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Thème

Techno-Economic Studty of Pumped Thermal Energy Storage

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Dedication

To my beloved Parents, Brothers, Sisters, Friends, and everyone I love, this work would not have been possible without your love, help, support, and encouragement.
Thank you.

Abstract

As renewable energy continues to play an increasingly important role in modern power systems, the need for energy storage technologies capable of delivering large amounts of energy over extended periods is becoming more critical. Pumped Thermal Energy Storage (PTES) has emerged as a promising solution that stores electrical energy in the form of thermal energy and converts it back into electricity when required.

This study focuses on the techno-economic assessment of a Brayton-cycle PTES system under the climatic conditions of Ain TEMOUCHENT, Algeria. The study employed the System Advisor Model (SAM) to simulate and evaluate the technical and economic performance of the proposed system.

The simulation results were used to assess the thermodynamic performance, energy storage capacity, thermal losses, and overall economic feasibility of the PTES system. In addition, a parametric analysis was conducted to investigate the effects of storage duration and hot storage temperature on system performance. The results demonstrate that PTES is a promising technology for long-duration energy storage and offers significant technical and economic benefits for the integration of renewable energy into modern power systems.

Keywords: Pumped Thermal Energy Storage (PTES), Brayton Cycle, Long-Duration Energy Storage (LDES), Renewable Energy Integration, Techno-Economic Analysis, Round-Trip Efficiency (RTE), Thermal Energy Storage (TES), Simulation, System Advisor Model (SAM).

Résumé

Avec l’intégration croissante des énergies renouvelables dans les réseaux électriques modernes, le besoin de technologies de stockage capables de stocker et de fournir de grandes quantités d’énergie sur de longues périodes devient de plus en plus important. Le stockage thermique d’énergie par pompage (Pumped Thermal Energy Storage – PTES) apparaît comme une solution prometteuse permettant de stocker l’énergie électrique sous forme d’énergie thermique et de la reconvertir en électricité lorsque cela est nécessaire.

Cette étude porte sur l’évaluation technico-économique d’un système PTES basé sur un cycle de Brayton dans les conditions climatiques d’Aïn Témouchent, en Algérie. Le logiciel System Advisor Model (SAM) a été utilisé afin de simuler et d’évaluer les performances techniques et économiques du système proposé.

Les résultats de la simulation ont permis d’évaluer les performances thermodynamiques, la capacité de stockage d’énergie, les pertes thermiques ainsi que la faisabilité économique globale du système PTES. En outre, une analyse paramétrique a été réalisée afin d’étudier l’influence de la durée de stockage et de la température du réservoir chaud sur les performances du système. Les résultats indiquent que le PTES constitue une technologie prometteuse pour le stockage d’énergie de longue durée et qu'il offre des avantages techniques et économiques significatifs pour l'intégration des énergies renouvelables dans les réseaux électriques modernes.

Mots-clés : Stockage thermique d'énergie par pompage (PTES), Cycle de Brayton, Stockage d'énergie de longue durée (LDES), Intégration des énergies renouvelables, Analyse technico-économique, Rendement aller-retour (RTE), Stockage d'énergie thermique (TES), Simulation, System Advisor Model (SAM)

ملخص

مع تزايد الاعتماد على مصادر الطاقة المتجددة في أنظمة الطاقة الكهربائية الحديثة، أصبحت الحاجة إلى تقنيات تخزين الطاقة القادرة على تخزين وتوفير كميات كبيرة من الطاقة لفترات زمنية طويلة أكثر أهمية من أي وقت مضى. ويُعد نظام تخزين الطاقة الحرارية بالضخ (PTES) من الحلول الواعدة التي تتيح تخزين الطاقة الكهربائية على شكل طاقة حرارية، ثم إعادة تحويلها إلى طاقة كهربائية عند الحاجة.

تركز هذه الدراسة على التقييم التقني والاقتصادي لنظام تخزين الطاقة الحرارية بالضخ المعتمد على دورة برايتون تحت الظروف المناخية لولاية عين تموشنت، الجزائر. وقد استُخدم برنامج System Advisor Model (SAM) لإجراء المحاكاة والتقييم التقني والاقتصادي للنظام المقترح.

استُخدمت نتائج المحاكاة لتقييم الأداء الديناميكي الحراري، وسعة تخزين الطاقة، والخسائر الحرارية، والجدوى الاقتصادية الشاملة لنظام PTES. كما أُجريت دراسة لتقييم تأثير المتغيرات التشغيلية، بهدف تحليل أثر مدة التخزين ودرجة حرارة الخزان الحراري الساخن على أداء النظام.

أظهرت النتائج أن تقنية PTES تمثل خيارًا واعدًا لتخزين الطاقة على المدى الطويل، إذ توفر مزايا تقنية واقتصادية مهمة تدعم دمج مصادر الطاقة المتجددة في أنظمة الطاقة الكهربائية الحديثة.

الكلمات المفتاحية :تخزين الطاقة الحرارية بالضخ(PTES) ، دورة برايتون، تخزين الطاقة طويل الأمد(LDES) ، دمج مصادر الطاقة المتجددة، التقييم التقني والاقتصادي، كفاءة الدورة الكاملة(RTE) ، تخزين الطاقة الحرارية(TES) ، المحاكاة، برنامج System Advisor Model (SAM)

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Summary

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List of Abbreviations

PTES .... Pumped Thermal Energy Storage
TES.. Thermal Energy Storage
SHS .... Sensible Heat Storage
LHS .... Latent Heat Storage
CAES .... Compressed Air Energy Storage
PHS .... Pumped Hydro Storage
BES .... Battery Energy Storage System
SAM .... System Advisor Model
RTE .... Round-Trip Efficiency
LCOS .... Levelized Cost of Storage
LCOE .... Levelized Cost of Energy
CAPEX……………………………………………… Capital Expenditure
OPEX .... Operational Expenditure
O&M .... Operation and Maintenance
NPV.. Net Present Value
IRR…………………………………………………. Internal Rate of Return
PBP .... Payback Period
DCF .... Discounted Cash Flow
ROI.. Return on Investment
NPC.. Net Present Cost
CF.. Capacity Factor
HTF .... Heat Transfer Fluid
HE .... Heat Exchanger
HR.. Hot Reservoir
CR .... Cold Reservoir
HS .... Hot Storage
CS.. Cold Storage
MS.. Molten Salt

Nomenclature

Symbol	Description	Unit
C_{tot}	Total capital cost	$
C_i	Cost of component i	$
C_E	Specific energy cost	$/kWh
C_P	Specific power cost	$/kW
E_d	Discharged energy capacity	kWh
P_d	Discharged power capacity	kW
Q	Heat transfer rate	kW
Q_H	Heat stored in hot reservoir	kW
Q_C	Heat stored in cold reservoir	kW
W	Work	kW
W_C	Compressor work	kW
W_E	Expander work	kW
m	Mass	kg
ṁ	Mass flow rate	kg/s
T	Temperature	K
P	Pressure	Pa
h	Specific enthalpy	kJ/kg
s	Specific entropy	kJ/kg·K
C_P	Specific heat capacity	kJ/kg·K
K	Thermal conductivity	W/m·K
L	Latent heat	kJ/kg
n	Project lifetime	year
r	Discount rate	%
CF_t	*Cash flow in year t*	*$*
R_t	*Revenue in year t*	*$*
O_t	*Operating cost in year t*	*$*
I_0	*Initial investment cost*	*$*
E_t	*Annual energy delivered*	*kWh/year*

General Introduction

General Introduction

The world is rapidly transitioning toward renewable energy systems, driving the deployment of various renewable energy technologies, particularly solar and wind power. Despite their numerous environmental benefits, these renewable energy sources are inherently intermittent, making it challenging to maintain a continuous balance between electricity generation and demand. As a result, efficient energy storage systems have become essential for ensuring grid stability and reliability, as well as facilitating the large-scale integration of renewable energy into existing power grids.

At present, conventional energy storage technologies, such as Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), and lithium-ion battery systems, are widely used around the world. However, these technologies face several limitations, including geographical constraints, high capital investment costs, environmental concerns, and performance degradation over time.

Among emerging energy storage technologies, Pumped Thermal Energy Storage (PTES) has attracted considerable attention as a promising solution for large-scale and long-duration energy storage applications. PTES operates by storing electrical energy in the form of thermal energy within hot and cold thermal reservoirs and converting it back into electrical energy when required. In addition to its large storage capacity, PTES offers several advantages over conventional energy storage technologies, including a long operational lifetime, low environmental impact, flexible installation, and reduced dependence on geographical conditions.

This thesis investigates the potential of a Brayton-cycle Pumped Thermal Energy Storage (PTES) system and evaluates its technical and economic feasibility using the System Advisor Model (SAM). The study focuses on assessing the performance of the proposed system under the climatic conditions of Ain TEMOUCHENT, Algeria, and examining its potential to support renewable energy integration while enhancing the flexibility and reliability of future power systems.

This thesis is organized into five chapters. Chapter I presents the research background, problem statement, and objectives of the study. Chapter II provides a literature review of existing energy storage technologies and PTES systems. Chapter III describes the proposed PTES system and its associated thermodynamic modeling. Chapter IV presents the simulation methodology and the techno-economic analysis conducted using SAM. Finally, Chapter V discusses the obtained results and presents the main conclusions and recommendations.

Chapter I:

Research Background, Problem Definition and Objective

Chapter I: Research Background, Problem Definition and Objective

I. Context and Motivation

I.1 Energy Transition

The energy transition is the shift from reliance on fossil fuels to renewable and cleaner energy sources. This change addresses the urgent need for sustainable, environmentally friendly energy solutions. [1]

Why is an energy transition needed now?

The escalating impacts of climate change make this transition imperative. Addressing climate change, reducing environmental pollution, and securing a sustainable energy future is urgent.

Recent decades have experienced a rise in carbon dioxide (CO_2) emissions, contributing significantly to climate change. Transitioning to renewable and cleaner energy sources is a critical strategy to reduce these emissions and mitigate environmental damage.

While the transition to renewable energy is necessary for a sustainable future, it presents several challenges that must be navigated effectively.

- **Technical Challenges**: Energy Storage and Grid Reliability

Efficient energy storage and grid reliability are key technical challenges in the energy transition. Integrating intermittent renewable sources like solar and wind into the existing grid requires advanced energy storage solutions to ensure a stable and consistent energy supply.

- **Economic Challenges**: Investments and Market Dynamics

The transition to clean energy requires significant investments in new technologies and infrastructure. Changing subsidies and incentives, along with evolving market dynamics, affect the adoption of renewable energy and the financial strategies of companies and investors in the sector.

- **Societal Challenges**: Job Displacements and Reskilling

The shift toward renewable energy risks job displacements in fossil fuel-dependent industries. Reskilling workers for roles in the renewable sector is crucial for a just transition.

- **Policy and Regulatory Hindrances**

Policy and regulatory frameworks can sometimes slow the energy transition. Challenges include outdated regulations and insufficient support for renewable energy, necessitating strategic navigation to ensure smooth progress in adopting new energy technologies.

- **Complexity in Integrating Renewables**

Incorporating renewables into the existing energy mix poses complex challenges. It requires not just technological upgrades, but also adjustments in energy and distribution system management to balance the intermittent nature of renewable sources with energy grid demands. [1]

Figure 1 Fossile fuel vs renewable [2]

I.2 Renewable Energy intermittency

Intermittent energy is energy whose availability fluctuates enormously without it being really possible to regulate it. This concept is relatively new, as it applies primarily to renewable energy sources.

When addressing the problem of energy intermittency, two sources are often singled out. The first is **solar/photovoltaic energy**, which is only available during the day, depending on solar radiation and Weather conditions. As for the second, you may have guessed it, it is **Wind energy**. It can only be produced when the wind is blowing.

On a global scale, intermittent renewable energies still represent a small percentage of global production. However, the trend should be reversed given the transition policy initiated by several countries and the production costs which are tending to fall. [3]

I.3 The Role of Pumped Thermal Energy Storage

Figure 2 *P*umped Thermal Energy Storage (PTES) [4]

Pumped Thermal Energy Storage (PTES), also known as Pumped Heat Energy Storage (PHES), is an emerging large-scale energy storage technology that stores electrical energy in the form of thermal energy and converts it back into electricity when required.

The technology operates through a heat pump during charging and a heat engine during discharging, using hot and cold thermal reservoirs to store energy.[5]

The increasing use of renewable energy sources such as solar and wind power has increased the demand for energy storage technologies capable of storing large amounts of energy for long periods.

While lithium-ion batteries and pumped hydro energy storage are currently the most widely used technologies, they have several limitations. Batteries are affected by cost, lifetime degradation, and material availability, whereas pumped hydro storage requires suitable geographical conditions and large infrastructure.

PTES has attracted growing interest because it can provide large-scale energy storage without geographical restrictions. In addition, it offers a long service life, low environmental impact, and the possibility of using low-cost storage materials. The technology is based on creating and storing a temperature difference between hot and cold thermal reservoirs, allowing energy to be stored and recovered when needed.

Several PTES configurations have been proposed, including Brayton-cycle and Rankine-cycle systems, with ongoing studies focusing on improving system efficiency and reducing costs. Although the technology is still under development, research results indicate that PTES has the potential to become an important option for long-duration energy storage and for supporting the integration of renewable energy into modern power systems.[6][7] [8][9][5]

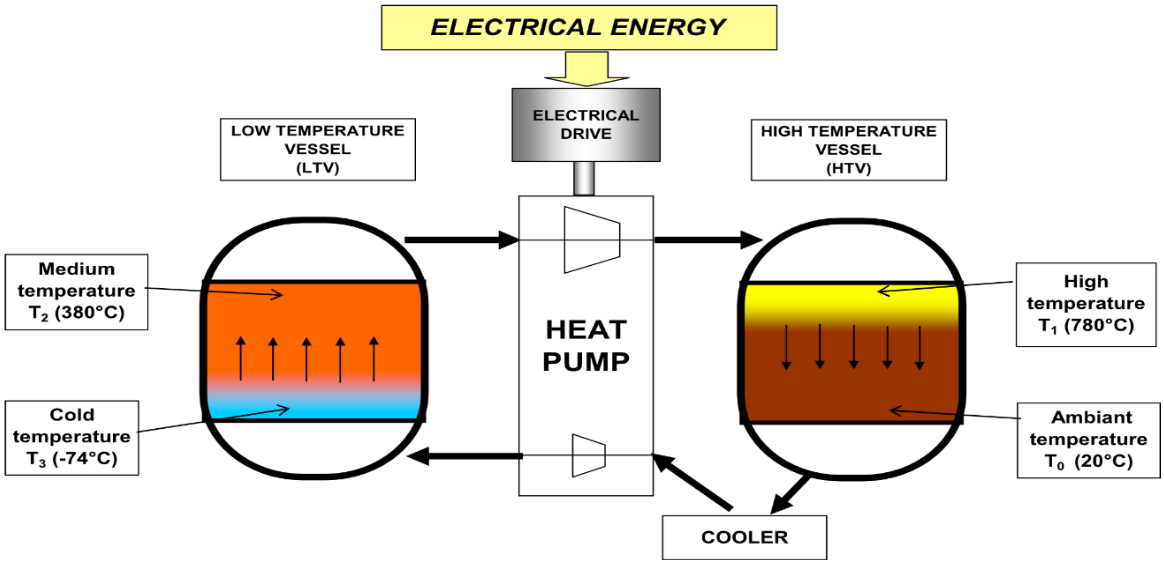

Figure 3 Schematic of a PTES system *[10]*

I.2 Problem Statement

Following the discussion on the energy transition, renewable energy intermittency, and the role of Pumped Thermal Energy Storage (PTES) systems, it becomes evident that this technology represents a key strategic solution for addressing the mismatch between electricity generation and demand.

Renewable energy sources such as solar and wind have experienced significant growth in recent years. However, this growth has presented challenges for electrical grids because these resources generate electricity intermittently. As a result, electrical systems require efficient and reliable methods of storing excess energy when production exceeds demand and delivering that stored energy when a mismatch between generation and demand occurs.

Currently, the two most widely used energy storage technologies are Pumped Hydro Storage (PHS) and lithium-ion batteries. However, both technologies have several limitations.

Lithium-ion batteries involve high capital costs, experience performance degradation over time, raise environmental concerns related to raw material extraction, and pose potential safety risks. Similarly, pumped hydro storage is limited by geographic constraints, requires substantial investment in infrastructure, and may result in environmental and social impacts.

The challenges associated with renewable energy storage are particularly significant in countries where a large proportion of electricity is generated using imported fossil fuels. Such dependence increases electricity costs and hinders the transition toward a more sustainable energy system.

This situation can be observed in countries such as Lebanon and several European countries that are actively working to increase the share of renewable energy within their energy systems.

Consequently, innovative energy storage technologies must be developed to support the continued expansion and integration of renewable energy sources into the electrical grid.

One of the most promising technologies, which has already gained considerable attention for large-capacity and long-duration energy storage applications, is Pumped Thermal Energy Storage (PTES).

Therefore, this research is primarily concerned with analyzing and evaluating the feasibility of PTES as a solution for increasing the integration of renewable energy into the electrical grid while maintaining grid stability.

I.2.1 Limitation of Conventional Energy Storage Technologies

The transition to renewable energy sources such as wind and solar is transforming the global energy landscape. However, the intermittent nature of these energy sources poses a significant challenge.

To address this issue, energy storage systems are essential for storing excess energy generated during peak production periods and discharging it when demand exceeds supply.

- **Lithium-ion Batteries**

Lithium batteries, especially lithium-ion (Li-ion) batteries, have emerged as a leading technology for grid-scale energy storage. Their high energy density, fast charge/discharge capabilities, and relatively long lifespan make them ideal candidates for this role.

Despite their potential, lithium batteries for grid storage face several challenges that must be addressed to maximize their efficiency, cost-effectiveness, and overall performance. Namely,

- **High Initial Costs**

Despite significant cost reductions in recent years, lithium-ion batteries remain expensive for large-scale energy storage applications. The high cost per unit of storage capacity can limit their widespread deployment compared to alternatives such as pumped hydro and compressed air energy storage.

- **Limited Lifespan and Degradation**

lithium-ion batteries have a long lifespan compared to other battery technologies; their capacity gradually decreases over time due to chemical changes within the cells. This capacity fade is influenced by charge/discharge cycles, temperature, and charging rates.

- **Environmental Impact and Resource Constraints**

Lithium-ion batteries require materials such as lithium, cobalt, and nickel, whose extraction raises environmental and ethical concerns. The mining of these materials can contribute to environmental degradation, water scarcity, and ecosystem disruption.

