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Proceedings of the 7th International Seminar on ORC Power Systems

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COMPREHENSIVE ANALYSIS OF ORC-VCC SYSTEM FOR AIR CONDITIONING FROM LOW-TEMPERATURE WASTE HEAT

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ABSTRACT

Due to the need to reduce electricity consumption, methods of increasing the efficiency of energy use are being sought. One of the possibilities is the use of low-temperature waste heat for the production of electricity or cooling. Systems that convert heat into cold seem particularly attractive. This approach allows, above all, the removal of the generator. It eliminates the electrical part of the expander and, as a consequence, increases the efficiency of waste heat utilization, simplifies the construction of the ORC turbogenerator, and removes certain restrictions.
The paper presents an analysis of the ORC-VCC cycle using waste heat at a temperature of 95°C and heat up to 130kW. Various novel working fluids (e.g. R1224yd(Z), R1233zd(E), R1336mzz(Z)) are considered. Selected fluids are characterized by low global warming potentials. An in-house code was developed and used to calculate cycle parameters. Single and multi-objective optimization was performed, aiming at the maximization of the ORC efficiency, Net Present Value (NPV) and the Internal Rate of Return (IRR). Pareto frontiers were obtained, and a decision-making method was used to select an optimum solution. The obtained ORC efficiency was 5.25%, COP_{VCC} 0.47 and the cycle efficiency was above 27.1%.

1 INTRODUCTION

The Organic Rankine Cycle (ORC) and Vapor Compression Cycle (VCC) are two prominent thermodynamic processes employed in various industrial applications for energy conversion and refrigeration purposes, respectively (Lecompte *et al.*, 2015). Recently, the integration of these two cycles, known as the ORC-VCC system, has garnered substantial attention from researchers and industry practitioners due to its potential for increased energy efficiency and waste heat recovery. The primary benefit of the suggested technological approach lies in the integration of both the turbine and compressor stages on a singular shaft. This design effectively eliminates the need for a coupling mechanism as well as a generator for driving the turbine or compressor, thereby eradicating supplementary mechanical and electrical components. As a result, the overall system is streamlined to its most elementary configuration (Fig. 1). In summary, the generation of cooling by the VCC system is possible thanks to the harnessing of waste heat by the ORC system and the use of a turbocompressor. Furthermore, a cooling water system is necessary for heat dissipation from each of the condensers.

