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ORC Power Systems

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COST-EFFECTIVE OPTION OF COLD ENERGY UTILIZATION IN PHARMACEUTICAL INDUSTRY

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ABSTRACT

In pharmaceutical industries, nitrogen is used for several purposes, including inerting storage containers to prevent chemical reactions with oxygen at a temperature range of 2 to 8 °C. To meet these specifications, the regasification of liquefied nitrogen (LIN), transforming the liquefied nitrogen into gas phases at certain temperatures and pressures, is necessary. One potential solution that can be applied to increase efficiency and reduce costs while maintaining strict quality and safety standards in the pharmaceutical industry is a replacement of the conventional LIN regasification process with an organic Rankine cycle (ORC). This process could utilize cold energy from the process while using nitrogen as a cooling source and ambient air as the hot side of the thermodynamic cycle. Using the ORC system for this cold energy utilization is promising as the technology is now more developed, compact, relatively reasonable cost, and reliable. Since there are few investigations in cold energy utilization as power generation, this article discusses the techno-economic feasibility of the ORC system in the case of its application in pharmaceutical industries with a particular focus on cold energy utilization in LIN regasification. In this analysis, propane was selected as the working fluid of the ORC system as it has good criteria such as thermal properties, zero ozone depletion potential, and low global warming potential. The analysis was optimized for different heat source conditions. Several designs (with and without the direct expansion system) were developed. In the end, their techno-economic performances and cost-effectiveness were compared. The obtained results show that replacing the conventional LIN regasification in the pharmaceutical industry with an ORC system may improve the efficiency of the system and reduce power consumption. The results of the study additionally indicate that, in terms of cost-effectiveness, reusing existing components of the prior system – specifically, the nitrogen vaporizers and pump – would result in a 23.81% reduction in investment costs and a 22.00% decrease in levelized cost of energy (LCOE).

1 INTRODUCTION

According to the International Energy Agency (IEA), the demand for nitrogen will be significantly growing for several applications and industries by 2030 and 2050 (IEA, 2022). Pure nitrogen, which manufacturers obtain in liquid form, is necessary for several pharmaceutical operations that include inerting storage containers to prevent chemical reactions with oxygen at a temperature range of 2 to 8 °C. When nitrogen is utilized, it must be regasified and the temperature and pressure was set to desired condition before use. The energy required to separate nitrogen from the air and then liquefy the nitrogen is high, and often all of this energy is lost when nitrogen is regasified without proper reutilization. In regasification, heat is required to evaporate the liquefied nitrogen (LIN) to the gas phase. The regasification can be done in several approaches: by vaporizing without utilization, absorbing the cold energy directly for other purposes or even acting as a cold solution for power generation.

In literature studies, several studies were found discussing the utilization of LIN cold energy as power generation. Recent articles (Gao *et al*., 2022; Tian *et al*., 2023; Wang *et al*., 2022) reported the experimental investigation on the utilization of liquid nitrogen as a heat sink for a 1 kW small-scale organic Rankine cycle (ORC). In these studies (Gao *et al*., 2022; Tian *et al*., 2022), the performance of basic ORC was also compared to regenerative ORC and the result shows that regenerative ORC outperforms basic ORC. Moreover, several studies (Tafone *et al*., 2017; Wojcieszak, 2019) have reported the utilization of LIN cold energy via a direct expansion system as power generation in which the expander is directly used to expand the nitrogen gas. For the use of cold energy from LIN, both ORC and a direct expansion system are promising; therefore, it appears that they may be employed in the pharmaceutical industries.

Data taken from the one of pharmaceutical industries in Hungary reported that the monthly consumption of LIN, from which the average daily consumption could be inferred as the production is non-stop. In the opinion of the authors, there is still room to improve the performance of the system based on the utilization of cold energy taken from LIN. Due to the likely lack of studies related to the use of LIN regasification in this industry, therefore, in this study, the aim is to present the utilization of the cold energy taken from LIN regasification to generate electricity. An ORC and a direct expansion were considered in this application as promising solutions. The current work explores the performance and cost-effectiveness of the designed ORC and the direct expansion in the application in order to identify the cost-effective option for the improvement of the industry. The economic evaluation includes the calculation of the levelized cost of electricity (LCOE) which is a parameter for determining the economic feasibility of power generation.

