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**F**aculty of **T**echnology

# Final Master's Degree Dissertation

Field: Process Engineering
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## Exergoenvironmental Analysis of an Energy Storage System

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## *Dedication*

I dedicate this humble work with all my heart to:

My beloved father **Mohamed**, whose tireless efforts in raising me, educating me, and guiding me have shaped who I am today. His unwavering support, patience, and love have been my foundation and my greatest blessing.

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**ملخص**

تتناول هذه الدراسة تحليلًا إكسرجياً وبيئياً لنظام بطارية كارنو قائم على مبدأ الطاقة إلى الحرارة ثم إلى الطاقة(PTES) ، بهدف تقييم كفاءته في دمج الطاقة المتجددة وتقليل الفاقد الطاقي. تم تطوير نموذج حسابي باستخدام برنامج MATLAB لتحليل مكونات النظام، مع تطبيق موازنات الطاقة والإكسرجي إلى جانب تقييم الأثر البيئي (تحليل دورة الحياة). يستخدم النظام سائل R245fa والماء كوسيطين حراريين. وقد أُجريت دراسة بارامترية لفحص تأثير شروط التشغيل الرئيسية على الأداء، وحددت المكونات المسؤولة عن أكبر قدر من فقدان الإكسرجي والأثر البيئي، مما يبرز أهمية المنهج الإكسرجي- البيئي في تقييم النظام ككل.

**الكلمات المفتاحية :**بطارية كارنو ، PTES، تحليل الإكسرجي، التحليل الإكسرجي-البيئي، R245fa

***Abstract***

This study conducts an exergo-environmental analysis of a Carnot Battery system based on Power-to-Heat-to-Power (PTES) principles, aiming to assess its effectiveness in integrating renewable energy and minimizing waste. A MATLAB model was developed to simulate system components, using energy and exergy balances along with life cycle assessment (LCA). The system employs R245fa and water as working fluids. A parametric study evaluated the impact of operating conditions on performance, highlighting components with major exergy destruction and environmental impact, thus showcasing the relevance of the exergo-environmental approach.

**Keywords:** Carnot Battery, PTES, Exergy Analysis, Exergo-environmental Analysis, R245fa.

**Résumé**

Cette étude réalise une analyse exergo-environnementale d’un système de batterie de Carnot basé sur le principe Power-to-Heat-to-Power (PTES), dans le but d’évaluer son efficacité pour l’intégration des énergies renouvelables et la réduction des pertes énergétiques. Un modèle de simulation a été développé sous MATLAB pour analyser les composants du système, en utilisant les bilans d’énergie et d’exergie ainsi qu’une analyse du cycle de vie (ACV). Le fluide R245fa et l’eau sont utilisés comme fluides caloporteurs. Une étude paramétrique a été menée pour évaluer l’influence des conditions de fonctionnement sur les performances, en identifiant les composants responsables des principales destructions d’exergie et impacts environnementaux, démontrant ainsi la pertinence de l’approche exergo-environnementale.

**Mots-clés :** Batterie de Carno, PTES, Analyse exergetique, Analyse exergo-environnementale, R245fa.

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## Symbols and Abbreviation

### Symbols

| | | |
|---|---|---|
| $C_p$ | Specific heat capacity | kJ/kg·K |
| Ex | Exergy | kW |
| $\dot{m}$ | Mass flow rate | kg/s |
| P | Pressure | bar |
| $\dot{Q}$ | Heat transfer rate | kW |
| S | Specific entropy | kJ/kg·K |
| ΔT | Logarithmic Mean Temperature Difference (LMTD) | K |
| φ | Exergetic efficiency | % |
| μ | Dynamic viscosity | Pa·s |

**Abbreviation**

| | |
|---|---|
| CB | carnot battery |
| CAES | compressed air energy storage |
| HP | heat pump |
| ORC | organic Rankine cycle |
| PTES | pumped thermal energy storage |
| PHES | pumped hydro energy storage |
| TES | thermal energy storage |

# *Introduction*

# *Introduction*

The increasing global demand for energy, combined with growing concerns over climate change and the depletion of fossil fuel resources, has placed immense pressure on energy systems to evolve toward more sustainable and efficient solutions. A key aspect of this transition is the development and deployment of reliable energy storage technologies, which are essential for balancing energy supply and demand, especially as renewable energy sources such as wind and solar characterized by their intermittency and variability become more widespread. Among the various technologies under consideration, thermal energy storage (TES) has emerged as a cost-effective and technically viable option, particularly for large-scale applications.

To address these challenges, advanced energy storage systems (ESS) have become critical, enabling supply-demand balance, renewable integration, and improved energy efficiency [1,2]. Among the diverse ESS technologies available each with distinct characteristics in capacity, duration, and efficiency thermal energy storage systems, particularly Carnot Batteries (CB), stand out as a promising solution. CBs store electricity as high-temperature thermal energy and later convert it back to power, offering several advantages, including potentially long discharge durations, high energy density, and a relatively long operational lifespan compared to some other storage methods.

To fully understand the potential and limitations of Carnot Batteries, a comprehensive analysis that goes beyond simple energy efficiency is required. Exergy analysis, a powerful thermodynamic tool, provides a more insightful perspective by evaluating the quality of energy and identifying sources of irreversibility and potential for improvement within a system. Furthermore, integrating environmental impact assessment with thermodynamic analysis (exergo-environmental analysis) allows for a holistic evaluation of the system's performance, considering both resource utilization efficiency and ecological consequences throughout its lifecycle.

This thesis focuses on the exergo-environmental analysis of a Carnot Battery system based on the Power-to-Heat-to-Power (PTES) schema. The primary objective is to conduct a detailed modeling of the system to evaluate the exergy efficiency and environmental impact at the component level for the three main equipment sections of the Carnot Battery. By developing and utilizing a computational model, specifically implemented in MATLAB, this study aims to quantify the exergy destruction and environmental burden associated with each component.

This detailed analysis will provide valuable insights into the key areas for potential optimization, enabling the identification of components that contribute most significantly to exergy losses and environmental impact. Ultimately, this research seeks to contribute to the understanding and development of more efficient and environmentally sustainable Carnot Battery systems, thereby supporting efforts to reduce energy waste and enhance the integration of renewable energy sources.

This study is divided into three distinct chapters, following a general introduction and preceding a final conclusion.

- The first chapter, provides an overview of energy storage technologies, with a focus on Carnot Batteries (CBs**)**, and examines their fundamental principles, key components, advantages, various configurations, and potential applications. A summary consolidates the key insights on CBs and their role in energy storage.
- The second chapter focuses on the exergetic, exergo-environmental and LCA analysis. It outlines the fundamental principles and theoretical framework of this methodology, which will serve as a basis for the modeling and optimization phases.
- The third chapter is dedicated to the thermodynamic and environmental modeling of a Carnot Battery system. A calculation code in MATLAB has been developed for this purpose to support the different stages of this modeling. This chapter presents the findings related to exergy efficiency and environmental impact, including results from the parametric studies conducted to evaluate the performance of each component under varying operating conditions.

# *Chapter I*

# *Introduction to energy storage system*

## I.1 Introduction

The increasing penetration of variable energy sources in modern power systems has intensified the need for efficient energy storage solutions. Energy storage systems enable the temporal decoupling of energy supply and demand, enhance system flexibility, and contribute to operational stability. Among the various technologies, thermal energy storage particularly Carnot batteries offers a promising approach for large-scale applications. By converting electricity into heat and reconverting it when needed, Carnot batteries provide an efficient and sustainable means of managing energy flows.

In this chapter, the main categories of energy storage are outlined, followed by a focused overview of Carnot batteries. Their fundamental principles, essential components, advantages, configurations, and applications are presented within the context of thermal energy storage solutions.

## I.2 Energy Storage System

Energy storage systems (ESS) refer to technologies designed to absorb energy, store it for a period of time, and release it when needed. These systems are critical for balancing energy supply and demand, enhancing grid stability, and facilitating the integration of intermittent renewable energy sources. ESS can store energy in various forms, such as electrical, thermal, mechanical, or electrochemical, depending on the application and technology used.

As stated by Chen et al. [3], energy storage plays an essential role in efficient energy utilization and is key to improving the reliability and quality of power supply systems. Similarly, Dunn et al. [4] emphasized that ESS are critical components in the deployment of renewable energy technologies and in ensuring a stable and sustainable energy infrastructure.

## I.3 Categories of Energy Storage System

Energy storage systems (ESS) can be classified based on several aspects, including their function, reaction time, storage duration, and the sort of energy they keep. This topic is largely concerned with identifying ESS based on the type of stored energy. Energy can be stored mechanically, electrochemically, chemically, or thermally, as well as via electric or magnetic fields [5].

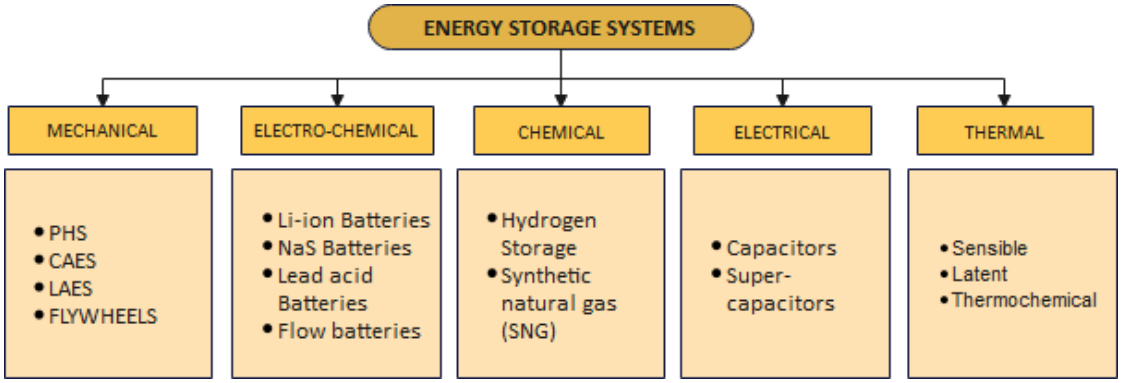



***Figure I.1**: Classification of Energy Storage Systems (ESS) [5].*

### I.3.1 Mechanical Energy Storage

Mechanical energy storage systems are extensively used worldwide for their efficiency in storing and releasing energy. Their primary advantage is the swift conversion between mechanical and electrical energy, whether in kinetic or potential form. These systems are essential for integrating renewable energy into the power grid. Unlike fossil fuel power plants, which can be easily adjusted to meet changing demand, renewable sources like solar and wind are naturally variable. Mechanical energy storage helps mitigate this issue by storing excess energy during low-demand periods and releasing it when needed to stabilize the grid, manage peak loads, and provide backup power. The most common types of mechanical energy storage include pumped hydro, flywheel, compressed air, and gravity-based storage, all of which are widely used in energy storage technologies [6].

