.4	-	5.6	91.1	124.7
	3	47.9	214.3	11.9	-	5.4	118.5	121.4
	5	49.4	220.1	5.5	-	5.4	118.5	121.3
	9	49.2	221.1	4.5	-	5.4	120.5	121.3
5 h	1	49.4	201.1	6.4	-	5.6	91.1	122.7
	3	47.3	215.0	11.8	-	5.3	116.7	121.1
	5	47.2	214.1	12.7	-	5.3	116.0	121.1
	9	49.1	221.0	1.4	-	5.4	119.2	120.4

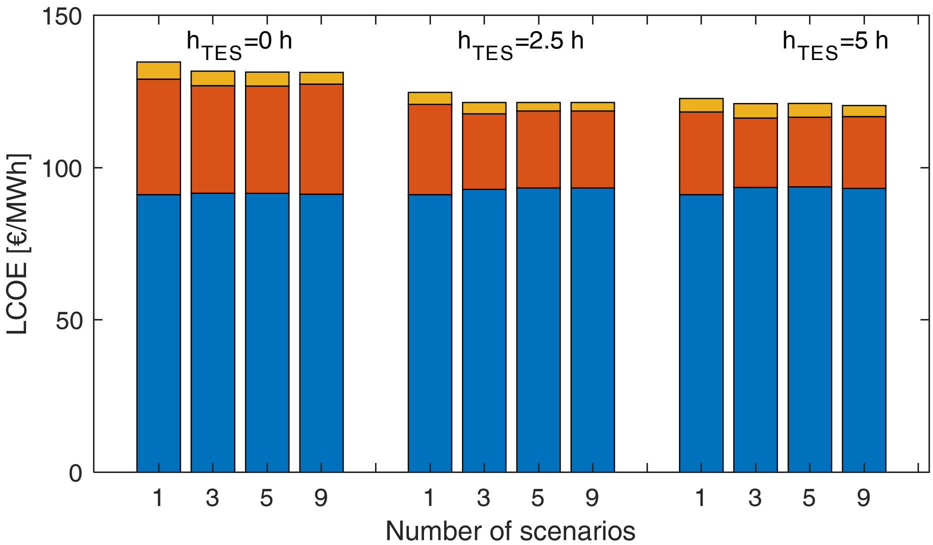

Figure 5 - Levelized cost of energy obtained for different storage capacities using Toluene

This leads to an increase of the nominal net power output of the ORC unit, which can be exploited for a higher operating time compared to the no-TES case, allowing to offset the corresponding increase of the ORC initial costs. This fact is particularly evident for the case with nine scenarios where the ambient temperature variation is involved in the optimization process. A decrease in both the design and operating LCOE is achieved with the inclusion of a TES section compared to those obtained without considering any storage system. On the other hand, although a decrease in the operating LCOE is obtained by adopting a multi-scenarios approach compared to that obtained by using a single scenario, this reduction becomes more and more marginal with the rise of the storage capacity. This is due to the attenuation of the negative effects on the LCOE led by the ORC part-load operations, as confirmed by Figure 5, where a reduction of the orange bars are observed for the case h_{TES} = 2.5 h and h_{TES}=5 h.

5. CONCLUSIONS

Although the possibility of exploiting different heat sources for the electricity production makes ORC units a useful and flexible technology, the variations in the heat source and heat sink characteristics during the ORC lifetime could strongly penalize the overall system performance. For this reason, the proper characterization of the heat source and heat sink, including their foreseen variations, could be beneficial even during the ORC design process, leading to more robust design solutions able to achieve better mean performance during the overall plant operation phase. In this framework, the approach for the robust preliminary design of ORC systems proposed by the author in a previous paper was tested by referring to an ORC unit fed by a solar field with and without the introduction of a TES system. The variability of the HTF mass flow rate due to solar radiation fluctuations, together with the variation in the ambient temperature, are introduced through the generation of proper scenarios with a corresponding probability of occurrence and the minimization of the expected LCOE has been set as objective function. The major outcomes of the study are highlighted as follows:

- The adoption of a multi-scenario approach leads to an ORC configuration less sensitive to the variation of external parameter and with an operating LCOE lower than that obtained with a single scenario approach;
- The advantages in using a multi-scenario approach instead of a single scenario approach is common to all the working fluids examined and becomes more and more evident with the increase of the uncertainty of the input parameters. Important economic benefits could therefore arise from the adoption of the proposed design methodology;
- A reduction of the operating LCOE is achieved with the rise of the number of scenarios considered even if the marginal increment becomes more and more negligible with an important rise in the computational time required to find the optimal solution.

NOMENCLATURE

C_{ANN}	annual costs	(€/year)	
C_{IN}	installation costs	(€)	
h_{TES}	TES capacity	(h)	
LCOE	levelized cost of energy	(€/MWh)	
$\dot{m}$	mass flow rate	(kg/s)	
p_s	probability of occurrence	(-)	
t_{OP}	ORC operating time	(h)	
T	temperature	(°C)	
$\dot{W}$	electrical power	(MW)	
$\overline{W}_{EXP}$	expected annual energy production	(MWh)	
$\overline{W}_{EFF}$	effective annual energy production	(MWh)	
ε	heat exchanger effectiveness	(-)	
Subscript			
HTF	heat transfer fluid	REC	recuperator
EV	evaporator	SH	superheating
CD	condenser		

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