- **Safety Concerns**

Although lithium-ion batteries are generally safe, they can pose risks if damaged or improperly managed. Thermal runaway, which can lead to overheating, fire, or explosion, is a major safety concern, particularly in large-scale energy storage systems.. [11]

• Pumped Hydro Storage

As the share of wind and solar power increases, larger energy storage capacities are required to manage intermittency and ensure a reliable electricity supply. Although pumped hydro energy storage and batteries play a major role in this process, pumped hydro faces several limitations

- **Environmental and Land-Use Impacts**

Pumped hydro and grid-scale battery plants may have environmental and land-use impacts depending on the selected site. While battery facilities require relatively small areas of land, environmental concerns are mainly associated with battery disposal and the extraction of raw materials

- **Pumped hydro requires a range of different resources and materials**,

Include common building materials such as concrete and steel, the quantities of these materials and the construction impacts can be significant.

- **Social Risk**

The main risk associated with pumped hydro storage is dam failure, which can affect downstream communities and the environment. However, pumped hydro is a mature technology, and dam safety risks are generally well understood and managed.[12]

Figure 4 Pumped Hydro and Lithium Battery Storage *[12]*

I.3 Objective of the Study

The primary goal of this study is to evaluate the technical and economic feasibility of a Pumped Thermal Energy Storage (PTES) system for long-term and large-scale energy storage to support renewable energy integration through a techno-economic assessment.

The study also focuses on a Brayton-cycle PTES system and investigates its technical performance through the analysis of key operating parameters.

To achieve this goal, the PTES system will be simulated for a specific climate zone -Ain TEMOUCHENT, Algeria) using the System Advisor Model (SAM) to assess its applicability for local implementation and to better understand how to design the system for optimal performance at the design stage.

The final objective of this research is to provide evidence of whether PTES has the potential to be an effective, economical, and sustainable energy storage solution that supports the integration of renewable energy into the electric grid while increasing the overall flexibility and reliability of future power systems.

CHAPTER II

Literature Review

II.1 Introduction

A large penetration of variable intermittent renewable energy sources into the electric grid has increased the need for installing large-scale Energy Storage units.

Pumped Hydro Storage, Compressed Air Energy Storage and Flow Batteries are the commercially available large-scale energy storage technologies.

However, these technologies suffer from geographical constrains (such as Pumped Hydro Storage and Compressed Air Energy Storage), require fossil fuel streams (like Compressed Air Energy Storage) or are characterized by a short cycle life (Flow Batteries).

For this reason, there is the need to develop new large-scale Energy Storage Technologies which do not suffer from the above-mentioned drawbacks.

Among the in-developing large-scale Energy Storage Technologies, Pumped Thermal Electricity Storage or Pumped Heat Energy Storage is the most promising one due to its long cycle life, no geographical limitations, no need of fossil fuel streams and capability of being integrated into conventional fossil-fueled power plants. Based on these evidences, in the present work, a literature survey on the Pumped Thermal Electricity Storage technology is presented with the aim of analyzing its actual configurations and state of development[5].

II.2 Energy Storage Technology

Energy storage is the ability to capture energy at one time for use at a later time. Storage devices can save energy in many forms (e.g., chemical, kinetic, or thermal) and convert them back to useful forms of energy like electricity.

Although almost all current energy storage capacity is in the form of pumped hydro and the deployment of battery systems is accelerating rapidly, a number of storage technologies are currently in use.[13]

Storage systems are fundamental to the future of renewable energy. They store electricity and make it available when there is greater need, acting as a balance between supply and demand and thus helping to stabilize the grid.

Year after year, new materials and cutting-edge technological solutions are being introduced, providing greater efficiency, lower costs and a design-to-recycle approach, in order to obtain a more sustainable product.[14]

II.2.1 Working principle of energy storage

When the frequency of the electrical grid falls because of heightened demand, the storage system is able to deliver stored energy in just a few seconds; if the frequency increases due to a drop in demand, the system charges with the excess energy. This double function is fundamental to the stabilization of electrical grids. [14]

II.2.2 Types of energy storage

There are basically five types of energy storage: electrochemical, thermal, mechanical, chemical and electrical/electromagnetic.[14] In our study, we aim to focus on the three types of energy storage that are directly related to Pumped Thermal Energy Storage, which are **Mechanical**, **Thermal** and **Electrical** energy storage

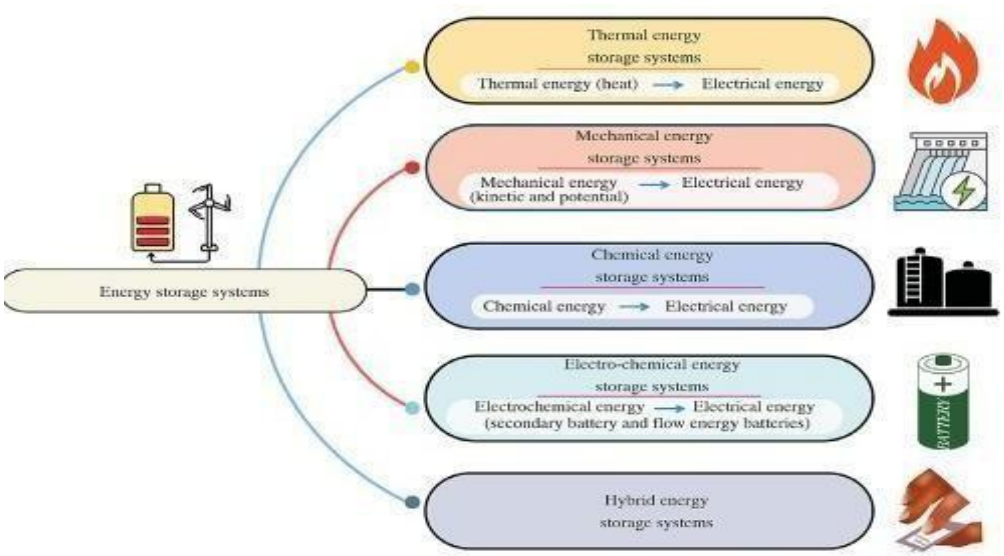

Figure 1 Classification of energy storage [15]

II.2.2.a Mechanical Energy Storage

Mechanical energy storage systems (ESSs) encompass technologies that store energy through the manipulation of mechanical components, such as **gravitational potential energy**, **compressed air**, or **rotational inertia**.

These systems convert electrical energy into mechanical energy during storage and release it back as electricity when needed. Their effectiveness is largely determined by parameters such as efficiency, power density, scalability, and cost-effectiveness [26,27,28]. Common mechanical storage technologies include pumped hydro energy storage (PHES), compressed air energy storage (CAES), flywheel energy storage systems (FESS), gravity energy storage, and liquid air energy storage (LAES) [28,29].

These technologies are well suited for grid applications due to their ability to provide high-capacity, long-duration storage solutions with varying degrees of efficiency and flexibility [27]. However, mechanical storage systems often require specific geographical or infrastructural conditions, which can limit widespread deployment [28].

-Pumped hydro energy storage (PHES) is the most widely implemented mechanical ESS, contributing to over 90% of global energy storage capacity [26,30]. PHES operates by using surplus electricity to pump water from a lower reservoir to a higher one, where it is stored as gravitational potential energy. During peak demand, the water is released to drive turbines, generating electricity. The round-trip efficiency of PHES ranges between 70 and 85%, making it one of the most efficient large-scale storage solutions [30]. Despite its long lifespan of over 50 years and low operational costs, PHES is highly location-dependent, requiring mountainous terrains and large water reservoirs, which restrict its scalability [31,32,33]. The capital expenditure (CAPEX) for PHES is estimated at USD 500–USD 2000 per kW, and it has an energy density of 0.5–3 kW/m3, significantly lower than battery-based storage systems [11,34].

-Compressed air energy storage (CAES) functions by compressing air into underground reservoirs when electricity supply exceeds demand, then releasing it through turbines to generate power when needed. CAES systems typically achieve a round-trip efficiency of 45–70%, depending on whether thermal energy from compression is recovered or lost [28,35]. While CAES has lower efficiency than PHES, its scalability and energy storage capacity ranging from 50 MWh to 1 GWh make it suitable for grid-scale applications [36,37]. The CAPEX of CAES varies between USD 800 and USD 1500 per kW, which is lower than that of PHES, but its reliance on underground caverns for air storage poses geological constraints [37,38]. Adiabatic CAES, a newer variant, aims to improve efficiency by recovering heat generated during compression, increasing the system's performance closer to 70% efficiency [39,40].

-Flywheel Energy Storage Systems (FESSs) use rotating masses to store kinetic energy, which is converted back to electricity when required. The FESS has exceptionally high-power densities (20–80 kW/m3) and round-trip efficiencies exceeding 85–95%, making them suitable for applications requiring rapid charge and discharge cycles [22,27,41]. Unlike PHES and CAES, which serve long-duration energy storage needs, flywheels excel in short-duration applications such as frequency regulation and grid stabilization [42,43]. One of the primary advantages of the FESS is its extremely high cycle life (>1,000,000 cycles) and near-instantaneous response time (milliseconds) [42,44]. However, self-discharge losses remain high, as friction and air resistance gradually dissipate stored energy, making FESSs unsuitable for extended storage durations. Additionally, the capital cost of the FESS exceeds USD 1000 per kW, making it less economically attractive than other mechanical ESS technologies [22,43].

-Gravity energy storage is an emerging mechanical storage technology that operates on principles similar to PHES but eliminates the need for water reservoirs. Instead, it uses surplus electricity to lift massive weights, which can be lowered to drive generators during peak demand [28,44]. The technology boasts a round-trip efficiency of 75–90% and a projected system lifespan exceeding 50 years, making it a promising alternative to PHES in regions lacking water resources. However, the high initial cost of infrastructure and limited real-world deployment hinder its commercial adoption [45,46].

-Liquid air energy storage (LAES) utilizes surplus electricity to liquefy air at cryogenic temperatures (−196 °C), storing it in insulated tanks. When energy is required, the liquid air can expand rapidly, driving a turbine to generate electricity [27,47]. LAES provides grid-scale energy storage with an efficiency of 50–70% and has the advantage of being completely site-independent, unlike PHES or CAES [28,43]. The primary challenge for LAES is energy losses associated with liquefaction processes, which reduce its efficiency relative to alternative storage methods [28]. [16]

II.2.2.b Thermal Energy Storage (TES)

Thermal energy storage (TES) refers to the process of storing energy in a material by heating or cooling it for later use in power generation, industrial applications, and buildings [95]. TES is vital for renewable energy integration, improving energy efficiency, and reducing peak loads [96]. TES systems store heat in three main forms, **sensible heat storage** (SHS), **latent heat storage** (LHS), and **thermochemical storage** (TCS) [97,98]. Each of these categories offers distinct advantages in terms of energy density, efficiency, and discharge duration [99].

Sensible heat storage (SHS) stores energy by increasing or decreasing the temperature of a solid or liquid without a phase change [95]. Typical materials include water, concrete, and rocks, which can withstand temperatures up to 1000 °C. SHS is widely employed in solar thermal power plants and district heating systems due to its simplicity and low cost, although its relatively low energy density (20–50 kWh/m3) and inherent thermal losses remain challenging [98,100].

Latent heat storage (LHS) uses phase-change materials (PCMs) that absorb and release thermal energy through solid–liquid or liquid–gas transitions [97]. Common PCMs—such as paraffin wax, salt hydrates, and eutectic mixtures—exhibit high energy densities (~100–200 kWh/m3) and stable thermal performance [96]. LHS is particularly suited for building heating, solar energy storage, and industrial cooling; however, low thermal conductivity and slow charging rates often necessitate the use of composite materials or integrated heat exchangers for improved performance [99,101].

Thermochemical energy storage (TCS) relies on reversible chemical reactions to store and release energy, offering the highest energy densities (~300–500 kWh/m3) and the potential for long-term storage with minimal heat loss [102]. TCS finds application in solar power plants, industrial waste heat recovery, and hydrogen storage systems [103,104]. Despite its promise, issues such as slow reaction kinetics and high material costs currently hinder large-scale deployment [98]. [16]

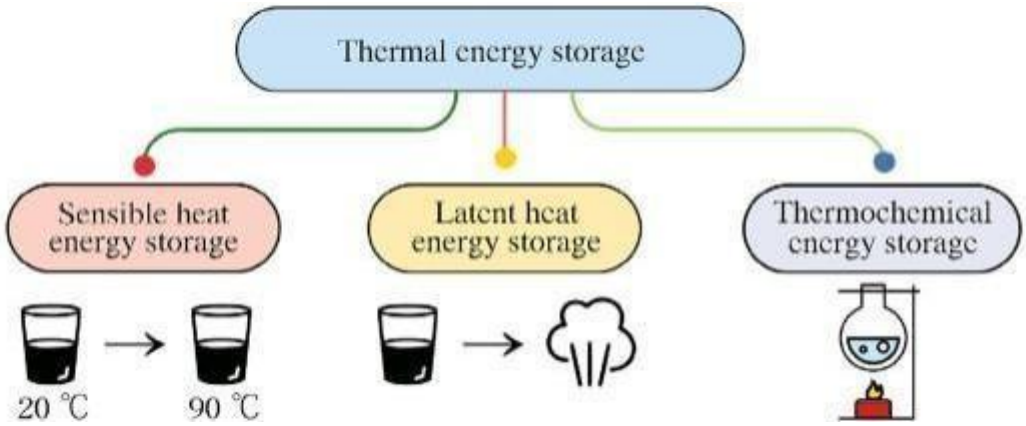

Figure 2 Classification of thermal energy storage [15]

II.2.2.c Electrical Energy Storage

Electrical energy storage (EES) systems store electricity in a form that allows rapid discharge and recharging, making them crucial for grid stability, renewable energy integration, and power quality management [105]. Unlike mechanical, chemical, or thermal storage, EES directly stores electrical charge or potential energy without additional conversion steps, thereby enhancing overall efficiency and response time [106]. EES technologies can be broadly classified into supercapacitors, superconducting magnetic energy storage (SMES), and dielectric capacitors.

Supercapacitors store energy through electrostatic charge separation at the electrode–electrolyte interface, enabling very high-power densities and ultra-fast charge/discharge cycles. They are typically divided into electrochemical double-layer capacitors (EDLCs) and pseudo capacitors. EDLCs, which use activated carbon or graphene-based electrodes, can achieve efficiencies of 90–98% and support millions of cycles.

In contrast, pseudo capacitors leverage fast redox reactions at the electrode surface to achieve higher energy densities using materials such as MXenes, metal oxides, and conducting polymers, although issues with cycle life and stability still need to be addressed [108].

Superconducting magnetic energy storage (SMES) systems store electrical energy in the magnetic field generated by superconducting coils. SMES can deliver energy nearly instantaneously and with very high efficiencies (95–98%), making them attractive for high-frequency power regulation and grid stabilization. However, their widespread application is currently limited by high costs and the need for complex cryogenic cooling systems [109].

Dielectric capacitors store energy via the polarization of dielectric materials under an applied electric field. They are capable of operating at high voltages and discharging energy within nanoseconds, which makes them suitable for pulsed power applications, electric vehicles, and space technologies. Despite these advantages, their low energy storage capacity restricts their use in grid-scale applications [110]. EES technologies vary in energy density, efficiency, and power output [107]. Supercapacitors excel in rapid energy delivery, while SMES offers near-instantaneous discharge with high efficiency [15]

Thermal Energy Storage (TES) systems have attracted significant attention due to their relatively low cost, long service life, high stability, scalability, and reduced environmental impact compared with other energy storage technologies.

Previous studies have shown that PTES offers competitive combination of energy density, cost, efficiency and lifetime compared with other large-scale energy storage systems as presented in table-2

Energy storage technology	Energy density [Wh/l]	Price per energy unit stored [$/kWh]	Round trip efficiency [%]	Lifetime [years]
PHS	0.5–1.5	5–100	65–87	30–60
GES	0.5–1.5	N/A	70–86	30–40
CAES	3–12	2–200	40–95	20–60
LAES	50	260–530	40–85	20–40
Flow Batteries	16–60	120–1000	57–85	5–15
Hydrogen	500–3000	1–10	20–50	5–30
PTES	110–170	60	70–80	25–30

Table 1 Energy density, specific costs, round-trip efficiency and the lifetime of different energy storage systems *[5]*

After a comprehensive study and considering all factors in our today's world, **Thermal Energy Storage systems** (TES) have attracted attentions due to their low cost, long lifespan, high stability and scalability and reduce environmental impact compared with other energy storage technologies.

In terms of types, Thermal energy storage systems are generally divided into three types as it is mentioned previously. Among these technologies, **sensible** and **latent heat storage** are the most widely investigated for PTES application due to their thermal sensibility and practical feasibly

Therefore, this research project focuses on a Brayton-cycle Pumped Thermal Energy Storage system based on sensible heat storage.

II.3 Pumped Thermal Energy Storage (PTES)

II.3.1 Working Principle

Pumped Thermal Energy Storage (PTES) is an energy storage technology that stores electrical energy in the form of thermal energy and later converts it back into electricity when needed [51].

A schematic diagram of a PTES system is shown in Figure II-3

The main components of a PTES system include compressors, expanders, heat exchangers, thermal energy storage (TES) media, and storage tanks.

PTES systems operate through two main processes: charging and discharging.

During charging, electrical energy is converted into thermal energy and stored in hot and cold thermal energy storage tanks.

Different storage materials can be used, including molten salts, rocks, concrete, water, ice, and phase change materials.

During discharging, the stored thermal energy is used to operate a heat engine and generate electricity

Heat exchangers transfer thermal energy between the storage tanks and the working fluid.

The performance of the system depends on the temperature difference between the hot and cold storage tanks, the properties of the working fluid, and the thermodynamic cycle employed, such as the Brayton or Rankine cycle.. [17]

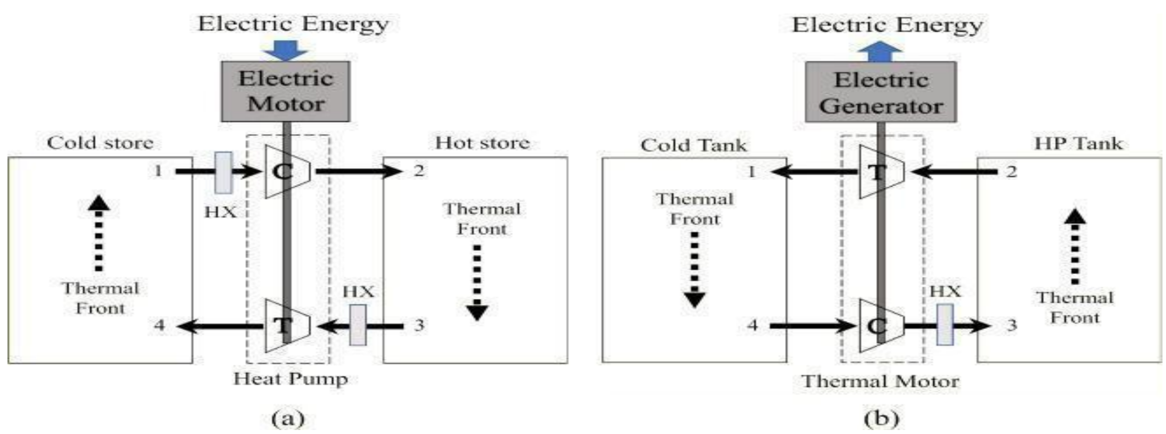

Figure 3 Schematic diagram of PTES systems. (a) Charging mode and (b) Discharging mode. *[8]*

II.3.2 Main Components of the system

A closed-loop circuit filled with the working gas interconnects the main PTES components, including the compressor, expander, heat exchanger, electrical motor/generator, working fluid, control system, and the hot and cold thermal storage tanks.

