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Review

Design, Integration, and Control of Organic Rankine Cycles with Thermal Energy Storage and Two-Phase Expansion System Utilizing Intermittent and Fluctuating Heat Sources—A Review

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Abstract: In order to lessen reliance on fossil fuels, a rise in interest in the utilization of fluctuating and intermittent heat sources derived from renewable energy (such as solar thermal, ocean thermal, and geothermal) and waste heat has been observed. These heat sources could be used to generate electricity at relatively low and medium temperatures, for example, through the organic Rankine cycle (ORC). In some case studies, various approaches have been developed to deal with and design ORCs in the desired operating condition utilizing suitable working fluids. This article aims to review some designs and integrated systems of ORC with thermal energy storage (TES) and a two-phase expansion system focusing on the utilization of medium- and low-temperature heat sources in which some subcritical ORCs are presented. Moreover, several possible control systems (both conventional and advanced ones) of ORC with TES and a two-phase expansion system are reported and compared. At the end of this article, the possible future developments of design and control systems are discussed to describe advanced ORC for utilizing low-grade heat sources. This study aims to provide researchers and engineers with an insight into the challenges involved in this process, making industrialization of ORC technology more extensive, in particular when combined with TES and a two-phase expansion system.

Keywords: intermittent heat sources; fluctuating heat sources; ORC; TES; phase change; phase equilibria; PID; fuzzy; MPC

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Citation: Imre, A.R.; Daniarta, S.; Błasiak, P.; Kolasiński, P. Design, Integration, and Control of Organic Rankine Cycles with Thermal Energy Storage and Two-Phase Expansion System Utilizing Intermittent and Fluctuating Heat Sources—A Review. *Energies* **2023**, *16*, 5948. https://doi.org/10.3390/en16165948

Academic Editor: Luisa F. Cabeza

Received: 21 July 2023
Revised: 10 August 2023
Accepted: 10 August 2023
Published: 11 August 2023

1. Introduction

A key aspect of the energy transition to achieve current climate targets and decrease the dependency on fossil fuels, in addition to the growth of photovoltaic (PV) and wind power production systems, is the utilization of reliable low- and-medium-temperature heat sources. This could be achieved by using organic Rankine cycle (ORC) technology, considered one of the possible approaches and solutions to increase the usage of renewable and waste energy sources (which are likely intermittent and fluctuating). Some challenges have been addressed in current research on ORC [1,2], which is indicative of both the wide range of applications [3,4] and the great potential for future performance improvements [5,6]. According to a recent study [7], about 2900 projects from more than 30 manufacturers have been collected and evaluated, providing information on trends and market evolution classified by application, macro region, installed plants, capacity, and manufacturer. Moreover, it was reported that the ORC market as a whole increased by 40% in installed capacity (equivalent to an increase of 1.18 GW) and by 46% in installed plants (equivalent to 861 additional installed plants) [7]. Some of the installed plants can be found on this website:

orc-world-map.org (accessed on 7 August 2023) [8]. The current market situation appears to be likely robust, yet the investment cost is still quite high; therefore, achieving a low payback period for various applications would be an important challenge and affecting the industrialization of ORC technology. Although a review article [9] has described an integration approach for ORC with waste heat, market-driven industrialization of ORC technology needs to be extensively developed through some comprehensive integrated systems.

The utilization of fluctuating and intermittent heat sources could be achieved in one of two possible approaches: indirect or direct ORC systems. The direct system refers to the utilization of heat sources to raise the temperature of the working fluid and change its phase to the desired condition (typically in a superheated state), and then the working fluid immediately enters the expander to drive the shaft and generator. However, occasionally, a heat source fluctuation might result in unsuccessful evaporation, which would allow the working fluid to enter the expander in a two-phase state, leading to possible erosion damage (assuming a turbomachinery expander is applied in the system). However, volumetric expanders might be used to handle this problem [10–12]. An ORC system employing two-phase expansion might be a solution to this challenge. Based on literature studies, there are a few experimental studies [13,14] and modelling simulations [15–17] on ORC with a two-phase expansion system. On the other hand, an indirect system means that the heat from fluctuating and intermittent sources is stored and separately accumulated in the heat storages (or thermal energy storage/TES), and then it could be used later to supply the ORC system. This integration of ORC with separate TES devices is typically found in the application of solar thermal power plants [18,19]. Moreover, a recent review article reported that there is a possible configuration of TES applied directly to the ORC system (as TES-evaporator, TES-condenser, or TES-heat exchanger built into one device) [20]. The possible configurations mentioned above could be the future of ORC. However, there is still a lack of experiments and modelling simulations on this topic.

A recent review article discussed the progress and effort for development of ultra-low temperature ORC utilizing heat at or below 150 °C [21]. In addition, another article provided overview on exergy assessment of ORC for waste heat recovery (WHR) [22]. However, based on studies in the literature, there is still a lack of information and no comprehensive review on the integrated system of ORC technologies, including a two-phase expansion system and TES, including the design. Therefore, this article aims to review and discuss the possible design and integration of ORC technologies with TES and a two-phase expansion system in order to utilize the intermittent and fluctuating heat sources that are typically in the range of low and medium temperatures. In that case, this review article could be state-of-the-art. Moreover, both modelling and experimental studies are reported, including some novel approaches. In addition, this review covers the conventional and advanced control systems required to automatically operate the ORC with TES and a two-phase expansion system. Only the most used reliable control systems are described and summarized. The future control strategy and comparison of the selected control system are described. Finally, some directions of research on this topic, including the integrated system, are discussed. The primary goal of this study is to offer researchers and engineers a deeper understanding of the obstacles associated with this procedure, facilitating the broader advancement of ORC technology, especially in conjunction with TES and two-phase expansion system in order to utilize intermittent and fluctuating heat sources.

This article is structured as follows. Section 2 describes an overview of the design and integrated ORC system for low- and medium-temperature heat sources. Section 3 reports and discusses operating conditions, various control systems designed for ORC with TES, and a two-phase expansion system. In addition, the presented control system is compared. Section 4 discusses several possible future directions of ORC research with TES and a two-phase expansion system. Then, in the end, the article is summarized with the conclusion of the study.

2. Design and Integrated System of Organic Rankine Cycle for Medium- and Low-Temperature Heat Sources

Various designs have been developed for ORC such as regenerative, multistage, cascaded, and reheating cycles [2,23,24], but in most cases, they assume a constant heat flow rate. This article focuses on design and integration for the utilization of low- and medium-temperature heat sources which are likely intermittent and fluctuating, for instance, the waste heat and some renewables. The selection of an appropriate working fluid is still essential for basic ORC since the kind of working fluid as well as its thermal properties, ecological effects, and safety concerns have a great impact on the design and operation of the cycle. Because of this, the performance of the ORC system is substantially impacted when the heat source fluctuates. In that case, there are three common conditions in the operation of a power plant which are derived from the performance of the expander, as follows:

- Design-point conditions, in which the operation is in a good or the best performance of the cycle,
- Off-design conditions, in which the operation is with significantly reduced performance, and
- Not working conditions, in which the operation is not recommended due to some financial constraints, lack of profitability, safety issues, reliability of components, regulation, and so on. For example, the generated power of the system is lower than its power consumption, resulting in an undesired overall efficiency. As a consequence, the business case for this system is unprofitable due to the inefficiency and associated cost of operation. For these reasons, it must shut down.

Based on the literature, it is found that in most circumstances, ORC systems operate far from the design point, and the average output power may be reduced to 50% less than when it is fully operational under constant design-point conditions [25,26]. This shift might be caused by several reasons, like the decomposition issue of the working fluid, the effectiveness of heat exchangers, the efficiency of machines, and so on [26]. Therefore, several alternative designs and integrated ORC systems have been recently developed to tackle these issues and utilize the intermittent and fluctuating heat sources, illustrated in Figure 1.

Figure 1 shows that in a partially evaporated ORC (PE-ORC) or ORC with a two-phase expansion cycle in the designed system and the temperature vs. entropy diagram (*T*-*s* diagram), the working fluid evaporates only in part, and it enters the expander under two-phase conditions instead of superheated or saturated vapor. In the *T*-*s* diagram, it can be easily seen, because point 3 (expander inlet stage) is below the saturation dome, encompassing two-phase states. In this method, the latent-to-sensible heat ratio of a working fluid in the evaporator inlet stage is reduced compared to the fully evaporated ORC. Therefore, it might effectively absorb the waste heat/renewable heat sources at lower temperatures, enhancing the efficient utilization of heat sources. As an alternative to PE-ORC, a trilateral flash cycle (TFC) could be also employed to utilize intermittent and fluctuating heat sources. The design of TFC is similar to that of ORC, but the working fluid directly enters the expander under saturated liquid condition (after being heated in the liquid heater without evaporation). This cycle also employs a two-phase expander. In the literature, PE-ORC and TFC are insufficiently investigated, and only a few numerical and experimental studies have been conducted. Numerical studies have been conducted for both PE-ORC and TFC to compare their performance with standard ORCs [16,17,27]. Recently, a few experimental investigations on micro PE-ORC were conducted below 150 °C. Employing a reciprocating piston expander, the PE-ORC was able to provide a maximum electrical output of approximately 1.2 kW, and the partially evaporated state significantly increased the performance of the evaporator [13]. Moreover, another PE-ORC research which employs a twin screw expander was carried out, and the results indicate that under all examined heat source conditions, PE-ORC performs up to 80% better than standard ORC [14].