2 METHODS

The thermodynamic model and the economic analysis were developed for the design of a single ORC and direct expansion system for the utilization of cold energy which is computed using computer-based simulation via MATLAB and the thermal properties data taken from REFPROP 10.0 (Lemmon *et al*., 2018). In this case, the designed power generation system from the LIN regasification is illustrated in Figure 1. Moreover, the principle of operation of this system can be described based on Figure 1.

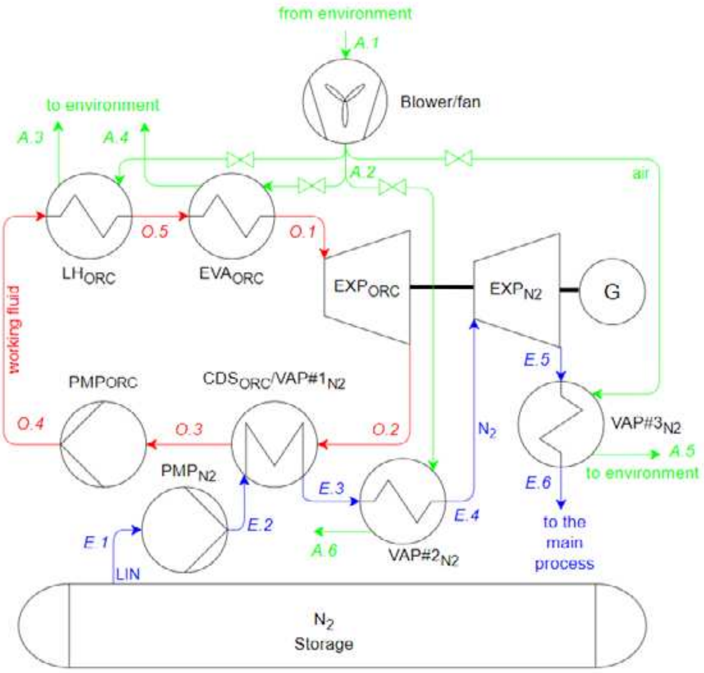

Figure 1: A flow process diagram of the designed system, where LH, EVA, EXP, G, CDS, PMP, VAP, and LIN represent liquid heater, evaporator, expander, generator, condenser, pump, vaporiser, and liquid nitrogen, respectively.

The ORC, is a system that includes an expander, heat exchangers (condenser and evaporator), a pump, and a generator, could be installed in the LIN regasification system utilizing the cold energy of LIN through the condenser. The condenser is used to condense the working fluid of ORC (from the process point O.2 to O.3), while simultaneously evaporating the LIN into the gas phase under specific temperature and pressure (see, process E.2-E.3). For the short distribution system, the LIN is pressurized up to 3 MPa (Darvishmanesh *et al.*, 2011). Moreover, an additional system like a direct expansion system could be installed for LIN regasification. Vaporizing of nitrogen (see, process E.3-E.4) requires heat to increase the temperature so then it could be directly expanded (see, point E.5). Since the temperature of nitrogen is still low after the expansion, it needs further heat addition to reach desired temperature according to the requirements, that is why the vaporizer is required to be installed (see, process E.5-E.6). It is worth noting that heat sources in the process of evaporation utilize the air from the environment, so the blower/fan is required in this case.