Note: The figures presented in this section are provided for illustrative purpose only and do not necessarily represent the exact components used in the modeled PTES system.

II.3.2.a Compressor

It is one of the most essential components of the charging process. The compressor compresses the working fluid (air, CO_2, etc.) and increases its temperature and pressure before it is used to charge the hot thermal storage system.[8], [18], [19]

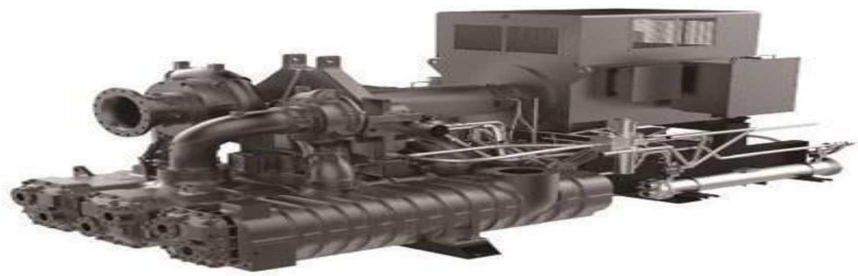

Figure 4 Centrifugal Compressors *[20]*

II.3.2.b Expander (Turbine)

It is one of the main components of the system, and its primary role is during the discharging process.

The expander expands the high-pressure, high-temperature working fluid to lower pressures and temperatures, converting thermal energy into mechanical work during the expansion process. This mechanical work is then used to drive a generator, producing electricity.

The expander also plays an important role during the charging process by expanding the working fluid and reducing its temperature, thereby enabling cold thermal energy storage. [17]

It should be noted that different types of turbines can be used in Pumped Thermal Energy Storage (PTES) systems. One of the most commonly used types is the radial turbine.

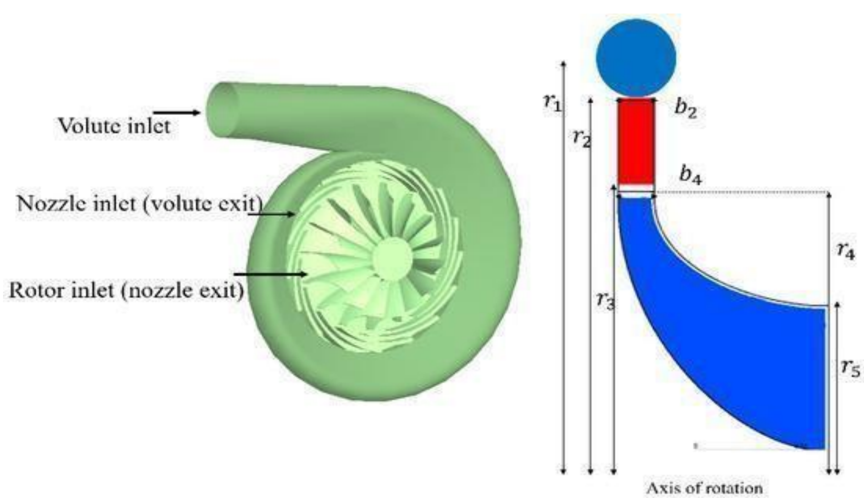

Figure 5 Radial Turbine *[21]*

II.3.2.c Thermal Energy Storage medium

-Hot Thermal Storage Tank

It is typically filled with thermal storage materials such as molten salts or packed-bed materials (rocks, ceramics).

Its main role is to store the high-temperature thermal energy generated during the compression of the working fluid in the charging mode. During the discharging mode, the stored thermal energy is released to reheat the working fluid before expansion.

-Cold Thermal Storage Tank

It is the second thermal storage component and operates at low temperatures.

It stores the thermal energy removed during the expansion (cooling) process and helps maintain low-temperature conditions for later use during the discharging mode.

The operating principle of all PTES systems involves the use of two thermal storage tanks: a hot storage tank and a cold storage tank. [7], [17]

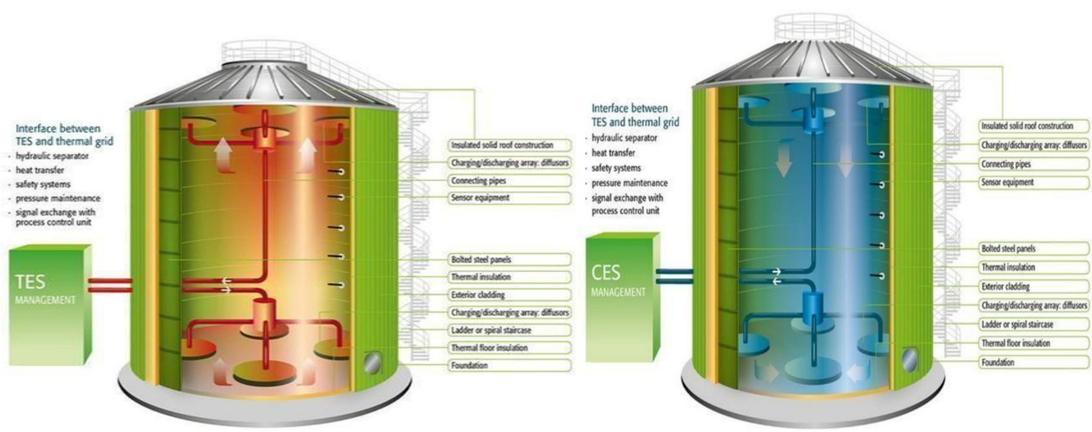

Figure 6 Hot and Cold Tank [24]

II.3.2.d Heat Exchanger

Heat exchangers are commonly used in PTES systems with different roles, types, and positions depending on the system configuration and operating conditions.

The main role of a heat exchanger is to transfer heat between the working fluid and the thermal storage units.[19]

The performance of the systems considered in this study is strongly dependent on the design of the heat exchangers due to the high heat-to-work ratio (i.e., the ratio of total heat exchanged to network transfer). [22]

The heat generated is transferred to the thermal storage system either directly or through a heat exchanger, depending on the system configuration.

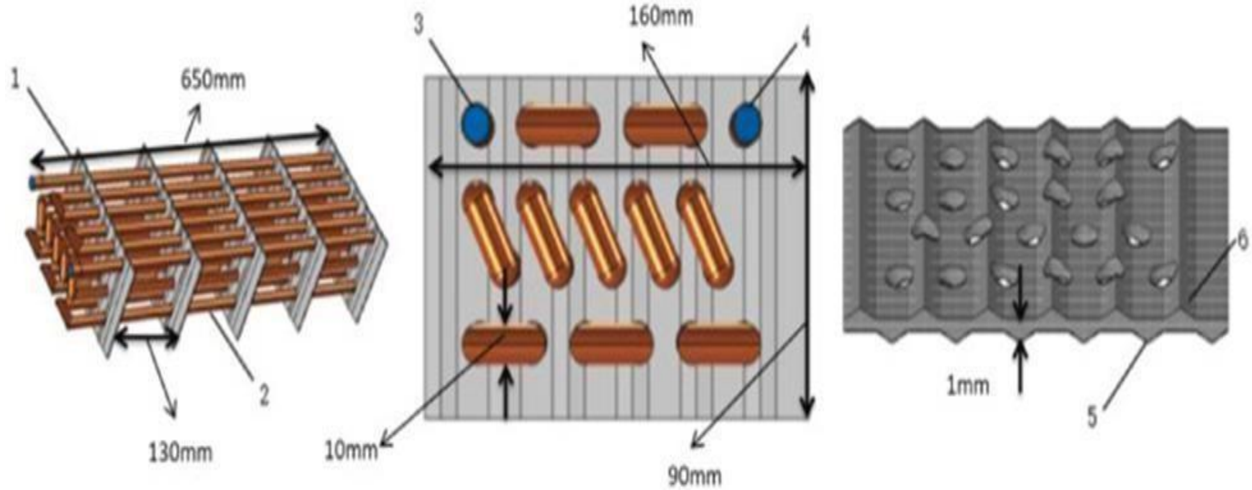

Figure 7 Heat exchanger structure and fin structure.

II.3.2.e Working Fluid

It is considered one of the most important components in a PTES system, as it is responsible for transferring thermal energy throughout the thermodynamic cycle.

There are different types of working fluids that can be used in PTES systems, including air, CO_2, nitrogen, argon, and others.

The selection of the working fluid significantly affects the efficiency, thermal performance, and operational characteristics of the system. [7], [8]

II.3.2.f Electric Motor/Generator

It is a key component of the PTES system. Conceptually, it is a single device; however, for the sake of simplicity in modeling, it is represented as two discrete components.

The motor-generator is assumed to be a synchronous permanent magnet machine with IE3 efficiency-class performance when operating as a motor and with the same efficiency when operating as a generator.[23]

Figure 8 Motor generator 2 in 1 with controller and inverter*[24]*

II.3.3 PTES Performance Indictors

II.3.3.a Round-Trip Efficiency

Pumped Thermal Energy Storage (PTES) is a thermo-mechanical energy storage technology classified under the concept of Carnot battery, which includes systems such as Liquified Air Energy Storage (LAES).

PTES stores electrical energy in the form of thermal energy by operating reversible heat pump and heat engine cycles. During the charging phase, electricity is consumed to transfer heat from a cold reservoir to a hot reservoir using a heat pump. During the discharging phase, the stored heat is recovered and converted back into electricity through a heat engine as heat flows from the hot reservoir to the cold reservoir. Different thermodynamic cycles can be used in PTES systems, including the Carnot cycle, Brayton cycle, and Organic Rankine cycle.

Among these, Brayton-cycle-based PTES systems are considered the most suitable for large-scale applications because of their feasibility and promising technical performance, while Organic Rankine cycle systems are mainly applied to low-temperature heat sources and small-scale applications.

The performance of PTES systems is evaluated using the concept of round-trip efficiency (RTE), which represents the ratio between the electrical energy produced during discharge and the electrical energy consumed during charging.

In an ideal reversible system, the efficiency could theoretically reach 100%; however, real systems experience energy losses due to irreversibility's such as heat leakage, friction, pressure drops, and component inefficiencies.

The charging efficiency of the system is determined by the coefficient of performance (COP) of the heat pump, while the discharging efficiency depends on the thermal efficiency of the heat engine.

In addition, the storage process itself affects overall performance because thermal energy losses occur during the storage period in both the hot and cold reservoirs. Therefore, the total efficiency of PTES systems depends on several operating and design parameters, including the **isentropic efficiencies of compressors** and **turbines**, **heat exchanger effectiveness**, **thermal storage efficiency** (storage material), **working fluid**, **electrical machine efficiency**, **circuit pressure losses**, and **heat leakage** to the surroundings.

According to several studies with different PTES types, PTES systems are capable of achieving round-trip efficiencies in the range of 40–70% for systems designed to store approximately 600 kWh of electrical energy.

$$\eta_{RT} = \frac{W_{out}}{W_{in}} \times 100\% \qquad 1$$

[19], [25], [26], [27]

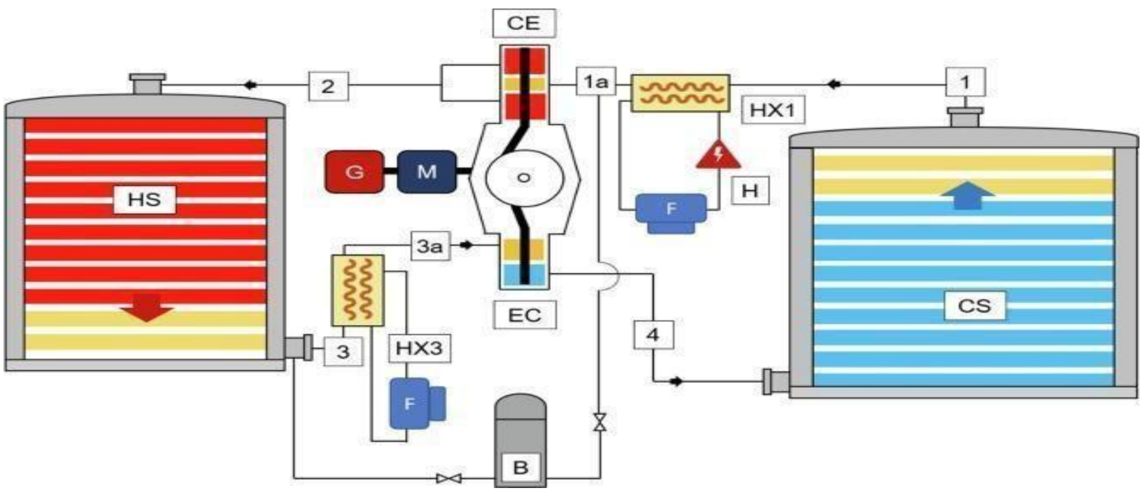

Figure 9 Basic layout of PHES demonstrator (not to scale).*[25]*

II.3.3.b System Configuration

PTES (also referred to as 'pumped-heat electricity storage', or PHES, in the literature) is another recently proposed energy storage technology that stores electricity in the form of sensible heat in insulated storage vessels containing of an appropriate storage medium, such as a packed bed of gravel or pebbles [17].

PTES (presented in Fig. 10) comprises primarily two hot/cold thermal reservoirs (HR, CR) at different pressures, two compression/expansion devices (C, E), and two heat exchangers (HE1, HE2) which are essential for accommodating the system's irreversibility's by heat rejection [17].

A PTES system runs reverse and forward Joule-Brayton cycles, for charging and discharging respectively.

During the charge period, a high pressure-ratio heat-pump cycle is driven using electricity. This process removes heat from the cold vessel and supplies heat to the hot vessel.

During the discharge period, the working fluid's flow direction is reversed within the system, and the difference in temperature between the two (hot/cold) thermal stores is used to drive a Joule-Brayton heat-engine cycle in order to generate work, and thereafter electrical energy [28]

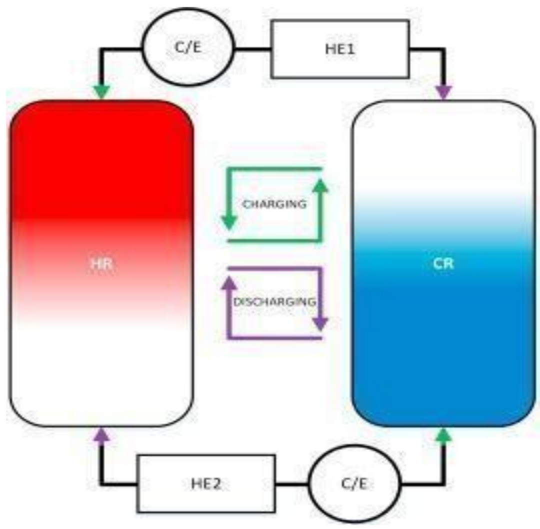

Figure 10 PTES system configuration with main components. Adapted from Ref*[28]*

II.3.3.c Energy Density

Energy density in Pumped Thermal Energy Storage (PTES) refers to the amount of thermal energy that can be stored per unit volume (kWh/m³) or per unit mass (kWh/kg). Unlike electrochemical batteries, PTES stores energy as sensible heat (or sometimes latent heat) in thermal storage materials such as packed beds of solids (rocks, pebbles) or phase change materials (PCMs).

The energy density of PTES depends mainly on the specific heat capacity of the storage material, its density, and the temperature difference between the hot and cold reservoirs. A simplified expression for sensible heat storage

$$E = \rho \, c_p \, \Delta T \qquad 2$$

Where:

E= energy density

ρ= density of the storage material

c_p= specific heat capacity

ΔT= temperature difference between storage levels [29]

II.3.3.d Storage Duration

Storage duration is an important characteristic of Pumped Thermal Energy Storage (PTES) systems and refers to the length of time energy can be stored before it is discharged. It is influenced by several factors, including system configuration, storage capacity, operating temperatures, and insulation quality. Thermal losses from the hot and cold storage tanks, mainly through heat conduction, can significantly affect the storage duration and overall system performance.

From a thermodynamic perspective, longer storage durations generally lead to higher thermal and exergy losses, which may reduce the round-trip efficiency of the system. Therefore, effective insulation and optimized thermal storage designs are essential for maintaining system performance during extended storage periods.

Recent developments in PTES focus on improving storage performance through advanced insulation materials, enhanced system configurations, and improved heat transfer technologies. Although increasing storage duration may require larger storage units and additional investment, PTES remains a promising long-duration energy storage technology capable of supporting renewable energy integration and improving grid reliability. [5], [9], [27], [30] [31]

II.3.4 PTES economic Assessment

The economic assessment of Pumped Thermal Energy Storage (PTES) focuses on evaluating the relationship between system performance and overall cost.

Several factors influence the economic viability of PTES systems, including renewable energy capacity, storage size, system configuration, component costs, and operating strategy.

Economic evaluation is essential to determine whether PTES can compete with other large-scale energy storage technologies and provide a cost-effective solution for long-duration energy storage applications.

The total capital cost of a PTES system or (CAPEX) is determined by summing the costs of all major components, including compressors, expanders, thermal storage tanks, heat exchangers, insulation materials, and auxiliary equipment. Installation and contingency costs are commonly included in the overall investment cost according to:

$$C_{tot} = f \sum C_i$$

Where $C_{tot} =$ is the total capital cost, and C_i represents the cost of each system component, and (f) is the installation and contingency factor.

To compare different energy storage technologies on a common basis, the capital cost may also be expressed per unit of energy capacity and power capacity:

$$C_E = \frac{C_{tot}}{E_d} \qquad C_P = \frac{C_{tot}}{P_d}$$

Where E_d is the discharged energy capacity (kWh) and P_d is the discharged power capacity (kW)

In Addition, one of the most widely used indicators for evaluating the cost-effectiveness of energy storage technologies is the Levelized Cost of Storage (LCOS). LCOS represents the average cost of delivering one unit of electricity throughout the lifetime of the storage system and is calculated as:

$$LCOS = \frac{\text{Total Lifetime Costs}}{\text{Total Energy Delivered Over Lifetime}}$$

"The total lifetime costs include capital expenditures, operation and maintenance costs, replacement costs, and other expenses incurred during the project lifetime.