#### I.3.1.1 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) systems use a compressor, storage tank, and turbine operating on a Brayton cycle. During charging, air is compressed and stored; during discharging, it's heated and expanded through a turbine to generate electricity. Although they emit $CO_2$, CAES systems can produce three times more power than conventional turbines using the same fuel amount. [7].

The major limitations to the implementation of CAES system are its dependence on favorable geography, fossil fuel combustion, and CO2 emission problem during operation conditions.

CAES system has application potential in renewable energy such as in wind energy for energy management purposes, due to the high power and energy capacity rating of the storage [6].

### I.3.1.2 Liquid Air Energy Storage

Liquid air energy storage (LAES) cryogenically cools and liquefies air using off peak electricity during charging and during discharge the stored liquid air is pumped, heated, and expanded in turbines to generate electricity. LAES stores electricity in the form of temperature potential and later utilizes it when needed. The major drawback is the low round trip efficiency and only practical on a large scale [6].

### I.3.1.3 Flywheels

A flywheel stores energy that is based on the rotating mass principle. It is a mechanical storage device which emulates the storage of electrical energy by converting it to mechanical energy. The energy in a flywheel is stored in the form of rotational kinetic energy. The input energy to the FESS is usually drawn from an electrical source coming from the grid or any other source of electrical energy.

The flywheel speeds up as it stores energy and slows down when it is discharging, to deliver the accumulated energy. The rotating flywheel is driven by an electrical motor-generator (MG) performing the interchange of electrical energy to mechanical energy, and vice versa. The flywheel and MG are coaxially connected, indicating that controlling the MG enables control of the flywheel [8].

### I.3.2 Electrochemical energy storage

Electrochemical energy storage is one of the most popular solutions widely used in various industries, and the development of technologies related to it is very dynamic. This system undergoes chemical process to store and produce electricity [7]. Electrochemical energy storage is based on systems with high energy density (batteries) or power density (electrochemical capacitors). Fundamentally, a battery is a combination of electrodes soaked in an electrolyte substance that enables an ion exchange to happen so as to conduct electricity [9]. EES systems are categorized in two types: secondary batteries and flow batteries. The secondary batteries have again classified into following types: lead–acid, Li-ion, sodium sulfur [10].

### I.3.3 Chemical Energy Storage

Chemical energy storage systems (CESS) are being actively researched as a potential alternative to conventional fuels to help reduce carbon emissions. These systems primarily focus on storing hydrogen and synthetic natural gas, while biofuels are also considered part of CESS [3, 11].

### 1.3.4 Electrical Energy Storage

It includes systems such as supercapacitors and superconducting magnetic energy storage (SMES). These technologies provide high power density and fast response times, making them appropriate for grid stabilization and short-term balancing tasks [4].

### 1.3.5 Thermal Energy Storage

These systems are designed to store heat or cold for later use and are typically based on sensible heat, latent heat, or thermochemical processes. Common applications include solar thermal power plants, district heating networks, and heating and cooling systems in buildings [5]. A typical TES system consists of a heat storage medium enclosed in a tank or reservoir, a refrigeration or chiller unit (either integrated or standalone), piping networks, pumps, and a control system. TES technologies are generally categorized based on operating temperature into low-temperature TES such as aquifer thermal energy storage and cryogenic energy storage and high-temperature TES, which includes latent heat storage using phase change materials undergoing fusion [12]. The performance and operational behavior of TES systems are strongly influenced by the thermal properties of the storage material, which determine whether energy is stored through temperature variation, phase transitions, or reversible chemical transformations [13].

## I.4 Fundamentals of Carnot Batteries

Carnot batteries, also known as Pumped Thermal Electricity Storage (PTES) systems, are an emerging class of high-temperature thermal energy storage technologies by converting electricity into thermal energy and reconverting it into electricity when needed. These systems differ from conventional storage technologies by utilizing thermodynamic cycles and thermal energy storage, rather than electrochemical processes. This process involves three main steps: charging (electricity to heat), storage (thermal energy storage), and discharging (heat to

electricity) [14]. The concept is inspired by the Carnot cycle, aiming to maximize efficiency in energy conversion processes.

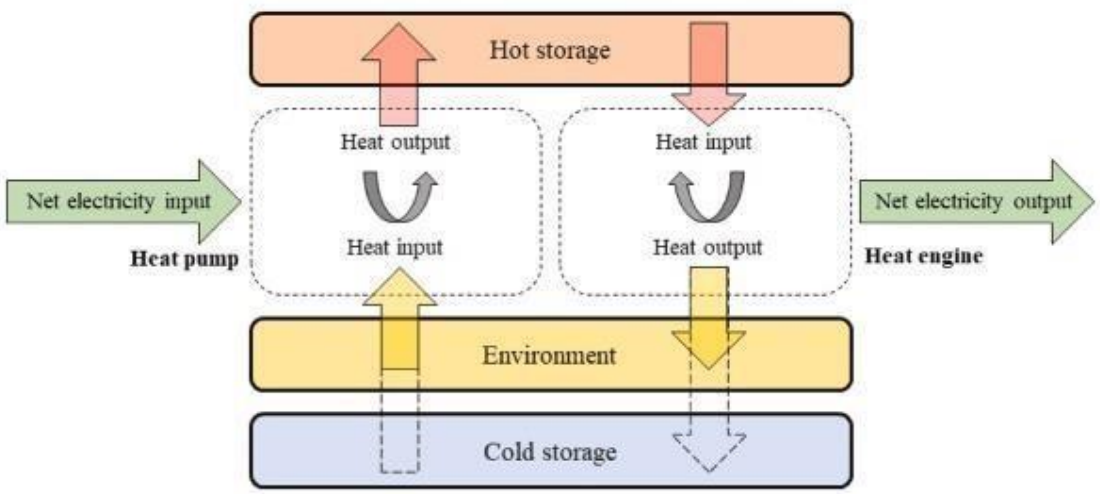



***Figure I.2**: Illustration of the Carnot Battery Cycle Including Charging, Storage, and Discharging [14].*

### I.4.1 Principle

The operational concept of a Carnot Battery revolves around three key stages: converting electricity into thermal energy (Stage A), storing this thermal energy (Stage B), and subsequently reconverting it into electricity (Stage C). Achieving high overall efficiency requires precise integration and optimization of all three stages.

A variety of technological options are available for each stage, resulting in a broad spectrum of system configurations, scales, and applications.

For Stage A (electricity to heat conversion), the transformation may be accomplished using:

- Heat pumps operating on a Brayton cycle
- Heat pumps utilizing a Rankine cycle
- Alternative heat pump technologies
- Direct resistance heating

Stage B (thermal energy storage) can involve:

- Sensible heat storage using molten salts

- Latent heat storage with phase change materials
- Regenerative storage systems
- Hybrid combinations of the above technologies

Stage C (heat-to-electricity conversion) might employ:

- Brayton cycle engines
- Rankine cycle systems
- Other thermally driven power generation cycles [15]

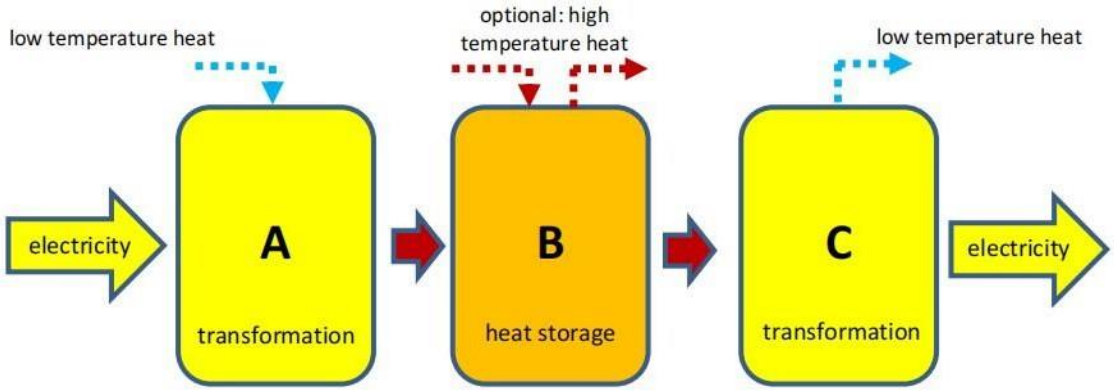



***Figure I.3**: Principle of Carnot battery [15].*

### I.4.2 Key Components

A typical Carnot battery system comprises three primary components:

- Electric-to-thermal converter: This component, often a high-temperature heat pump or resistive heater, converts electrical energy into thermal energy during the charging phase.
- Thermal energy storage (TES): The TES system stores the thermal energy, which can be in the form of sensible heat, latent heat, or thermochemical energy, depending on the storage medium used.
- Thermal-to-electric converter: During the discharging phase, this component converts the stored thermal energy back into electricity. Common technologies include steam turbines and ORCs.