2.1 Thermodynamic model and assumptions

In this study, the power generation is designed based on ORC utilizing cold energy as heat sinks and the air as heat sources (which is the same manner as in these articles (Habibi *et al.*, 2018; Wajs *et al.*, 2022)), while the direct expansion system is used to expand the cooling source (which is the similar method as in these articles (Tafone *et al.*, 2017; Wojcieszak, 2019)). Mass and energy balance equations for various components illustrated in Figure 1 are described using Equations (1) and (2), where $\dot{m}$, h, $\dot{W}$, and $\dot{Q}$ represent the mass flow rate in kg/s, specific enthalpy in kJ/kg, power in kW, and heat transfer rate in kW, respectively. The LIN is pressurized to 3 MPa (Darvishmanesh *et al.*, 2011) and the mass flow rate is varied based on the monthly consumption data from the factory, while the air temperature is assumed using the monthly mean temperature in Hungary taken from this data (The World Bank, 2021). Moreover, the list of components and the processes are listed in Table 1.

$$\sum \dot{m}_{\mathrm{inlet}} = \sum \dot{m}_{\mathrm{outlet}} \tag{1}$$

$$\dot{Q} + \sum \dot{m}_{\mathrm{inlet}} h_{\mathrm{inlet}} = P + \sum \dot{m}_{\mathrm{outlet}} h_{\mathrm{outlet}} \tag{2}$$

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Table 1: List of components and specific processes referred to in Figure 1.

List of component	Specific enthalpy (kJ/kg)	Mass flow rate (kg/s)	Product (kW)
ORC expander	$h_{\mathrm{O.1}} - h_{\mathrm{O.2}}$	$\dot{m}_{\mathrm{wf}}$	$P_{\mathrm{ORC,EXP}}$
ORC condenser	$h_{\mathrm{O.2}} - h_{\mathrm{O.3}}$	$\dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{ORC,CDS}}$
ORC pump	$h_{\mathrm{O.4}} - h_{\mathrm{O.3}}$	$\dot{m}_{\mathrm{wf}}$	$P_{\mathrm{ORC,PMP}}$
ORC liquid heater	$h_{\mathrm{O.5}} - h_{\mathrm{O.4}}$	$\dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{ORC,LH}}$
ORC evaporator	$h_{\mathrm{O.1}} - h_{\mathrm{O.5}}$	$\dot{m}_{\mathrm{wf}}$	$\dot{Q}_{\mathrm{ORC,EVA}}$
Nitrogen pump	$h_{\mathrm{E.2}} - h_{\mathrm{E.1}}$	$\dot{m}_{\mathrm{N2}}$	$P_{\mathrm{N2,PMP}}$
Nitrogen vaporizer #1	$h_{\mathrm{E.3}} - h_{\mathrm{E.2}}$	$\dot{m}_{\mathrm{N2}}$	$\dot{Q}_{\mathrm{N2,VAP\#1}}$
Nitrogen vaporizer #2	$h_{\mathrm{E.4}} - h_{\mathrm{E.3}}$	$\dot{m}_{\mathrm{N2}}$	$\dot{Q}_{\mathrm{N2,VAP\#2}}$
Nitrogen expander	$h_{\mathrm{E.4}} - h_{\mathrm{E.5}}$	$\dot{m}_{\mathrm{N2}}$	$P_{\mathrm{N2,EXP}}$
Nitrogen vaporizer #3	$h_{\mathrm{E.6}} - h_{\mathrm{E.5}}$	$\dot{m}_{\mathrm{N2}}$	$\dot{Q}_{\mathrm{N2,VAP\#3}}$
Blower/fan	$h_{\mathrm{A.2}} - h_{\mathrm{A.1}}$	$\dot{m}_{\mathrm{air}}$	$P_{\mathrm{air,fan}}$