The total energy delivered corresponds to the electrical energy supplied by the storage system over its operational life. "

LCOS is a deciding factor in large-scale energy storage systems. Therefore, it is reasonable to investigate it more.

LCOS depends on several uncertain parameters, including

- ✓ Electricity purchase price
- ✓ Plant lifetime,
- ✓ Operation and maintenance factor
- ✓ Discount rate
- ✓ Number of operating days per year.

Another commonly used economic indicator is the Levelized Cost of Energy (LCOE), which represents the average cost of generating one unit of electrical energy over the lifetime of a system. It is expressed as

$$LCOE = \frac{\text{Total Lifetime Costs}}{\text{Total Energy Produced Over Lifetime}}$$

The LCOE is particularly useful when evaluating power generation systems, whereas LCOS is more appropriate for energy storage technologies because it accounts for the cost of storing and subsequently delivering electricity.

Since the costs of PTES components may vary significantly, uncertainty analysis techniques such as Monte Carlo simulations can be applied to evaluate the impact of cost variations on the overall economic performance. Therefore, the combined use of capital cost analysis, LCOS, and LCOE provides a comprehensive framework for assessing the economic feasibility and competitiveness of PTES systems compared with alternative storage technologies such as lithium-ion batteries, compressed air energy storage (CAES), and pumped hydro storage (PHS). [7] [31], [32], [33] [22]

II.3.5 Thermodynamic Principle of PTES

Pumped thermal energy Storage is also called as Carnot battery, mainly because it stores electricity as thermal energy and later converts the thermal energy back into electricity.

The Name 'Carnot battery' comes from the fact that the system operates using thermodynamic heat engine principles similar to the Carnot Cycle

Carnot battery is a promising energy storage method that stores electricity in the form of thermal exergy.

During the charging phase, a temperature difference is established between a high-temperature (HT) and a low-temperature (LT) reservoir through a power-to-heat system, such as a heat pump or an electric heater. The produced heat is stored in thermal energy storage (TES) units, which can be sensible, latent, or thermochemical.

During the discharging phase, a heat engine, such as a power cycle, is fed by the stored thermal energy and generates electricity [8,9]. Typically, the HT reservoir is a heat storage system, while the LT reservoir may be the ambient or a cold storage system.

In some cases, Carnot battery systems can be thermally integrated, receiving heat from a low-grade heat source, such as solar heat, geothermal energy, or waste heat [10]. A schematic representation of a typical Carnot battery configuration is shown in Fig. 1a, while a thermally-integrated Carnot battery unit, where an LT heat source feeds the heat pump, is illustrated [34] in Figure III-1

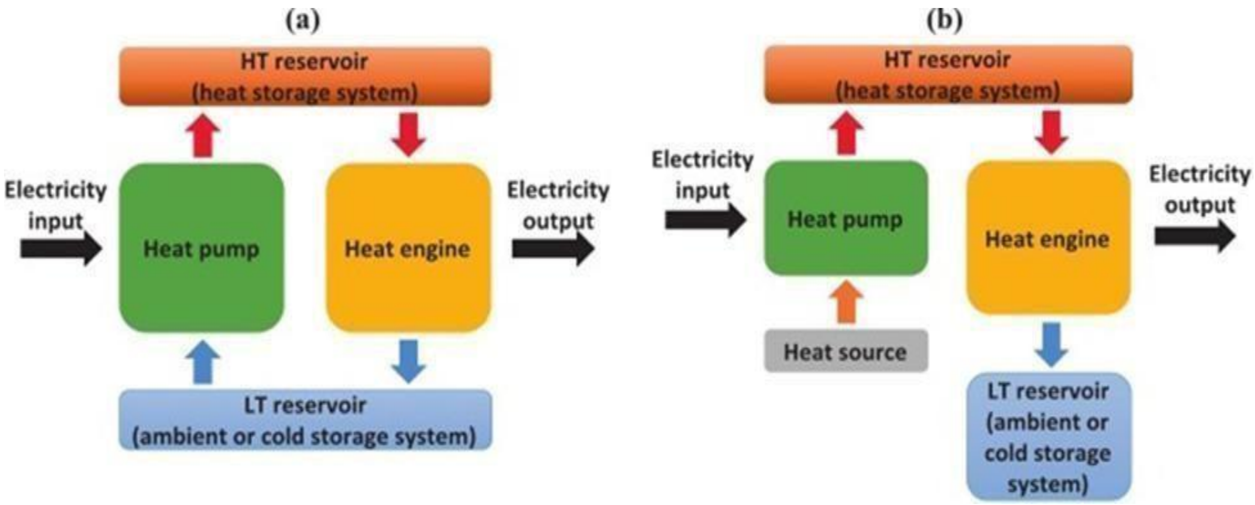

Figure 11 Typical Carnot battery system (a), and thermally-integrated Carnot battery system (b**).***[34]*

The main categories of Carnot battery units are pumped thermal energy storage (PTES) and liquid air energy storage (LAES) systems. There are also additional concepts with limited applications, such as Lamm-Honigman storage. The classification of Carnot battery units is illustrated in Fig. 2. It is worth noting that PTES systems are classified into Rankine-based and **Brayton-based** [34]

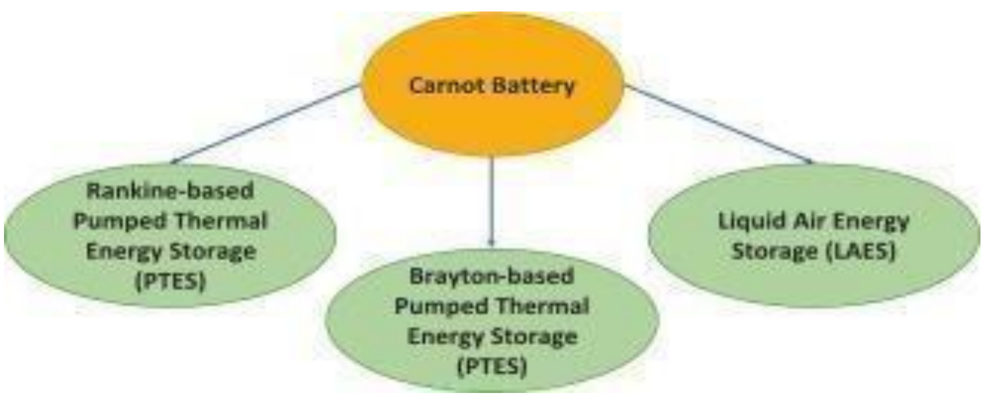

Figure 12 Classification of Carnot battery systems. *[34]*

II.4.5 Thermodynamic cycles applicable to PTES

The PTES systems can be broadly categorized into three groups based on the type of cycle they incorporate. Within each category, several variations have been proposed, including Joule–Brayton cycles, Rankine cycles, and transcritical cycles. In this section, the major systems within each category are reviewed, along with a brief comparison of each system. Figure 3 demonstrates the difference between the three types of PTES thermodynamic cycles.[9]

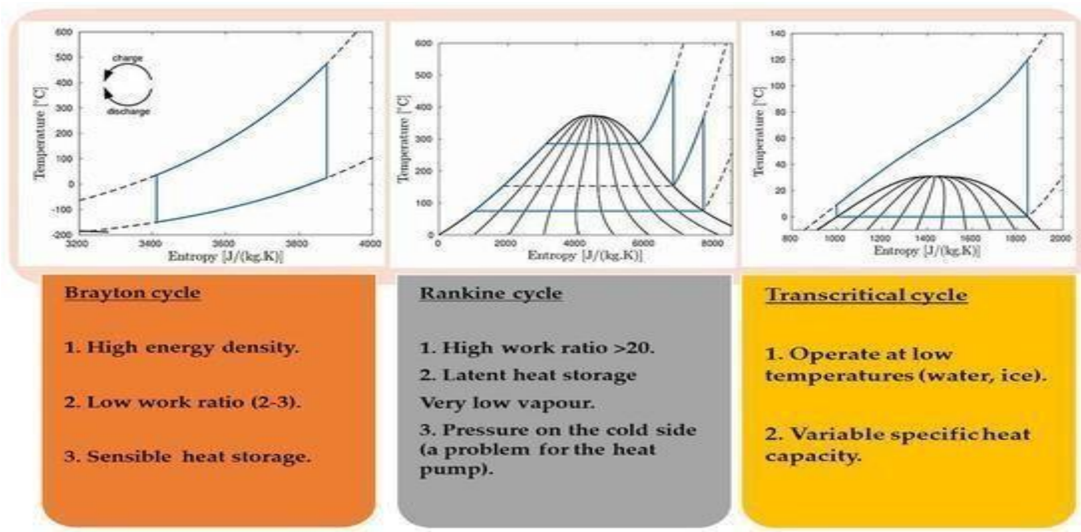

Figure 13 Comparison between the common PTES thermodynamic cycles.*[9]*

In each case, the power cycle selection determines the type of storage system, which can be sensible or latent heat storage [7], or thermo-chemical storage. [35]

This study presents a PTES system based on Joule Brayton (Brayton) thermodynamic cycle due to its simplicity, high energy density and suitability for large scale energy storage applications.

Many previous studies have showed that Brayton-based PTES system can achieve competitive round-trip efficiency while maintaining relatively low system complexity and capital costs compared with other thermodynamic configurations, as discussed in the previous study presented in CHAPTER-II.

Joule Brayton (Brayton) thermodynamic cycle

The Brayton cycle is a thermodynamic cycle that describes the working of gas turbine engines and jet engines. It uses air or another gas as the working fluid and is widely used in modern power generation and aviation systems.

It consists of four main processes:

Isentropic Compression: Air is compressed in a compressor without heat exchange, increasing its pressure and temperature.

Constant Pressure Heat Addition: The working fluid has heat energy added to it at a constant pressure:

Isentropic Expansion: The high-temperature gas expands in a turbine, producing mechanical work.

Constant Pressure Heat Rejection: The working fluid has heat energy removed from it at a constant pressure.[36]

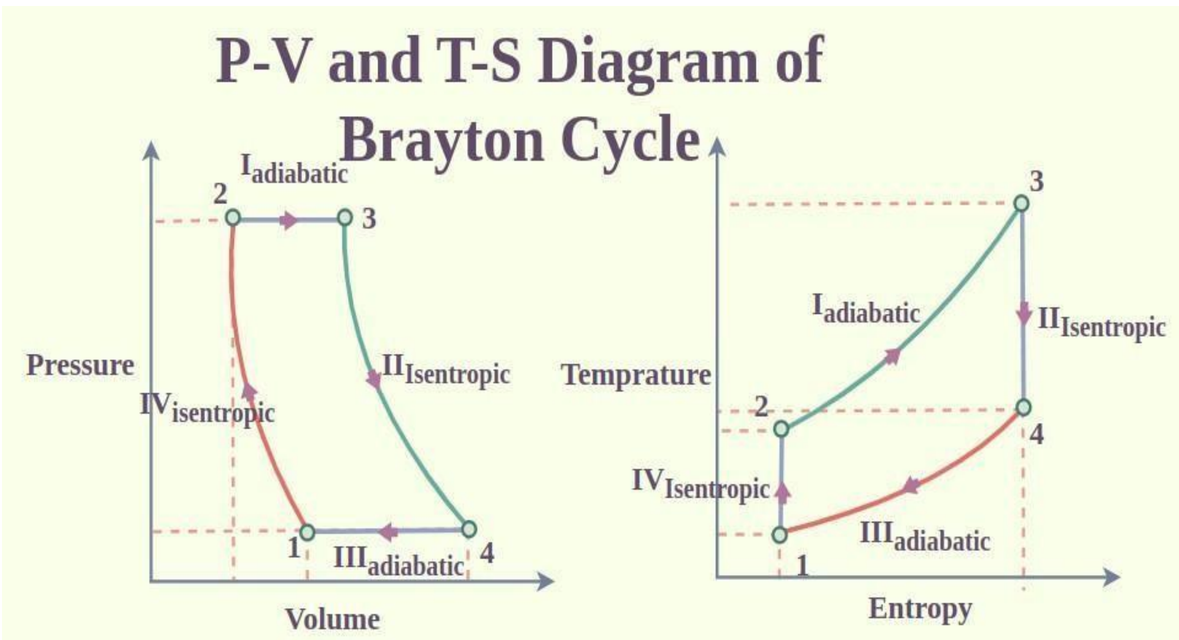

Figure 14 PV and TS diagram of Brayton Cycle [36]

PTES uses a theoretically reversible thermodynamic cycle involving compression and expansion stages with constant pressure heat addition and rejection to hot and cold thermal stores. [9]

Brayton heat pumps and heat engines are used in the Joule–Brayton PTES thermodynamic cycle. Brayton PTES is typically comprised of two thermal storage tanks, two expanders, and two compressors.

In the standard configuration, both heat pumps and heat engines have a single compressor and expander. Reversible machines have also been proposed as a means of reducing costs for Brayton PTES; however, they produce lower performance. Volumetric [24] and dynamic [23] machines are both used in the Brayton PTES.

The adoption of a reversible configuration is more accessible by using volumetric machines. The Brayton cycle requires sensible heat storage to overcome the temperature glide experienced during gas cooling and heating. There are two main configurations [23]: a packed-bed regenerator was proposed by Howes [15]; whereas, Laughlin [25] suggested a two-tank liquid storage system. [9]

It uses a single-phase gas like air or argon and it is equipped with a low and a high pressure and temperature reservoirs. The electricity is stocked as sensible heat in these reservoirs [5]

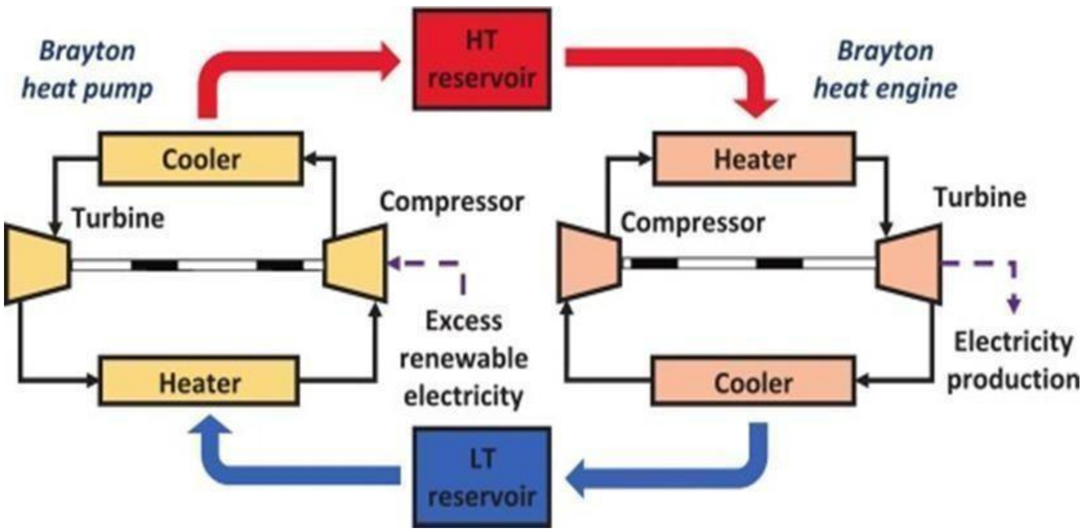

Figure 15 Typical Brayton-based pumped thermal energy storage system [40]

Rankine Cycles

Rankine PTES systems store electrical energy using the Rankine cycle with compressors, expanders, and thermal storage systems. They usually operate at relatively low temperatures and use latent heat storage, liquid sensible heat storage, or both together. Common storage materials include water, thermal oils, ice, and nitrate salts.

These systems are classified into transcritical and subcritical cycles. Transcritical systems commonly use CO_2, while subcritical systems use fluids such as ammonia, water, and organic refrigerants. Organic fluids simplify system design but generally provide lower efficiencies.

Rankine PTES systems typically achieve round-trip efficiencies between 50% and 60%. Although their efficiency is usually lower than Brayton PTES systems, they operate at lower temperatures and may face fewer technical difficulties.

External heat sources such as solar thermal energy, geothermal energy, and industrial waste heat can also be integrated to improve system performance. In addition, the Organic Rankine Cycle (ORC) is considered suitable for low-grade heat recovery because it can convert part of the waste heat into electricity.

The performance of Rankine PTES systems mainly depends on compressor and turbine efficiencies. [9]

II.4 Previous research studies

II.4.1 T. DESRUSE (2010) PTES STUDY

DESRUSE et al. (2010) presented one of the first studies on a Brayton-cycle Pumped Thermal Energy Storage (PTES) system for large-scale electricity storage. During the charging phase, the system operates as a high-temperature heat pump, converting electricity into thermal energy stored in two insulated reservoirs. During discharge, it operates as a heat engine, converting the stored thermal energy back into electricity.

The proposed system consists of Two compressor–turbine pairs, two thermal storage tanks (hot and cold), two heat exchangers, and Argon as the working fluid.

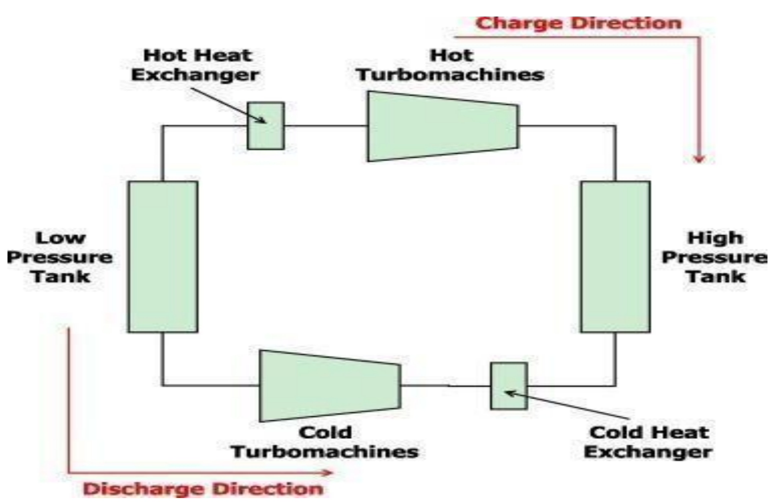

Figure 16 Sketch of the plant scheme proposed by Desrues et al *[5]*

The storage tanks contain refractory material that stores energy as sensible heat. During charging, argon is compressed to 1000°C and 4.6 bar, heating the hot storage from 25°C to 1000°C, while the cold storage is cooled from 500°C to −70°C. The total storage volume is 21,622 m³.