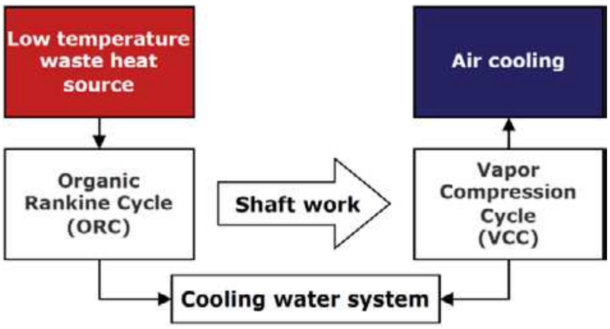

Figure 1: Conception of ORC-VCC

In the past decade, several studies have sought to investigate and optimize the performance of ORC-VCC systems. Karellas and Braimakis (2016) investigated the thermodynamic modeling and economic assessment of a micro-scale tri/cogeneration system, integrating an Organic Rankine Cycle (ORC) and a Vapor Compression Cycle (VCC) for combined heat, power, and refrigeration production. The system's performance is evaluated under various operating conditions, and its economic viability is analyzed using a case study on a Greek Island. The base case scenario yields a net electric efficiency of 2.38% and an exergy efficiency of about 7%. The system offers an Internal Rate of Return (IRR) of approximately 12% and a payback period of 7 years due to fuel oil and electricity savings. Nasir and Kim (2016) explored the thermal performance of working fluid combinations in ORC-VCC for domestic air conditioning. Among the seven fluids analyzed, Isobutane and R134a exhibited the best performance in standalone VCC and ORC-VCC, respectively. The optimal combination was R134a ORC-Isobutane VCC, which, when optimized, achieved a COP of 0.219 with dry air and 0.281 with 50% relative humidity air at the VCC evaporator inlet. The cycle's performance is analyzed by Aphornratana and Sriveerakul (2010) using a mathematical model. The research highlights the significant impact of the expander-to-compressor piston area ratio on the system's COP, with R22 outperforming R134a across all temperature ranges. Furthermore, incorporating a liquid-preheater substantially decreases generator energy input, subsequently enhancing the COP. In the work of Toujeni *et al.* (2017), authors investigate the impact of system parameters on the performance metrics of a novel combined ORC-VCC system for cogeneration of electricity and refrigeration. The study aims to introduce and assess the proposed configuration, finding that the system's feasibility and performance are contingent upon the availability of the hot source and the desired cold temperature. Optimization results demonstrate that the use of two generators improves system performance under appropriately chosen conditions. Four systems - single-fluid and dual-fluid ORC-VCC systems, and ORC-FTVIC systems utilizing single-fluid and dual-fluid - are examined, with an emphasis on performance optimization at various heat source temperatures using six different working fluids (Bao *et al.* 2020). The results reveal that the cooling capacity, COP and second law efficiency of the dual-fluid ORC-FTVIC-D system are always maximum among the four systems, but the optimum working fluid of systems will change with the variation of heat source temperature The study also finds that parameters such as the turbine inlet pressure and temperature, evaporation temperature, and intermediate vapor injection temperature significantly influence the cycle performance of the systems. Asim *et al.* (2021) showed an innovative integrated vapor compression cycle-organic Rankine cycle system (i-VCC-ORC), which recovers waste heat rejected by the condenser of a VCC. The study identifies the optimal working fluid pair as R600a-R141b, with a net COP of 3.54 and ORC thermal efficiency of 3.05%. This integrated system improves the system's COP by 12.5% compared to a standalone VCC system. The research also determines an optimal operating condition through sensitivity analysis, demonstrating the potential of the i-VCC-ORC system for electricity generation from waste heat. An investigation into a combined power and cooling system, incorporating an ORC and a VCC, demonstrated almost double the thermal efficiency in the ORC–VCC mode compared to the standalone ORC mode (Kim). Employing six different working fluids, the study revealed a significant improvement in thermal efficiency when a VCC cycle was introduced alongside the ORC cycle. Further, Kim demonstrated that the inclusion of a recuperator amplified both thermal and second-law efficiencies, achieved by reducing the load on the solar collector and condenser and harnessing residual heat from the turbine outlet. Under the explored operational conditions, R245fa was identified as the working fluid yielding the highest thermal efficiency. Seiti *et al.* (2022) investigates the use of ultra-low temperature waste heat to drive a thermo-mechanical refrigeration (TMR) system, particularly focusing on an expander-compressor unit (ECU) based design. The study examines the system's performance with various commercial refrigerants within a temperature spectrum of 50 °C to 85 °C, identifying optimal operating conditions. Results demonstrate improved system efficiency at higher heat source temperatures and enhanced cooling quality through refrigerant substitution. These findings contribute significantly to waste heat recovery practices and suggest future exploration with sustainable refrigerants. It was shown that an ORC-VCC, can significantly enhance power generation and cooling efficiency in rural areas (Aryanfar, *et al*., 2022). By utilizing a Parabolic Trough Solar Collector (PTC) and exploring four different working fluids (R245fa, R114, R600, R142b), the study identified R245fa as the fluid with the least exergy destruction. Optimal performance was found to be dependent on specific turbine inlet temperature and pressure conditions. Moreover, it was observed that the turbine inlet pressure holds substantial influence over the system's overall cost and thermal efficiency, highlighting the importance of optimization in such renewable energy systems. In order to illustrate the used working fluids and heat source and its temperature, a summary of mentioned works is presented in Table 1.