Many of the components used in Carnot Battery (CB) systems are readily available as standard industrial equipment. Figure 6 illustrates the main shared elements typically found in

CB configurations: (i) mechanical devices such as expanders, compressors, and pumps; (ii) thermal energy storage units, which may rely on sensible heat, latent heat, or thermochemical storage methods; (iii) heat exchangers, including evaporators, condensers, and recuperators; and (iv) auxiliary components such as buffer tanks and resistive heaters. Moreover, the selection of the working fluid plays a critical role in system performance, as different CB cycles employ various fluids based on the thermodynamic requirements of the application [14].

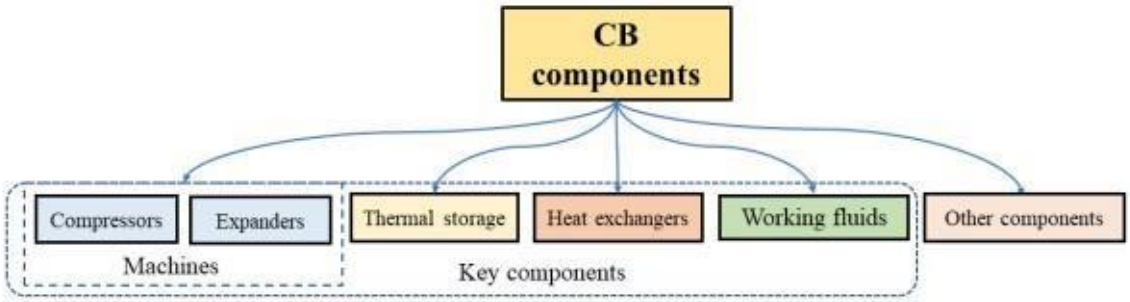



***Figure I.4**: Main components of CB systems [14].*

### I.4.3 Working fluids

Selecting an appropriate working fluid is essential for optimizing the performance of a thermodynamic cycle. The right choice can significantly boost system efficiency and enhance both economic and operational reliability. However, no single fluid is universally ideal for all conditions [16]. In a recent study, Saleh et al identified 31 working fluids as suitable for Organic Rankine Cycles (ORCs). These fluids were evaluated and ranked based on key thermophysical properties such as critical temperature, normal boiling point, critical pressure, environmental impact and safety, which help determine their applicability in ORC systems.

Among them, R245fa (1,1,1,3,3-pentafluoropropane) is frequently chosen for lowtemperature heat sources due to its relatively high critical temperature and pressure. Additionally, at 298 K, its pressure is close to atmospheric pressure, making it convenient and efficient for use in such systems [17].

Wang et al. conducted a performance analysis of nine pure organic working fluids within specific operating conditions and found that R245fa stands out as the most environmentally friendly option for engine waste heat recovery applications in PTES systems [18].

In this analysis, water is selected as the heat storage medium in the TES system due to its convenience, availability, environmental benefits, high specific heat capacity, and stability, and the same working fluid r245fa is used for both the heat pump and Organic Rankine Cycle (ORC) to maintain system consistency [16].

### I.4.4 Advantages and disadvantages

The Carnot Battery, also referred to as Pumped Thermal Electricity Storage (PTES) or Pumped Heat Electricity Storage (PHES), is an emerging large-scale energy storage technology. It has gained attention for its potential to provide flexible and site-independent storage solutions. Key advantages associated with Carnot Batteries include:

- Flexibility in site selection;
- Minimal environmental impact;
- Long operational lifespans, typically ranging from 20 to 30 years;
- The possibility of integrating low-cost backup capacity;
- The potential to repurpose components from decommissioned fossil-fuel power plants in constructing the storage system.

However, a notable limitation of this technology lies in its roundtrip efficiency the ratio of electricity output during discharge to the electricity input required for charging. Carnot Batteries typically exhibit efficiencies between 40% and 70%, which is lower compared to pumped hydro storage systems that generally achieve values between 65% and 85% [19].

### I.4.5 Variants and Configurations of Carnot Batteries

**Brayton-based pumped thermal energy storage**

A Brayton-cycle-based Pumped Thermal Electricity Storage (PTES) system typically employs a supercritical gas as the working fluid. The overall operation is depicted in Figure 5. During the charging phase, the working fluid is compressed, increasing its temperature (process 1–2), and the resulting thermal energy is transferred to a hot storage reservoir (2–3). Subsequently, the fluid expands (3–4), decreasing in pressure and temperature, before being directed to the cold reservoir. In the discharging phase, the cold working fluid is compressed to

a higher pressure (4′–3′), absorbing heat from the hot reservoir (3′–2′). It then undergoes expansion (2′–1′) to generate electricity, and is subsequently cooled by the cold reservoir (1′–4′), which reduces the compression work and enhances the net power output in future cycles [20].

To manage cycle irreversibilities, auxiliary heat exchangers (HEX A and HEX B) are incorporated. HEX A helps stabilize the inlet temperature of the expander during charging and supports consistent heat delivery from the hot reservoir during discharging. HEX B ensures a constant inlet temperature to the cold reservoir during discharging and assists in maintaining stable compressor inlet conditions during charging.

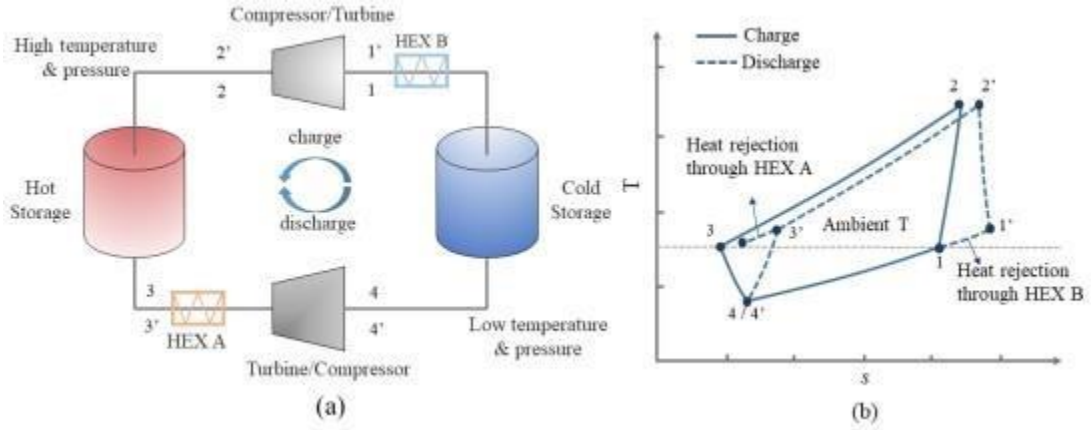



***Figure I.5 :*** *(a) Process flow diagram of a Brayton-based PTES and (b) the associated T-s diagram [14].*

**▯ Rankine-based pumped thermal energy storage**

Figure 6 presents the operating principle of a Rankine-based Pumped Thermal Electricity Storage (PTES) system, which involves a phase change of the working fluid enabling the storage of both sensible and latent heat within a narrow temperature range [21]. During the charging phase, the fluid is evaporated (1–2), compressed (2–3), and then releases heat to the hot storage during condensation (3–5) before expansion (5–1). In discharging, the fluid is pressurized (1′–2′), recovers stored heat (2′–4′), expands through turbines (4′–5′), and is finally condensed (5′–1′).

Rankine-based PTES systems include steam Rankine, organic Rankine (ORC), and transcritical $CO_2$ cycles, as well as cascade configurations using ammonia-water or $CO_2$-$NH_3$ working pairs. Roundtrip efficiency (RTE) typically ranges from 40% to 70%, and can exceed 100% when supplemented with external low-grade or waste heat sources [14].