Simulation results showed a storage capacity of approximately 602.6 MWh, a charging time of 6 hours 3 minutes, a discharging time of 5 hours 52 minutes, and a round-trip efficiency of 66.7%. The authors concluded that experimental validation using large-scale storage tanks is necessary to confirm the model predictions. [37]

II.4.2 Howes (2010) PTES Study

Howes developed a Pumped Heat Electricity Storage (PHES/PTES) concept based on the early work of John Ericsson (1833). The proposed system is similar to the Brayton-cycle PTES of Desrues et al., but it uses reciprocating compressors and expanders instead of turbomachinery.

The study first analyzed the thermodynamics of an ideal heat pump and then built several prototypes to investigate pressure losses in valves and heat transfer during compression and expansion. A unique feature of the design was the integration of heat exchangers directly into the piston of the reciprocating machine.

Although the first prototype showed poor performance, additional prototypes were developed to better understand system losses. Based on these experimental results, Howes proposed a commercial-scale PTES system. [38]

Parameter	**Value**
Thermodynamic Cycle	Brayton-based
Compressor/Expander Type	Reciprocating machines
Working Fluid	Argon
Power Output	2 MW
Storage Capacity	16 MWh
Mass Flow Rate	12.56 kg/s
Hot Storage Temperature	500°C
Hot Storage Pressure	12.13 bar
Cold Storage Temperature	−166°C
Cold Storage Pressure	1.0135 bar
Machine Configuration	Four-cylinder machine
Compression/Expansion Stages	Two stages
Estimated Footprint	17 m × 7 m

Table 2 Key Specifications of the PTES System Proposed by Howes*[38]*

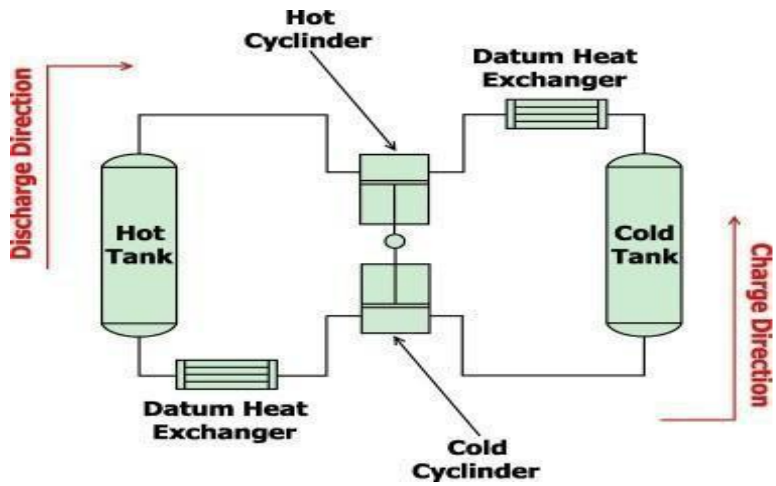

Figure 17 Simplified sketch of the plant scheme proposed by Howes *[5]*

Howes concluded that pumped heat energy storage has significant potential as a low-cost and efficient large-scale energy storage technology. [5]

II.4.3 White et al. Studies (2011)

White [74] investigated the thermal and pressure losses occurring in the packed-bed thermal storage reservoirs of a PTES system.

The system used argon as the working fluid and gravel-packed beds as sensible heat storage media.

The hot and cold storage temperatures were 773 K and 123 K, respectively. The study showed that although thermal and pressure losses exist due to irreversible heat transfer and friction, their magnitude is relatively small and does not prevent the practical integration of thermal storage into PTES systems.

Building on this work, White et al. [75] performed a thermodynamic analysis of the complete PTES system to identify the main sources of irreversibility and their effects on round-trip efficiency, energy density, and power density.

Their results indicated that increasing the compressor temperature ratio improves both efficiency and storage density, but requires higher pressure ratios and therefore more expensive storage vessels.

The study also found that reciprocating compressors and expanders can achieve higher efficiencies than turbomachinery-based devices. Furthermore, reducing the temperature difference between the hot and cold reservoirs during discharge can decrease irreversibility losses and enhance both power and energy density. [5]

II.4.4 .d Study by Ebrahimi and HOUSHFAR (2026)

Ebrahimi and HOUSHFAR performed a comprehensive techno-economic analysis of a large-scale Pumped Thermal Energy Storage (PTES) system. The objective was to evaluate the influence of storage temperature, thermal storage medium, climate conditions, and system size on the round-trip efficiency (RTE) and levelized cost of storage (LCOS). [7]

Parameter	Value
Cycle Configuration	Recuperated Closed Brayton Cycle
Working Fluid	Nitrogen (N_2)
Storage Method	Sensible Heat Storage
Storage Configuration	Two-tank thermal storage
Storage Medium	Li_2CO_3–Na_2CO_3–K_2CO_3 molten salt
Power Capacity	300 MW
Energy Capacity	3000 MWh
Charging Time	8 h
Discharging Time	10 h
Operating Temperature Range	417–794 °C
Maximum Storage Temperature	794 °C
Plant Lifetime	30 years
Discount Rate	5%
Optimization Method	Genetic Algorithm (GA)
Climate Scenarios	Montreal (Canada) and Phoenix (USA)

Table 3 System Configuration and Operating Parameters *[7]*

Parameter	Value
Optimal Storage Medium	Li_2CO_3–Na_2CO_3–K_2CO_3 molten salt
Round-Trip Efficiency (RTE)	73.3 %
Levelized Cost of Storage (LCOS)	0.146 $/kWh
Charge Pressure Ratio	1.77
Discharge Pressure Ratio	2.00
Capital Cost (Montreal)	1.20 B$
Capital Cost (Phoenix)	1.65 B$
RTE in Montreal	73.3 %
RTE in Phoenix	70.71 %
LCOS in Montreal	0.146 $/kWh
LCOS in Phoenix	0.181 $/kWh

Table 4 Main Technical and Economic Results *[7]*

It was determined through this study that the principal factors influencing PTES efficiency are climate conditions, system size, storage medium temperature, and environmental conditions during storage.

Among the 24 different storage materials evaluated, the Li_2CO_3–Na_2CO_3–K_2CO_3 molten salt mixture produced the best results, achieving a round-trip efficiency (RTE) of 73.3% and a levelized cost of storage (LCOS) of $0.146/kWh.

Systems located in colder climates performed better than those in warmer climates, while systems implemented at larger plant capacities exhibited a significant reduction in storage costs.

As a result, PTES represents an attractive and commercially viable option for large-scale, long-duration energy storage and the integration of renewable energy sources [7]

II.5 Conclusion

This chapter presented the fundamental concepts of energy storage technologies and highlighted the increasing importance of Pumped Thermal Energy Storage (PTES) as a promising solution for large-scale, long-duration energy storage.

The core operating principles, key components, different thermodynamic cycles, performance indicators, and economic aspects of PTES were presented and discussed.

Previous studies reviewed in this chapter demonstrated that PTES development, combined with economic analysis, is both technically feasible and economically viable for renewable energy-integrated systems.

Therefore, based on this review, PTES can be considered a flexible and sustainable energy storage technology with significant potential for future application in power systems.

The knowledge presented in this chapter provides the foundation for the system modeling, simulations, and analyses carried out in the subsequent chapters.

Chapter III

System Description and Thermodynamic Modeling

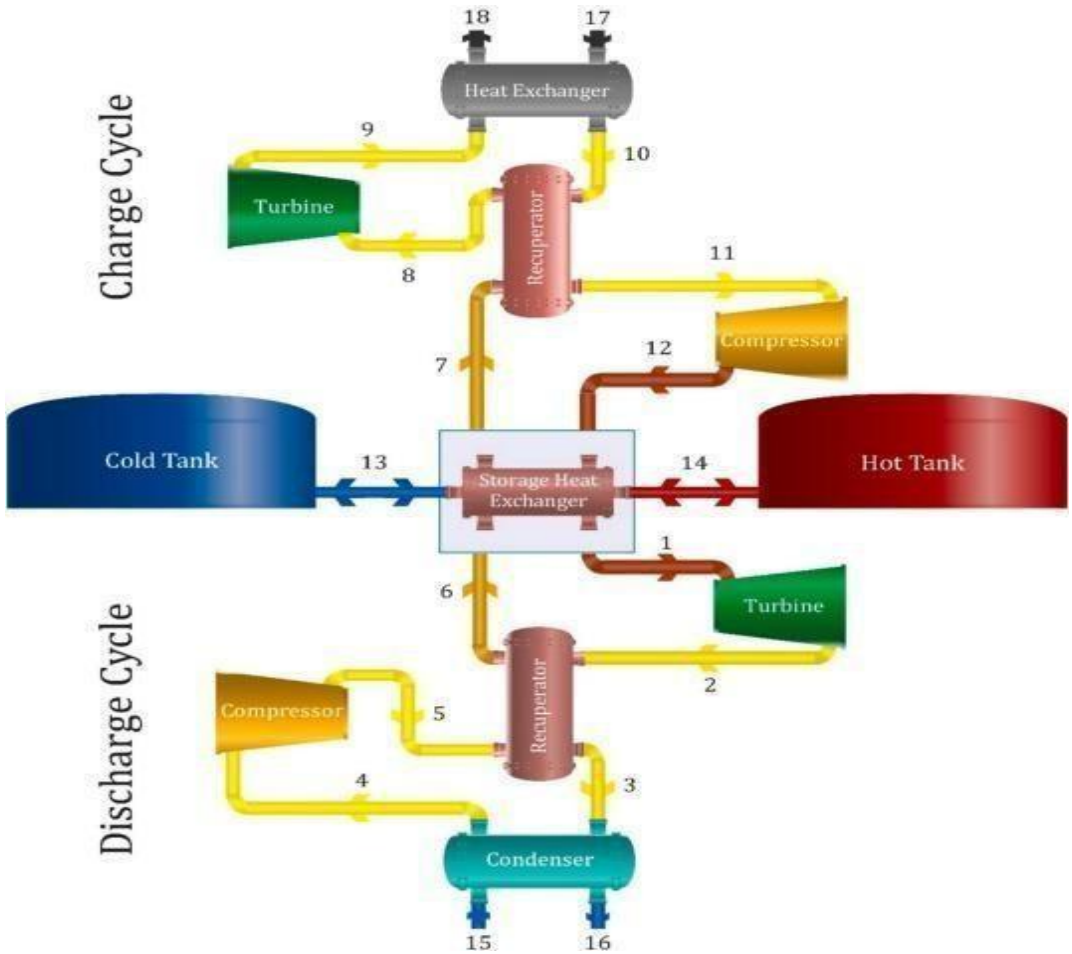

Figure 1 Schematic layout of the designed pumped thermal energy storage (PTES) plant.*[7]*

III.1 Introduction

This chapter presents the system description and thermodynamic modeling of the proposed Pumped Thermal Energy Storage (PTES) system. A schematic layout of the system is shown in **Figure III-1**, illustrating the main components and the energy flow during both the charging and discharging processes.

The first section of this chapter describes the operating principle of the Brayton-cycle PTES system. The following sections discuss the working fluid, thermal energy storage materials, storage tanks, and the key operating parameters affecting system performance. Subsequently, the major sources of energy losses within the system are identified and analyzed.

Finally, a thermodynamic model based on the principles of mass and energy conservation is developed to evaluate the performance of the PTES system and to provide the foundation for the simulation and analysis presented in the following chapter.

III.2 Operating Principle of PTES

In a PTES system, the off-peak electricity is converted into heat using a high temperature heat pump and stores in two man-made tanks. This process is called "storing phase". Then, the conversion of the stored heat into electricity is done by means of a heat engine. This phase is usually called "delivering" or "discharging" phase [5]

A simplified layout of the PTES system during the charging phase running on a standard Brayton cycle is shown in Fig. 7[8]

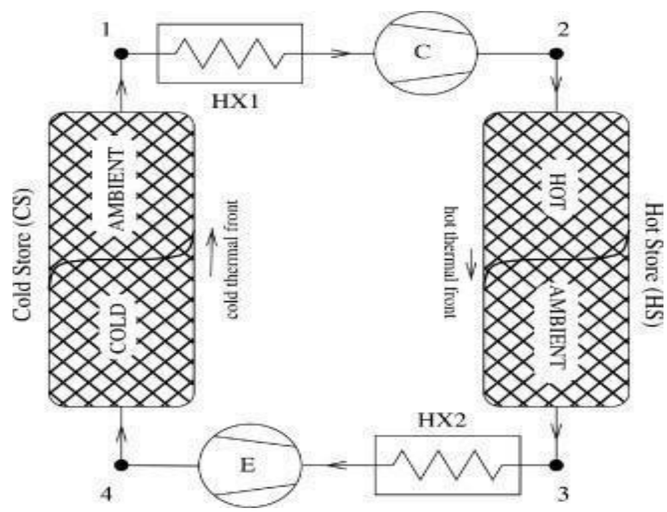

Figure 2 Schematic of a Brayton cycle*[8]*

This section describes the charging and discharging process of PTES using Argon as working fluid.

III.2.1 Charging Cycle

During charging, the working fluid (Argon), at temperature T1, is compressed through process 1 – 2 (isentropic compression) and exits the compressor at high temperature, T2.

The gas loses heat to the storage material as it moves through the hot storage tank HS in process 2 – 3 (isobaric heat rejection) and drops to temperature T3.

The hot and cold fronts gradually progress in the direction of the fluid flow.

The gas is then expanded in process 3 – 4 (isentropic expansion) and attains the initial stage temperature, T1, as it gains heat after passing through the cold storage tank CS in process 4 – 1 (isobaric heat addition). [8]

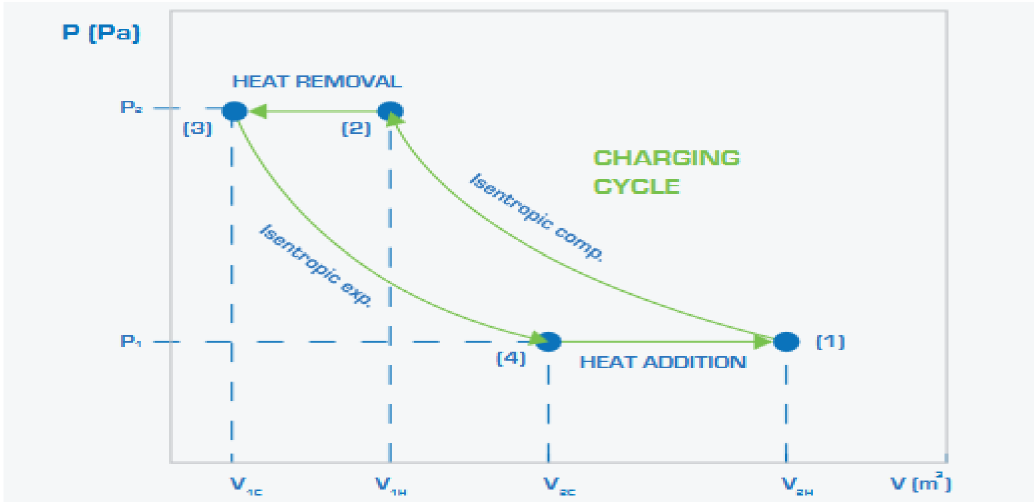

Figure 3 Illustration: charging cycle *[39]*

III.2.2 Discharging Cycle

Discharging – To recover the power, the gas flow is simply reversed.

Argon at ambient temperature and pressure enters the cold tank (1) and flows slowly down through it, warming the particulate and therefore becoming cold.

It leaves the bottom of the tank at -160 °C (4) and enters the compressor. It is compressed to 12 bars, heating back up to ambient temperature (3).

It then enters the bottom of the hot tank.

It flows up, cooling the particulate and warming to +500 °C (2). The hot pressurized gas then enters the expander where it gives up its energy, producing work which drives the motor/generator to return to (1).[39]

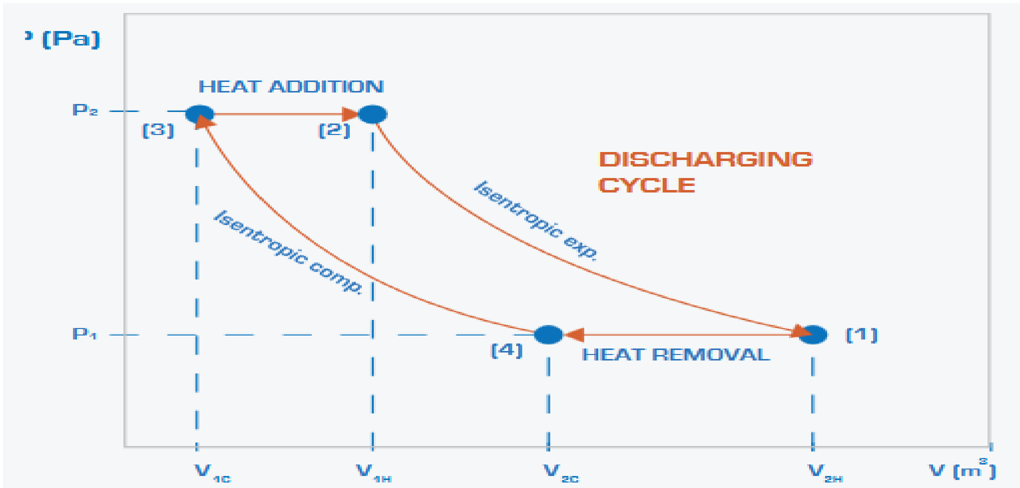

Figure 4 Illustration: charging cycle *[39]*

III.3 PTES Components and Operating Parameters

III.3.1 Working Fluid

The selection of working fluids is a critical focus in PTES research. Zhao et al. [27] highlighted that the primary criterion for initial working fluid selection in PTES is the compatibility of the fluid's physical properties with the operating cycle.

A variety of working fluid have been studied for PTES applications, including Air, Argon, N_2, He, CO_2.[40]

Brayton cycles commonly use argon, nitrogen, helium, and air due to their critical temperatures being far below ambient conditions. In contrast, carbon dioxide, with a critical temperature slightly above ambient, is often used in transcritical Rankine cycles. [40]

Working fluid	Cycle operation	Efficiency (%)
Argon	Brayton cycle	41.99
Argon	Brayton cycle	<72
N_2	Brayton cycle	65
N_2	Brayton cycle	67.05
Air	Brayton cycle	61.48
He	Brayton cycle	54.5
He	Brayton cycle	64.9
CO_2	Brayton cycle	62.83
CO_2	Rankine cycle	69.28
CO_2	Transcritical cycle	63.4

Table 1 Performance of Different working fluid in PTES systems By different references*[40]*

In Addition, several have been conducted to investigate and identify the most promising working fluids for Pumped Thermal Energy Storage systems. The selection of the working fluid plays a crucial role in thermodynamic performance, round-trip efficiency, operating temperature range and the levelized cost of storage (LCOS) [41]

The fluid selection broadly influences several system aspects, such as the thermodynamic cycle, the first law efficiency, the components cost (especially the turbine and heat exchangers), the heat transfer process, the plant configuration, safety issues, and environ- mental restrictions.[42]

Recent studies have highlighted the growing potential of Pumped Thermal Energy Storage (PTES) systems for large-scale energy storage applications.