Table 1: An overview of investigations into ORC-VCC technology

Author	Heat source	Heat input	Working fluid
Aphornratana and Sriveerakul (2010)	Thermal energy at a temperature higher than 80°C	≤ 7 kW	R22, R134a
Wang *et al.* (2011)	Hot water - 190°C	≤ 10 kW	R245fa
Karellas and Braimakis (2016)	Biomass combustion, solar energy – up to 110°C	≤ 50 kW	R134a, R152a, R245fa
Nasir and Kim (2016)	Hot water – 100°C	-	R245fa, R123,R134a, R1234yf, R1234ze, Butane, Isobutane
Toujeni *et al.* (2017)	Low temperature heat sources (solar energy, biomass)	-	R600 (ORC) and Ammonia (VCC)
Kim (2022)	Thermal oil – up to 150°C	≥100 kW ≤ 250 kW	R245fa, R114, R600, R142b, R152a, R1234yf
Sleiti *et al.* (2022)	Hot water – between 48°C and 120°C	≤ 1 kW	R134a
Aryanfar *et al.* (2022)	Parabolic solar collector (PTC), Therminol VP-1	-	R245fa, R114, R600, R142b
Witanowski (2023) [This work]	Hot water - 95°C	≤ 130 kW	R1233zd(E), R1336mzz(Z), R1224yd(Z)

The article presents an analysis of the small scale ORC-VCC system for air conditioning from low temperature waste heat source. The heat source parameters were set at 95°C and 1 kg/s, guided by the obtained parameters of available waste heat sources. The cost of the installation was determined based on an estimate of the order value made with local suppliers of installation components, intended for the submitted grant application. Initially, nine objective functions are employed in the optimization process, which utilizes a hybrid genetic algorithm. In a single optimization process, optimization is conducted for three distinct working fluids. Only the fluid R1233zd(E) is applied in the Pareto optimization. The selected working fluids are characterized by a low environmental impact, as indicated by their Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) values. The study analyzes the techno-economic parameters of the installation, enabling the selection of an installation characterized not only by relatively high efficiency but also largely justified from an economic perspective. 205

2 ORC-VCC model optimization methodology

2.1 System description and parameters

The schematic of thermodynamic cycle of the ORC-VCC system has been presented in Fig .1. The system is composed of and ORC subsystem (with regenerator) and a VCC subsystem. The turbine and compressor components are integrated within single structure. The expander and compressor share a common housing and are connected by a single shaft. The cycle was analyzed using only one working fluid in a given study, meaning that the working fluid in both the ORC and VCC cycles was identical. The assumptions regarding the system are presented in Table 2. The efficiencies of the machines under examination were chosen with a high safety margin in mind. For instance, the internal efficiency of a turbine was established at 80%. This value is notably lower than the efficiencies reported in the literature for low power axial (Engineer *et al.*, 2021) or low power high-speed radial-inflow turbines; (Uusitalo *et al.*, 2020, Witanowski et al., 2023).