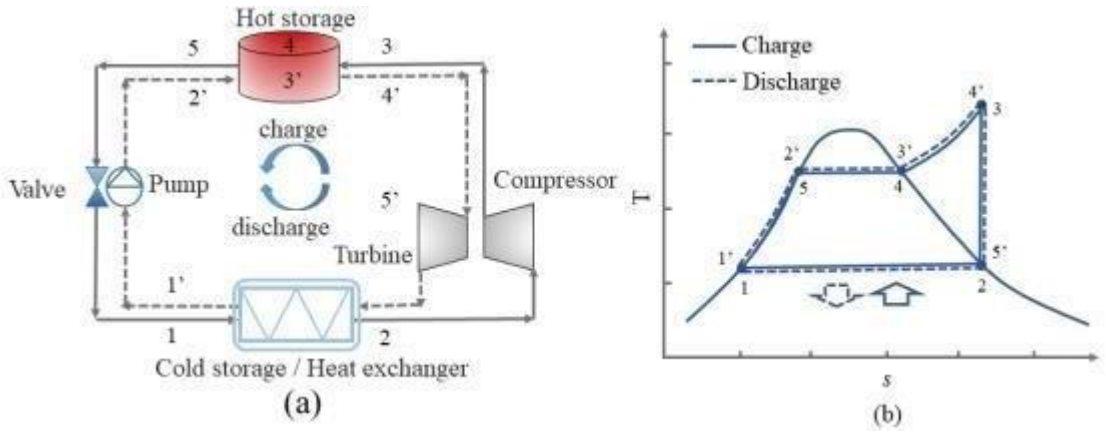
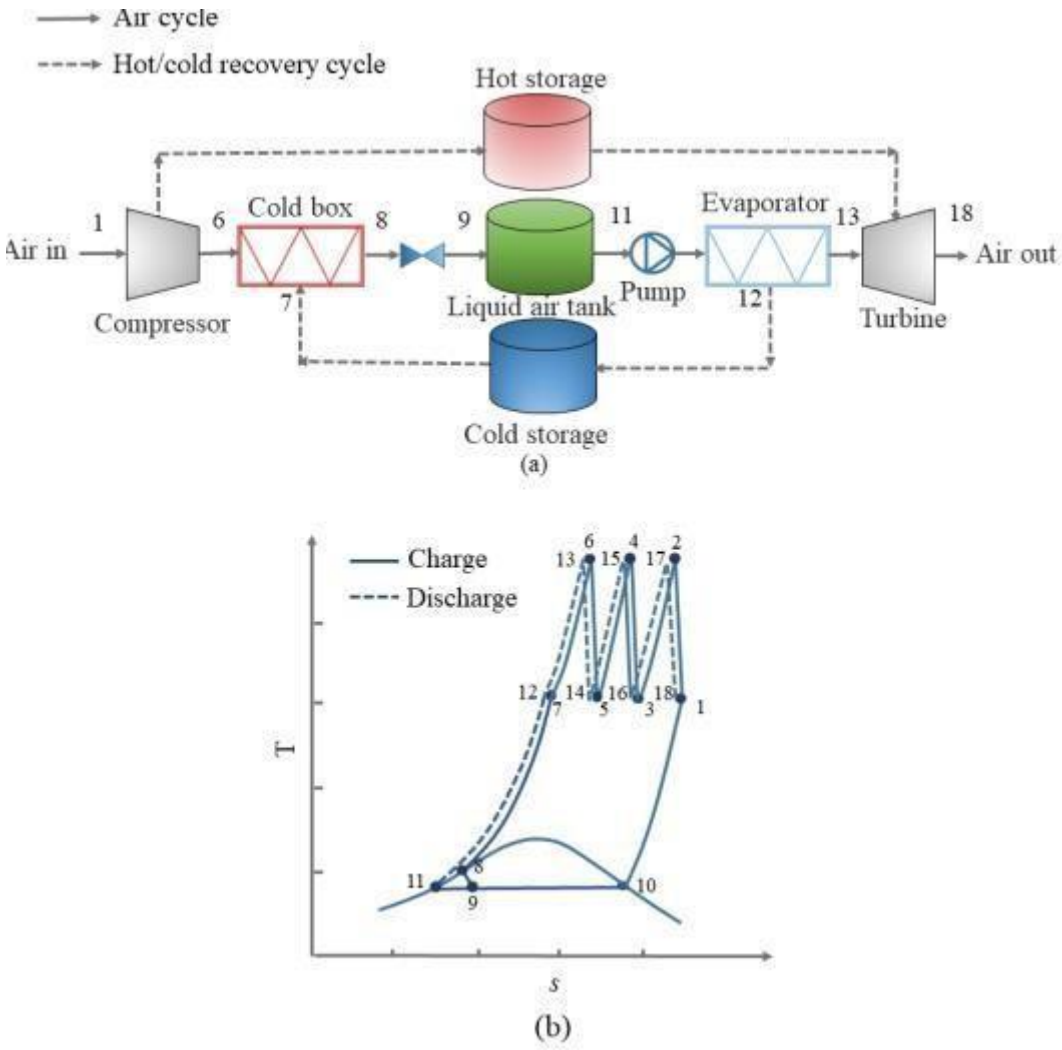



***Figure I.6**: (a) Process flow diagram of a Rankine-based PTES and (b) the associated T-s diagram [14].*

- **Liquid air energy storage**

Liquid Air Energy Storage (LAES), depicted in Figure 7, stores electricity by converting air into a cryogenic liquid. The system comprises three main subsystems: a liquefaction unit, a cryogenic storage tank at near-ambient pressure, and a power recovery unit. During charging, ambient air is compressed and cooled into liquid form using electricity, then stored. In the discharging phase, the liquid air is pressurized, vaporized, heated using thermal storage or external heat sources, and expanded through turbines to generate electricity.

To enhance roundtrip efficiency (RTE), both compression heat and cold from evaporation can be recovered and reused, as indicated by optional thermal loops in Figure 4. Typical operating pressures range from 10–18 MPa for charging and 7–12 MPa for discharging. Heat and cold storage systems such as packed beds and two-tank configurations have been extensively investigated. Standalone LAES systems report RTEs between 40% and 60%, with performance improvements observed when integrated with absorption chillers, Rankine or Brayton cycles, and external heat/cold sources.




***FigureI.7:*** *(a) Process flow diagram of a LAES (solid line – air cycle, dashed line – hot/cold recovery cycle) and (b) the associated T-s diagram [14].*

**Lamm-Honigmann storage**

The LHS cycle is depicted in Fig. 8, which uses thermochemical energy storage and a reversible sorption reaction to store and recover heat. The LHS consists of two heat exchangers/reactors and an expansion machine. The first heat exchanger contains an absorbent, such as NaOH/H2O or LiBr/H2O, which absorbs the low-pressure vapour from the expansion machine. Vapour is desorbed when the absorbent is heated, and possible heat sources include waste heat or compression heat, corresponding respectively to the heat-to power and power-topower cycle concepts. The second heat exchanger acts as an evaporator or a condenser, to produce or accommodate the vapour in the absorbing or desorbing process [14].

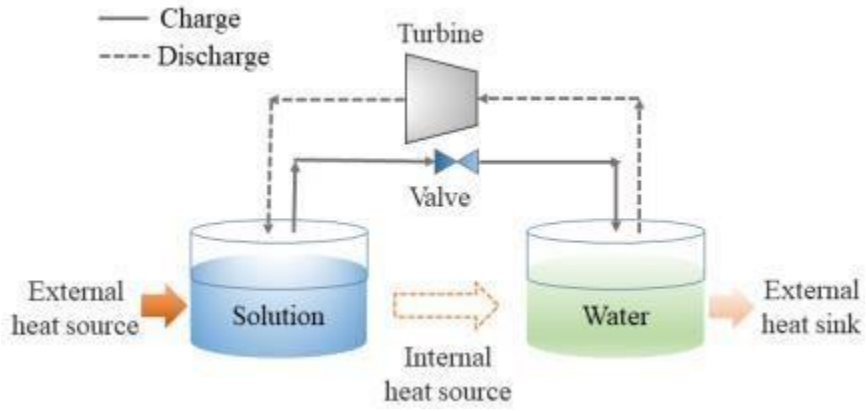



***Figure I.8**: Process flow diagram of a LHS [14].*

### I.4 6 Applications

The principal application of Carnot Batteries lies in their potential to serve as effective load-shifting devices for photovoltaic (PV) energy generation, or as viable storage solutions for grid-scale applications at the distribution level. Their ability to absorb excess electricity during periods of high renewable output and dispatch it during peak demand makes them highly attractive for stabilizing electricity grids with high renewable penetration.

However, applications at the residential or domestic scale remain relatively unexplored. Only a limited number of studies have investigated the feasibility of deploying Carnot Batteries or analogous thermal-to-electricity storage systems at the household level, and even fewer have provided comprehensive techno-economic analyses to assess their financial viability in such settings [22].

### I.4.7 Storage Performance Factors

It is crucial to evaluate storage energy systems to understand their performance and identify the most effective solutions by «defining the following technical parameters may be useful:

- Capacity (energy density): Capacity, in kWh/m3, measures the amount of energy stored in 1 m3 of storage medium. It specifies the size of the storage system and is generally proportional to the capital cost.
- Power density: in kW/m3, measures the total power output during discharge per volumetric flow rate of the working fluid.

- Round-trip efficiency: it describes the proportion of electricity put into the storage system during charging returned to the user during discharge.
- Power rating: in W, measures the storage mechanism ability to output power during discharge» [23].

Otherwise, to store some form of energy, three steps need to be done: charging, storing and discharging. Each step can occur more than one time during each storage cycle and some of the steps can take place simultaneously [24].

## I.5 Conclusion

In response to the growing integration of intermittent renewable energy sources, the role of energy storage technologies has become increasingly critical for ensuring grid reliability and operational flexibility. This chapter provided a foundational overview of energy storage systems, with a particular emphasis on thermal-based solutions. Among these, Carnot batteries have emerged as a promising large-scale storage option, offering a pathway for decoupling electricity generation and consumption through thermodynamic conversion processes. By examining their underlying principles, core components, configurations, advantages, and potential applications, this chapter highlights the strategic importance of Carnot batteries in future energy systems. Their scalability, compatibility with existing technologies, and potential for sector coupling make them a compelling solution for addressing the challenges associated with the energy transition.

# *Chapter II*

# *Exergo-environmental Analysis*

## II.1 Introduction

This chapter presents the exergoenvironmental analysis, which integrates exergy analysis and environmental impact evaluation to assess both the thermodynamic performance and environmental consequences of energy systems. The chapter first outlines the principles of exergy analysis and Life Cycle Assessment (LCA), then introduces their combination as a comprehensive method for evaluating system performance and sustainability.

## II.2 Fundamental Concepts of the Exergetic Approach

### II.2.1 Exergy

Energy consists of two parts: a useful, convertible portion known as **exergy**, and a nonconvertible portion referred to as anergy**.** The sum of both constitutes the total energy. Exergy is defined as the maximum work that can be obtained from a flow or a system when it comes into equilibrium with a specified environment [25]. Unlike energy, exergy is a nonconserved quantity; it can be destroyed. This destruction results from the irreversibilities present within the system.

### II.2.2 Different forms of exergy

Like energy, the exergy of a material stream can be divided into different components. According to Kotas [26] and Szargut et al [27], exergy (Ex) is expressed through various forms, making it an additive extensive property:

$$\dot{E} = \dot{E}_k + \dot{E}_p + \dot{E}_{ph} + \dot{E}_{ch} \tag{II.1}$$

where:

- $E_k$: kinetic exergy
- $E_p$: potential exergy
- $E_{ph}$: physical exergy
- $E_{ch}$: chemical exergy

### II.2.3 Exergy balance equation

Exergy analysis leads to an accounting approach that incorporates both the first and second laws of thermodynamics. Only this type of accounting allows for a qualitative and quantitative evaluation of energy degradation.