Chai and Tassou (2025) reviewed CO_2-based PTES technologies and reported that trans-critical CO_2 Rankine cycles can achieve round-trip efficiencies of up to 74.5%, outperforming supercritical CO_2 Brayton cycles due to better thermal matching with storage media, although significant technical challenges remain before commercialization.

Tafur-Escanta et al. (2025) demonstrated that replacing pure supercritical CO_2 with CO_2-based mixtures can improve both technical and economic performance, with the CO_2/Kr mixture achieving the highest round-trip efficiency (59.7%) and the CO_2/Xe mixture providing the lowest storage cost (138.26 $/MWh).

Furthermore, Hu et al. (2025) investigated a recuperated Brayton PTES system with staged compressors and found that helium was the most effective working fluid because of its lower pressure losses. Their integrated compression PTES configuration improved round-trip efficiency by 9.58% and increased energy density by 2.07 kWh/m³ compared with conventional PTES systems. Collectively, these studies demonstrate that the selection of working fluids, cycle configurations, and system components plays a crucial role in enhancing PTES efficiency, energy density, and economic viability. [17] [41] [43]

III.3.2 Thermal Energy Storage Material

TES systems store heat in three main forms, sensible heat storage (SHS), latent heat storage (LHS), and thermochemical storage (TCS) [97,98]. Each of these categories offers distinct advantages in terms of energy density, efficiency, and discharge duration [99].[15]

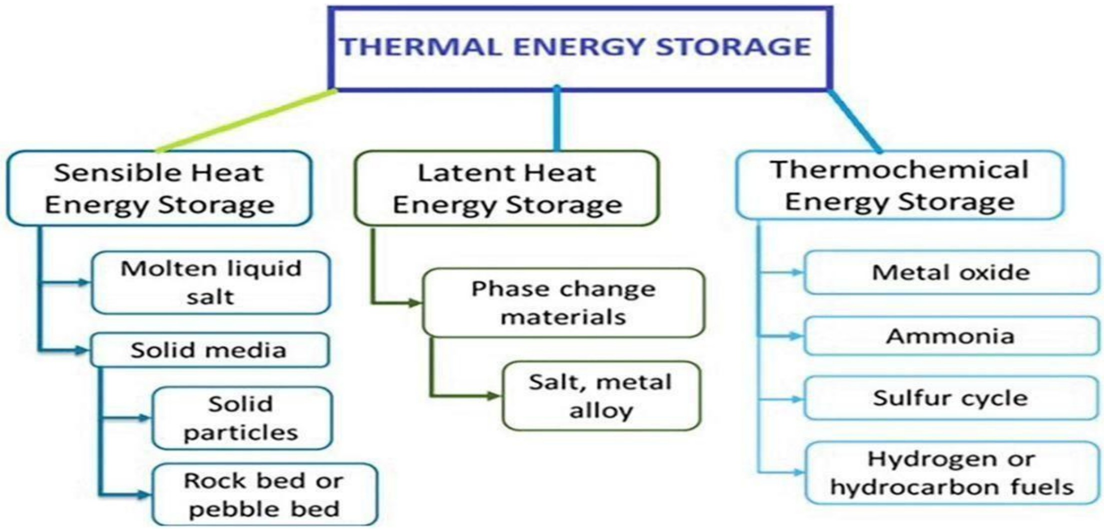

Figure 5 TES classification*[44]*

The selection of the storage system depends on the application.

In PTES systems, electricity is Stored in the form of thermal energy which requires heat to be retrievable for employing charging and discharging cycles. [8]

The heat can be stored in the form of sensible or latent heat [54], [55].

In the first case, the thermal energy is stored in the change of the storage medium temperature consequences of a variation in the internal energy while, in latent heat storage, the thermal energy is stored as the phase change latent heat of some media. Solid or liquid media are usually good for sensible heat storage while media able to change the phase from solid to liquid or from liquid to vapor are suitable for latent heat storage.

Sensible heat storage which employs solid media like concrete, rocks or sand is the most inexpensive, safety and easy way to store thermal energy. For this reason, in literature a large number of studies on this topic can be found.[5]

III.3.2.a Sensible heat thermal storage systems

Thermal energy storage has been studied for more than four decades and the number of materials available today for thermal storage is higher than 150,000 [46].

The materials store thermal energy in the form of sensible heat without undergoing any phase change. For efficient utilization, the material needs to have a high energy density, high thermal conductivity, high thermal diffusivity for quick charging and discharging, and low cost [46,47].

BENATO et al. [48] studied nine different materials for packed-bed storage: aluminum oxide (Al_2O_3), copper (Cu), Hematite (Fe_2O_3), magnetite (Fe_3O_4), Silicon dioxide (SiO_2), Titanium Dioxide (TiO_2), Concrete, Limestone and Masonry brick material.

Copper spheres provide higher energy density compared to concrete, limestone, or masonry but also require longer charging duration. Material selection depends on several factors such as storage temperature, delivery time, power requirements. [8]

III.3.2.b Latent heat thermal storage systems

Latent heat storage (LHS) systems utilize phase change materials which absorb or release heat at a constant temperature while undergoing phase change [52,53].

Compared to sensible heat systems, LHS systems provide higher energy density per unit mass and per unit volume [54].

Phase change materials are available for operation in a wide range of temperatures depending on their composition. Phase change materials may be organic, non-organic, or eutectic mixtures and the utilization depends on the application.[8]

- Note that sensible heat storage is the most simple and inexpensive way to store thermal energy[45]

At present, for pumped thermal electricity storage based on the Joule-Brayton cycle, packed beds filled with sensible heat storage media are widely adopted as the thermal store,[46]

The selection of the packed bed material is a complicate task and, to the Authors knowledge, no one has performed an in-depth analysis. [45]

Sensible thermal energy Storage (STES) systems entail the increment of the internal energy of the storage material using a heat source carried by a heat transfer fluid (HTF) , which raises the temperature of the storage material.

STES systems have been used in several applications ranging from 120 °C to 1250 °C.

Moreover, STES systems can be divided into three main categories:

(1) Those that operate using high-temperature working fluids as direct storage media,

(2) Systems that use a solid storage material that is heated using an intermediate fluid

(3) Processes that transfer heat from one fluid to another through a third storage material.

-Molten Salt

Molten salts are becoming increasingly important in the sustainable energy sector, particularly in storing thermal energy in concentrating solar power plants (CSP). They have desirable properties as heat transfer media, such as high operating temperatures with high thermal stability, high density, high heat capacity, and low vapor pressure. [47]

The most common salt mixture (MS) is the so-called solar salt, a binary mixture of potassium and sodium nitrate (60%NaNO + 40%KNO) which has a limited range of operating temperatures (Table 1). Desirable characteristics for new HTFs are higher thermal stability, lower melting point, and better specific heat and density. These aspects are highly determinants of the TES energy density, heat transfer rate and system size [48]

-Packed-bed System

Packed-bed systems have been tested using concrete, natural rock, and compound materials, among other alternatives for the solid matrix.

Recently, the use of waste from the steel making and mining industries as filler materials in packed-beds has been analyzed.

The goal is to reduce the investment cost inherently involved in two-tank molten salts designs, which are commonly used in concentrated solar power systems.[49]

As shown in **Figure-11**, for packed-bed heat storage, all heat transfer mechanisms apply among the solid particles, the tank walls, and the fluid.

During charge operation, the hot fluid enters through the top of the tank and transfers heat to the solid material, accumulating energy as sensible internal energy.

During the discharge process, when the demand is higher than the power generated directly by the plant, the cold fluid goes to the bottom of the tank to obtain heat from the solid that will be used by the demand block [9]. [49]

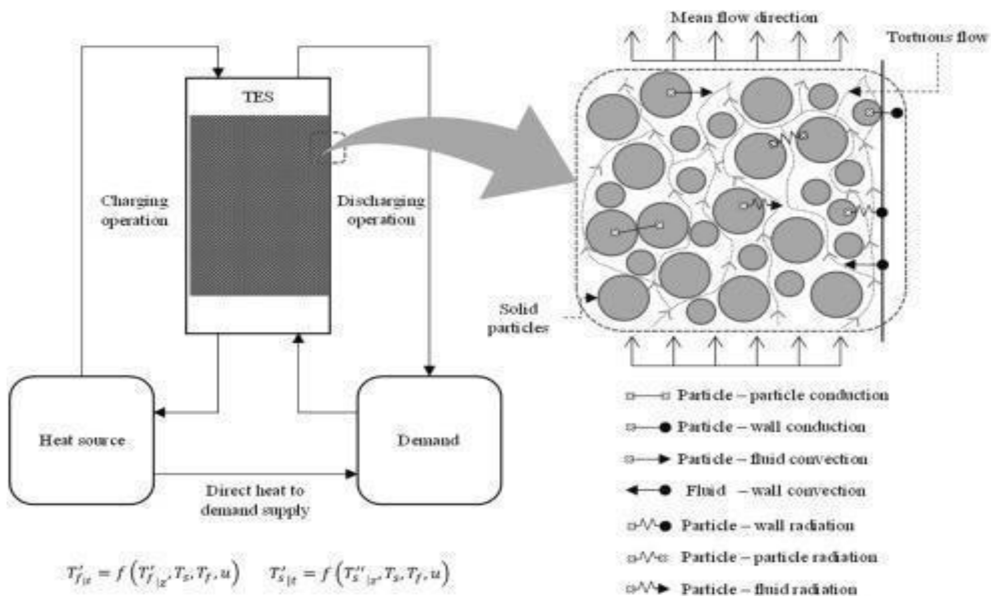

Figure 6 General scheme of a solid thermal energy storage system and internal heat transfer mechanisms.*[49]*

A number of operating, material and other parameters can influence the charging and discharging performance of energy storage systems.

Experimental evidence has demonstrated that the parameters affecting charging behavior are initial thermal stratification within the storage medium, control of charging temperature, and operating conditions during the charging process. [49]

In addition, thermal properties of the material used for energy storage have a particularly significant impact on both how much total energy can be stored, and the rate of increase in temperature when charging occurs. Increasing the density of a material, as well as the amount of heat added (specific heat capacity), increases the total amount of energy stored; however, this will decrease the rate that temperature increases at the time of charging.

On the other hand, an increase in the thermal conductivity of the storage material results in faster heat transfer and higher charging rates, therefore increasing the effectiveness of energy storage. [49]

III.3.3 Storage Tank

A more widely used configuration of the PTES system utilizes two separate tanks for hot and cold storages [27,29,31,32]. The reversible heat pump and heat engine cycles work between hot storage (HS) temperature, , and cold storage (CS) temperature, . A simplified layout of the PTES configuration involving a hot storage tank and a cold storage tank running on a standard Joule-Brayton cycle is shown in **Figure-12** [8]

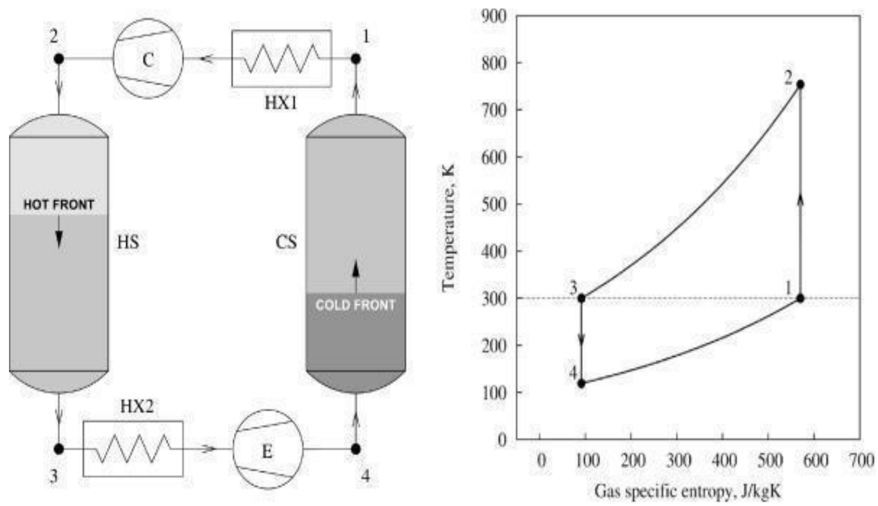

Figure 7 Layout of a two-tank Brayton PTES system during charging cycle by White et al [8]

They are designed to live up to the standards needed for the hot tank, i.e., the two tanks are identical in terms of design characteristics.

This is because the cold tank may be used as the hot tank in an emergency [33]. **Fig. 12** demonstrates a layout of the designed tanks. [7]

The tanks have a cylindrical form with a spherical cap. The tanks are erected on a refractory brick foundation [34].

The material of the tanks is varied according to the maximum temperature. This is applied to mitigate the corrosion effect caused by the storage medium.

The materials from which tanks are manufactured are presented in Table 2 [13]. The tanks are insulated to minimize heat loss during the standby and discharging phases.[7]

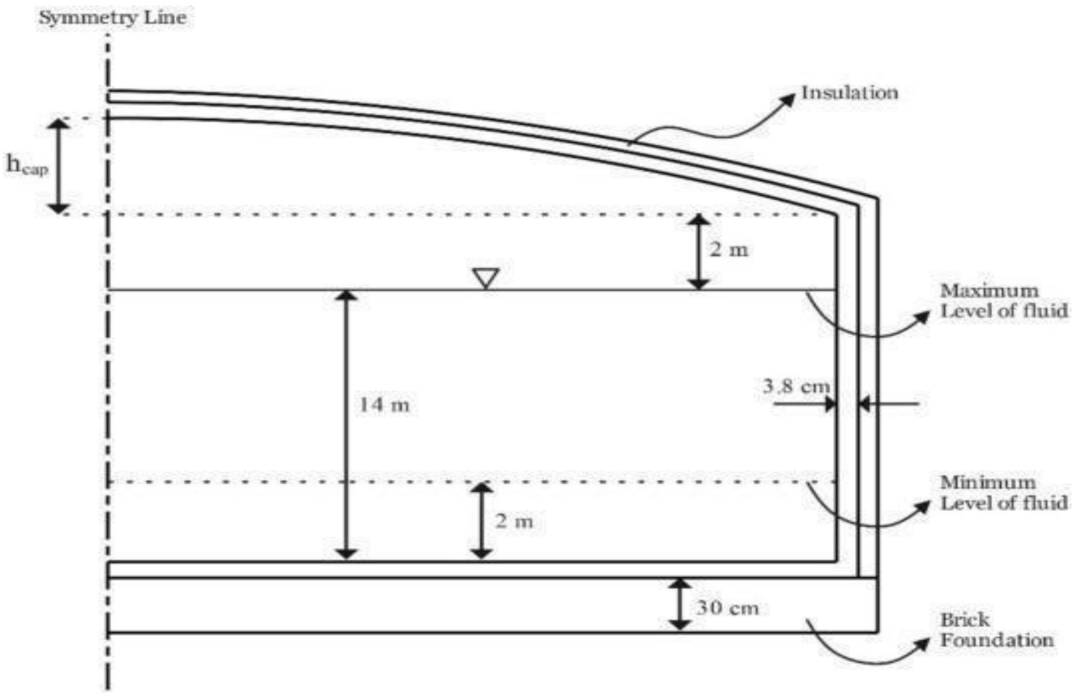

Figure 8 Schematic representation of the storage tank geometries and specifications.[7]

Temperature range	Material
***T* ≤ 400 °C**	Carbon Steel
400 °C < *T* ≤ 600 °C	Stainless Steel
600 °C < *T*	Inconel 600 (nickel alloy)

Table 2 Materials used for tank construction categorized by operating temperature.*[7]*

When designing a PTES system with liquid tanks, a balance must be struck between the performance of

the thermodynamic cycles, the suitability and cost of the storage fluids, and practical engineering

implications.

For instance, thermodynamic analysis of PTES typically suggests that hot storage temperatures should be maximized, and cold storage temperatures should be minimized.