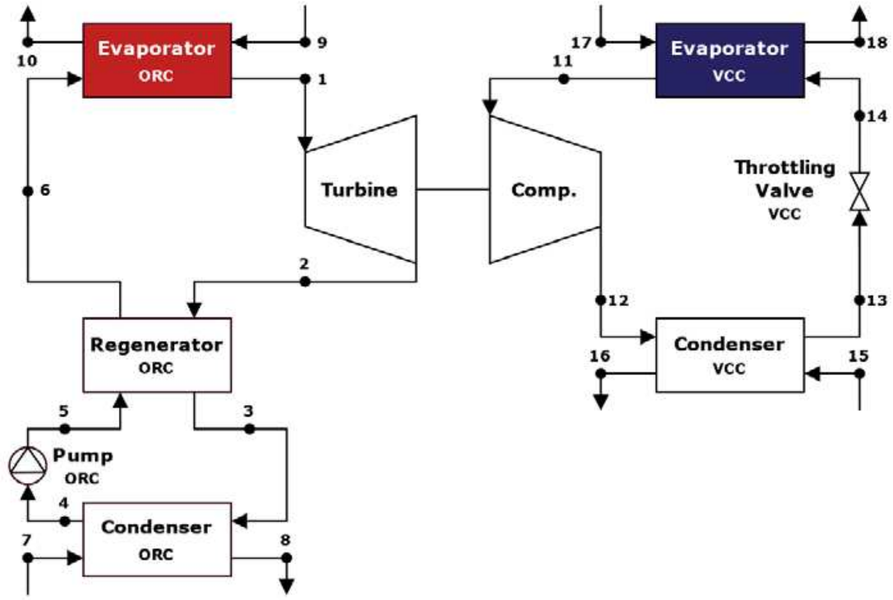

Figure 2: Schematic diagram of the ORC-VCC

Table 2: Efficiency and thermodynamic assumptions of the ORC-VCC system

Parameter	Symbol	Unit	Value
Chilled water temperature (cold side)	T_{18}	°C	8
Chilled water temperature (hot side)	T_{17}	°C	12
Cooling water temperature (cold side)	T_7, T_{15}	°C	15
Heat source mass flow	m_9	kg/s	1
Heat source temperature (hot side)	T_9	°C	95
Compressor efficiency (VCC)	η_c	-	80%
Pump efficiency (ORC)	η_p	-	50%
Turbine efficiency (ORC)	η_t	-	80%

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2.2 Economic parameters

Simple Payback Time, Net Present Value (NPV) and Internal Rate of Return (IRR)were used to assess the financial viability of the investment project (2-4). Each method provides a different perspective on the potential profitability and risks associated with an investment. The analysis was carried out for European Union countries: Greece, Italy, Poland and Spain. However, in the optimization process, the value of the energy price assigned to Greece was assumed. Table 3 summarizes some assumptions for the economic evaluation of the ORC-VCC system.

$$C_i = \left(P_{comp} - P_{p_{orc}} - P_{p_{cs}}\right) * AOT * C_{ei} \quad (1)$$

$$SPBT = C_s/C_i \quad (2)$$

$$NPV = \sum_{j=1}^{t} \frac{C_{ij}}{(1+d)^j} - C_s \quad (3)$$

$$\sum_{j=1}^{t} \frac{C_{ij}}{(1+IRR)^j} = C_s \quad (4)$$

Table 3: Economic assumptions of the ORC-VCC system

Parameter		Symbol	Unit	Value
Electricity prices for non-household consumers (*Electricity Price Statistics. Eurostat Statistics Explained*, 2022)	Greece	C_{e1}	€/kWh	0.3042
	Italy	C_{e2}	€/kWh	0.2525
	Poland	C_{e3}	€/kWh	0.1555

Spain	C_{e4}	€/kWh	0.1879
Cost of ORC-VCC system (up to 35 kW_{th})	C_s	€	30000
Discount rate (NPV analysis)	d	%	5
Operation time	t	years	8
Annual operation time	AOT	h	8000

2.3 Optimization approach

A hybrid algorithm optimization which is embedded in MATLAB was used in the optimization task. The method consist of Genetic Algorithm (GA) and Pattern Search method (PA). After the termination of the GA, the best point is selected as an initial point for the Pattern Search method. This approach allows to perform a faster and more efficient local search instead of performing stochastic algorithm alone. The NPV (f_1), IRR (f_2) and cycle efficiency (f_3) are selected as the single objective function. Each function, from f_1 to f_3, was executed for three working fluids. As a result, functions f_4 to f_6 were created for fluid R1336mzz(Z), and functions f_7 to f_9 for factor R1224yd(Z). For mutli-criteria optimization (functions f_{10} to f_{12}), the process was carried out using the R1233zd(E) fluid. The mutli-criteria optimization objective functions are defined as follows:,

$$f_{10} = 0.3 \times \text{NPV} + 0.7 \times \eta_{cyc} \tag{5}$$
$$f_{11} = 0.5 \times \text{NPV} + 0.5 \times \eta_{cyc} \tag{6}$$
$$f_{12} = 0.7 \times \text{NPV} + 0.3 \times \eta_{cyc} \tag{7}$$

During the constrained optimization, 11 parameters (decision variable) related with ORC-VCC cycle calculation were modified. The changing parameters and boundaries are showed in Table 4. The boundaries are set based on preliminary calculations. Each of the changing parameters was modified and tested to prepare a wide range of possible solutions.

