# EXERGETIC AND ECONOMIC ANALYSIS OF A SOLAR DRIVEN SMALL SCALE ORC

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## ABSTRACT

The continuous increase in the energy demand, the reduction on the fossil fuels reservoirs as well as their malevolent impact on the environment has turned interest towards more "green" alternatives for decentralized power production. In this study, the performance of a small scale low temperature solar driven ORC is investigated for application in South-East Mediterranean region. The study includes the assessment of multiple scenarios, in terms of the working fluid, the site of installation and the solar collector's type. For each scenario a multi-objective genetic algorithm has been developed and executed in order to optimize the payback period and the mean exergy efficiency for each solar driven ORC for an annual operation using an hourly step. The results indicate that the optimum was located for all scenarios in the minimum heat storage tank capacity. On the other hand, the correlation between the solar field area and the optimization parameters is more complicated and directly connected to the climatic conditions of each considered location. The maximum exergy efficiency among the considered scenarios is in the range of 6.2% for a flat plate collectors' driven ORC using R245fa as working fluid. The minimum payback period was reported for the case of Larnaca, using parabolic trough collectors and R152a as the ORC's fluid. Finally, for a more broad comparison of the system's results, the annual energy production of the ORC was translated in primary energy savings. For this analysis, it was observed that in all cities R152a was achieving the highest savings for the maximum area of the solar field.

## 1. INTRODUCTION

Towards the direction of promoting the decentralized fossil-free power production, Organic Rankine Cycle (ORC) has gained significant attention over the last decade, both scientifically as well as in commercial scale. Based on data collected by Tartière and Astolfi (2017), the total installed capacity of ORCs was estimated to be 2701 MW, by the end of 2016.

ORC is one of the most attractive technologies towards the exploitation of medium and low grade heat sources, including solar energy (Delgado-Torres and García-Rodríguez 2007), biomass (Tchanche et al. 2011) and geothermal energy (Heberle et al. 2016). Among them, solar thermal collectors represent the most promising candidate for providing the driving heat to the ORC, given the abundance of solar irradiance in the investigated region and the maturity of the collectors' market (Karellas et al. 2018).

Several theoretical and experimental investigations have been conducted on the evaluation of solar driven ORC systems. For low grade heat sources, flat plate collectors (FPC) are most commonly used, thanks to their low cost (Wang et al. 2010). On the other hand, for higher temperatures applications, parabolic trough collectors (PTC) are preferred owing to their efficient operation under higher temperatures (Kalogirou 2004).

Desai and Bandyopadhyay (2016) compared the performance of PTC driven conventional water-steam Rankine cycles and ORCs. With a peak collector's temperature of 400 °C and a heat input of up to 4.7 GW, the levelized cost of electricity (LCOE) was estimated to be around 0.334 $/kWh and

0.364 \$/kWh using R113 and isohexane, respectively; the respective value for conventional water-steam Rankine cycle was 0.353 \$/kWh. Quoilin, Orosz, et al. (2011) performed a theoretical investigation on a PTC driven ORC. The results of the analysis indicated that the maximum overall efficiency of 7.9% could be achieved using Solkatherm (SES36) as working fluid, with a maximum temperature of 169 $^{o}$C. On the other hand, from a techno-economic point of view, the optimal working fluid was determined to be R245fa, which resulted in an overall system efficiency of 6.9%.

Calise et al. (2015) evaluated the performance of a regenerative ORC, driven by evacuated tube collectors (ETC) for the meteorological data of Naples, Italy. For a varying driving temperature between 180-230 °C, the maximum obtained thermal efficiency of the ORC was in the range of 10%, using R601 as the working medium of the cycle. On the other hand, Abam et al. (2018) compared several ORC configurations using as working fluids R245fa, R1234yf and R1234ze. For the optimum configuration, using R245fa, the maximum calculated exergetic efficiency ranged between 22-31%. The relatively high exergetic efficiency is highly attributed to the considered isentropic efficiencies of the pump and the expander -75% and 85% respectively- as well as the fact that the system was powered by a gas fired boiler, which introduces less irreversibilities with respect to the solar collectors.