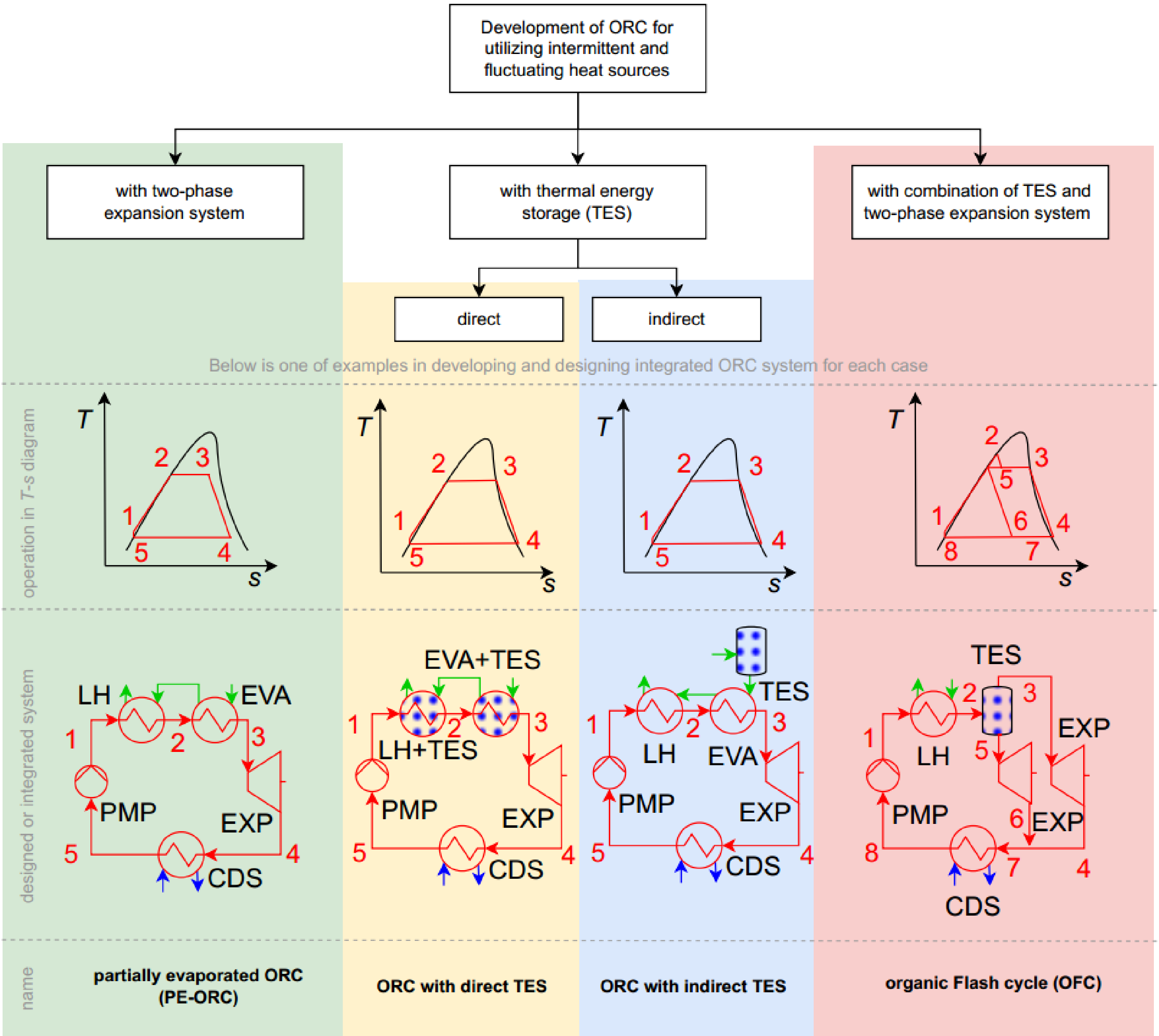


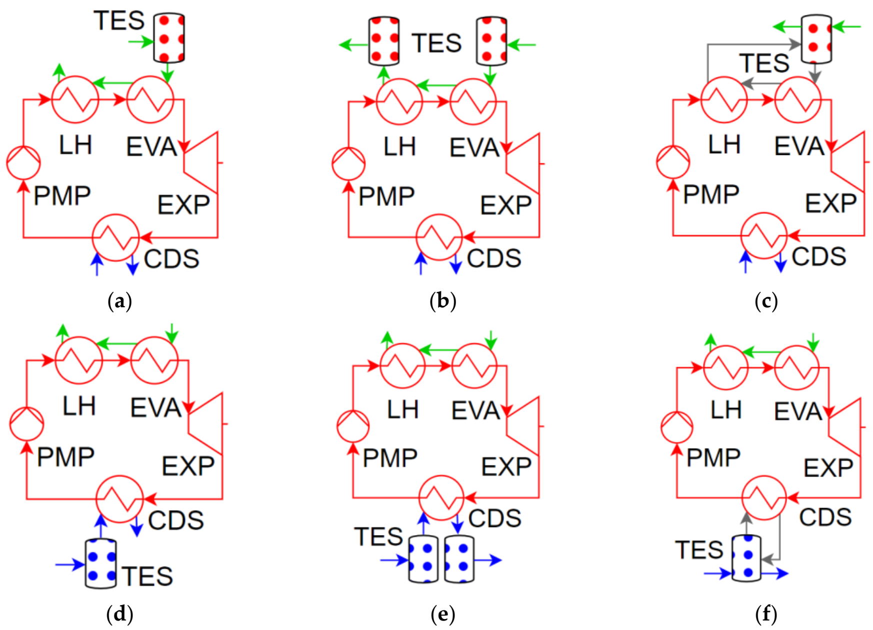
Figure 1. Development of ORC utilizing intermittent and fluctuating low- and medium-temperature heat sources via a two-phase expansion system (direct), TES (direct and indirect), or combined system. In this illustration, LH, EVA, EXP, CDS, PMP, and TES refer to liquid heater, evaporator, expander, condenser, pump, and thermal energy storage, respectively.

Furthermore, adopting heat storage or TES, as is shown in Figure 1, might be an option to utilize intermittent and variable heat sources. This TES can be used to store and accumulate heat. According to a review [20], there are two approaches to integrating TES with ORC, as follows:

- Indirect TES system, in which TES is separately installed in the ORC system (see Figure 2). Various solar thermal power plants use this kind of design [19,28]. In addition, there are a number of configurations in these solar thermal power plants (e.g., concentrated solar power/CSP) where the hot TES is used to store and accumulate the hot source after the working fluid or thermal oil has been heated using a solar collector and the cold TES is used to store and accumulate the working fluid or thermal oil after it has been used in the heat exchanger. In addition to storing hot sources, it is also possible to store cooling sources, such as those derived from liquefied natural gas

(LNG) [29], hydrogen, dimethyl ether (DME), or other cryogenic substances. It is also feasible to store and accumulate both hot and cold substances before using them if they are intermittent and fluctuating, as shown in Figure 2. Additionally, it is feasible to develop the Carnot battery, a future storage system that uses a high-temperature heat pump to raise the temperature of a storage medium utilizing excess electrical energy and waste heat using the indirect TES technology [30–32]. The use of cooling sources as a storage medium is another option [33]. For this Carnot battery, additional heat pump technology is required to raise the temperature of the hot sources or to decrease the temperature of the cooling sources so that it may be used later.

- Direct TES system, in which the TES is installed in the cycle; it could be combined with heat exchangers, evaporators, liquid heaters, condensers, and so on (see, Figure 3). Some studies [20,34] have described the possible configuration of this TES-evaporator, TES-liquid heater, and TES-condenser. However, only a few experimental studies have been conducted using this design. Since the TES is included in the heat exchangers, there are several challenges in designing the TES-heat exchangers, as follows:
    - Selection of proper heat exchangers,
    - Selection of suitable TES materials (sensible, phase change materials/PCM, thermochemical),
    - Proper placement and distribution of TES within heat exchangers,
    - Potential flow blockage issues or solidification,
    - Geometry and spacing consideration in the heat exchangers,
    - Effectiveness and efficiency,
    - Sizing materials of the storage system,
    - Thermal properties,
    - Economic and life cycle analysis, and
    - Hazard and safety issues.



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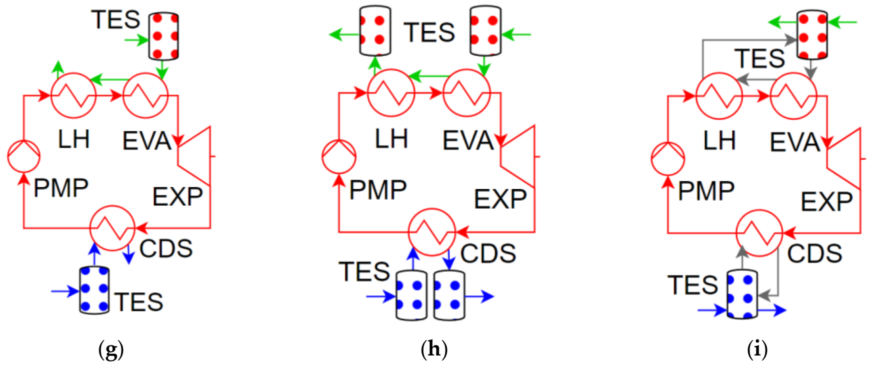


Figure 2. Several indirect systems of TES integrated into the ORC system for (**a**–**c**) hot sources, (**d**–**f**) cooling sources, and (**g**–**i**) both sources. In this illustration, LH, EVA, EXP, CDS, PMP, and TES refer to liquid heaters, evaporator, expander, condenser, pump, and thermal energy storage, respectively.