However, the cost of heat exchangers, pipework and (externally insulated) storage vessels increase substantially if stainless steels or nickel alloys have to be used, which occurs above 400°C and 600°C, respectively. [35]

III.4 Detailed loss Analysis

The aim of this section is to describe the various sources of loss and provide preliminary estimates of their impact on round-trip efficiency. Several of the loss parameters (for example, the compression and expansion efficiencies for reciprocating devices) are difficult to specify with great certainty at this stage. The approach adopted here is therefore to determine the sensitivity of the round-trip efficiency to these loss parameters. The chief sources of loss are as follows:

- Electrical and mechanical losses. It is worth noting that electrical/mechanical energy conversion can be achieved very efficiently; $\eta e \geq 97\%$ is not unreasonable for large devices. Mechanical losses are more uncertain and are likely to be greater for reciprocating devices than for turbomachinery. In total, electrical and mechanical losses might reduce the round-trip efficiency by 10% or more.
- Compression and expansion losses. For turbomachinery this stem chiefly from viscous effects and are quantified here by specifying a polytropic (infinitesimal stage) efficiency. In the case of reciprocating devices, compression and expansion occur relatively slowly such that there may be significant heat transfer with the cylinder walls. It is important to distinguish between net heat exchange with the surroundings and the periodic exchange to and from the walls which, although globally adiabatic, is an irreversible process and incurs an entropy rise.
- Pressure losses. These occur through piping, valves (as described above), diffusers (especially for turbomachinery) and through the hot and cold reservoirs. In terms of impact on the round-trip efficiency, it is the fractional pressure loss, $f= \Delta p/p$, in each device that is most relevant since this is proportional to the entropy increase and hence to the lost work. Individual values of f are expected to be small and so can be summed to give an overall pressure loss factor F.
- Thermal reservoir losses. Aside from pressure losses, there are two other loss mechanisms within the thermal stores. Firstly, heat exchange with the exterior means that the available energy stored within each reservoir is depleted with time. This is quantified by specifying an energy loss factor, ε, defined below. Secondly, the process of heat transfer between the gas and storage medium requires a finite temperature difference and thus incurs a net entropy increase. The associated losses are quite complex and depend on the mode of operation of the storage system (e.g., regular periodic cycling or long-term storage). [29]

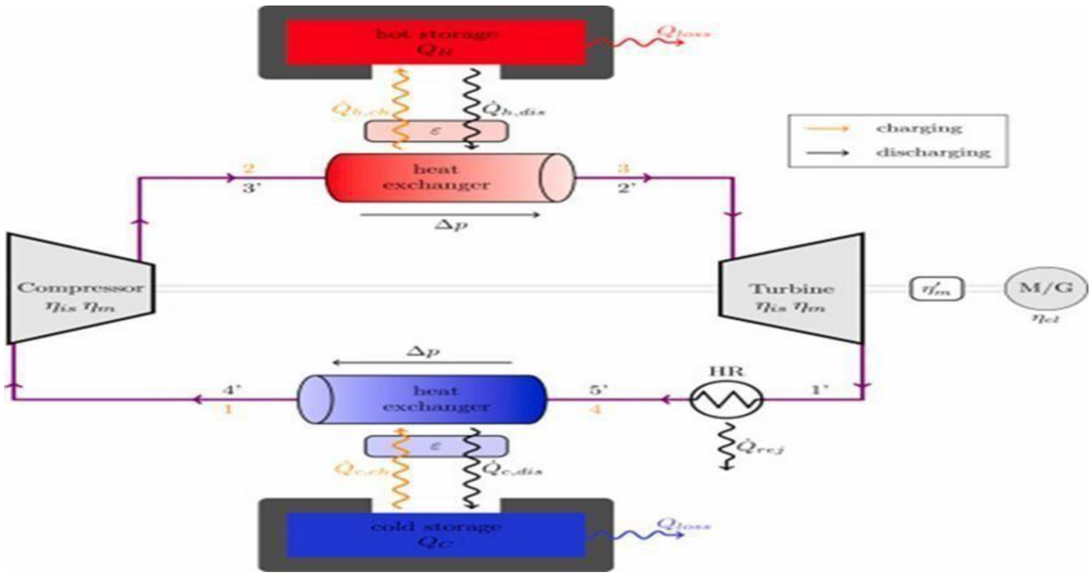

Figure 9 Simplified schematic of the model with the considered loss factors[19]

III.5 Thermodynamic Modelling

Thermodynamic modeling of the PTES system uses mass and energy balance equations for each component to determine their thermodynamic states during the charging and discharging processes.

The thermodynamic model associated with the proposed PTES (Pumped Thermal Energy Storage) system is developed in accordance with the principles of mass and energy conservation.

The model describes the charging and discharging cycles, as well as the state of the working fluid throughout the cycle. The working fluid is assumed to behave as an ideal gas and operates under steady-state conditions.

The compressor and expander are modeled using constant isentropic efficiencies to represent irreversibility's, while pressure losses in the connecting pipes are neglected.

Thermal energy is stored as sensible heat in the hot and cold reservoirs.

This model provides a basis for evaluating parameters such as pressure, temperature, enthalpy, heat transfer, and work interactions and is therefore valuable for determining the overall performance of the system.

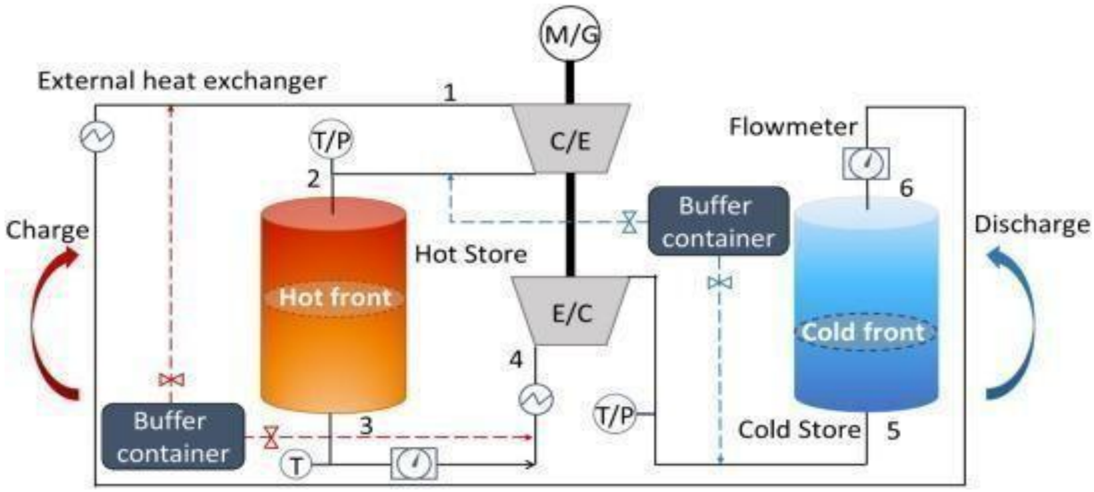

Figure 10 Diagram of the newly developed PTES system.*[46]*

III.5.1 Mass Balance

The Mass Balance for a PTES (Phase Transition Energy Storage) System (in a closed-loop process) guarantees that the working fluid (e.g., Argon or Nitrogen) will be returned to its original location after going through an entire operational cycle. The fundamental equation of mass balance in all control volumes (or components) is:

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out} \qquad 3$$

III.5.2 Energy Balance

Each component's energy performance in a Pumped Thermal Energy Storage (PTES) system is evaluated by means of the steady state energy balance equation. According to thermodynamics' First Law, energy entering and exiting a control volume must be in balance. A system component's general energy balance can be described as

$$\dot{Q}_{in} - \dot{W}_{t,out} + \dot{m}_i h_i - \dot{m}_o h_o = 0 \qquad 4$$

where $\dot{Q}_{in}$ is the rate of heat input to the system, $\dot{W}_{t,out}$ is the rate of the work output to generate electricity, h_i and h_o are the inlet and outlet specific enthalpy, respectively. [46]

III.5.3 Hot and cold reservoirs

The energy storage processes inside the reservoirs satisfy the following relation:

$$\dot{Q}_{Total} = \dot{Q}_{Reservoir} \qquad 5$$

where Q_{Total} is the heat transfer rate of the working fluid to storage medium, $Q_{Reservoir}$ is the energy storage rate of Storage medium in the hot/cold reservoirs.

The heat transfer rate of the working fluid to the storage medium can be expressed as:

$$\dot{Q}_{Reservour} = \dot{m} c_{p,fluid}(T_{fluid,in} - T_{fluid,out}) \qquad 6$$

Where $T_{fluid,in}$ and $T_{fluid,out}$ are the temperature of the working fluid at the inlet and outlet of the reservoirs, respectively. The energy storage rate of the storage medium in the hot/cold reservoirs can be expressed as:

$$\dot{Q}_{Reservoir} = \frac{dQ_{Reservoir}}{dt} \qquad 7$$

$$Q_{\text{Reservoir}} = m_s\, c_{p,s}\, \Delta T \qquad 8$$

The total energy stored in the system is the difference between the energy stored in the hot reservoir and that stored in the cold reservoir:

$$Q_{Stored} = Q_{HR} - Q_{CR} \qquad 9$$

III.5.4 Compressor and expander

The compression process is assumed to be irreversible with ηc and βc being the isentropic efficiency and the compression ratio, respectively. The pressure and temperature of the working fluid after a polytropic process at the outlet of the compressor can be obtained by

$$p_2 = \beta_c p_1 \qquad 10$$

$$T_2 = T_1 \beta_c^{(\kappa-1)/\kappa} / \eta_c \qquad 11$$

Then, the enthalpy of the working fluid at the outlet of the compressor during the charging process can be calculated by

$$h_2 = \frac{h_2^{is} - h_1}{\eta_c} + h_1 \qquad 12$$

where the subscripts 1 and 2 represent the inlet and outlet of the compressor as shown in **Fig-10**, thus the rate of work input to the compressor according to the energy balance process is

$$\dot{W}_{in} = \dot{m}_c (h_2 - h_1) = \dot{m}_c \frac{h_{2}^{is} - h_1}{\eta_c} \qquad 13$$

where the subscripts 1 and 2 represent the inlet and outlet of the compressor as shown in Fig. 1, thus the rate of work input to the compressor according to the energy balance process is

$$\dot{W}_{in} = \dot{m}_c (h_2 - h_1) = \dot{m}_c \frac{h_{2}^{is} - h_1}{\eta_c} \qquad 14$$

Similarly, the pressure and temperature of the expansion process with **ηe** and **βe** being the isentropic efficiency and the expansion ratio, respectively, at the outlet of the expander can be obtained by

$$p_5 = \frac{p_4}{\beta_e} \qquad 15$$

$$T_5 = T_4 \left(\frac{1}{\beta_e}\right)^{(\kappa-1)/\kappa\, \eta_e} \qquad 16$$

and the enthalpy of the working fluid at the outlet of the expander during the discharging process can be calculated by

$$h_5 = h_4 - \eta_e (h_4 - h_5^{is}) \qquad 17$$

where the subscripts 4 and 5 represent the inlet and outlet of the expander, respectively. Thus, the rate of work output from the expander according to the energy balance process is given by:

$$\dot{W}_{out} = \dot{m}_e (h_4 - h_5) = \dot{m}_e \eta_e (h_4 - h_5^{is}) \qquad 18$$

The total power generated during the discharging process can be expressed as:

$$\dot{W}_{gen,dis} = \dot{m}_{dis}(h_2 - h_1 + h_5 - h_4)_{dis} \qquad 19$$

III.5.5 Heat Exchanger

The heat released to the environment after the working fluid passes through the heat exchanger can be calculated as:

$$\dot{Q}_{HE} = \dot{m}(h_{fluid,out} - h_{fluid,in}) \qquad 20$$ [46], [52], [53]

III.6 Conclusion

This chapter detailed the construction, operation, and functioning of the proposed Pumped Thermal Energy Storage (PTES) system.

The charging and discharging processes of the system, along with its main components and their respective functions (energy conversion and energy storage), were explained.

An evaluation of various thermal energy storage media and systems was presented, with particular emphasis on the practical application of sensible heat storage in PTES systems.

The characteristics of packed-bed thermal energy storage systems, thermal energy storage tanks, and the main factors contributing to thermal energy losses were also discussed.

Finally, a thermodynamic model of the proposed system was established through the application of the principles of mass and energy conservation. This model provides the theoretical foundation for the simulation and performance evaluation presented in the next chapter.

Chapter IV
Techno-Economic Analysis Using SAM-Simulation

IV.1 Introduction

The energy system has become increasingly complex with the introduction of new technologies and energy sources.

To optimize the design and operation of energy systems, simulators have become an indispensable tool for engineers and decision-makers.

IV.2 Softwire Overview

IV.2.1 SAM

The System Advisor Model™ (SAM™) is a free desktop application for techno-economic analysis of energy technologies. It is used by project managers and engineers, policy analysts, technology developers, and researchers to investigate questions about the technical, economic, and financial feasibility of power generation projects. [54]

-SAM can model many types of power generation systems:

• Photovoltaic systems, from small residential rooftop to large utility-scale systems

• Battery storage with Lithium ion, lead acid, or flow batteries for front-of-meter or behind-the-meter applications

• Concentrating Solar Power systems for electric power generation, including parabolic trough, power tower, and linear Fresnel

• Industrial process heat from parabolic trough and linear Fresnel systems

• Wind power, from individual turbines to large wind farms

• Marine energy wave and tidal systems

• Solar water heating

• Fuel cells

• Geothermal power generation

• Biomass combustion for power generation

• High concentration photovoltaic systems[54]

-SAM's financial models are for the following types of projects:

- Residential and commercial projects where the power generation system is on the customer side of the electric utility meter (behind the meter), and power from the system is used to reduce the customer's electricity bill.
- Power purchase agreement (PPA) projects where the system is connected to the grid at an interconnection point, and the project earns revenue through power sales. The project may be owned and operated by a single owner or by a partnership involving a flip or leaseback arrangement.
- Third party ownership where the system is installed on the customer's (host) property and owned by a separate entity (developer), and the host is compensated for power generated by the system through either a PPA or lease agreement.[54]

IV.2.2 Key Reasons for Using SAM

1. Comprehensive Project Analysis: SAM simulates both technical performance (hourly energy output) and financial viability (cash flows, tax credits, incentives) for projects.
2. Wide Range of Technologies: It models solar PV (rooftop to utility-scale), concentrating solar power (CSP), battery storage, wind, geothermal, biomass, and hybrid systems.
3. Decision-Making Tool: It helps project developers, engineers, and researchers analyze site-specific data, such as weather and electricity rates, to optimize design and maximize earnings.
4. Financial Flexibility: SAM handles both behind-the-meter (residential/commercial) and front-of-meter (power purchase agreement) financial structures.
5. Free and Open-Source: As a publicly accessible tool provided by the U.S. Department of Energy, it serves as a standardized industry benchmark

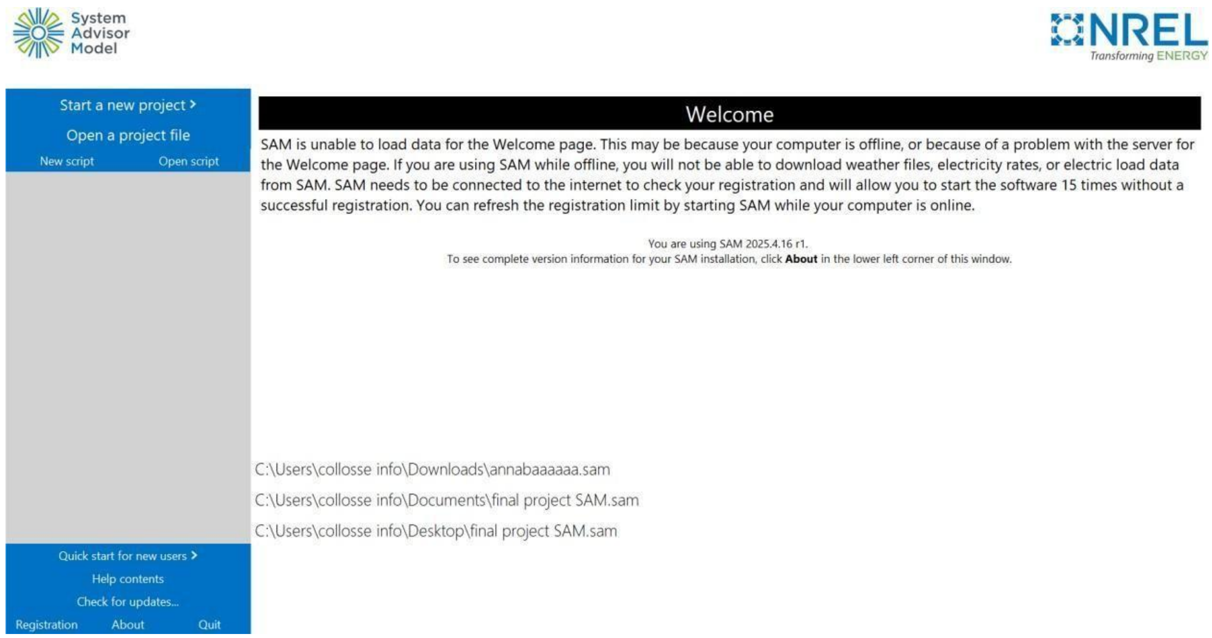

Figure 1 SAM Homepage

IV.3 Simulation

Before starting the simulation of the proposed PTES system, it is important to note that the PTES model contained within SAM is a lumped-cycle model applicable to Pumped Thermal Energy Storage systems employing a Joule–Brayton (Brayton) cycle.

Therefore, individual parameters of system components, such as the pressure ratio or isentropic efficiency of turbines and compressors, are not accessible to the user.

Instead, performance evaluation is conducted using overall cycle parameters (i.e., efficiency and power output).

The lumped-cycle model combines the system cycles into a single equivalent cycle for the purpose of performing a techno-economic analysis.

Although the lumped-cycle model allows accurate evaluation of overall energy flows and annual energy balances, it does not provide detailed mechanical design specifications for turbomachinery.

IV.3.1. Location and Resources

Add environmental parameters using local weather data (e.g., average temperature) as input for the selected geographic location.

The site selected for the PTES simulation was Ain TEMOUCHENT, Algeria.

The SAM software used to create the simulation imported a weather file containing representative local climatological conditions.

The geographic coordinates of the site are approximately 35.3° N latitude and 1.15° W longitude, with an elevation of 239 meters above sea level.

Using the corresponding weather file, the average annual ambient temperature was determined to be 18.2°C, with an average wind speed of 2.3 m/s.

These meteorological boundary conditions were used to evaluate the performance of the PTES system.

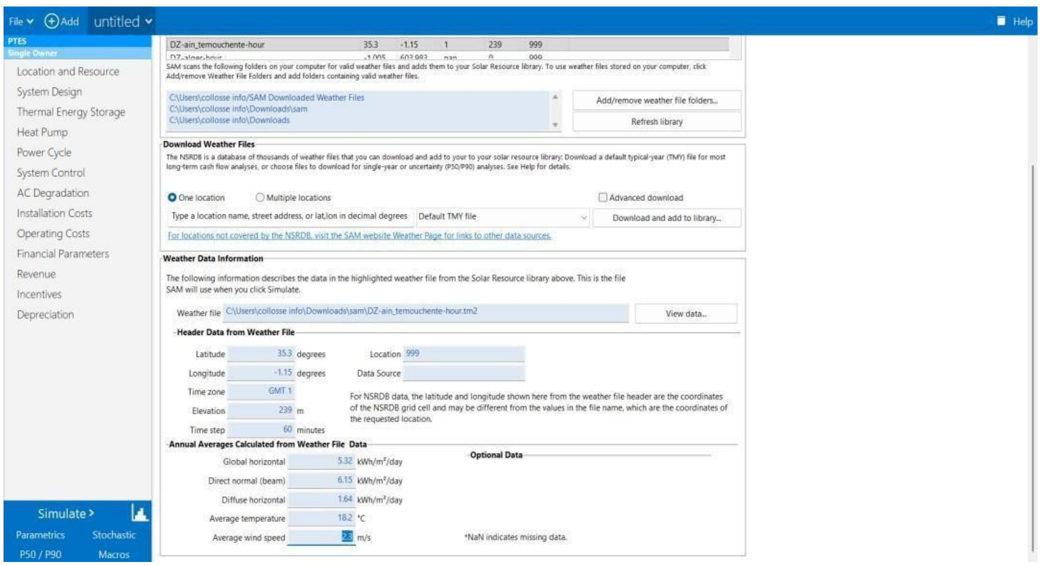

Figure 2 Location and resource page

IV.3.2. System Design

The PTES design parameters such as thermal energy storage were selected based on the previous studies.