Yang et al. (2019) investigated the implementation of a customized operating mode to maximize the performance of a PTC driven ORC system for various working fluids. The results of the simulations indicated that the proposed solution enhanced the system's efficiency by 4%, resulting in a maximum thermal efficiency of 17.9% for a driving temperature of 375 °C using toluene as working fluid.

In the current study, the exergetic and economic performance of a solar driven small scale ORC has been assessed on annual basis, as shown in Figure 1. The analysis was conducted with respect to exergy to allow for a more direct comparison to similar systems of various driving temperatures. Three types of solar collectors have been evaluated for a number of working fluids and four locations in the South-East Mediterranean region –Athens(Greece), Thessaloniki (Greece), Istanbul (Turkey) and Larnaca (Cyprus)-. A genetic algorithm was developed to optimize the system's performance in each case with respect to the solar field area and the capacity of a heat storage tank having as objective functions the payback period of the investment and the overall exergy efficiency. The selection of genetic algorithm as the optimization method ensures a more accurate approach of the solution avoiding local optima and the dependency of gradient based methods on initial points.

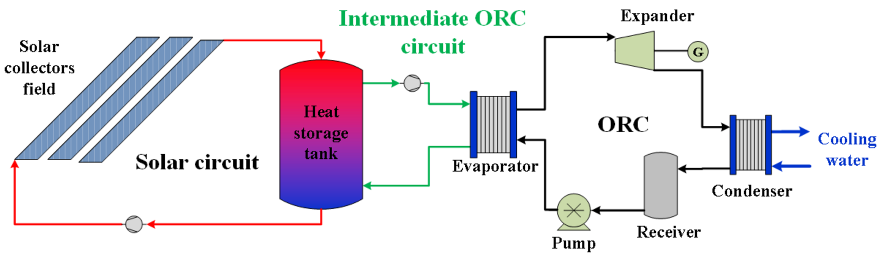


**Figure 1:** Schematic of the considered solar driven small scale ORC

## 2. MATHEMATICAL MODELING

### 2.1 Solar subsystem

The solar collector efficiency was estimated using an empirical polynomial (Infante Ferreira and Kim 2014):

$$\eta = c_0 - c_1\left(\frac{T_{col} - T_{amb}}{I_{col}}\right) - c_2 I_{col}\left(\frac{T_{col} - T_{amb}}{I_{col}}\right)^2 \tag{1}$$

with $I_{col}$ referring to global irradiance for FPCs and ETCs and to direct irradiance for PTCs. The values of the coefficients for each type of collector are listed in Table 1.

For all types of collectors, there was no axis-tracking considered for simplification. The tilt angle was selected such for each of the considered locations to maximize the annual absorbed solar energy, for each type of collector. The results for the optimal tilt angles are presented in Table 2.
With respect to the modeling of the storage tank, the assumption of a number (n=25) of mixing zones was considered within the tank. For each mixing zone, a uniform temperature is considered and an energy balance is applied to each zone to model the heat and mass transfer within the boundaries (Wischhusen 2006).

**Table 1:** Eq. (1) coefficients for each type of collector (©Viessmann Luxembourg sarl 2019)[1],(©AkoTec 2014)[2],(Infante Ferreira and Kim 2014)[3]

| Coefficient | FPC[1] | ETC[2] | PTC[3] |
|---|---|---|---|
| $c_0$ | 0.868 | 0.774 | 0.76 |
| $c_1$ | 3.188 | 1.936 | 0.22 |
| $c_2$ | 0.018 | 0.006 | |

**Table 2:** Optimal tilt angles (in degrees) for each location and type of collector

| Type of collector | Athens | Thessaloniki | Istanbul | Larnaca |
|---|---|---|---|---|
| FPC/ETC | 32.7 | 35.6 | 31.4 | 32.4 |
| PTC | 18.2 | 19.8 | 16.3 | 18.5 |