Some assumptions are taken into consideration as follows. Propane (R-290) is selected as a working fluid for ORC since this substance has been tested for experimental investigation (Gao *et al.*, 2022; Tian *et al.*, 2023; Wang *et al.*, 2022). The mass flow rate of nitrogen was calculated based on the monthly consumption of LIN consistent throughout 254 working days. All components are operating in a steady-state condition. In the heat exchanger, the change of kinetic and potential energy of the stream is negligible, no heat and pressure losses occur, and it operates in constant pressure, constant overall heat transfer coefficient, and constant specific heat. The pinch temperature of the heat source and the evaporator is set at 5°C. This value also applies to condensers and nitrogen. Moreover, the isentropic efficiency of the pump and expander is assumed at 0.8 (Astolfi *et al*., 2017; Habibi *et al*., 2018), and the efficiency of the fan is 0.6 (Walraven *et al*., 2015). The expander of ORC is operating in the two-phase conditions. Operation in these conditions is possible for some rotary volumetric expanders (Daniarta and Kolasiński, 2021; Francesconi *et al*., 2022; van Heule *et al*., 2022). In addition, the power of the fan was calculated using the function (Walraven *et al*., 2015) that can be expressed in Equation (3).

$$P_{\mathrm{air,fan}} = \frac{\Delta p_{\mathrm{air}} \dot{m}_{\mathrm{air}}}{\rho_{\mathrm{air}}} \tag{3}$$

The specific enthalpy and the mass flow rate of the components listed in Table 1 could be used to calculate the power consumption, power production, and heat transfer rate. By using these parameters, the net efficiency of the cold energy utilization could be determined as a function of net power output over the heat transfer rate input as described in Equation (4). It is worth noting that the heat transfer rate input includes the liquid heater and evaporator. Some existing components such as vaporizer #2 and vaporizer #3 (that were the modified components from the prior system), the liquid pump of nitrogen, and the blower/fan are not taken into consideration in the calculation of the efficiency.

$$\eta_{\mathrm{system}} = \frac{P_{\mathrm{net}}}{\dot{Q}_{\mathrm{input}}} = \frac{P_{\mathrm{ORC,EXP}} + P_{\mathrm{N2,EXP}} - P_{\mathrm{ORC,PMP}} - P_{\mathrm{N2,PMP}} - P_{\mathrm{air,fan}}}{\dot{Q}_{\mathrm{ORC,LH}} + \dot{Q}_{\mathrm{ORC,EVA}} + \dot{Q}_{\mathrm{N2,VAP\#2}} + \dot{Q}_{\mathrm{N2,VAP\#3}}} \tag{4}$$

2.2 Estimation and cost analysis

The investment cost is calculated based on the additional purchased components such as the ORC system (expander, condenser, pump, evaporator and liquid heater), nitrogen expander, and generator. The cost (C_p^0) for each component could be estimated based on their capacities (X), for example, the estimated cost for the rotary component is determined from the power or volumetric flow rate ($\dot{V}$), the estimated cost for stationary components (liquid heater, evaporator, and condenser) from the area of the heat exchanger (several functions of the estimated cost for selected components are described in Equation (5) and summarized in Table 2). Other components are listed in Table 3. In this case, power consumption and power production could be computed using the enthalpy change and the mass flow rate aforementioned. Moreover, the area of the heat exchanger (A) could be determined using obtained heat transfer rate ($\dot{Q}$), the logarithmic mean temperature difference (LMTD) and the overall heat transfer coefficient (U) (Habibi *et al*., 2018). Using several assumptions that are classified by (Silla, 2003), the overall heat transfer coefficient for different components of heat exchangers have been assumed. The specific value assumed for the overall heat transfer coefficient is 0.600 kW/m^{2}K for the air-cooled heat exchangers and 2.029 kW/m^{2}K for the condenser. These coefficients represent the conditions of heat transfer between a fluid and its surroundings/other fluids per unit area and per degree of temperature difference.

$$C_{\mathrm{p}}^{0} = 10^{K_1 + K_2 \log_{10}(X) + K_3 (\log_{10}(X))^2} \tag{5}$$

Table 2: List of the estimated cost function for selected components based on Equation (5).