In the optimization process, the prices adopted were those of Greece, driven by the highest price for electricity. This approach represents an optimistic variant when considering prices in other EU countries, but in light of the decarbonization strategy, such a price could become standard throughout the EU. The adopted price influenced the minimum values achieved, and if the process was guided solely by one objective function and a limited set of solutions, it could potentially introduce bias into the results. However, the construction of multiple objective functions and the identification of the Pareto frontier effectively eliminated the impact of the adopted energy price on the optimization. **207**

Table 4: Efficiency and thermodynamic assumptions of the ORC-VCC system

Argument	Parameter	Symbol	Unit	Lower Bounds	Upper Bounds	Best value
x_1	Evaporator pinch temperature difference (VCC)	ΔT_{vcc_ev}	K	3	10	9.82
x_2	Degree of superheating in evaporator (VCC)	ΔT_{vcc_sup}	K	3	10	5.24
x_3	Degree of subcooling in condenser (VCC)	ΔT_{vcc_sub}	K	3	10	9.28
x_4	Regenerator pinch temperature difference (ORC)	ΔT_{orc_reg}	K	3	15	13.97
x_5	Degree of superheating in evaporator (ORC)	ΔT_{orc_sup}	K	3	15	4.65
x_6	Degree of subcooling in condenser (ORC)	ΔT_{orc_sub}	K	7	15	8.38
x_7	Evaporator pinch temperature difference (ORC)	ΔT_{orc_ev}	K	3	10	5.81
x_8	Condenser pinch temperature difference (ORC)	ΔT_{orc_con}	K	3	10	4.17
x_9	Saturation temperature in evaporator (ORC)	T_{1sv}	°C	50	85	64.9
x_{10}	Saturation temperature in evaporator (ORC)	T_{4sv}	°C	25	55	41.26
x_{11}	Chilled water mass flow rate	m_{16}	kg/s	0.7	2	1.99

3 RESULTS OF OPTIMIZATION

Twelve optimization runs were carried out in the study, including nine single optimization runs and three multi-criteria runs. About 10 000 evaluation of objective function were performed. The NPV in comparison with η_{orc}, COP_{vcc}, η_{cyc} are shown in Fig. 3 and Fig 4. The highest NPV values do not correspond to the highest efficiencies and COP obtained. The efficiency of the ORC cycle is close to 9%, the COP_{vcc} is 7, and the efficiency of the cycle is up to 50%. On the other hand, the highest NPV value was obtained at the level of 68 k€, where the efficiency orc is 5.27%, COP_{vcc} is 4.75 and the efficiency of the cycle is 27.1%. The points illustrated in the given context represent a collection of Pareto front points, denoted by red crosses. Within this set, the optimal point is determined based on the criterion of the maximum Net Present Value (NPV). In the case of waste heat recovery, the most crucial issue is often economic justification. Therefore, in this instance, the Net Present Value (NPV) indicator was used as a most important metric. The design parameters, thermodynamic preferences and economic specification of optimal cycle design are shown in Table 5 and Table 5. The mechanical power of the turbine and compressor is about 7 kW, while transferred heat in the VCC evaporator is 33.49 kW.