**2.2 Organic Rankine Cycle**
For the considered small scale low temperature application, a single stage conventional ORC was considered. The modeling of the expander was based on the experimental data from Dumont et al. (2017), which correlated the isentropic efficiency of a scroll expander, with the rotational speed and the pressure ratio of the expansion process. For a rotational speed of 3000 rpm, the isentropic efficiency as function of the pressure ratio can be estimated as follows:

$$\eta_{is} = 0.005618\pi^3 - 0.08169\pi^2 + 0.3408\pi + 0.2931 \quad (2)$$

By considering a 5% heat losses (Lemort et al. 2011), as well as taking into account the efficiencies of the inverter and the generator as polynomial functions of the expander's rotational speed and the power generated at the expander (Ziviani et al. 2016), the power output to the grid is equal to:

$$P_{el} = \frac{\eta_{is} P_{\text{exp,is}}}{0.95} \eta_{inv} \eta_{gen} \quad (3)$$

The performance of the pump was based on performance correlations provided by a manufacturer (Wanner Engineering 2014):

$$\dot{V} = \frac{N - 22,681}{46,705} \quad (4)$$

$$\dot{W}_{mech} = 15\frac{N}{84,428} + \frac{\dot{V}\Delta p}{511} \quad (5)$$

Finally, with respect to the heat exchangers, their design was based on the LMTD method (Chemieingenieurwesen 2010) for commercial models of plate heat exchangers. The off-design performance of the heat exchangers, was based on a quasi-steady state model developed on the basis of moving boundaries method (Quoilin, Aumann, et al. 2011). In order to compare all cases on a common basis, some assumptions were considered with respect to the nominal conditions of the ORC, as listed in Table 3.

**Table 3:** Design specifications for the considered ORC

| **Nominal driving temperature (°C)** | $\dot{Q}_{evap}$ **(kW)** | **Level of superheating (°C)** | **Condenser's subcooling (°C)** | **Cooling water temperature (°C)** |
|---|---|---|---|---|
| Value | 20 | 10 | 5 | 25 |

For the driving temperatures lower than the nominal value, a ramp scenario was considered to simulate the operation of the ORC as realistically as possible.

### 2.3 Performance parameters

In order to allow for a more general comparison of the proposed system with alternative options on low temperature applications, the analysis of the overall efficiency was conducted with respect to the second law efficiency. The overall exergy efficiency of the solar driven ORC can be estimated as follows (Maraver et al. 2014):

$$\eta_{ex} = \frac{\dot{E}x_{cw} + P_{el,net}}{Ex_{sol}} \tag{6}$$

With,

$$\dot{E}x_{sol} = \left(1 - \frac{T_{amb}}{5770}\right)\dot{Q}_{col} \tag{7}$$

$$\dot{E}x_{cw} = \dot{m}_{cw}\left[h_{cw,o} - h_{cw,i} - 298.15\left(s_{cw,o} - s_{cw,i}\right)\right] \tag{8}$$

With respect to the economic performance, it was selected to evaluate the system using the payback period, considering that the entire production of the system is supplied to the grid, sold at the current national price per case (Table 4):

$$PbP = \frac{C_{tot}}{W_{net,\text{an}} c_{el} - C_{main}} \tag{9}$$

At this point has to be stated that the specific cost of FPCs was considered equal to 210.4 €/m$^2$,(Balaji et al. 2018), the respective cost for the ETCs equal to 700 €/m$^2$ (Carlos J. Porras-Prieto 2016) and for the PTCs 178 €/m$^2$ (Turchi 2015).

**Table 4:** Cost of electricity and primary energy factors for the considered countries (Eurostat 2018)[1], (International Energy Agency 2018) [2]

| **Type of collector** | **Greece** | **Turkey** | **Cyprus** |
|---|---|---|---|
| $c_{el}$ (€/kWh) [1] | 0.162 | 0.0959 | 0.1826 |
| PEF (-) [2] | 2.073 | 2.268 | 2.7 |

## 3. RESULTS

Given the fact that all considered cities are located in the south-east Mediterranean the system's performance is similar. Athens and Larnaca, as shown in the Pareto fronts of Figures 2-3, tend to result in better economic performances thanks to the higher solar irradiance in comparison to Istanbul and Thessaloniki.