The formulation of an exergy balance under steady-state conditions is similar to that of an energy balance, with one crucial difference: while energy is conserved, exergy can be destroyed, meaning the balance must include a term for exergy destruction (See Figure II.1) [28].

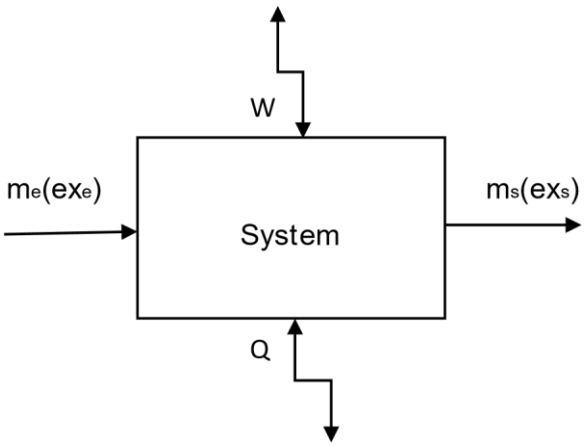



***Figure II.1**: Exergy Balance of an Open System [28].*

The general equation representing the exergy balance applied to a control volume under steadystate conditions is expressed as follows:

$$\sum_{e} \dot{m}_e \; ex_e - \sum_{s} \dot{m}_s \, ex_s + \sum_{k} (1 - \frac{T_0}{T_k}) \dot{Q}_k - \dot{W} - \dot{E}x_D = 0 \qquad \text{(II.2)}$$

The exergy balance for an open system is structured around three fundamental elements.

- The first is the specific exergy (Ex), which characterizes the thermodynamic quality of the material flow.
- The second is the contribution from high-value energy forms—such as electrical, mechanical, kinetic, and potential energy—grouped under the term "pure exergy" and denoted by $W_1$.

- The third term accounts for the exergy destruction ($Ex_d$ ), representing the degradation of useful energy due to system irreversibilities. This exergy destruction is directly proportional to the entropy generated within the system and is expressed as $T0 \times S_{generated}$ , where $T_0$is the ambient temperature.

### II.2.4 Exergy Assessment Criteria

To evaluate the exergetic performance of a component or, more broadly, an entire process, the most commonly used criterion is [28]:

- Exergy efficiency: It is defined as the ratio of the total exergy leaving the system represented by the sum of all outgoing ($\sum E_{out}$) to the total exergy entering the system, which corresponds to the sum of all incoming exergy streams ($\sum E_{in}$). This relationship is expressed by the following equation

$$\eta_{ex} = \frac{\sum E_{out}}{\sum \dot{E}_{in}} \tag{II.3}$$

## II.3 Exergoenvironmental Approach to Thermodynamic Systems

Exergoenvironmental analysis is a method that integrates exergy analysis with environmental impact assessment to evaluate the performance and sustainability of thermodynamic systems. The analysis consists of three main steps. The first step involves the exergy analysis of the system. In the second step, a Life Cycle Assessment (LCA) is conducted for (a) each component of the system under consideration, and (b) all input and output streams. In the final step, the environmental impact results obtained from the LCA are assigned to the exergy streams.

### II.3.1 Life Cycle Assessment

The Environmental Impact Assessment (EIA) definition adopted by the International Association for Impact Assessment (IAIA, 2009) is: "the process of identifying, predicting, evaluating, and mitigating the biophysical, social, and other relevant effects of proposed development proposals prior to major decisions being taken and commitments made" [29]. The environmental impacts of products are commonly assessed using Life Cycle Assessment (LCA)

[30], a method that is aligned with ISO standards (14040:2006) and (14044:2006). LCA is designed to evaluate the potential environmental impacts of a product, process, or service throughout its entire life cycle. Often referred to as a "cradle-to-grave" analysis, LCA covers all phases, from raw material extraction to end-of-life, including material processing, manufacturing, distribution, use, repair, and maintenance.

By definition, LCA gathers an inventory of significant energy and material inputs, as well as environmental emissions, across the full life cycle of a product. Based on this inventory, the method assesses the associated environmental impacts and interprets the results according to the initially defined objectives. An LCA typically follows four main stages:

- Goal and Scope Definition
- Inventory of Relevant Inputs and Outputs
- Assessment of Environmental Impacts associated with the inventory
- Results Interpretation in relation to the defined goal (analysis of the results) [31].

### II.3.2 Exergo-environmental Analysis

Evaluating the environmental performance of an energy conversion system requires analyzing the contribution of each individual component. The materials and manufacturing processes used play a crucial role, as components like gas and steam turbines, which rely on advanced materials and complex production methods, tend to have a higher environmental impact compared to simpler devices such as heat exchangers.

In this context, the term "environment" specifically refers to the physical environment, distinct from the "thermodynamic environment" considered in exergy analysis. Exergo-environmental analysis is founded on the principle that exergy is the most rational basis for assigning not only economic costs but also environmental impact values to energy flows and inefficiencies within a system.

Typically, an exergo-environmental analysis follows three primary steps:

1. Performing an exergy analysis of the energy conversion system;
2. Assessing the environmental impacts using the Life Cycle Assessment (LCA) method;
3. Allocating these environmental impacts to the corresponding exergy streams.

Once these steps are completed, the exergo-environmental evaluation can be finalized, and various exergo-environmental performance indicators can be calculated [32].

The exergo-environmental balance of a component (k) can be expressed as follows:

$$\sum_{s} \dot{B}_{s,k} + \dot{B}_{W,k} = \dot{B}_{q,k} + \sum_{e} \dot{B}_{e,k} + \dot{Y}_k \quad \text{(II.4)}$$

$$\dot{B}_j = b_j \, \dot{Ex}_j \quad \text{(II.5)}$$

Where :

- **Ẏ** represents the environmental impact of a system component (k), as determined through Life Cycle Assessment (LCA).
- Ḃ denotes the environmental impact expressed in Eco-indicator points per unit of time (Pts/s or mPts/s).

In general, the exergo-environmental model for an energy conversion system consists of the environmental impact balance for each component (k) along with auxiliary equations, which are derived by applying the F and P principles [33].

## II.4 Conclusion

The exergo-environmental analysis combines thermodynamic efficiency assessment with environmental impact evaluation, offering a complete perspective for analyzing energy systems. By establishing the theoretical basis of exergy analysis and exergo-environmental methodologies, including the integration of Life Cycle Assessment (LCA), a comprehensive framework is provided for the thermodynamic and environmental optimization of Carnot Batteries. This dual approach enables a precise identification of inefficiencies and their associated environmental burdens, supporting the development of more sustainable and efficient storage technologies.

# *Chapter III*

# *Exergo-environmental Modeling of an Energy storage system*

## III.1 Introduction

This chapter presents the Carnot battery storage system studied in this thesis. The system consists of a heat pump, two thermal storage units (hot and cold), and an Organic Rankine Cycle (ORC). A thermodynamic model is developed to describe the energy conversion processes within each component. Additionally, an exergo-environmental model is formulated to evaluate the exergy-based environmental impacts associated with the system's operation.

## III.2 System description

Figure III.1 shows the basic structure of the Carnot Battery, which integrates a heat pump (HP) unit, a thermal energy storage (TES) system, and an organic Rankine cycle (ORC) for power generation. The heat pump operates in the charging mode and is composed of an evaporator, compressor, condenser, and expansion device. In the discharging mode, the ORC system, including a turbine, evaporator, condenser, and pump, is responsible for converting stored heat into electricity.

The TES system, which links the heat pump and ORC, consists of two pressurized tanks operating at different temperature levels and associated pumps for fluid circulation. During charging, electrical energy drives the heat pump to extract heat from an external source and store it in the high-temperature tank. This thermal energy, combined with direct heat input from the source, remains stored until the discharge phase. When discharging, the ORC draws thermal energy from the TES and transforms it into electrical output, ensuring the continuous operation of the Carnot Battery system.

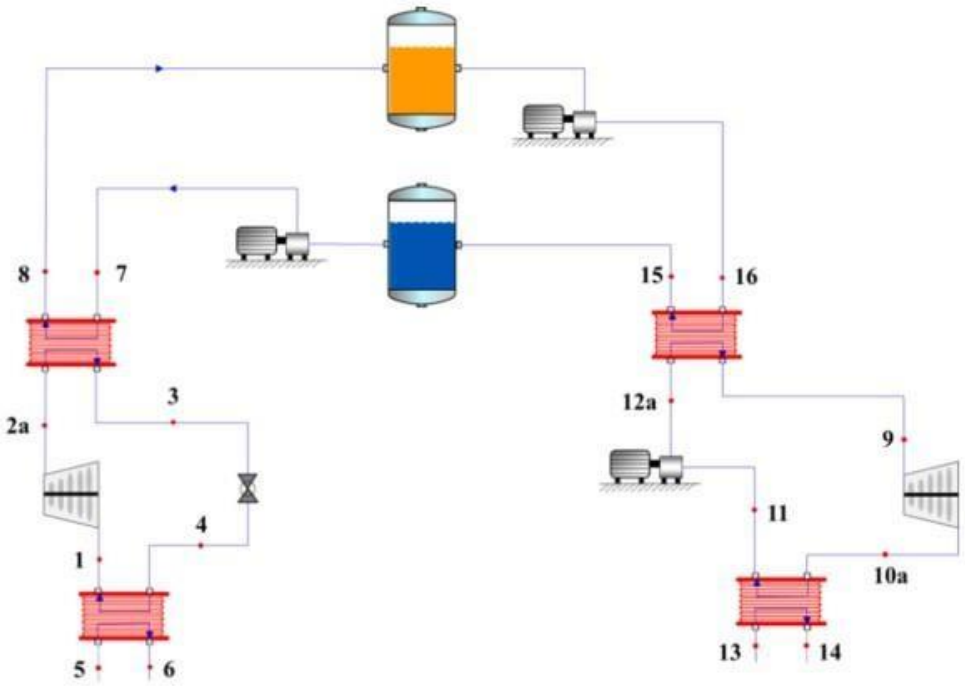



***Figure III.1**: Schematic diagram of the studied ORC system [34].*

### III.3 Exergo-Environmental modeling of the system

The Carnot battery system was modeled numerically using MATLAB (R2018b). R245fa was selected as the working fluid based on recommendations from prior research [34, 35]. Fluid properties were determined using the REFPROP software.