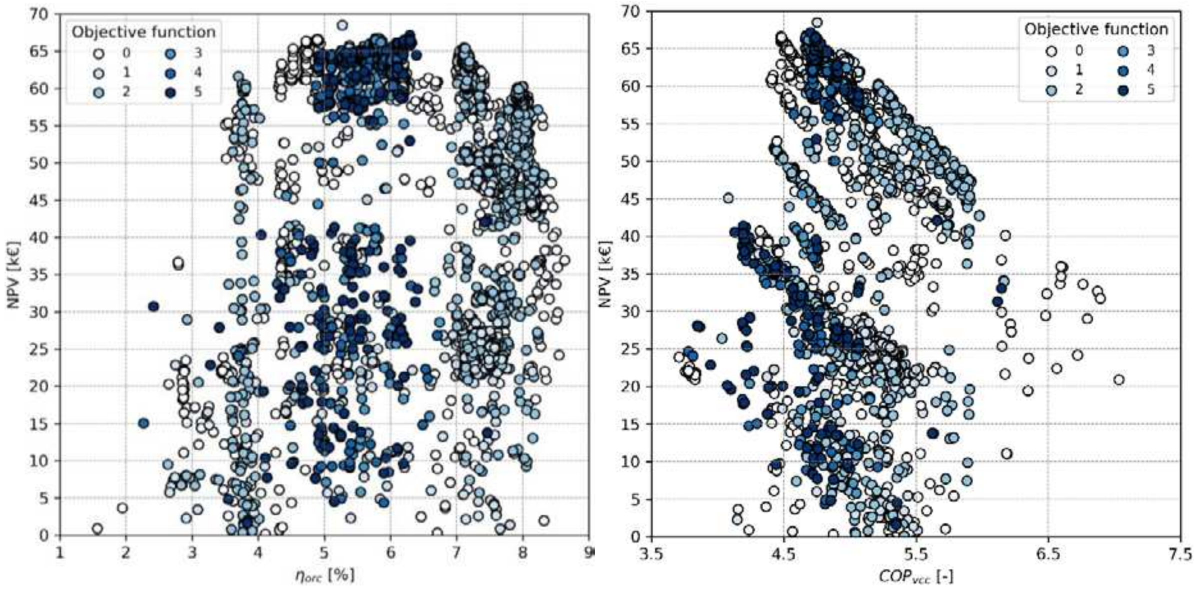

Figure 3: Comparison of NPV with η_{orc} (left) and COP_{vcc} (right)

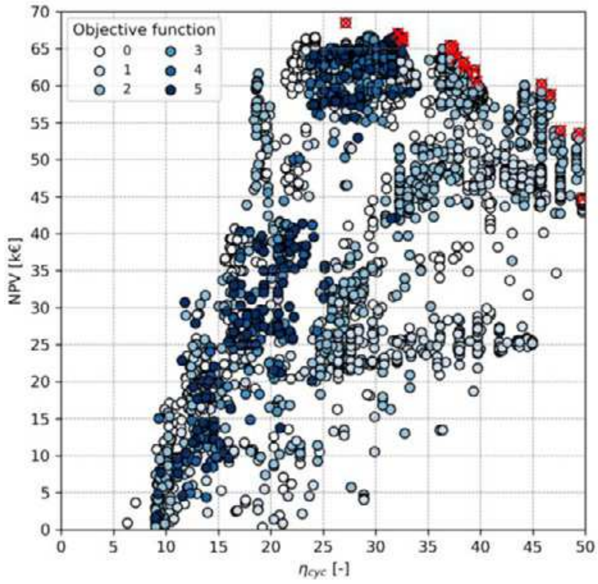

Figure 4: Comparison of NPV with η_{cyc}

Table 5: ORC-VCC thermodynamic points and system performance parameters

Point	T (°C)	p (kPa)	System parameters	
1	73.73	447	fluid	R1233zd(E)
2	55.06	210	P_{tur}	6.97 kW
3	48.82	210	P_{comp}	6.93 kW
4	34.61	210	P_{p_orc}	0.23 kW
5	34.85	447	P_{p_cs}	0.46 kW
6	39.19	447	Q_{e1}	123.62 kW
7, 15	15	200	Q_{r1}	3.21 kW
8, 16	31.11	200	Q_{c1}	116.88 kW
9	95	200	Q_{e2}	33.49 kW
10	65.62	200	Q_{c2}	40.43 kW
11	3.41	44	η_{cyc}	27.1 %
12	51.21	210	η_{orc}	5.27 %
13	29.97	210	COP_{vcc}	4.75
14	-1.83	44	IRR	48.65 %
17	12	200	NPV	68.47 k€
18	8	200	SPBT	1.97