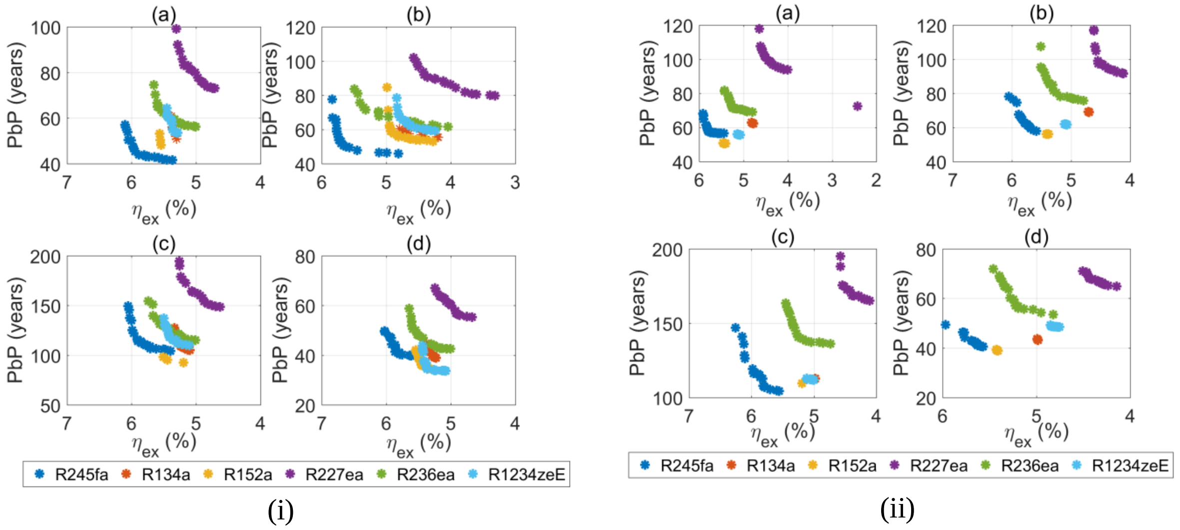


**Figure 2:** Pareto fronts for the considered working fluids in (a) Athens (b) Thessaloniki (c) Istanbul and (d) Larnaca using (i) FPCs and (ii) ETCs

More specifically, the lowest payback period is observed for all types of collectors in the city of Larnaca with values of 33.7 years for the FPC driven system using R1234zeE, 39.0 years for the ETCs scenario with R152a and 11.9 years for the PTC driven system using R152a. With respect to the exergy efficiency, in all cities and types of collectors the maximum efficiency is observed with R245fa as working medium. The overall maximum obtained exergetic efficiency was equal to 6.25% using ETCs, a value that is relatively small but is mainly justified by the high exergy losses imposed by equation (7).

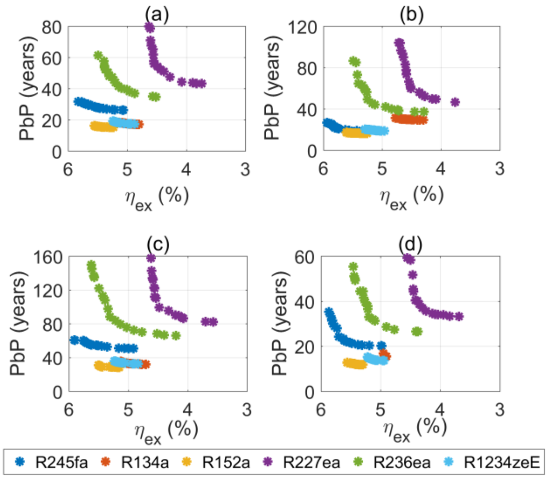


**Figure 3:** Pareto fronts for the considered working fluids in (a) Athens (b) Thessaloniki (c) Istanbul and (d) Larnaca using PTCs