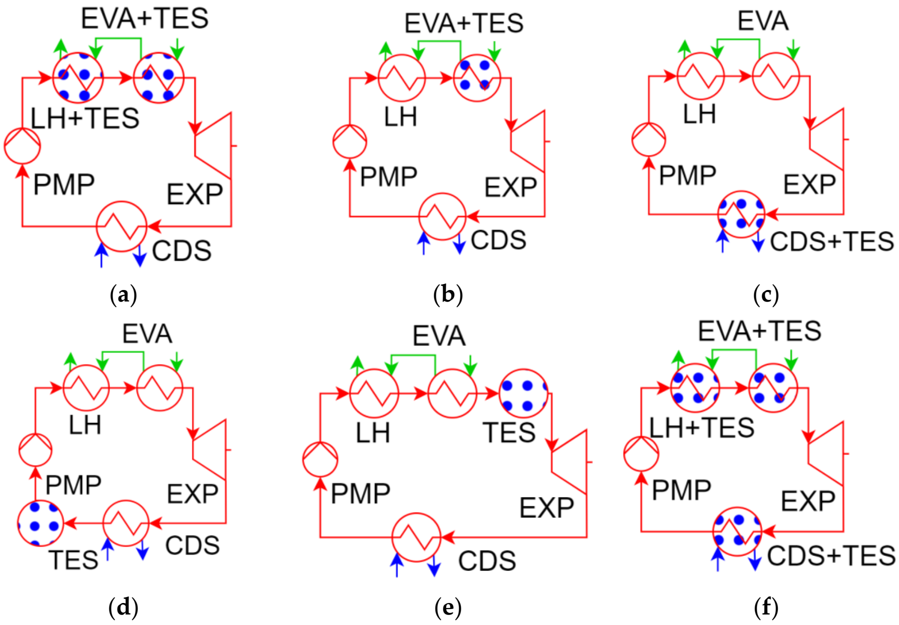


Figure 3. Several direct systems of TES integrated in ORC system for (**a**) liquid heater and evaporator, (**b**) evaporator, (**c**) condenser, (**d**,**e**) separate devices, and (**f**) liquid heater, evaporator, and condenser. In this illustration, LH, EVA, EXP, CDS, PMP, and TES refer to liquid heater, evaporator, expander, condenser, pump, and thermal energy storage, respectively.

Several challenges in designing the TES heat exchangers (direct TES system) above are likely also valid for indirect TES systems. The selection of direct and indirect TES systems should be conducted and analyzed based on the need of specific projects (e.g., available investment cost or financial constraints) and the area where it is installed (for example, related to safety and the available resources).

The two-phase expander and TES might be placed simultaneously in the ORC system as an alternative design and integrated system. For example, the design could be an organic flash cycle (OFC) illustrated in Figure 1. In the original OFC, a separator is used to separate the liquid and the vapor phases after the liquid heater [35]. The vapor phase is expanded to drive the shaft and generator, while the liquid phase enters the throttle valve without being used. Recently, a study [36] reported that flash (liquid phase) by replacing the throttle valve with a two-phase expander. Therefore, the cycle could generate more output power and increase the efficiency of the system. Additionally, by incorporating TES technology, this design might be enhanced to store and accumulate the hot side in the separator.

3. Operation and Control of Organic Rankine Cycle System with Thermal Energy Storage and Two-Phase Expansion System and Discussion

Brief summaries of fluctuating or intermittent heat sources are described in Table 1, and their characteristics could be classified as follows:

- Fluctuating/intermittent heat sources based on variables, which refers to changes or variations in some parameters within a system. In this case of thermodynamic power cycles, it refers to variations in mass flow rate, temperature, or both simultaneously. Understanding and managing these variables may help to maintain steady and effective operations. In addition, this could assist in forecasting and govern the behavior of the system under varying conditions. Then, the model is used to improve performance, safety reasons, and so on.
- Fluctuating/intermittent heat sources based on frequency, which refers to variation in the frequency of occurrence over time. These fluctuations could occur on different time scales, such as days, hours, minutes, or seconds in some heat sources. Understanding and analyzing the pattern of this frequency might be crucial in planning resources, optimizing systems, assessing performance, and making decisions when the thermodynamic cycles operate in the desired and good performance. Sometimes, it uses statistical analysis, time series modelling, and real-time monitoring approaches to collect and explain the fluctuation.

Table 1 shows that water and air are not just limited to being utilized as cooling sources in the current energy system; they may also serve as beneficial heat sources for power plants in the re-gasification system (see, the utilization of cold energy [37]). Air and water are abundant, intermittent, and fluctuating depending on the climate and location. In order to ensure the optimal operation and performance of the power plant, it is essential to sustain and manage the fluctuations of both hot and cold sources. As a result, Figure 4 outlines the possible operating scenarios of the ORC using intermittent and fluctuating sources for both the cold and the hot sides. There are two options for making use of intermittent and fluctuating heat/cold sources: either the heat is used directly, or it is stored for later use (indirect usage). In direct use, the ORC may employ a two-phase expansion system, and its performance of the system may reach its optimum condition (also known as the designed condition, indicated with A1 in Figure 4a), the off-design condition (see, A2 in Figure 4a), or possibly not operate at all under certain conditions if both the hot and cold sources are intermittent. This performance could be indicated by the temperature range of the running operation. Another option would be to store the heat for later use. Figure 4b shows how the operating temperature range might be maintained, allowing for more or less stable system performance (see, B1 and B2).

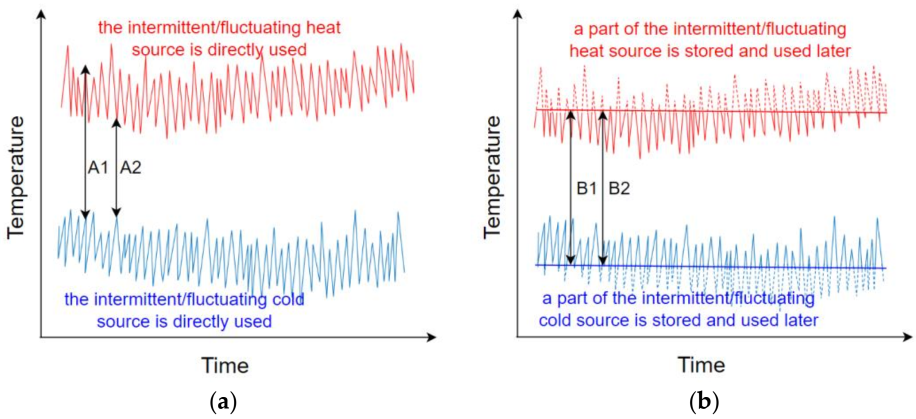


Figure 4. The illustration of (**a**) the direct utilization of intermittent and fluctuating heat/cold sources, and (**b**) the indirect utilization of intermittent and fluctuating heat/cold sources by using a TES system (direct TES or indirect TES systems), adapted from [38].

Table 1. A brief summary of fluctuating and intermittent heat sources, adapted from [26] with additional information.

Application	Heat Sources	Temperature (°C)	Mass Flow Rate (kg/s)	Fluctuating Variables	Fluctuating Frequency	Refs
Diesel engine	Exhaust	120–500	0–0.4	Temperature and mass flow rate	Seconds	[26]
Gasoline engine	Exhaust	120–700	0–0.1	Temperature and mass flow rate	Seconds	[26]
Cement clinker cooler	Exhaust air	150–350	53.75	Temperature	Minutes	[26]
Steel billet reheating furnace	Off-gas	800–950	1.5–8	Mass flow rate	Minutes	[26]
Steel electric arc furnace	Off-gas	100–750	5–32	Temperature and mass flow rate	Minutes	[26]
Solar	Thermal oil	230–280	0–12	Temperature and mass flow rate	Hours-days	[26]
Ocean thermal	Warm surface water or deep cooling water	5–30 * ΔT = ~5–15 **	8.3–2020	Temperature and mass flow rate	Hours-days	[39–41]
Geothermal	Geothermal water	80–350 * ΔT = ~40 **	0.001–229	Temperature and mass flow rate	Hours, days, months, years	[42–44]
Several applications	Air (for example, air cooling system of a geothermal power plant and air for evaporating the substance in the power plant utilizing the cooling from regasification system)	ΔT = ~40 **	>0.01	Temperature and mass flow rate	Hours, days, months, years	[45,46]
Several applications	Water (for example, the air-cooling system of a geothermal power plant, and water for evaporating the substance in the power plant utilizing the cooling from regasification system)	ΔT = ~20 **	>0.01	Temperature and mass flow rate	Days, months, years	[45,47]

* The range of temperature. ** The extension of temperature fluctuation.