Upon completion of the optimization task, it was discerned that the optimal solution closely approximates the upper boundary of parameter x_{11}, a correlation that is clearly evident in Fig. 5 and in Table 4. Consequently, an additional optimization iteration was conducted, in which the upper boundary of x_{11} was augmented to 5. Additional data results were denoted by a white square. The results confirmed that the optimal solutions were close to the original upper boundary of 2. Values greater than 2 were eliminated by the optimization process due to thermodynamic cycle relations and the lack of possible solutions. Future investigations should consider extending the upper boundary of this parameter to avoid potentially eliminating better solutions. 209

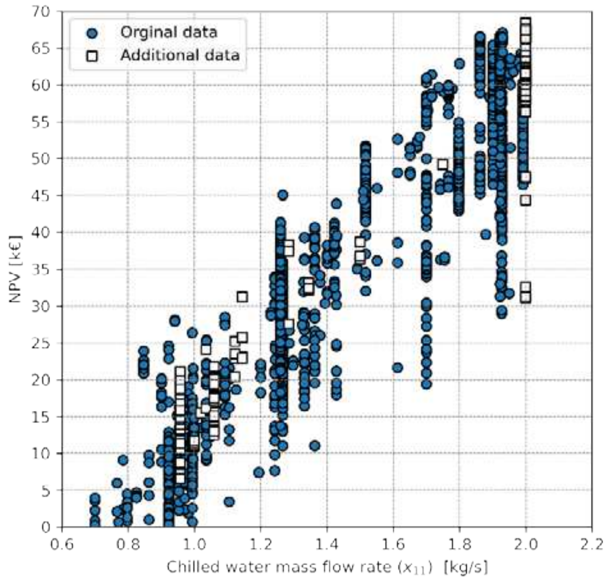

Figure 5: Comparison of NPV with chilled water mass flow

In order to compare the profitability of investments in selected EU countries, calculations were performed using project data obtained for the optimal variant. Greece, which was considered during the optimization, is the best compared to other countries, which is obviously related to the highest price of electricity. The lowest NPV values of 20 000 Euros were obtained for Poland. The SBPT for this country is close to 4 years (Fig 6).

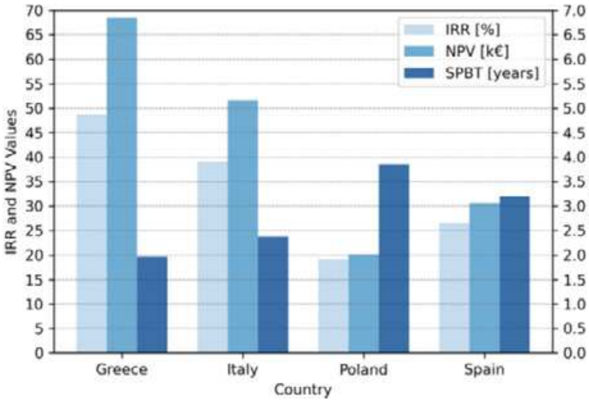

Figure 6: Comparison of economic indicators in selected UE countries

To determine the significance of individual of the objective function, multi-point linear regression was used. The data collected during all optimization runs were cleaned and standardized. The matrix of the significance of the individual parameters is shown in Fig. 7. The variable x_{11} has the highest value for objective functions related the most with the cost (NPV, IRR). In turn variable x_9 has the highest value for the η_{cyc} and η_{orc}. In case where COP_{vcc} was optimized x_{10} has the highest value. A common feature of all objective functions is the low significance of x_2-x_8 variables. The efficiency of the ORC-VCC system, COP, and economic coefficients are contingent upon the internal efficiency of the turbine, a variable that was not considered during the optimization process. To analyze the impact on the parameters of the optimal variant, a characterization of the influence of efficiency on the heat transfer in the VCC evaporator and the NPV index was conducted (Fig. 8). The NPV curve is typified by greater steepness, which is dictated by the escalating proportion of power required to operate auxiliary devices, subsequently impacting profit reduction. When the efficiency decreases from 80% to 60%, the NPV diminishes by 37%, whereas the power transferred in the VCC evaporator reduces by approximately 25%. 210