Figure 4 provides an overview of the genetic algorithms' results for the case of FPCs in Athens. At this point has to be stated that the boundaries set for the optimization variables were 1-200 $m^2$ and 0.5-5 $m^3$, for the solar field surface and the storage tank's volume, respectively. Hence, it is realized from Figure 4, there is an optimum solar field area to maximize the economic performance, while with respect to the storage tank volume; the fact that most solutions are localized in capacities of less than 1 $m^3$ concludes that the optimum strategy for the considered system is to directly consume the solar heat.

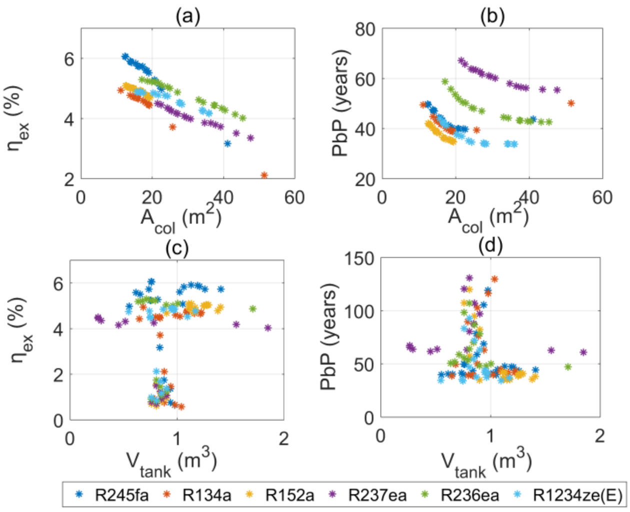


**Figure 4:** Overview of genetic algorithm results for the case of FPCs in Athens for the considered working fluids

Finally, the analysis was extended to quantify the energy savings of the proposed system for different solar field areas and minimum storage tank capacity (V=0.5 $m^3$). As expected, there is a parabolic behavior of the energy savings with respect to the solar field area. This is mainly justified by the fact that a specific scale for the ORC was considered and thus for higher areas there was an excess of solar heat that could not be utilized unless the ORC would be scaled up.

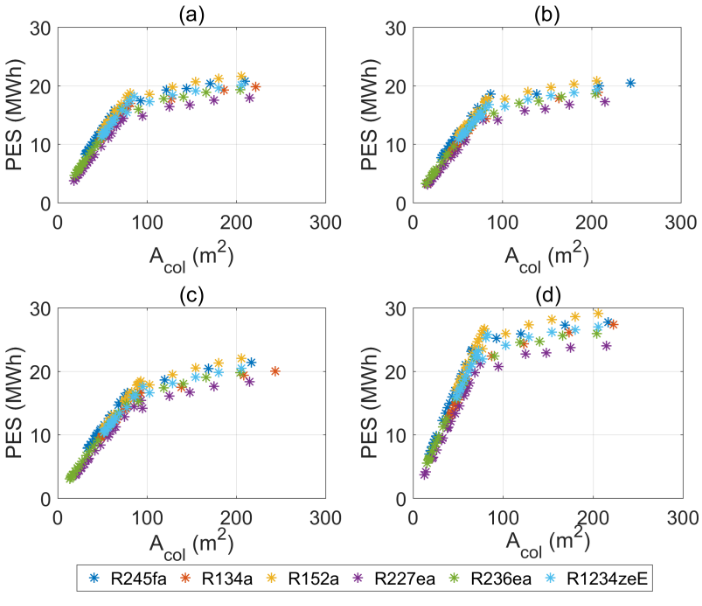


**Figure 5:** Primary energy savings using PTCs for (a) Athens (b) Thessaloniki (c) Istanbul and (d) Larnaca

## 4. CONCLUSIONS

In this analysis a solar driven small scale ORC has been optimized using a genetic algorithm with respect to the exergy efficiency and the payback period of the investment. The proposed system was evaluated for a number of different solar collectors, working fluids and locations in the South-East Mediterranean region. The main conclusions of the study are summarized below:.