3.1. System Identification

The design and achievement of optimal control systems performance depend substantially on understanding the dynamics of ORC systems. In that case, the description of reliable and accurate system behavior is provided by a process model built on the principles which describe the physical processes involved in ORC, such as heat and mass transfer, compression, expansion, and so on. These models include constitutive equations and dynamic mass, energy, and momentum balances, which are necessary to gather experimental data that provide enough details for precise calculation to estimate the model based on desired parameters [48,49]. In addition, some estimated parameters such as efficiency (pump, expander, other components), effectiveness, heat transfer coefficient, and chemical and physical properties are included in the model [50–52]. The most reliable parameter estimation method involves dynamic response programming (the model of input-response dynamics) or an empirical model (based on input-output data). Based on the literature [53], there are at least two different categories of dynamic models that may be used when collecting experimental data for the modelling of ORC systems, as follows:

- Non-parametric model, in which the main objective of the model is to characterize the dynamic behavior of the system without explicitly setting the values of certain parameters. Frequency response and step response models are two examples of non-parametric models. Step response models look at how the system responds to a quick shift or step input, whereas frequency response models investigate how the system responds to various frequencies. An article has described this non-parametric model, for example [51].
- Parametric model, which the model entails choosing precise parameter values that correctly depict the dynamics of the system. Differential equations define the relationship between variables in the time domain, and transfer functions, which relate input and

output variables in the frequency domain, are two examples of parametric models. While a more precise estimate of the model parameters is necessary for parametric models to offer a complete and accurate picture of the behavior of the system, methods like maximum likelihood estimation or dynamic programming can be used. For example, an article has described this parametric model [52].

An experimental approach called system identification is employed to determine the dynamic model of the system. There are four key steps that generally comprise the process [53] (illustrated in Figure 5), as follows:

- Acquisition of input/output data following an experimental protocol involves applying input signals to the system and recording the resulting output data. The experimentation methodology must be properly planned in order to capture a variety of operating situations and dynamics.
- Selection or estimation of the "model" structure (complexity): the next phase entails choosing or estimating the right model structure that accurately represents the dynamics of the system. This involves determining the level of the complex model, including the number of parameters and the mathematical equations employed to predict the behavior of the system.
- Estimation of the model parameters: after the model structure is established, the values of model parameters need to be estimated. This often entails using estimate techniques to fit the model to the obtained input/output data, such as least squares regression or maximum likelihood estimation.
- Validation of the identified model (structure and parameter values): the validation of the identified model is the last stage. By contrasting the predictions of models with new experimental data or established system behavior, one may evaluate the structure of the model and predicted parameter values. Through validation, it may be made sure that the chosen model accurately describes the dynamics of the system and can be used to create control systems or conduct future research.

Furthermore, system identification also modifies the existing model, enabling model-based optimization of the present control system. According to some articles [44–46], system identification is useful for enhancing the ORC control system for waste heat recovery. The design and execution of control algorithms may be guided by the data-driven insights discovered through system identification, enabling more effective usage of waste heat and optimizing power output. In the end, system identification is necessary for identifying a dynamic model of the system and enhancing and perfecting already-existing models. Some existing dynamic models for each component in the ORC system are found in these studies [48,50,54].

3.2. Control System of Organic Rankine Cycle Integrated with Thermal Energy Storage and Two-Phase Expansion System

In order to utilize the intermittent and fluctuating heat sources, the control system plays a crucial role for ORC integrated with thermal energy storage and a two-phase expansion system in managing the complex dynamics, optimizing the energy conversion process and efficiency of the system. The two-phase expansion system allows for greater energy extraction, which might lead to improved efficiency and performance of the system under some circumstances, while TES allows for the capture and storage of excess thermal energy during periods of low demand, which could then be utilized during peak demand or when the heat sources are intermittent.

Numerous process control techniques, classic and advanced ones, are categorized in Figure 6 and might be used for ORC. Proportional-integral-derivative (PID), cascaded control, feedforward (open loop), feedback (closed loop), and lead/lag compensation are all components of the classical control system. In addition, there are now additional possibilities for sophisticated control systems, such as artificial intelligence, model predictive control (MPC), neural network control, and optimal control. Such combined control methods may also be employed to enhance the system and lessen disruption. Only the most popular control system for ORC has been selected and described in this evaluation due to the large number of available control system alternatives [55–57].

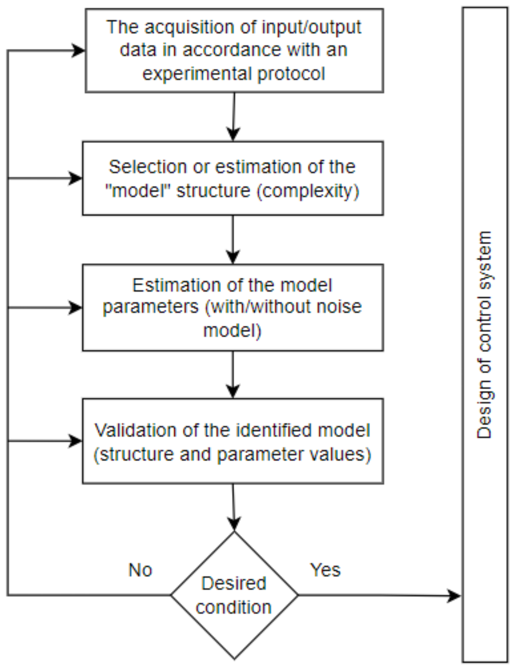


Figure 5. System identification based on experimental approach, adapted from [53].

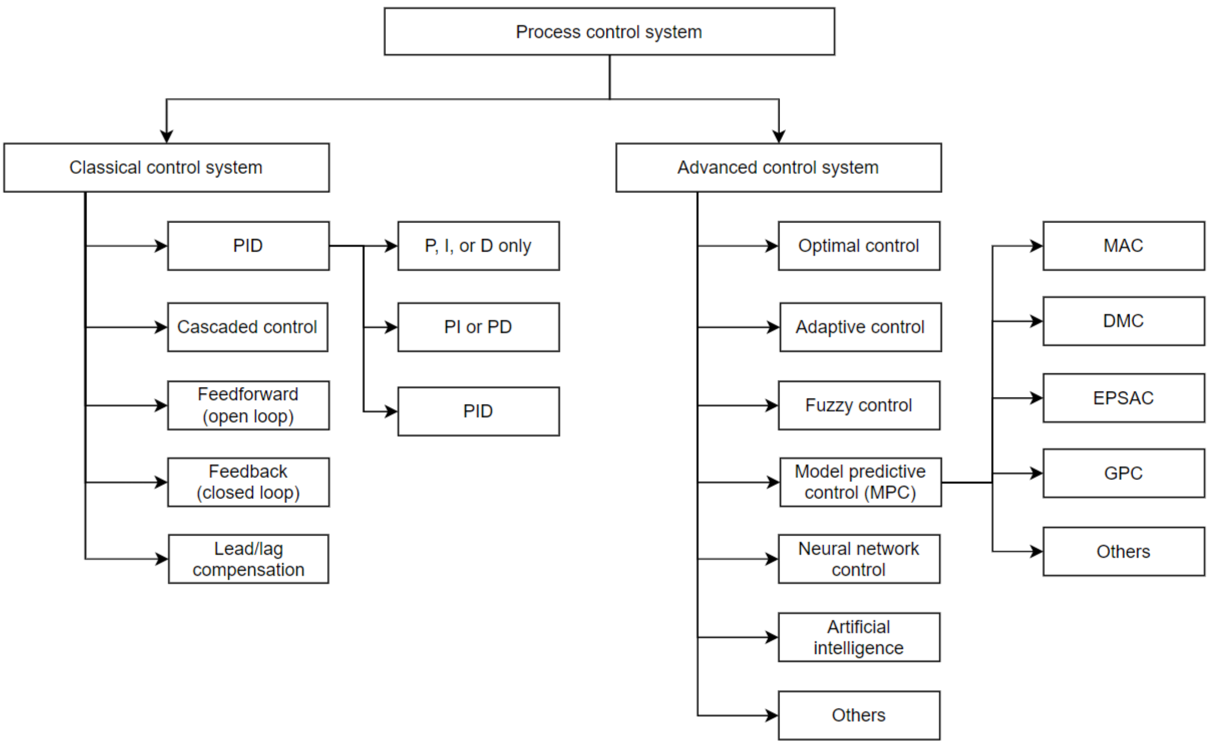


Figure 6. Overview of a possible control system for the ORC system.