Each component of the system will be analyzed in detail using mass and energy equations, as well as exergy and environmental balances, to assess exergy efficiency, system irreversibility, and environmental impact. To simplify the analysis, several assumptions from the literature [34] will be applied, including:

- Heat losses from all components are neglected.
- System operation is considered steady-state.
- Pressure losses in the piping are ignored.
- The pump and turbine are assigned constant isentropic efficiencies.
- Changes in kinetic and potential energies are assumed to be insignificant.
- Storage duration of 6 hours is considered.

### III.3.1 Mass balance

$$\dot{m}_1 = \dot{m}_{2a} = \dot{m}_3 = \dot{m}_4 \quad \text{(III.1)}$$

$$\dot{m}_9 = \dot{m}_{10a} = \dot{m}_{11} = \dot{m}_{12} \quad \text{( III.2)}$$

$$\dot{m}_7 = \dot{m}_8 = \dot{m}_{15} = \dot{m}_{16} \quad \text{( III.3)}$$

$$\dot{m}_5 = \dot{m}_6 \quad \text{(III.4)}$$

$$\dot{m}_{13} = \dot{m}_{14} \quad \text{(III.5)}$$

### III.3.2 Energy and exergy balance

- **Heat pump components**

**Compressor**

$$W_{comp} = \dot{m}\,(h_{2a} - h_1) \quad \text{(III.6)}$$

$$E_D = E_1 - E_{2a} + W_{comp} \quad \text{(III.7)}$$

**Condenser**

$$Q_{cond} = \dot{m}\,(h_{2a} - h_3) \quad \text{(III.8)}$$

$$\dot{E}_D = (\dot{E}_7 - \dot{E}_8) + (\dot{E}_{2a} - \dot{E}_3) \quad \text{(III.9)}$$

**Evaporator**

$$Q_{evap} = \dot{m}\,(h_1 - h_4) \quad \text{(III.10)}$$

$$E_D = (E_5 - E_6) + (E_4 - E_1) \quad \text{(III.11)}$$

**Throttling valve**

$$\dot{E}_D = \dot{E}_3 - \dot{E}_4 \quad \text{(III.12)}$$

- **ORC components**

**Pump**

$$W_{Pump} = \dot{m}\,(h_{12a} - h_{11}) \quad \text{(III.13)}$$

$$\dot{E}_D = \dot{E}_{11} - \dot{E}_{12a} + \dot{W}_{Pump} \quad \text{(III.14)}$$

**Evaporator**

$$Q_{evap} = \dot{m}\,(h_9 - h_{12a}) \quad \text{(III.15)}$$

$$E_D = (E_{16} - E_{15}) + (E_{12a} - E_9) \quad \text{(III.16)}$$

**Turbine**

$$W_{turbine} = \dot{m}\,(h_9 - h_{10a}) \quad \text{(III.17)}$$

$$\dot{E}_D = \dot{E}_9 - \dot{E}_{10a} - \dot{W}_{turbine} \quad \text{(III.18)}$$

**Condenser**

$$Q_{cond} = \dot{m}\,(h_{10a} - h_{11}) \quad \text{(III.19)}$$

$$E_D = (E_{10a} - E_{11}) + (E_{13} - E_{14}) \quad \text{(III.20)}$$

- **Storage tanks**

**Hot tank**

$$\dot{E}_D = \dot{E}_8 - \dot{E}_{16} \quad \text{(II.21)}$$

**Cold tank**

$$E_D = E_{15} - E_7 \quad \text{(III.22)}$$

## III.4 Exergo-Environmental Balance

- **Heat pump components**

**Compressor**

$$B_1 + B_{W\,comp} + Y = B_{2a} \quad \text{(III.23)}$$

**Condenser**

$$\dot{B}_5 + \dot{B}_4 + Y = \dot{B}_1 + \dot{B}_6 \quad \text{(III.24)}$$

$$b_5 = b_6 \quad \text{(III.25)}$$

**Evaporator**

$$B_{2a} + B_7 + Y = B_3 + B_8 \quad \text{(III.26)}$$

$$b_{2a} = b_3 \quad \text{(III.27)}$$

**Throttling valve**

$$\dot{B}_3 + Y = \dot{B}_4 \quad \text{(III.28)}$$

- **ORC components**

**Pump**

$$B_{11} + B_{WPump} + Y = B_{12a} \quad \text{(III.29)}$$

$$b_{w\,pump} = b_{w\,turbine} \quad \text{(III.30)}$$

**Evaporator**

$$B_{16} + B_{12a} + Y = B_9 + B_{15} \quad \text{(III.31)}$$

$$b_{15} = b_{16} \quad \text{(III.32)}$$

**Turbine**

$$B_9 + Y = B_{10a} + B_{W\ turbine} \quad \text{(III.33)}$$

$$b_9 = b_{10a} \quad \text{(III.34)}$$

**Condenser**

$$B_{10a} + B_{13} + Y = B_{11} + B_{14} \quad \text{(III.35)}$$

$$b_{10a} = b_{11} \quad \text{(III.36)}$$

- **Storage tanks**

**Hot tank**

$$B_8 + Y = B_{16} \quad \text{(III.37)}$$

**Cold tank**

$$B_{15} + Y = B_7 \quad \text{(III.38)}$$

The environmental impact rate, noted as $Y$ corresponds to the impact of a system component and is determined using the Life Cycle Analysis (LCV) method. In this work, $Y$ is calculated by considering only the construction phase of each equipment, without taking into account the impacts related to operation, maintenance, or end of life stages.

### III.5 Performance Study of the Proposed System

The performances investigated in this study include the exergy efficiency and the environmental impact of the net produced power expressed as follows:

$$\eta_{ex} = \frac{E_{ORC}}{\dot{E}_{hs} + \dot{E}_{HP}} \quad \text{(III.39)}$$

$$b_{p,sys} = \frac{B_{p,sys}}{\dot{E}_P} \quad \text{(III.40)}$$

## III.6 Parametric Study

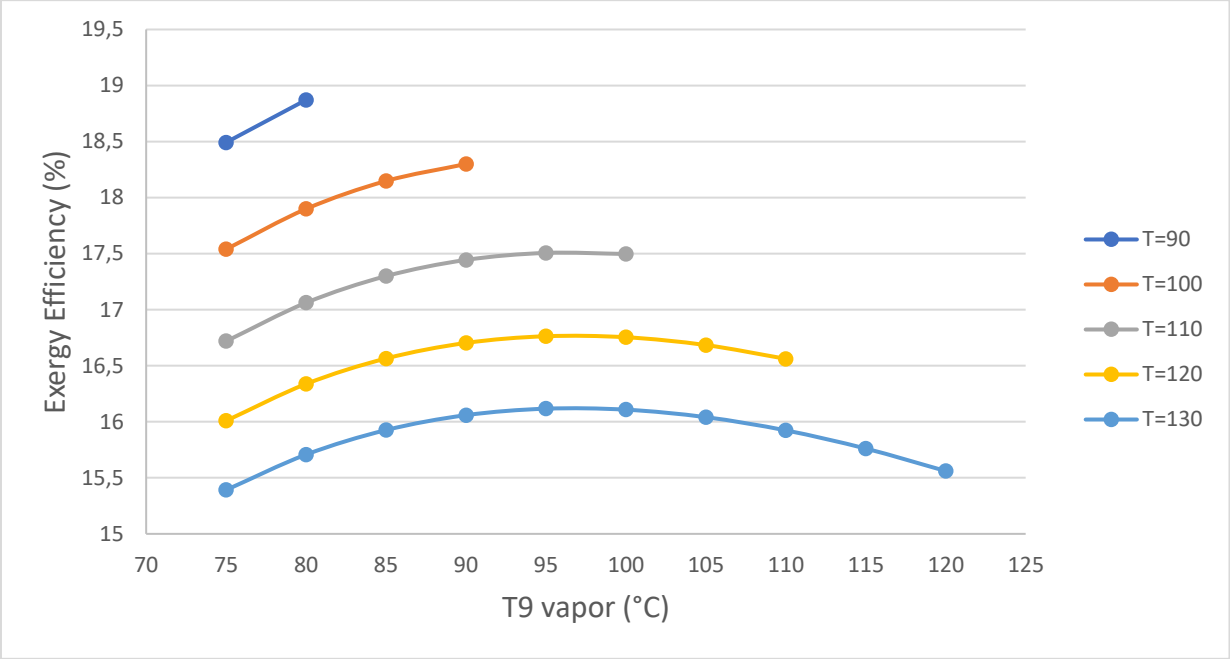
A detailed parametric analysis was conducted to investigate the effects of turbine inlet temperature and its associated pressure, thermal storage temperature, and compressor outlet temperature on system performance. The thermal storage temperature was varied between 90°C and 130°C. The operating ranges for the turbine inlet and compressor outlet temperatures were defined according to the following constraint:

$$T_{9,max} = [(T_{cr} - 10), (T_{ts} - 8)] \quad \text{(III.41)}$$

$$T_2 \in [T_{ts} + 8, T_{cr} - 10] \quad \text{(III.42)}$$

### III.6.1 Effect of turbine inlet temperature on exergy efficiency

Figure III.2 represents the effect of turbine inlet temperature ($T_9$) on the system exergy efficiency under different storage temperatures. The results indicate that exergy efficiency is strongly influenced by the storage temperature. For storage temperatures of 90°C and 100°C, the exergy efficiency increases steadily with rising T9, reaching its highest value at the maximum allowed T9. However, for higher storage temperatures of 110°C, 120°C, and 130°C, the trend changes. In these cases, the exergy efficiency may increase initially but then levels off or increases at a slower rate as T9 approaches its maximum value. This shift is due to a reduced temperature gradient between the storage medium and the turbine inlet, which limits the system's ability to convert thermal energy into useful work effectively.