List of components	Capacity in unit	Range of capacity	Estimated cost function		
			K_1	K_2	K_3
ORC pump and nitrogen pump in USD (Turton *et al*., 2012)	kW	1-100	3.4771	0.1350	0.1438
Generator (Pili *et al*., 2019)	kW	80-10,000	4.1055	0.0570	0.0797
An air-cooled heat exchanger (liquid heater, evaporator, vaporizer) in USD (Turton *et al*., 2012)	m^2	200-2,000	4.0336	0.0234	0.0497

Table 3: List of the estimated cost function for other components

List of components	Capacity in unit	Range of capacity	Estimated cost function
ORC expander and nitrogen expander in USD (Towler and Sinnott, 2021)	kW	100-20,000	$C^0_{\mathrm{p,EXP}} = -14 \cdot 10^3 + 1.9 \cdot 10^3 (P_{\mathrm{EXP}})^{0.75}$
Heat exchangers (condenser) in USD (Smith, 2005)	m^2	80-4,000	$C^0_{\mathrm{p,CDS}} = 32.8 \cdot 10^3 \left(\frac{A_{\mathrm{CDS}}}{80}\right)^{0.68}$
Blower/fan in EUR (Walraven *et al.*, 2015)	kW	1-100	$C^0_{\mathrm{p,fan}} = 1.31 \cdot 10^4 \left(\frac{P_{\mathrm{fan}}}{50}\right)^{0.76}$

The purchase cost of the condenser was obtained in 2000, the air-cooled heat exchangers (e.g., liquid heater, evaporator, and vaporizer) and pump in 2001, the expander in 2010, and the generator and the blower/fan in 2013. Moreover, the CEPCI for 2000, 2001, 2010, and 2013 are 391.0, 397.0, 532.9, and 567.3, respectively (Mignard, 2014; Rodgers, 2022). In this study, the purchase cost of all equipment was converted from USD to EUR and the annual average exchange rate of USD to EUR in 2000, 2001, 2010, and 2013 was 1.09, 1.11, 0.75, and 0.75, respectively (Statista, 2023). Then the total purchase cost ($C_{\mathrm{p,total}}$) was calculated using CEPCI for 2022 of 813 (Rodgers, 2022) and multiplied with the bare module factor (F_{BM}) for expanding the existing system to estimate the bare module of capital cost (C_{BM}), where the bare module factor for each component is taken from the book (Turton *et al.*, 2008). Furthermore, the capital cost of the bare module is multiplied by 1.18 to estimate the capital cost of the total module (C_{TM}) that includes contractor fees, auxiliary facilities, the cost of integration and installation, the cost of the project, and so on (Lemmens, 2016). These capital costs of the bare module and the total module aforementioned could be expressed as a function of the purchased cost, described as Equations (6) and (7), respectively. 188

$$C_{\mathrm{BM}} = \sum_{i=1}^{n} C_{\mathrm{p,i}} \cdot F_{\mathrm{BM}} \tag{6}$$

$$C_{\mathrm{TM}} = 1.18 \sum_{i=1}^{n} C_{\mathrm{BM,i}} \tag{7}$$

Two indicators, the specific investment costs (SIC) and levelized cost of electricity ($LCOE$), are chosen to evaluate the economic feasibility of the redesigned system. These specific investment costs and levelized cost of electricity can be expressed as functions by Equations (8) and (9). Some assumptions are taken into account in this analysis. The reference year is 2022. The annual discount rate (d) and inflation rate are 6.08% and 2.00%, respectively. The lifespan of the installed system (y) is 20 years and the operating time (t) is 254 working days. Moreover, the cost of operation and maintenance is 0.01 EUR/kWh.

$$SIC = \frac{C_{\mathrm{TM}}}{P_{\mathrm{net}}} \tag{8}$$

$$LCOE = \frac{C_{\mathrm{TM}} + \sum_{i=1}^{y} \frac{C_t}{(1+d)^i}}{\sum_{i=1}^{y} \frac{P_{\mathrm{net}} \cdot t}{(1+d)^i}} \tag{9}$$

3 RESULTS AND DISCUSSION

The obtained result demonstrates that the net power generation varies based on the ambient air temperature, with power generation in the winter being comparatively lower than in the summer. The ORC and direct expansion system may provide 8.5 kW and 39 kW of gross power in December, respectively. The potential gross power output of an ORC and a direct expansion system in July is 24.00 kW and 67.45 kW, respectively. Consequently, the system may generate 23.72 kW of net electricity (with a system efficiency of 13.16%) in December and 50.02 kW (with a system efficiency of 15.93%) in July, depending on the power consumption of the pump and blower/fan. Figure 2 shows the trend of the fluctuating net generated power.