3.2.1. Proportional Integral Derivative (PID)

A summary of the selected possible PID control systems for ORC is listed in Table 2. Peralez et al. [58] analyzed superheat control for an ORC system for engine waste heat recovery. They combined a PID with a dynamic feedforward term obtained from a non-linear reduced model. It was found that this combination performs better and increases the efficiency of the ORC system. The model was validated experimentally. The same authors [59] extended the developed model by adding a second controller to adjust the evaporating pressure. They validated it under real operating conditions and achieved good accuracy by designing an observer. The model was further developed [60] for the multivariable case where the bypass of the evaporator was used as an additional actuator. The double loop ORC for waste heat recovery of natural gas was analyzed in Simulink by Wang et al. [61]. Five working conditions were studied, and it was found that using PID control it is possible to obtain good adaptability when the working conditions are reduced from 100% to 60%. Additionally, the mass flow rate of the cooling water was investigated, and the authors found that it can enhance the output power of the ORC studied. The model was validated by data from the literature. To study small-scale ORC dynamic performance, Ni et al. [62] used Dymola software. Both cloudy and clear sky conditions were analyzed for the power plant driven by a parabolic through collector. The main conclusion was that applying the PID controller it is possible to improve the generated power by 24%. The model was compared to the experimental data and a very good match was achieved. Marchionni et al. [63] compared four PI control system for ORC using GT-SUITE^{TM} and the result showed that for the same transient thermal input, the pump-based strategies are able to keep the net electrical power output closer to the design point, while the turbine-based strategies may achieve higher thermodynamic system performance. Wang et al. [64] analyzed ORC to recover the waste heat from internal combustion engines using Simulink software. The impact of the design parameters on evaporating pressure, condensing pressure, exhaust outlet temperature, and working fluids on the dynamic behavior of the system was studied. The authors concluded that the same PID controller can be used for different design parameters but not for different working fluids. In work [65], the authors compared the ORC for the heat recovery performance of waste for conventional PID controllers and fuzzy-based self-tuning PID controllers. Various operating conditions were modelled, and the results showed that the fuzzy self-tuning PID controller is superior to the conventional one. Lin et al. [66] analyzed the dynamic performance of two types of ORCs. The model was programmed using Dymola software. The authors reported that after applying the PID controller, the drops in evaporation pressure decreased six times for the ORC system. It increases the safety of the system operation and prevents the case where the superheat is zero. Recently, Wang et al. [67,68] have developed a dynamic model to control an ORC system using deep reinforcement learning combined with the PID controller. They found that it can be applied successfully in the ORC system to dynamically control the superheat temperature.

Table 2. Summary of selected PID-based control system used in the ORC.

Authors	Type of Controller and Type of Studies	Main Component	Manipulated/Controlled Parameters	Sensors	Actuators	Performances
Peralez et al., 2013 [58]	PID, simulation and experiment	Evaporator	The temperature and pressure of the evaporator outlet and the speed of the pump	Pressure, mass flow rate, and temperature	Pump, bypass of the evaporator, bypass of the expander, and turbine speed	The maximum error is 1.9 °C in feedforward action
Peralez et al., 2014 [59]	PID, simulation	Evaporator	Superheat temperature of the evaporator outlet, evaporating pressure, and speed of the pump	Pressure, mass flow rate, and temperature	Pump, bypass of the evaporator, bypass of the expander, and turbine speed	The maximum error is 5 °C when the observer is used

Table 2. *Cont.*

Authors	Type of Controller and Type of Studies	Main Component	Manipulated/Controlled Parameters	Sensors	Actuators	Performances
Peralez et al., 2017 [60]	PID, simulation and experiment	Evaporator	Superheat temperature of the evaporator outlet, evaporating pressure, and speed of the pump	Pressure, mass flow rate, and temperature	Pump, bypass of the evaporator, bypass of the expander, and turbine speed	The maximum error is 5 °C when the observer is used
Wang et al., 2017 [61]	PID, simulation	Evaporator and cooling loop	Superheat temperature at evaporator outlet, evaporating pressure, speed of the pump, and cooling water mass flow rate	Mass flow rate and evaporating pressure, and temperature	Pump	The efficiency of the system increased from 9–10% up to almost 18%
Marchionni et al., 2018 [63]	PI, simulation	Evaporator	Turbine inlet temperature, the pump revolution speed, the turbine revolution speed, and the opening position of recirculating valve	Temperature	Pump and valve	Energy recovered using several PI control systems on the following: Only pump: 15.2 kWh Only turbine: 11.6 kWh Pump and turbine: 12.0 kWh Pump and valve: 14.7 kWh
Ni et al., 2018 [62]	PID, simulation	Evaporator	Superheat temperature of the evaporator outlet, evaporating pressure, output power, and speed of the pump	Mass flow rate and temperature	Pump	24% increase in generated power
Wang et al., 2018 [64]	PID, simulation	Evaporator	Evaporating pressure, condensing pressure, exhaust outlet temperature, and speed of the pump	Mass flow rate, temperature, and pressure	Pump	Satisfactory control of the system with the same PID and different design parameters and there was oscillation detection.
Chowdhury et al., 2019 [65]	PID, simulation	Evaporator	Evaporator temperature, expander output power, speed of the pump, and valve opening	Mass flow rate and temperature	Pump and valve	Conventional PID is ±0.58 °C
Lin et al., 2019 [66]	PID, simulation	Evaporator	Evaporator temperature, output power, evaporating pressure, and speed of the pump	Pressure and temperature	Pump and expander	Fluctuation of pressure is smoother. Using PID results in a 1.43 bar evaporation drop instead of an 8.69 bar
Wang et al., 2020 [67]	DRL-PID, simulation	Evaporator	Superheat temperature under fluctuating heat input and speed of the pump	Temperature and other heat transfer parameters (for DRL)	Pump	Average absolute tracking error - PID: 2.16 °C - DRL-PID: 0.19 °C
Wang et al., 2023 [68]	DRL-PID, simulation	Evaporator	Superheat temperature under fluctuating heat input and speed of the pump	Temperature and other heat transfer parameters (for DRL)	Pump	Average absolute tracking error - PID: 4.65 °C - DRL-PID: 0.28 °C

3.2.2. Fuzzy Logic

An improved control system for ORC is introduced as an alternative to PID, and several potential fuzzy control systems for ORC are mentioned in Table 3. Chowdhury et al. [69] developed a fuzzy-based evaporator and the overall ORC-WHR system could be used and performed under transient simulations to develop a control plan for real-time applications in which the dynamic model was developed using finite volume (FV) methods. Wang et al. [70] developed a fuzzy PID control design which is a combined control system. Fuzzy controllers can manage complex systems through intelligent control and logical reasoning, since they have the capacity to learn and adapt. The fuzzy combined PID control demonstrates that it is more accurate, has a faster reach, and has a higher steady-state performance [70]. Moreover, Chowdhury et al. [65] proposed a fuzzy self-tuning PID controller to improve the control performance which the fuzzy acts tuning system. The study demonstrates that the controller can deal with uncertainty disturbance in ORC and waste heat recovery. Cioccolanti et al. [71] proposed a fuzzy logic controller for small-scale solar ORC integrated with TES and the dynamic condition of the evaporator was modelled in the FV method including the transient condition, input–output ranges, and thermal inertia. The suggested controller exhibits good performance in completing the load in different operating modes. In addition, Enayatollahi, et al. [72,73] introduced a neuro-fuzzy controller based on the inverse dynamics to control the temperature of the outlet evaporator by regulating the pump speed which leads to regulating the mass flow rate.

Table 3. Summary of selected fuzzy-based control system used in the ORC.

Authors	Type of Controller and Type of Studies	Main Component	Manipulated/Controlled Parameters	Sensors	Actuators	Performances
Chowdhury et al., 2018 [69]	Fuzzy, simulation	Evaporator	Refrigerant mass flow rate, heat source mass flow rate, heat source temperature, the outlet temperature of refrigerant, outlet temperature of heat sources	Mass flow rate and temperature	Pump	The responses of the model to transient inputs are sufficiently steady, according to the results, and sufficient. It may be inferred from this that the model was solidly constructed to be applied to the WHR system's dynamic situation. The validation results show that the evaporator outputs can be predicted using the fuzzy inference method in a dynamic environment.
Wang et al., 2019 [70]	Fuzzy PID, simulation	Evaporator	The temperature of the evaporator outlet and mass flow rate	Mass flow rate and temperature	Pump	According to the simulation results, fuzzy PID control has increased steady-state performance, greater accuracy, and can react more quickly. To reach a new level, this new unified system makes effective use of each system.
Chowdhury et al., 2019 [65]	Fuzzy logic, simulation	Evaporator and expander	Evaporator temperature, mass flow rate, and pump speed	Mass flow rate and temperature	Pump and valve	The results demonstrate that, under all circumstances, the fuzzy self-tuning PID controller outperformed the traditional PID controller in terms of set point tracking and disturbance rejection capabilities.
Cioccolanti et al., 2021 [71]	Fuzzy logic, simulation and experiment	TES	The temperature of TES, the temperature of diathermic oil in the linear Fresnel reflectors (LFRs), and the collected thermal power	Temperature	n.a.	The suggested fuzzy logic control reduces the number of changes between the various operating modes while increasing the contribution of the TES unit to feeding the ORC unit.

Table 3. *Cont.*

Authors	Type of Controller and Type of Studies	Main Component	Manipulated/Controlled Parameters	Sensors	Actuators	Performances
Enayatollahi, et al., 2021 [72]	Neuro-fuzzy, simulation	Evaporator	The outlet temperature of the evaporator and mass flow rate	Temperature, rotating speed of the pump, and mass flow rate	Pump	The inverse neuro-fuzzy controller was successful in lowering the steady state error for regulating the temperature at the evaporator outlet. A PID controller's settling time is increased and the chattering effect on pump speed is decreased when combined with an inverse neuro-fuzzy controller.
Enayatollahi et al., 2021 [73]	Neuro-fuzzy, simulation	Evaporator	Evaporator outlet temperature, and evaporator outlet pressure	Temperature, pressure, and mass flow rate	Pump	The neuro-fuzzy models provide minimal computing complexity, high accuracy, and accurate predictions of the evaporator output pressure and temperature.