***FigureIII.2**: Effect of turbine inlet temperature on exergy efficiency.*

### III.6.2 Effect of turbine inlet temperature on the environmental impact the net produced power

Figure III.3 shows the variation of the environmental impact associated with the net produced power as a function of turbine inlet temperature for different thermal storage temperatures. The results show that the environmental impact decreases as the turbine inlet temperature increases, reaching a minimum around 95–100°C for all storage temperatures. After this point, the impact begins to rise again. This trend indicates that there is an optimal turbine inlet temperature range that minimizes the environmental burden of the net produced power. Higher storage temperatures slightly increase the overall impact values but the overall trend stays the same.

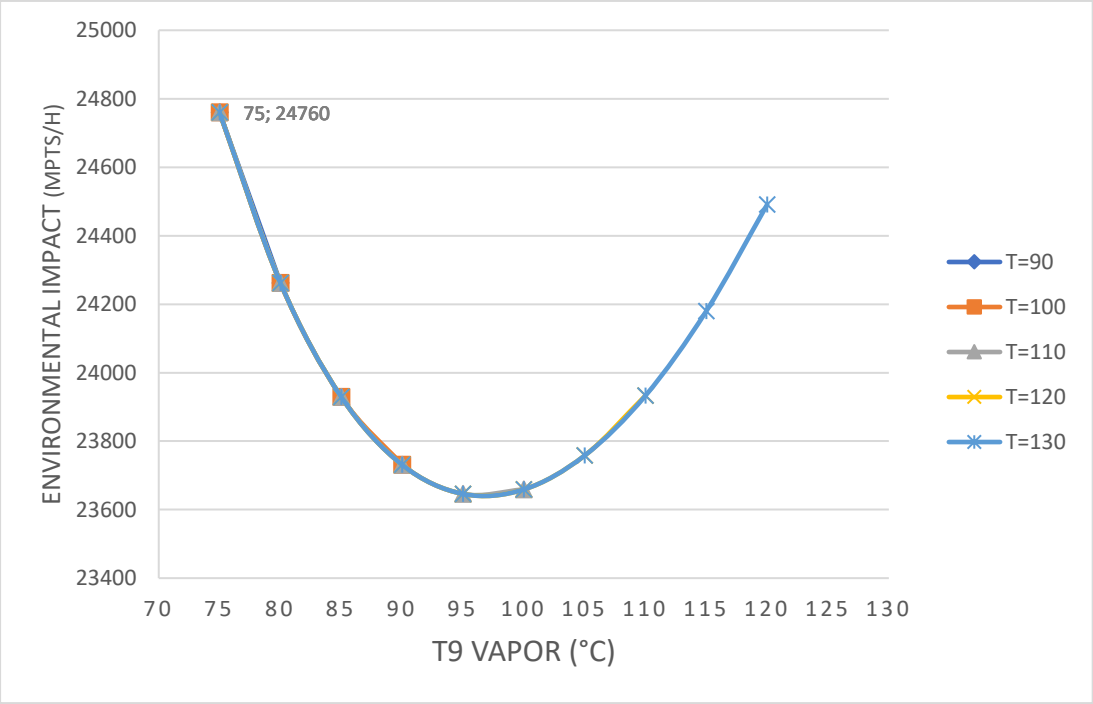



***Figure III.3**: Effect of turbine inlet temperature on environmental impact the net produced power.*

### III.6.3 Effect of compressor outlet temperature on exergy efficiency

In Figure III.4, the influence of compressor outlet temperature on exergy efficiency is depicted for various thermal storage temperatures. Across all scenarios, exergy efficiency consistently declines with increasing compressor outlet temperature. This reduction can be attributed to the increased irreversibilities associated with higher compressor outlet temperatures, which intensify exergy destruction within system components, particularly in the heat pump. Furthermore, at any fixed compressor outlet temperature, systems operating with lower storage temperatures (90 °C) demonstrate significantly higher exergy efficiencies compared to those operating at elevated storage temperatures (100 °C, 110 °C, and 120 °C). This behavior is indicative of a more favorable thermodynamic gradient between the heat source and sink at lower storage temperatures, which enhances the effectiveness of heat transfer and reduces entropy generation.

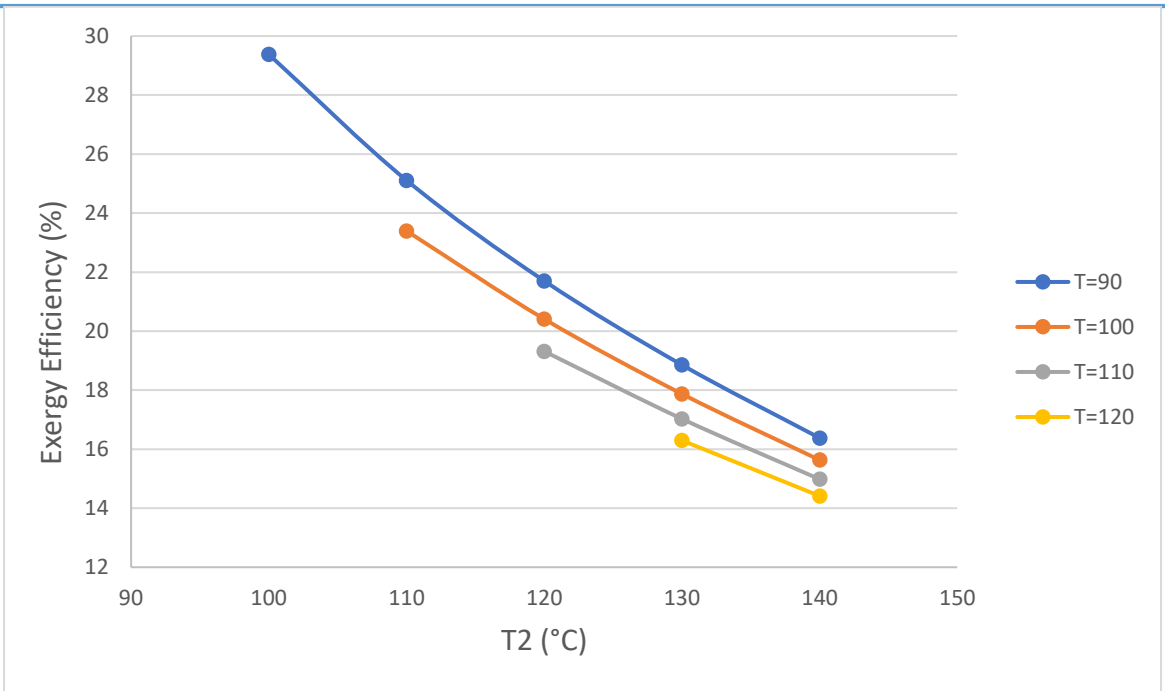



***Figure III.4**: Effect of compressor outlet temperature on exergy efficiency.*

### III.6.4 Effect of compressor outlet temperature on the environmental impact the net produced power

In Figure III.5, the effect of compressor outlet temperature on the environmental impact per unit of net power is shown for different storage temperatures (90 °C, 100 °C, 110 °C, and 120 °C). In all cases, the environmental impact increases steadily as the compressor outlet temperature rises from 100 °C to 140 °C. This increase is due to higher energy consumption by the compressor and lower overall system efficiency at higher temperatures. Among the cases, the system with a storage temperature of 90 °C shows the lowest environmental impact across all compressor outlet temperatures. As the storage temperature increases, the environmental impact becomes higher.

These results show that lower storage temperatures help reduce the environmental impact, especially when the compressor outlet temperature is kept moderate.