- PTC collectors, despite exploiting only the direct solar irradiance, tend to result in better performances and thus competitive payback periods of less than 12 years
- The investigated systems result in generally low exergetic efficiencies in the range of 2-6%, which are highly influenced by the poor exergetic efficiencies of the solar collectors

- The optimal economic performance was determined to be with R152a and R245fa as working fluids, while with respect to the location, Larnaca was resulting in the optimal solutions, with a minimum payback period of 11.9 years, due to the high solar irradiance and the electricity prices in Cyprus

## NOMENCLATURE

| | | |
|---|---|---|
| $c_{el}$ | cost of electricity | (€ $kWh^{-1}$) |
| $C_{main}$ | maintenance costs | (€ $year^{-1}$) |
| $C_{tot}$ | capital costs | (€) |
| $\dot{E}x$ | exergy rate of change | (W) |
| h | enthalpy | (J $kg^{-1}$) |
| I | solar irradiance | (W $m^{-2}$) |
| N | rotational speed | (RPM) |
| P | power | (W) |
| PbP | payback period | (years) |
| PEF | primary energy factor | (-) |
| PES | primary energy savings | (MWh) |
| $\dot{Q}$ | heat | (W) |
| s | entropy | (J $kg^{-1}$ $K^{-1}$) |
| T | temperature | (K) |
| $\dot{W}_{mech}$ | pump's mechanical power | (kW) |
| $V$ | storage tank capacity | ($m^3$) |
| $\dot{V}$ | volumetric flowrate | (lpm) |
| Δp | pressure difference | (bar) |
| η | efficiency | (–) |
| π | pressure ratio | (–) |

**Subscript**

| | |
|---|---|
| amb | ambient |
| col | collectors |
| cw | cooling water |
| ex | exergy |
| exp | expander |
| gen | generator |
| i | inlet |
| inv | inverter |
| is | isentropic |
| o | outlet |
| sol | solar |

## REFERENCES

©AkoTec. 2014. "OEM Vario 1000 Solar Keymark certificate." https://akotec.eu/wp-content/uploads/16-03-17-df-SolarKeymarkErklaerung.pdf.

©Viessmann Luxembourg sarl. 2019. "VITOSOL 300-F." https://www.viessmann.lu/de/wohngebaeude/solarsysteme/Flachkollektoren/vitosol-300-f.html.

Abam, F.I., Ekwe, E.B., Effiom, S.O., and Ndukwu, M.C. 2018. "A comparative performance analysis and thermo-sustainability indicators of modified low-heat organic Rankine cycles (ORCs): An exergy-based procedure." *Energy Reports* 4:110-118.

Balaji, K., Iniyan, S., and Swami, M.V. 2018. "Exergy, economic and environmental analysis of forced circulation flat plate solar collector using heat transfer enhancer in riser tube." *Journal of Cleaner Production* 171:1118-1127.

Calise, F., d'Accadia, M.D., Vicidomini, M., and Scarpellino, M. 2015. "Design and simulation of a prototype of a small-scale solar CHP system based on evacuated flat-plate solar collectors and Organic Rankine Cycle." *Energy Conversion and Management* 90:347-363.

Carlos J. Porras-Prieto, S.B.-S., Fernando R. Mazarrón and Rosa M. Benavente. 2016. "Profitability Variations of a Solar System with an Evacuated Tube Collector According to Schedules and Frequency of Hot Water Demand."

Chemieingenieurwesen, V.D.-G.V.u. 2010. "VDI heat atlas." In. Berlin ;: Springer.

Delgado-Torres, A.M., and García-Rodríguez, L. 2007. "Double cascade organic Rankine cycle for solar-driven reverse osmosis desalination." *Desalination* 216 (1):306-313.