3.2.3. Model Predictive Control

Toub et al. [74] developed a model predictive control (MPC) that is capable of providing a real-time optimal solution when choosing between using electrical energy from the grid to power the heat pump to heat the rooms or using solar energy to dispatch thermal energy from the TES to the ORC. In this scenario, the MPC might regulate interior temperature depending on forecast solar irradiation, the desired constraint and model, and the intended set points for both the present and the future. According to a study by López-Bautista et al. [75], MPC are appropriate and reliable enough to be used in solar thermal power plants that use nanofluids. The results show that MPC could correctly reject significant radiation disturbances and achieve satisfactory dynamic behavior even when wide-ranging uncertainty on the nanofluid parameter was imposed as a modeling error. For a heavy-duty diesel engine with an ORC system, Keller et al. [76] developed MPC and the results demonstrate the value of the suggested closed-loop controller by maintaining the ethanol more closely within the desired temperature range during engine load and speed steps, as well as during transient driving of an artificial highway cycle. Shi et al. [54] proposed a dual-mode fast DMC algorithm for ORC-based waste heat recovery systems. The simulation results demonstrate that the fast DMC algorithm trades off some performance in terms of speed compared to the traditional DMC algorithm, however, it can still guarantee that the system is driven to the setpoint nearby in the presence of disturbance and can significantly increase computation speed, which will support the widespread use of ORC-based waste heat recovery systems. A summary of the selected possible MPC control systems for ORC is listed in Table 4.

3.2.4. Comparison of the Present Control System and Outlook for the Future

The literature described above makes it clear that the pump has a significant impact on the mass flow rate, while the heat exchanger temperature and pressure are crucial in controlling the evaporation processes within the liquid heater, evaporator, and TES heat exchanger. The study shows that pump control systems offer higher output power (likely closer to the design condition), while the turbine control system may offer better performance of thermodynamic system [63]. These factors have a significant impact on how well various configurations operate, including standard ORC, PE-ORC, TFC, OFC, and ORC combined with TES. Since these factors are so important, efficient control procedures try to manage them inside the ORC system to improve effectiveness, stability, and overall operational performance. The analysis that follows provides a detailed breakdown of the comparison and evaluation of different control systems through the pros and cons, listed in Table 5.

Table 4. Summary of selected MPC-based control system used in the ORC.

Authors	Type of Controller and Type of Studies	Main Component	Manipulated/Controlled Parameters	Sensors	Actuators	Performances
Toub et al., 2019 [74]	MPC, simulation and experiment	Building HVAC system	The mass flow rate of the heat pump and room air temperature	Temperature	ORC with indirect TES and heat pump	In comparison to a conventional system, MPC for micro-concentrated solar power (CSP) incorporated into HVAC system of building results in 37% energy savings and a 70% decrease in energy costs.
López-Bautista et al., 2020 [75]	MPC, simulation and experiment	Storage tanks and boiler	Al_2O_3-water nanofluid flow rate and temperature of nanofluid at the outlet of solar collector	Temperature	Valve	Compared to conventional control theory, the temperature in the solar collector is successfully guided to surpass 63% of the required value.
Keller et al., 2020 [76]	MPC, simulation and experiment	Evaporator	Pump rotation speed and superheating temperature at the inlet of the expander	Temperature	Pump	Mean absolute error (MAE) and root mean square error (RMSE) for MPC are 4.5 K and 6.2 K
Shi et al., 2022 [54]	MPC (Fast DMC/FDMC and DMC), simulation and experiment	ORC dynamic model	Pump rotation speed, expander rotation speed, mass flow rate of cooling air, superheating, evaporating pressure, and condenser pressure	Temperature and mass flow rate	Pump	FDMC increases tracking efficiency and reduces processing load by pulling data from the unconstrained optimal solution rather than handling the constrained quadratic programming problem. DMC takes 0.21 s on average to compute online, but FDMC takes 0.0012 s (mode 1) and 0.013 s (mode 2).
Shi et al., 2023 [77]	MPC via quasi-linear parameter varying (QLPV), simulation and experiment	ORC dynamic model	Pump rotation speed, expander rotation speed, superheating temperature, and evaporating pressure	Temperature and pressure	Pump	Under the suggested controller, the integral squared error in-dex could be reduced by approximately 98.1% and 97.5% for the tracking performance for superheating and pressure, respectively

It appears that PID control is more suitable for systems with a relatively stable process, as fuzzy logic performs in uncertain and non-linear condition and MPC effectively manages complex interactions and constraints. Moreover, MPC emerges as a more robust control system for managing multivariable input and output than PID and fuzzy logic. Additionally, some control systems may either be updated while offline or are initially constructed with the possibility of doing so [78]. However, while attempting to incorporate modifications during real-time online procedures, the work becomes considerably more challenging. In our opinion, future studies in the area of the modified ORC control systems during real-time online process (i.e., real-time optimization) may take this issue into consideration, with the main goal being the decrease in operating losses.

To provide insight into the future control processes for ORC, Figure 7 describes the evolution of control systems including the integration of advanced technologies such as artificial intelligence (AI), machine learning (ML), and reinforcement learning (RL). The combination of control systems with AI, ML, and RL offers great potential to improve system performance, maximize energy use, enable adaptive operation, and minimize some losses in the operation.

Table 5. Summary of comparison of the PID, fuzzy logic, and MPC based on aforementioned literature study.

Control System	Pros	Cons
PID	- PID is widely used due to its simplicity and ease of implementation (i.e., it can effectively regulate the variables by adjusting the coefficient on the control model: proportional, integral, and derivative) [64]. - It is suitable for system with well-defined dynamics, simpler configurations, or moderate non-linear system. - It can be tuned to achieve the desired condition and performance [64]. - It can be combined with other control system to minimize the uncertainty (e.g., DRL [68]).	- It might be challenging with non-linear, time-varying processes, and complex models (it might require a tuning process). - It might not provide optimal control performance in a complex model.
Fuzzy logic	- Fuzzy logic could manage a complex system, which makes it ideal for complex ORC technology combined with TES [71] and a two-phase expansion system. - It may handle non-linear and uncertainties within the model [70]. - It can be adapted to varying parameters/conditions, making it more appropriate to encounter varying/fluctuating heat sources or load demands.	- It could be more complex to design and tune than PID. - It requires a large rule base to achieve desired performance of the system. - The interpretation of rules could lead to challenges in determining optimal performances [72]. - Tuning might be challenging.
MPC	- MPC utilizes a dynamic process model to predict future trend and optimize control actions. - It is suitable for variation of the setpoint and constraints [77]. - It could handle multivariable and complex system [74], making it ideal for complex ORC technology combined with TES [75] and two-phase expansion system. - The range of intermittent/fluctuating variable in the heat sources could be treated as constraints.	- If the design involves a more accurate model, it might be time-consuming to develop and requires expert knowledge. - The computational complexity of predictive algorithms might restrict their ability to be used in real-time applications [54] that require rapid action. - Tuning the prediction horizon and weighting constraint might be challenging

In literature study, the interest of an integrated advanced control system via AI, ML and RL has been increased. Only selected articles were described here to give an overview. An article [55] reported the multi-objective optimization to improve the actual 3 kW ORC system performance via ML methodology; however, there is still limitation to investigate the relationship between the input and output layer parameters. Wang et al. [67] reported the pioneer effort on design of DRL to control ORC superheat (which is considerably potential for AI). They also described that there will be potential for DRL in controlling the thermodynamic system, as it has not yet been comprehensively investigated. It becomes evident that using ML, AI, and RL offers a unique set of tools with the potential to considerably enhance optimization efforts. As a result, these findings encourage researchers to conduct studies that result in advances in optimization and control systems. Moreover, a recent review article [79] described and reported an overview of artificial intelligence in ORC design. Another review article [80] described the overview of ML for design and optimization of ORC including its classification These review articles are useful resources for summarizing the state of knowledge in this area and developing more integrated advanced control systems. Moreover, in our opinion, an intriguing topic that requires more research in the future is the identification of appropriate control systems that are specifically adapted to particular components. By developing an extensive understanding of optimal control methods for components (for example, the suitable control system for turbomachinery and volumetric expander), this approach seeks to improve the reliability, robustness, autonomous, efficiency, and cost-effectiveness of these components.

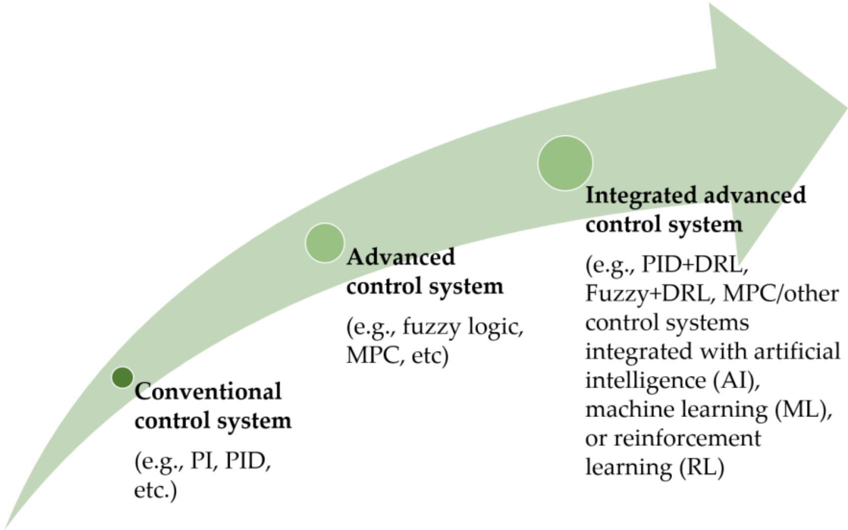


Figure 7. Illustration for the evolution of control systems for ORC in the future.