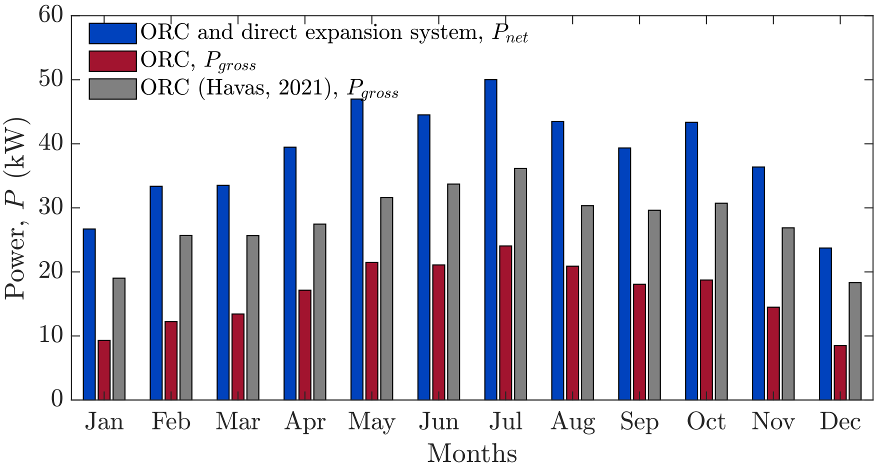
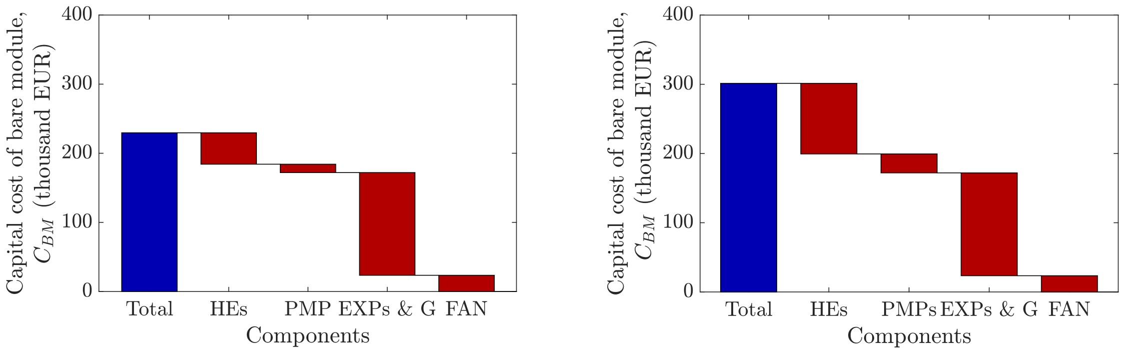


Figure 2: The monthly generated power.

In comparison, a Master thesis (Havas, 2021) reported the utilization of LIN cold energy using simplified ORC estimation. In this case, the cycle is assumed operating 5°C under ambient temperature and above LIN temperature. Although, it used ambient air as a heat source, slightly different average temperature data of ambient air were taken into consideration. Therefore, the fluctuating power generation was slightly different from this study. According to the ORC estimation (Havas, 2021), the system might generate 18.33 kW of gross electricity in December and 36.15 kW in July. The trend of both fluctuating gross ORC power based on the estimation (Havas, 2021) and this study is depicted in 189
Figure 2. The result demonstrates that when compared to gross ORC power for this study, the mean absolute percentage error (MAPE) is 41.72%. It appears that the ORC estimation (Havas, 2021) predicts more gross power generation than expected.