Desai, N.B., and Bandyopadhyay, S. 2016. "Thermo-economic comparisons between solar steam Rankine and organic Rankine cycles." *Applied Thermal Engineering* 105:862-875.

Dumont, O., Dickes, R., and Lemort, V. 2017. "Experimental investigation of four volumetric expanders." *Energy Procedia* 129:859-866.

Eurostat. 2018. "Electricity prices, first half of year, 2018." accessed Ιανουάριος 2019. https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics.

Heberle, F., Schifflechner, C., and Brüggemann, D. 2016. "Life cycle assessment of Organic Rankine Cycles for geothermal power generation considering low-GWP working fluids." *Geothermics* 64:392-400.

Infante Ferreira, C., and Kim, D.-S. 2014. "Techno-economic review of solar cooling technologies based on location-specific data." *International Journal of Refrigeration* 39 (Supplement C):23-37.

International Energy Agency. 2018. *Statistics:Electricity information*: IEA publications.

Kalogirou, S.A. 2004. "Solar thermal collectors and applications." *Progress in Energy and Combustion Science* 30 (3):231-295.

Karellas, S., Roumpedakis, T.C., Tzouganatos, N., and Braimakis, K. 2018. *Solar Cooling Technologies*: CRC Press.

Lemort, V., Declaye, S., and Quoilin, S. 2011. "Experimental characterization of a hermetic scroll expander for use in a micro-scale Rankine cycle." *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 226 (1):126-136.

Maraver, D., Royo, J., Lemort, V., and Quoilin, S. 2014. "Systematic optimization of subcritical and transcritical organic Rankine cycles (ORCs) constrained by technical parameters in multiple applications." *Applied Energy* 117:11-29.

Quoilin, S., Aumann, R., Grill, A., Schuster, A., Lemort, V., and Spliethoff, H. 2011. "Dynamic modeling and optimal control strategy of waste heat recovery Organic Rankine Cycles." *Applied Energy* 88 (6):2183-2190.

Quoilin, S., Orosz, M., Hemond, H., and Lemort, V. 2011. "Performance and design optimization of a low-cost solar organic Rankine cycle for remote power generation." *Solar Energy* 85 (5):955-966.

Tartière, T., and Astolfi, M. 2017. "A World Overview of the Organic Rankine Cycle Market." *Energy Procedia* 129 (Supplement C):2-9.

Tchanche, B.F., Lambrinos, G., Frangoudakis, A., and Papadakis, G. 2011. "Low-grade heat conversion into power using organic Rankine cycles – A review of various applications." *Renewable and Sustainable Energy Reviews* 15 (8):3963-3979.

Turchi, P.K.a.C.S. 2015. Parabolic Trough Collector Cost Update for the System Advisor Model (SAM).

Wang, J.L., Zhao, L., and Wang, X.D. 2010. "A comparative study of pure and zeotropic mixtures in low-temperature solar Rankine cycle." *Applied Energy* 87 (11):3366-3373.

Wanner Engineering, I. 2014. "D10 Series Specifications Datasheet." http://www.hydra-cell.com/product/D10-hydracell-pump.html.

Wischhusen, S. 2006. "An enhanced discretization method for storage tank models within energy systems." Proc. of the 5-th International Modelica Conference.

Yang, J., Li, J., Yang, Z., and Duan, Y. 2019. "Thermodynamic analysis and optimization of a solar organic Rankine cycle operating with stable output." *Energy Conversion and Management* 187:459-471.

Ziviani, D., Gusev, S., Lecompte, S., Groll, E.A., Braun, J.E., Horton, W.T., van den Broek, M., and De Paepe, M. 2016. "Characterizing the performance of a single-screw expander in a small-scale organic Rankine cycle for waste heat recovery." *Applied Energy* 181:155-170.

## ACKNOWLEDGEMENT

This scientific paper was supported by the Onassis Foundation - Scholarship ID: G ZO 025-1/2018-2019.