4. Future Directions of Research

Using ORC in conjunction with TES and two-phase expansion systems offers a potential approach for effectively using intermittent and fluctuating heat sources, such as geothermal energy, ocean thermal energy, solar thermal energy, and waste heat from industrial operations. In order to increase energy conversion efficiency, improve system dependability, and optimize overall performance, this study area focuses on the design, integration, and control of ORC systems. The development and use of ORC systems with thermal energy storage and two-phase expansion systems are advanced by examining numerous potential research paths in this sector and highlighting critical areas that need more research. Some possible configurations and designed systems have been discussed and described above.

Since intermittent and fluctuating heat sources are most likely in the range of low-to-medium temperatures, investigating new working fluids and thermodynamic analysis with improved properties could significantly enhance the efficiency and performance of the system. Concerning ecological effects, the two primary aspects are the potential for ozone depletion (ODP) and the potential for global warming (GWP). ODP is a measure of the ozone layer degradation caused by the provided fluid in comparison to the reference substance, trichlorofluoromethane (e.g., R-11). GWP is a measure of a gas contribution to global warming over time compared to carbon dioxide. According to environmental concerns, materials such as chlorofluorocarbons (CFCs), halons, and hydrochlorofluorocarbons (HCFCs) are not suitable for use as working fluids in any subsequent system, as the majority of them have already been prohibited by the Montreal and Kyoto Protocols or the Kigali Amendment, or are in the phase-out period. Such working fluids with zero ODP and relatively low GWP (e.g., mixtures or new organic working fluid) could be promising and suitable to be applied within the range of temperature of heat sources in the future. In that case, some typical fluids or classes might include NH_3, HFO, HCFO (e.g., R1234yf, R1233zd(E)), and natural refrigerants (e.g., hydrocarbons, carbon dioxide, etc.) where the historical development of working fluid for ORC technology could be found in this article [21,81]. In thermodynamics, the selection of working fluid could be conventionally classified as dry, wet, and isentropic efficiency. In recent years, a new classification has been derived, based on the critical temperature, triple point temperature, and maximal-minimal saturated curve [82]. Using this classification, more detail could be achieved in designing thermodynamic cycles and expansion processes. In addition, an intriguing prospect lies in the retrofitting of existing ORC systems to accommodate the potential future working fluid and the development of thermally power generation.

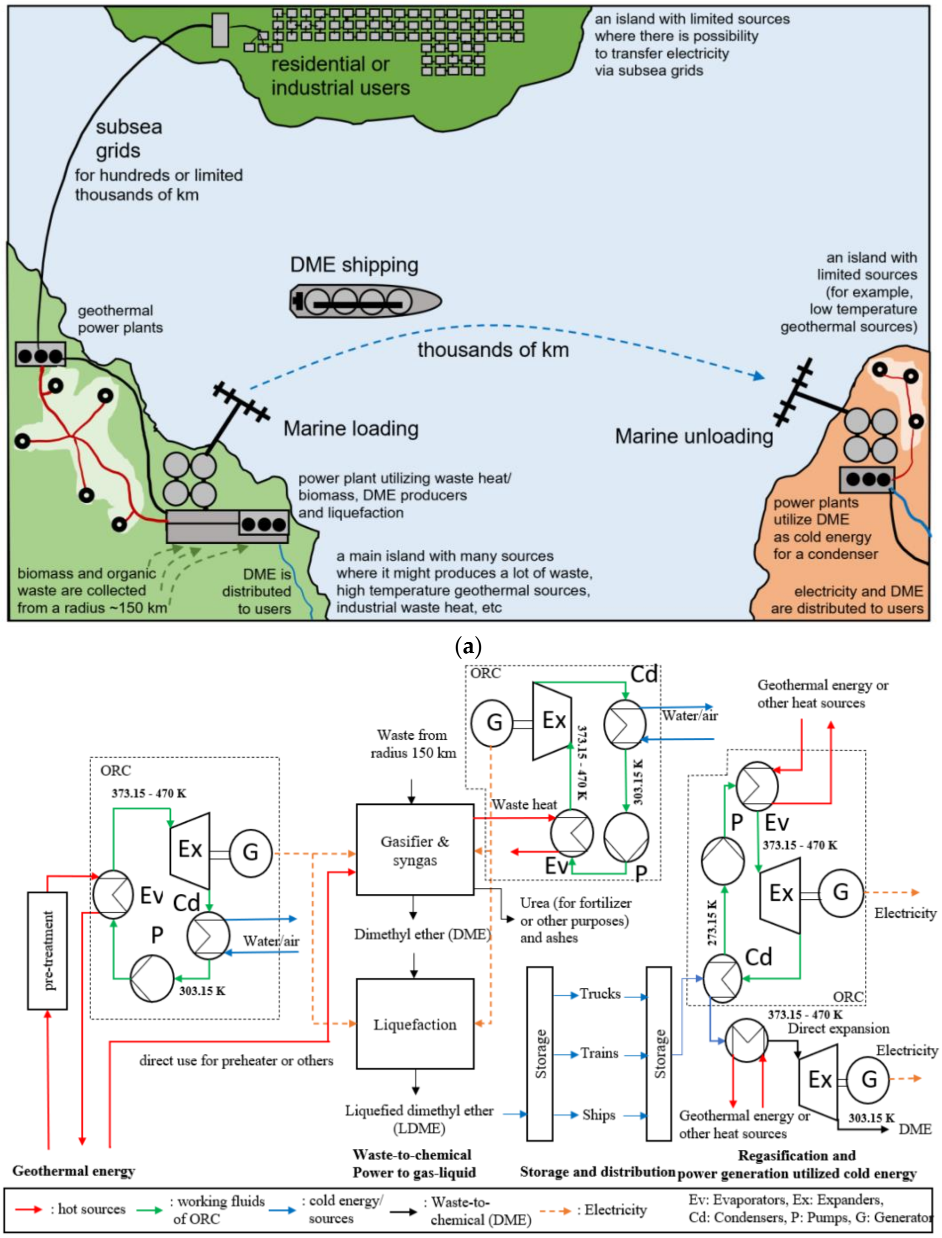
Further research focuses on the developing TES including phase change materials, sensible and latent heat storage, to improve the overall system performance. The investigation of optimal sizing [83,84], integration strategies [85], and control strategies for TES [86] would play a key role in the future in achieving higher energy efficiency and system flexibility.

Furthermore, a two-phase expansion system offers potential advantages over a conventional single-phase expansion system in ORC. Such a two-phase expander might replace an ejector or throttle valve that is involved in the existing thermodynamic cycle, such as OFC. In addition, it could be combined with TES as illustrated in Figure 1. Only a few types of volumetric expanders may be suitable for two-phase conditions [10–12]. Therefore, conducting experimental studies and demonstration projects is vital to validate both analytical and numerical models to provide fresh data and knowledge.

For ORC systems with TES and two-phase expansion, efficient control and optimization procedures are needed to guarantee optimal operation and efficiency. Future studies should concentrate on creating sophisticated control algorithms and optimization methods to control system parameters in real-time, such as mass flow rates, pressures, temperatures, vapor quality, and environment. The development of adaptive and artificial intelligent control systems that can adapt to changing operating conditions and enhance system performance can also be made possible by investigating predictive control and machine-learning-based techniques.

Finally, such an integrated system could also be considered to support sustainable development goals (especially SDG-7) in order to provide reliable, sustainable, and modern energy. Some articles have discussed possible integrated systems utilizing intermittent and fluctuating heat sources [26,38,87]. Grids could be one of the potential means for long-distance energy (electricity) transfer. Some heat sources must be entirely extracted and used to generate power at the place where they are located. This kind of transportation is feasible even between islands and might be carried out via subsea grids, as shown in Figure 8. However, it appears that there may be a financial barrier to creating a grid to transport power from one island to another (for instance, this would apply to creating a grid network for several small islands located in geothermally active regions like Indonesia).