For economic analysis, the calculation is performed based on the highest generated net power, which is shown in July (see, Figure 2). In this study, the economic analysis was performed using two different options. The first choice (i.e., Case #1) redesigns components (nitrogen pump and vaporizers) that are already in use (by reusing the existing vaporizers). Another option (i.e., Case #2) uses completely new components to replace the existing system (without reusing the existing vaporizers). These two possibilities are employed to see the cost-effective option and the difference between the choices for this utilization of LIN cold energy in the pharmaceutical business, where the difference is depicted in Figure 3 and summarized in Table 4. It shows that Case #1 might save the cost of a bare module by up to 56.52 thousand euros while reusing the nitrogen pump could cut the cost of a bare module by up to 15.25 thousand euros. In addition, case #1 offers a 23.81% capital cost reduction for the bare module.



(a) (b)

Figure 3: The capital cost of the bare module for (a) case #1 and (b) case #2.

Table 4: The obtained result of the economic analysis.

Options	C_{BM} **(EUR)**	C_{TM} **(EUR)**	SIC **(EUR/kW)**	$LCOE$ **(EUR/kW)**
Case #1	229,627.72	270,960.71	5,417.02	0.119
Case #2	301,394.12	355,645.07	7,110.03	0.153

Furthermore, the other obtained result in this study is indicated as the capital cost of the total module, investment cost, and LCOE which is summarized in Table 4. Case #2 offers an investment cost of 7.11 thousand euros per kW, and a total capital cost of 355.65 thousand euros, making its LCOE 0.034 euro/kW more expensive than Case #1. This study shows that utilization of LIN cold energy in pharmaceutical business using ORC and direct expansion in the Case #2 performs 31% investment cost more expensive than Case #1. It appears that Case #2 is less attractive compared to Case #1.

4 CONCLUSIONS

The industry is increasingly becoming more and more interested in increasing system efficiency. The potential utilization of LIN cold energy in the pharmaceutical business was discussed in this study. The result of this paper can be concluded as follows:

1. LIN cold energy can be used to generate power using an ORC and direct expansion system; taking into consideration the LIN regasification as the ORC's heat sink and expanding it to produce power.
2. The ORC estimation from (Havas, 2021) and the redesign of ORC were examined and compared.
3. The cost-effective solution for the use of LIN cold energy in pharmaceutical businesses was also discussed in this study. The outcome implies that reusing the system's existing components, such as the nitrogen vaporizers and pump (e.g., Case #1), may provide a more cost-effective solution than the suggested system making use of entirely new components (e.g., Case #2) that would save 23.81% on investment costs and 22.00% on LCOE.

It is worth noting that this paper highlights the potential benefits of implementing ORC and a direct expansion system on the utilization of LIN cold energy as power generation. Moreover, several areas could be also interesting to do in further work and research such as the dynamic simulation of the performance under different operating conditions as the system uses air as the heat source, testing the system in various cases scenarios, comparing the obtained simulation results with the validation through experimental study (that could be in lab scale or pilot project).

NOMENCLATURE

A	area	(m^2)	P	power	(kW)
C	cost	(EUR)	p	pressure	(Pa)
d	discount rate	(%)	ρ	density	(kg/m^3)
h	specific enthalpy	(kJ/kg)	$\dot{Q}$	heat transfer rate	(kW)
η	efficiency	(–)	SIC	specific investment cost	(EUR/kW)
K	constant	(–)	t	operating time	(hours)
$LCOE$	levelized cost of electricity	(EUR/kW)	X	capacity refers to A or P	(m^2 or kW)
$\dot{m}$	mass flow rate	(kg/s)	y	the lifespan of an installed system	(year)

Subscript

BM	bare module	p	purchase
CDS	condenser	PMP	pump
EVA	evaporator	t	operating time
EXP	expander	VAP	vaporizer
G	generator	wf	working fluid
LH	liquid heater	TM	total module

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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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