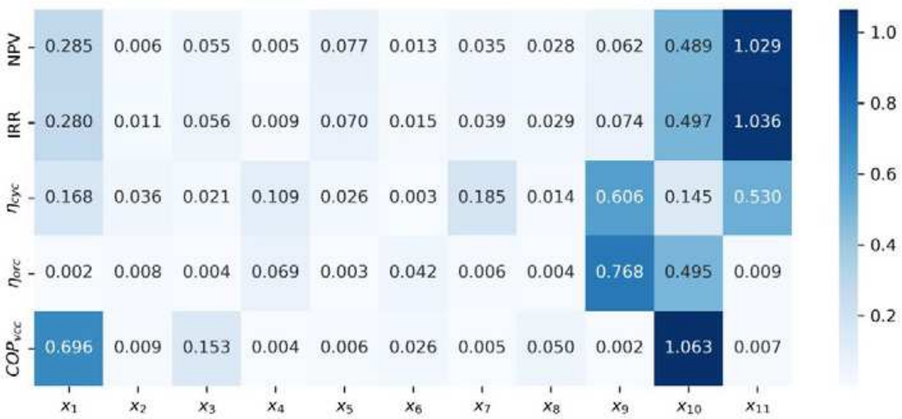

Figure 7: Summary of significance of the objective functions variables

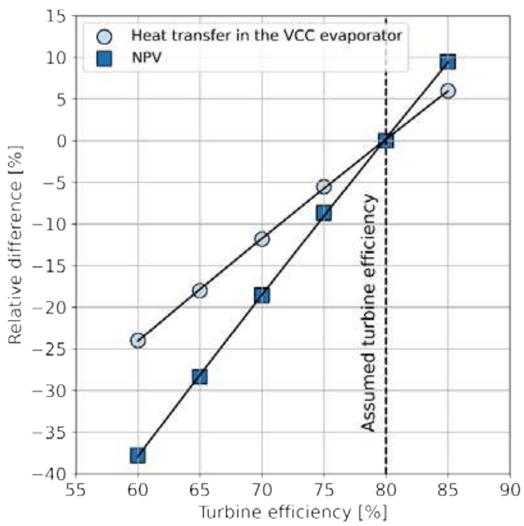

Figure 8: Influence of turbine efficiency on the heat transfer in the VCC evaporator and NPV

4 CONCLUSIONS

The paper presents the thermo-economic analysis of ORC-VCC system for air conditioning from low-temperature waste heat. A total of 12 optimization runs were conducted to generate an extensive and diverse array of potential solutions. Well-known economic parameters, such as NPV and IRR, alongside cycle efficiency, were selected to serve as objective functions for the optimization process. The created objective functions took into account the power required to supply the cooling system pump and the ORC circulation pump. The cost of the installation was estimated based on quotations from a Polish supplier. With this assumption, the SPBT of the investment amounted to less than two years, and the NPV was approximately 70 000 Euros. Based on these figures, it can be concluded that the aforementioned installation is economically justified.

The selected formulas for the objective functions allowed for the examination of a wide range of acceptable solutions. Considering both the Net Present Value (NPV) and the efficiency of the system appears to be an appropriate approach. NPV is closely tied to the net power generated by the system, which directly reflects the level of future revenues. Meanwhile, seeking the highest efficiency, which may not correspond to the highest NPV or power, allows for exploration in entirely new areas. In conclusion, multi-criteria or multi-functional optimization, performed sequentially for several objective functions, allows approximation towards the global optimum.

NOMENCLATURE

IRR	internal rate of ratio	(%)
NPV	net present value	(€)
P	power (kW)	
SPBT	simply payback time	(years)
Q	Heat transfer (kW)	
x	argument of objective function	

Subscript

comp	compressor
c1	ORC condenser
c2	VCC condenser
e1	ORC evaporator
e2	VCC evaporator
p_orc	ORC pump
p_cs	cooling system pump

r1 ORC regenerator
tur turbine

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The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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