Additionally, many low-temperature heat sources—like low enthalpy geothermal—tend to go unused since they might not be financially advantageous. Using an integrated system to address these issues might be a viable way to utilize this energy. This means that an integrated system like Figure 8 could be achieved in many aspects that could be utilized in the deployment of symbiosis networks illustrated in Figure 9. Energy symbiosis using ORC could play a key role in substantially reducing pollution by recuperating and distributing waste materials and energy resources like waste heat or steam [89]. The energy cascading within these symbiotic networks encompasses three potential pathways: the direct energy cascade that transfers energy from significant suppliers to minor users, the inverse energy cascade that moves energy from minor to major, and a combination of both flows [89]. This strategy of the circular energy transition (which is the same scenario of circular economy including reusing, recycling, etc.) and decentralized symbiosis network would hold greater promise for the future. Through the implementation of decentralized energy symbiosis, the prospective and broader application of ORC and other renewable energy could be increased, subsequently influencing the market-driven industrialization of these technologies in the future. Furthermore, the integration of symbiotic energy transition through a bottoming cycle using ORC and a sophisticated control system has potential to completely transform industry 4.0. By efficiently capturing intermittent/fluctuating waste heat from industrial operations and converting it into useful energy, this control system plays a key role in improving overall energy efficiency. By bottoming the cycle using ORC, the control system helps in maintaining the existing process (topping process, e.g., manufacturing and other industrial process) without any significant disturbance; therefore, the main process could keep operating in stable and desired condition. Moreover, it gives the system intelligence and automation, allowing for data-driven decision-making, preventative maintenance, and performance enhancement. Through remote capabilities, it also minimizes the need for on-site interventions, enables real-time data analysis, lowers operational costs, and successfully decreases energy waste and losses, paving the way for a more sustainable and effective industrial landscape.



(b)

Figure 8. A novel integrated system of intermittent and fluctuating heat sources: (**a**) an illustration and (**b**) an example of the design of an integrated system [88].

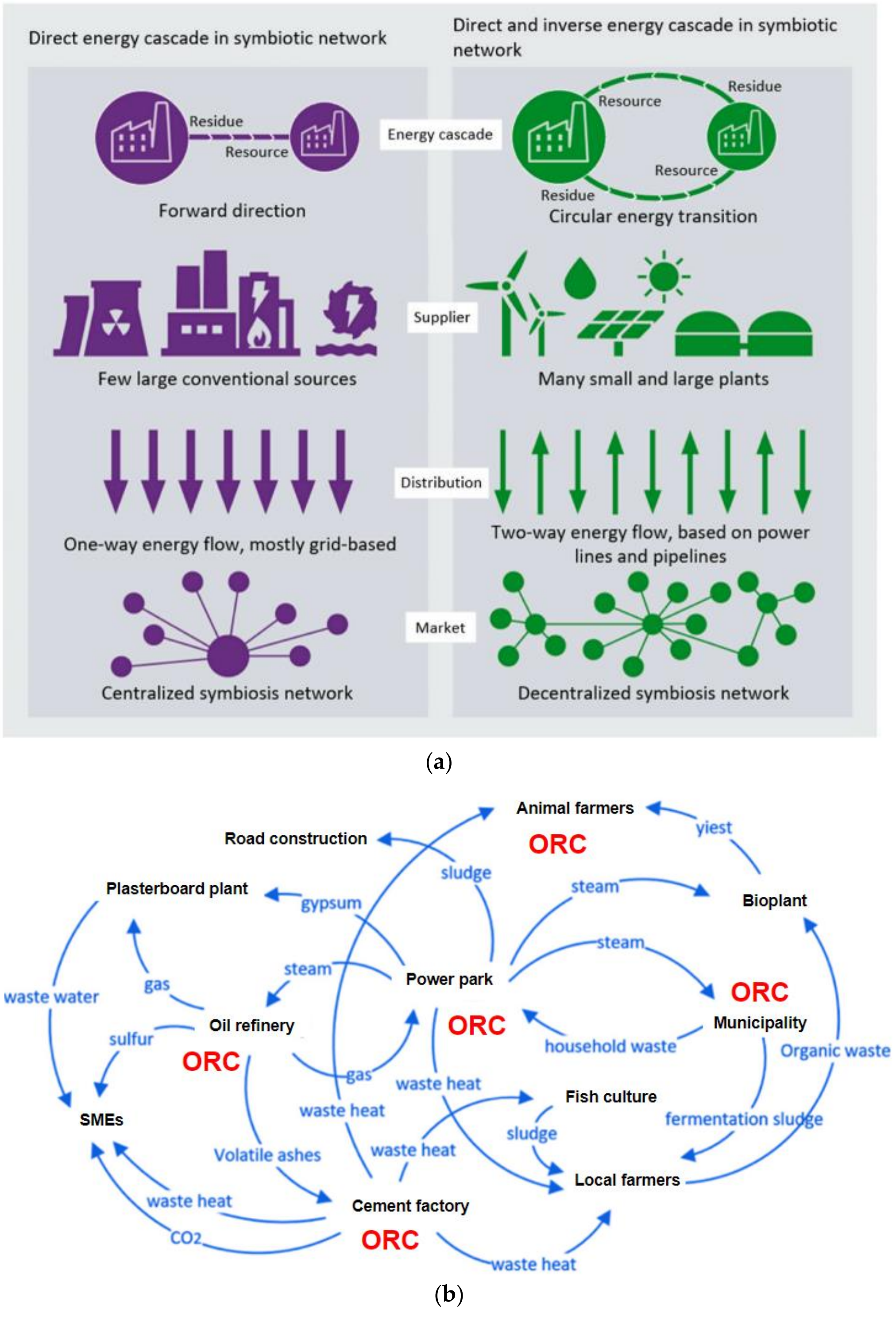


Figure 9. An example of (**a**) how energy cascades directly and inversely between industries, and (**b**) diagram of a causal loop showing how networks including conventional source, small- and medium-sized business, and possible locations for ORC systems [89].

5. Conclusions

This review gave insight into the integration of ORC in order to utilize the intermittent and fluctuating heat sources which might be taken from a low and medium temperature of geothermal heat sources, solar thermal, ocean thermal, waste heat, and so on. Some main conclusions are summarized as follows:

- Intermittent and fluctuating heat sources, which may result in an incomplete evaporation process, are analyzed and described in order to explain the performance of the cycle that could be below design points (e.g., off-design conditions or even non-working conditions). In such cases, there are several configurations of power cycle based on the ORC system that are feasible, including ORC with a two-phase expansion system, ORC with TES (direct or indirect system), and ORC with a combination of a two-phase expansion system and TES (e.g., OFC).
- In such a situation, intermittent and fluctuating heat sources might be classified according to variables and frequency depending on the evaluation of performance and the operating circumstances. While intermittent and fluctuating heat sources based on frequency might help in statistical analysis in time series modelling for resource planning and optimization, intermittent and fluctuating heat sources based on variables could assist in regulating operating conditions in the steady state and optimization.
- The fluctuating variables are temperature and mass flow rate. Some potential process control systems are categorized and described to regulate these parameters and optimize the power cycle while utilizing intermittent and fluctuating heat sources. The most popular control systems used in ORC, conventional ones (like PID) and advanced ones (such as fuzzy logic and MPC), are outlined. In this control system, the pump acts as the actuator to control the mass flow through the evaporator and the closed-loop cycle, while the evaporator is a critical component, since it absorbs intermittent and fluctuating heat sources. Based on the literature study, it shows that the pump control system might offer higher output power (which likely closes to the design point) and the turbine/volumetric expander control system tends to provide better performance of thermodynamic system. Moreover, the comparison of the presented control system has been described. In addition, the possible future control system has been discussed in order to provide insight into the integrated advanced control system for ORC that involves ML, AI, and RL.
- Furthermore, the literature study shows that the configurations and design of the thermodynamic cycle and the process control system also play a key role in utilizing intermittent and fluctuating heat sources. It assists in increasing steady-state performance, leading to greater output power and an efficient operating system.
- At the end of this study, the review offers insight into the future direction of research in the integration, design, and control system of ORC utilizing intermittent and fluctuating heat sources. Moreover, energy symbiosis using ORC via a circular energy transition and decentralized network might play a key role, making it very extensive for application and influencing the market-driven industrialization of ORC technologies.

Author Contributions: Writing—review and editing, supervision, A.R.I.; writing—original draft preparation, writing—review and editing, formal analysis, investigation, visualization, S.D.; writing—review and editing, supervision, P.B.; writing—review and editing, supervision, P.K. All authors have read and agreed to the published version of the manuscript.

Funding: Part of the research was funded by the Sustainable Development and Technologies National Programme of the Hungarian Academy of Sciences (FFT NP FTA).

Data Availability Statement: No applicable.

Acknowledgments: Part of the research was supported by the Faculty of Mechanical and Power Engineering, Wrocław University of Science and Technology through Wspieramy Młodych Naukowców 2022.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

T	Temperature (°C)
AI	Artificial intelligence
CFC	Chlorofluorocarbon
CSP	Concentrated solar power
DMC	Dynamic matric control
DRL	Deep reinforcement learning
FDMC	Fast dynamic matric control
FV	Finite volume
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HCFO	Hydrochlorofluoroolefin
HFO	Hydrofluoroolefin
HVAC	Heating, ventilation, and air conditioning
LNG	Liquefied natural gas
MAE	Mean absolute error
ML	Machine learning
MPC	Model predictive control
ODP	Ozone depletion potential
OFC	Organic flash cycle
ORC	Organic Rankine cycle
PCM	Phase change material
PE-ORC	Partially evaporated ORC
PID	Proportional integral derivative
PI	Proportional integral
PV	Photovoltaic
RL	Reinforcement learning
RMSE	Root mean square error
SDG	Sustainable development goal
TES	Thermal energy storage
TFC	Trilateral flash cycle
WHR	Waste heat recovery

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