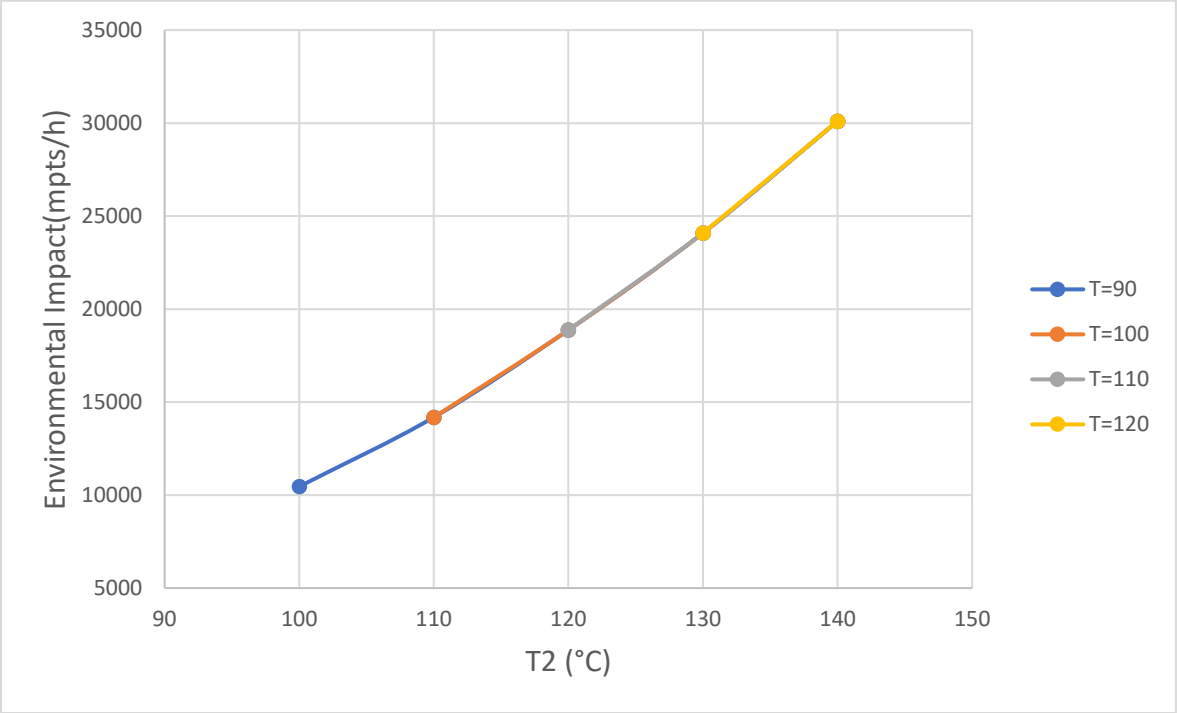



***Figure III.5**: Effect of compressor outlet temperature on environmental impact the net produced power.*

## III.7 Exergo-environmental analysis

### ▯ Exergy analysis

In Figure III.6, the exergy destruction across the main components of the Carnot battery system is presented. The throttling valve exhibits the highest exergy destruction, reaching approximately 210.7 kW, which is expected due to its inherently irreversible expansion process. The HP evaporator and the HP condenser follow with values of 189.2 kW and 153.0 kW, respectively, indicating that the heat transfer processes within the heat pump subsystem contribute significantly to overall irreversibilities. The compressor also shows a notable exergy destruction of 146.7 kW, reflecting losses due to non-isentropic compression and potential mechanical inefficiencies.

Regarding the ORC subsystem, the evaporator and condenser account for 154.6 kW and 94.4 kW of exergy destruction, respectively. Although these values are substantial, they are generally lower than those observed in the heat pump components, suggesting relatively better thermodynamic performance in the ORC. The turbine of ORC shows a comparatively low

exergy destruction of 78.4 kW, which highlights the efficiency of the expansion process. Interestingly, the pump records zero exergy destruction, which could be attributed to either its minor role in the cycle or ideal assumptions in the modeling.

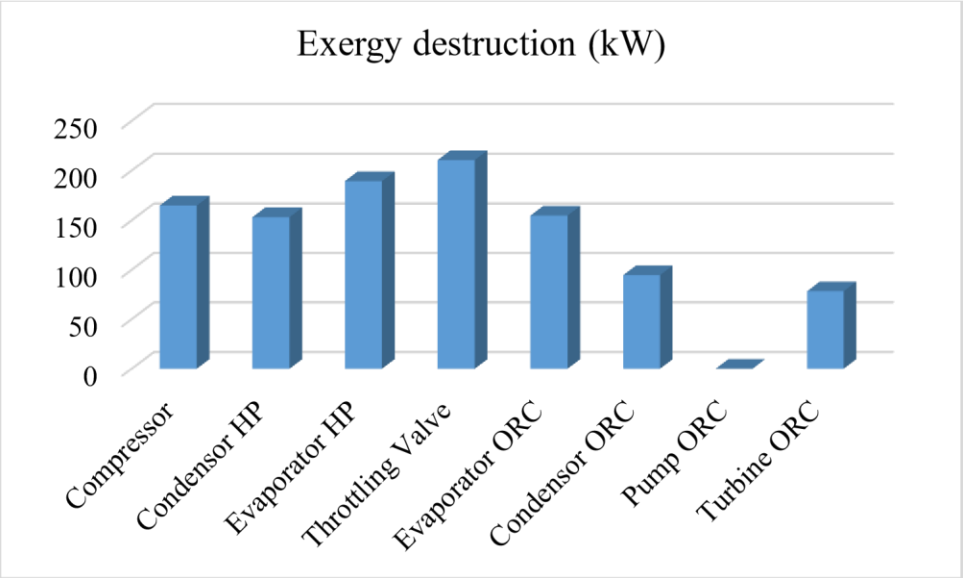



***Figure III.6**: Exergy destruction for each component.*

**Environmental analysis**

In Figure III.7, the environmental impact rate (Y) associated with each component of the Carnot battery system is depicted. The results clearly show that the most environmentally impactful components are the compressor, the turbine, the throttling valve, and the pump, all of which exhibit impact rates exceeding 0.35 pts/h. The highest value is attributed to the compressor at 0.3604 pts/h, closely followed by the Turbine (0.3565 pts/h), the throttling valve (0.3547 pts/h), and the pump (0.3548 pts/h). These elevated rates are not solely a result of thermodynamic irreversibilities, but are largely attributed to the constructive phase characteristics of these components, particularly the type and quantity of materials used, as well as the complexity of their manufacturing processes. Components such as turbines and pumps typically require high-grade alloys, precision machining, and specialized assembly, all of which contribute significantly to their embodied environmental burden.

In contrast, the heat exchangers including the HP Condensor (0.0319 pts/h), HP Evaporator (0.1779), ORC Evaporator (0.0033 pts/h), and ORC Condensor (0.0051 pts/h) demonstrate considerably lower environmental impact rates. While these components may contribute to

thermodynamic inefficiencies, their relatively simple geometries, modular designs, and use of conventional construction materials such as aluminum or copper reduce their environmental load during production. Additionally, the hot and cold thermal storage tanks exhibit zero environmental impact under the current analysis, indicating that their influence is negligible compared to the active mechanical components. This further highlights that the environmental impact in this context is dominated by the material and fabrication demands of rotating and high-pressure equipment rather than static or passive units.

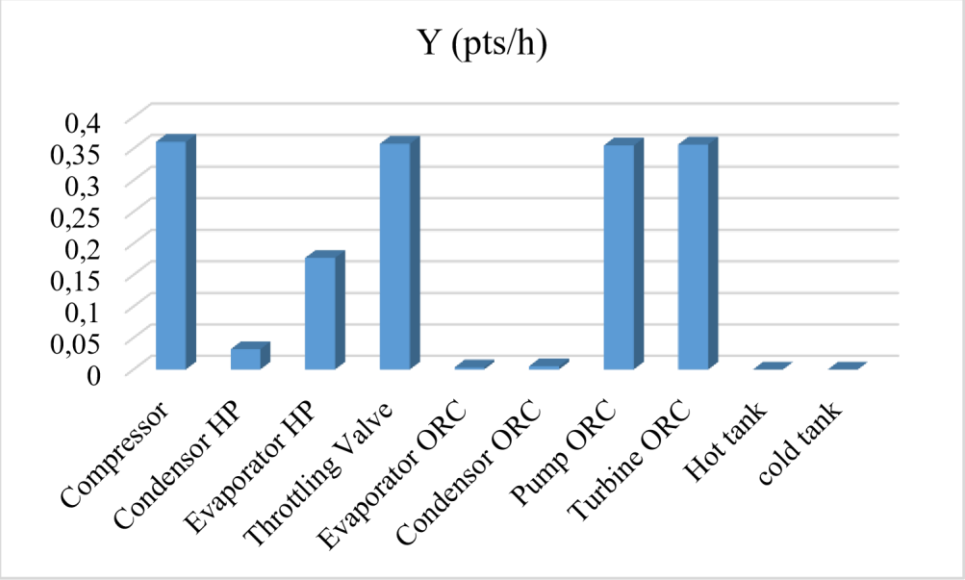



***Figure III.7**: Environmental impact rate (Y) associated with each component.*

## III.8 Conclusion

This chapter provided a comprehensive thermodynamic and exergo-environmental analysis of a Carnot battery storage system, which integrates a heat pump, two thermal storage units, and an Organic Rankine Cycle (ORC) for power generation. The study revealed that exergy efficiency is significantly influenced by storage temperature. An optimal turbine inlet temperature range (95–100°C) was identified for minimizing the environmental impact of the net produced power. Conversely, increasing compressor outlet temperature consistently reduced exergy efficiency due to heightened irreversibilities, and also increased the environmental impact. The exergo-environmental analysis indicated the throttling valve, HP evaporator, HP condenser, and compressor as major contributors to exergy destruction. From an environmental perspective, the compressor, turbine, throttling valve, and pump exhibited the highest impact

rates, largely due to their material and manufacturing demands, while heat exchangers and storage tanks had considerably lower impacts.

# *Conclusion*

# *Conclusion*

The exergo-environmental analysis of energy storage systems, such as Carnot Batteries, represents a promising path to enhance energy efficiency while simultaneously mitigating environmental impact. This approach combines an in-depth analysis of exergy with consideration of environmental implications, thereby enabling the design of more performant and sustainable systems.

In conclusion, our study focused on the exergo-environmental modeling of a Carnot Battery system based on the Power-to-Heat-to-Power (PTES) schema. Utilizing R245fa as the working fluid in the Heat Pump (HP) and Organic Rankine Cycle (ORC) loops, and water in the cold and hot tanks, we conducted a detailed analysis. Employing a computational code developed in MATLAB, we specifically measured the exergy efficiency and environmental impact of key components, namely the turbine and compressor, and quantified the exergy destroyed and the environmental impact factor (Y) for all components within the system.

The results obtained provided valuable insights into the exergo-environmental performance of the studied Carnot Battery configuration. A parametric study was also carried out to investigate the influence of key operating parameters on the exergo-environmental performance of the system. The analysis successfully identified the components that contribute most significantly to exergy destruction and environmental burden, highlighting critical areas for potential optimization and design improvement. The study demonstrated the utility of a component-level exergo-environmental assessment in pinpointing inefficiencies and environmental hotspots within the system.

This research opens the door to new perspectives in the field of Carnot Battery optimization, emphasizing the importance of a combined thermodynamic and environmental evaluation. By continuing to explore this approach, we can develop innovative solutions to address contemporary energy and environmental challenges, contributing to the transition towards more efficient and environmentally friendly energy storage systems. Future work could extend this analysis by exploring alternative working fluids, investigating different PTES configurations, or incorporating economic factors for a comprehensive exergo-environomical assessment.

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