-Thermal Energy Storage

Storage Tank	Temperature Condition	Temperature (°C)
Hot Storage Tank	Hot Temperature	794
Hot Storage Tank	Cold Temperature	420
Cold Storage Tank	Hot Temperature	25
Cold Storage Tank	Cold Temperature	-70

Table 1 Hot and Cold thermal storage Levels

The performance of the PTES system is evaluated using a series of performance indicators. Three of the most important performance indicators considered in this project are the cycle thermodynamic efficiency, the thermodynamic round-trip efficiency, and the net round-trip efficiency.

These indicators are calculated automatically by the System Advisor Model (SAM) after the system configuration and operating conditions have been defined.

• **Cycle Thermodynamic Efficiency**

The cycle thermodynamic efficiency is defined as the amount of electricity generated by the power cycle divided by the thermal energy supplied from the hot thermal energy storage unit.

The cycle thermodynamic efficiency provides an indication of how effectively the Brayton cycle converts thermal energy into electricity, as shown in Figure 3. This indicator is used to assess the thermodynamic performance of the power cycle.

• **Thermodynamic Round-Trip Efficiency**

The thermodynamic round-trip efficiency represents the amount of electrical energy recovered during discharge relative to the amount of electrical energy used to charge the system.

This parameter provides an indication of how effectively energy is converted throughout the complete storage cycle and is useful for evaluating the overall thermodynamic performance of the PTES system.

• **Net Round-Trip Efficiency**

The net round-trip efficiency offers a more realistic measure of system performance because it takes into account auxiliary power consumption and parasitic losses as part of the system's operating characteristics.

Therefore, the net round-trip efficiency is generally lower than the thermodynamic round-trip efficiency.

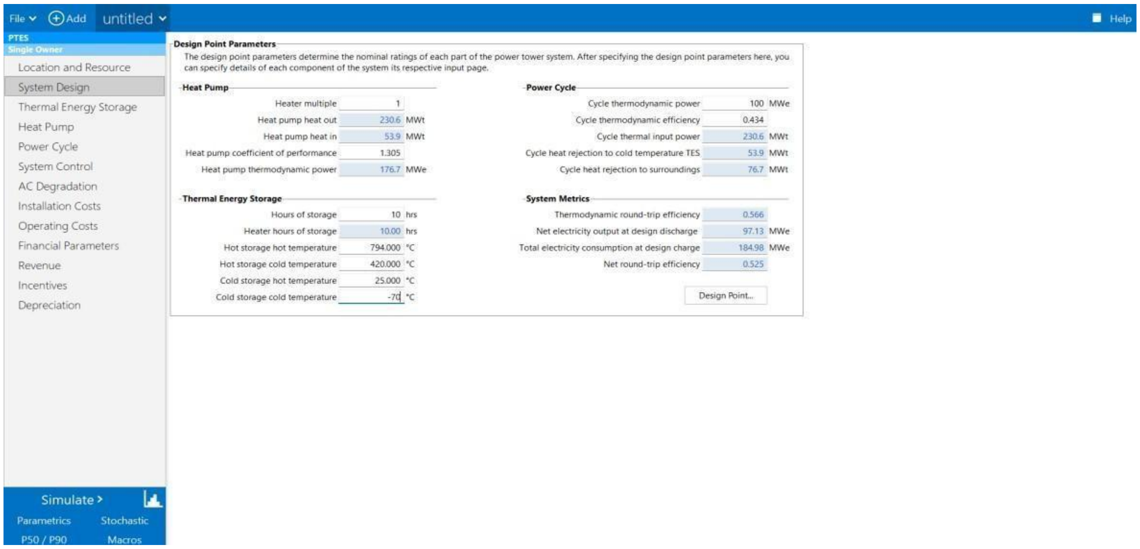

Figure 3 System Design Page

Nitrogen was selected as **Working Fluid** due to its availability, chemical stability and widespread use in PTES systems reported in previous studies.

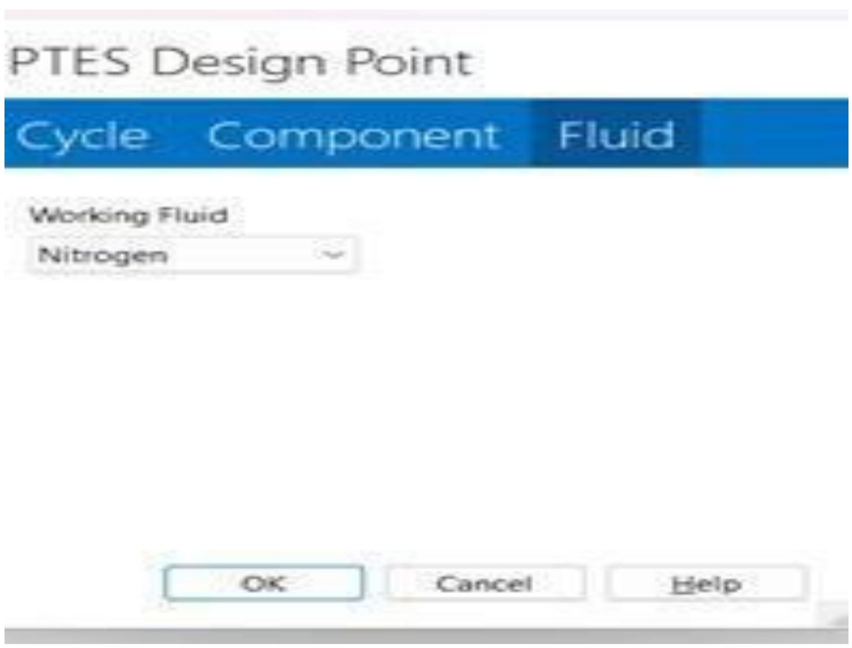

Figure 4 Working Fluid

➢ **Thermal Energy Storage**

A Molten Salt mixture consisting of (60% $NaNO_3$ – 40% KNO_3) was selected as hot storage medium, while in the cold tank Methanol was selected as cold storage medium, because they are readily available in SAM and have thermophysical properties comparable to other material storage commonly used in PTES systems.

The other thermal storage parameters were maintained at their default values in SAM.

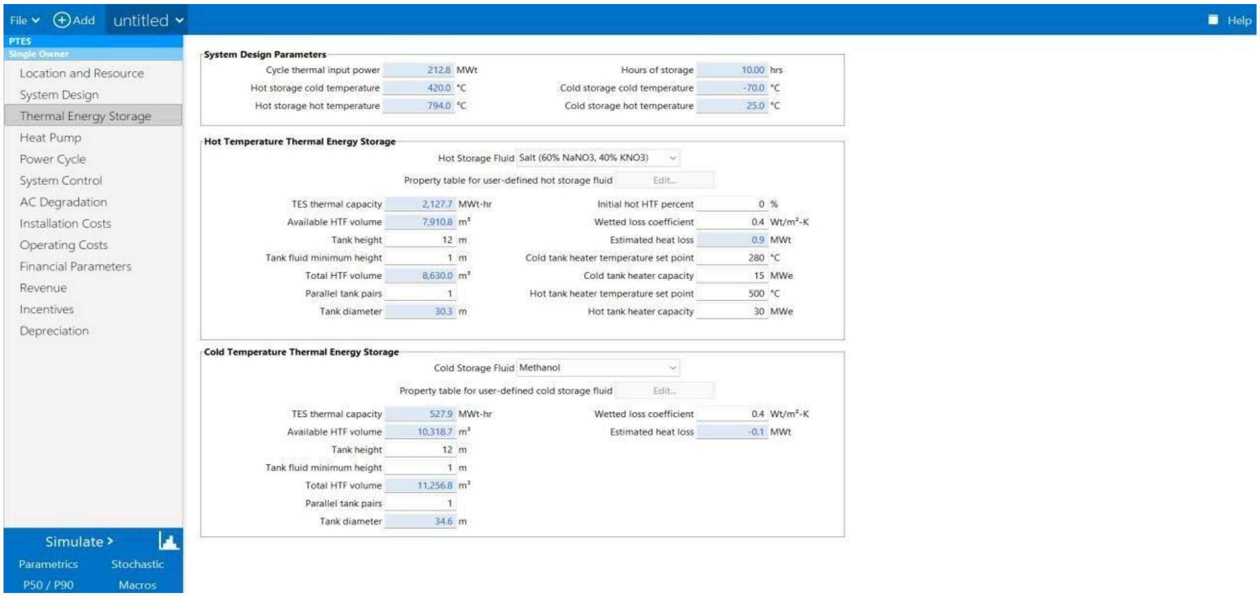

Figure 5 Thermal Energy Storage Page

IV.3.3 Heat Pump and Power Cycle

Heat Pump and Power Cycle Parameters were maintained at their default values in SAM which are calculated automatically.

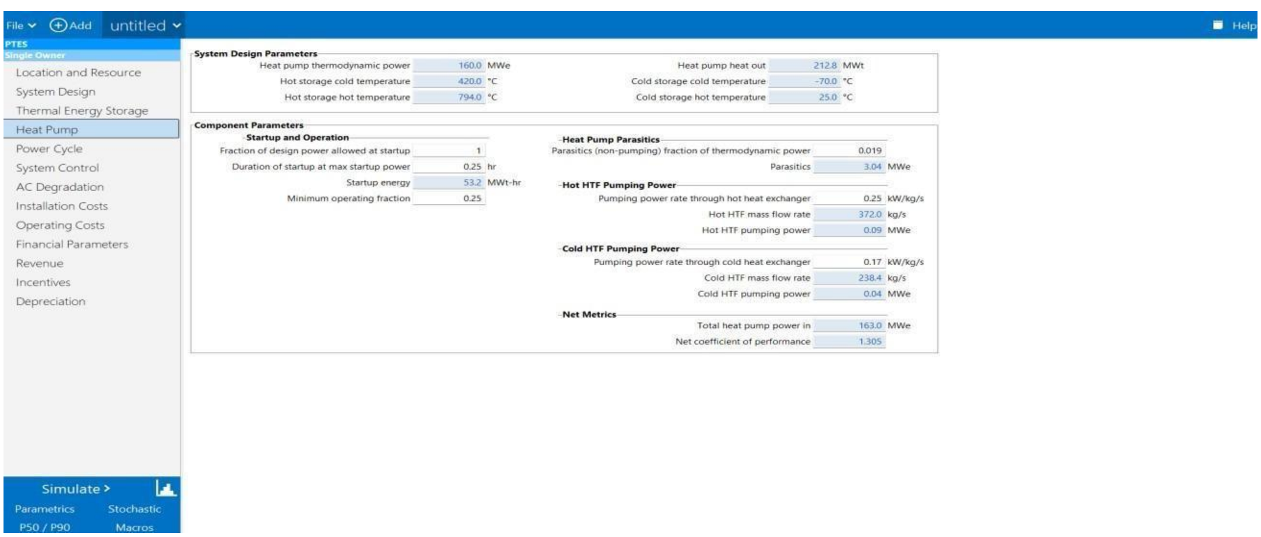

Figure 6 Heat Pump Page

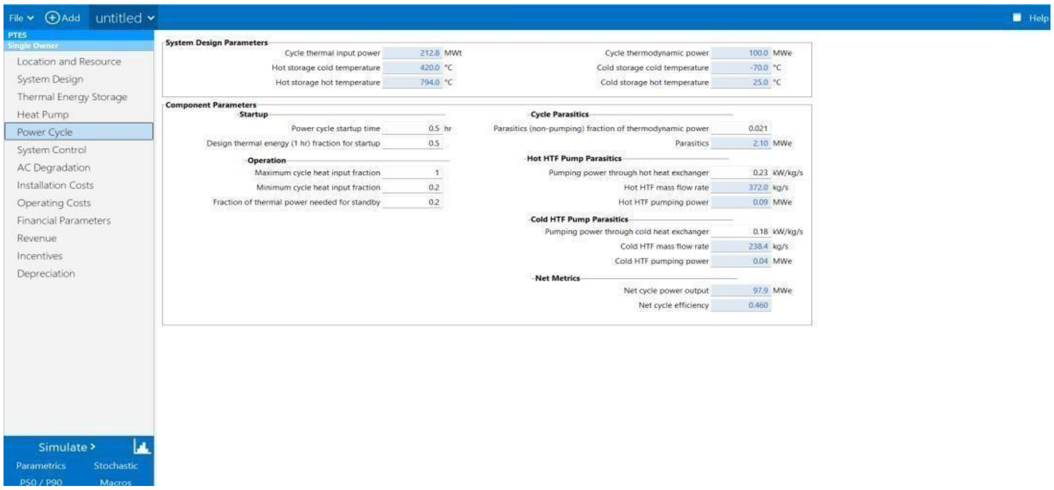

Figure 7 Power Cycle

IV.3.4 Installation Costs

The cost of installing the various system components was calculated using SAM's default cost model.

All costs were maintained at their default values, with the exception that SAM provided cost estimates for the capital costs associated with the heat pump, thermal energy storage equipment, and power generation cycle based on the selected PTES configuration. These cost assumptions were then incorporated into the techno-economic evaluation of the system.

The Installation Costs page is divided into four main categories. The first two categories, Direct Capital Costs and Indirect Capital Costs, are combined into the third category, Total Installation Costs.

Since only the total installed cost affects cash-flow calculations, capital costs can be allocated to different cost categories as required for the analysis. For example, the collector design cost may be allocated either to the collector cost category or to the engineering, procurement, and construction (EPC) category, with equivalent results.

These categories are provided to facilitate cost tracking and do not affect the economic calculations. After allocating costs to the different categories, the total installed cost should be verified to ensure that it meets the expected value.

The fourth cost category covers operation and maintenance costs.

The total capital cost of a PTES system (CAPEX) is determined by summing the costs of all major components, including compressors, expanders, thermal storage tanks, heat exchangers, insulation materials, and auxiliary equipment. Installation and contingency costs are commonly included in the overall investment cost through direct capital costs, indirect capital costs, and total installation costs.

Operation and maintenance costs are treated separately as annual operating expenses throughout the system lifespan.

- **Direct capital costs**

A direct capital cost represents an expenditure for a piece of equipment or a service of specific installation that applied to year zero of cash flow.

The total direct capital cost for the proposed PTES system was $247.57 million.

The primary component was the heat pump at $150.97 million, followed by the hot thermal storage system at $24.89 million, and the cold thermal storage system cost $10.61 million, and the power cycle cost $44.90 million.

- **Indirect capital costs**

An indirect capital cost refers to expenses that cannot be identified directly with a piece of equipment, or a specific installation service.

The indirect capital costs were given at $42.09 million, including EPC and owner costs of $32.18 million and sales tax costs of $9.90 million.

- **Total installation Costs**

The total installed cost is the sum of all direct and indirect capital costs required to construct the system.

The Total Installation costs reached $289.65 million, related to an installed cost of about 2982 USD/kW of net capacity

- **Operating and maintenance costs**

It represents the annual expenses with operating and maintain the PTES system after installation.

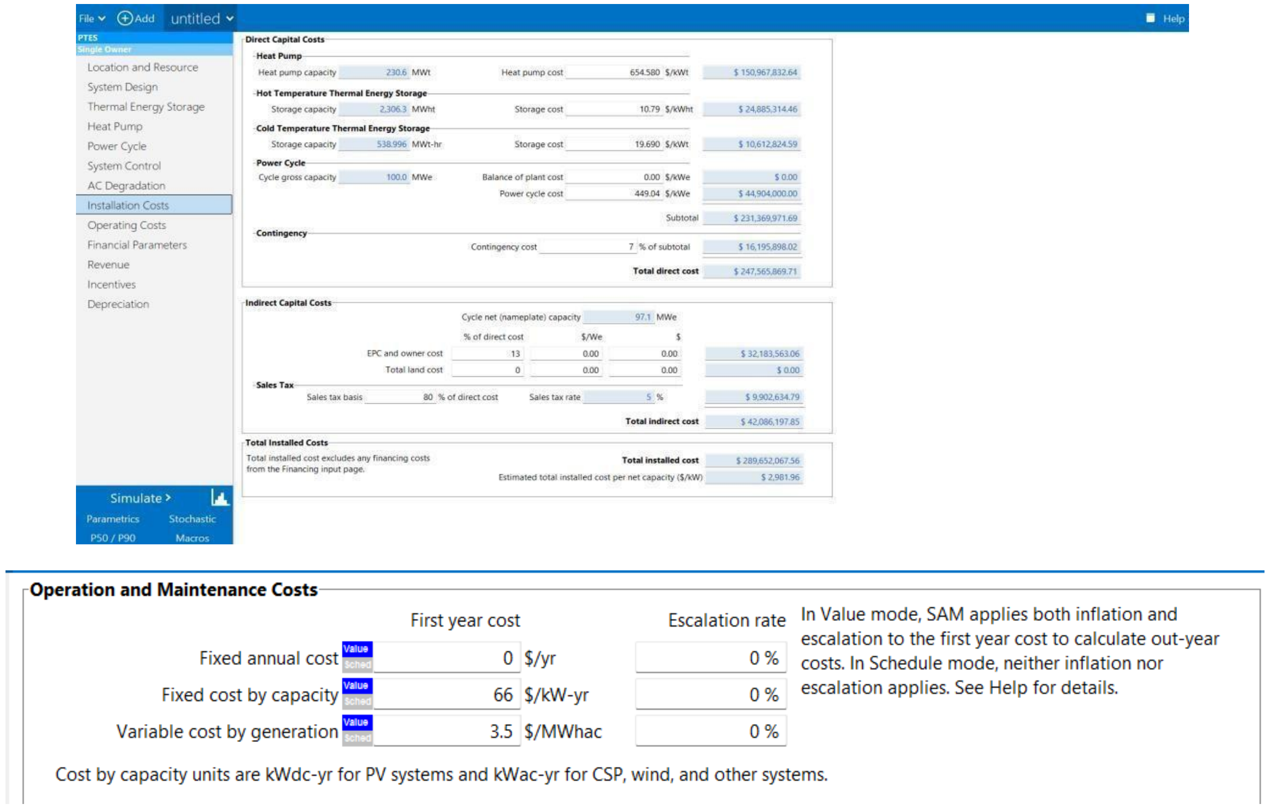

Figure 8 Installation and Operating Costs

IV.3.5 Financial Parameters

The techno-economic analysis of the PTES system was conducted using SAM and was based on specific financial inputs configured within the software.

The majority of these financial assumptions were maintained at their default values. However, some parameters were modified to meet the requirements of this study, including the analysis period, discount rate, tax rates, and project financing conditions.

The analysis period (project lifespan) was set to 30 years, and the real discount rate was fixed at 5%. .All tax-related parameters were excluded from the analysis by setting both income and sales taxes to zero.

All other financial parameters were maintained at their default values in SAM

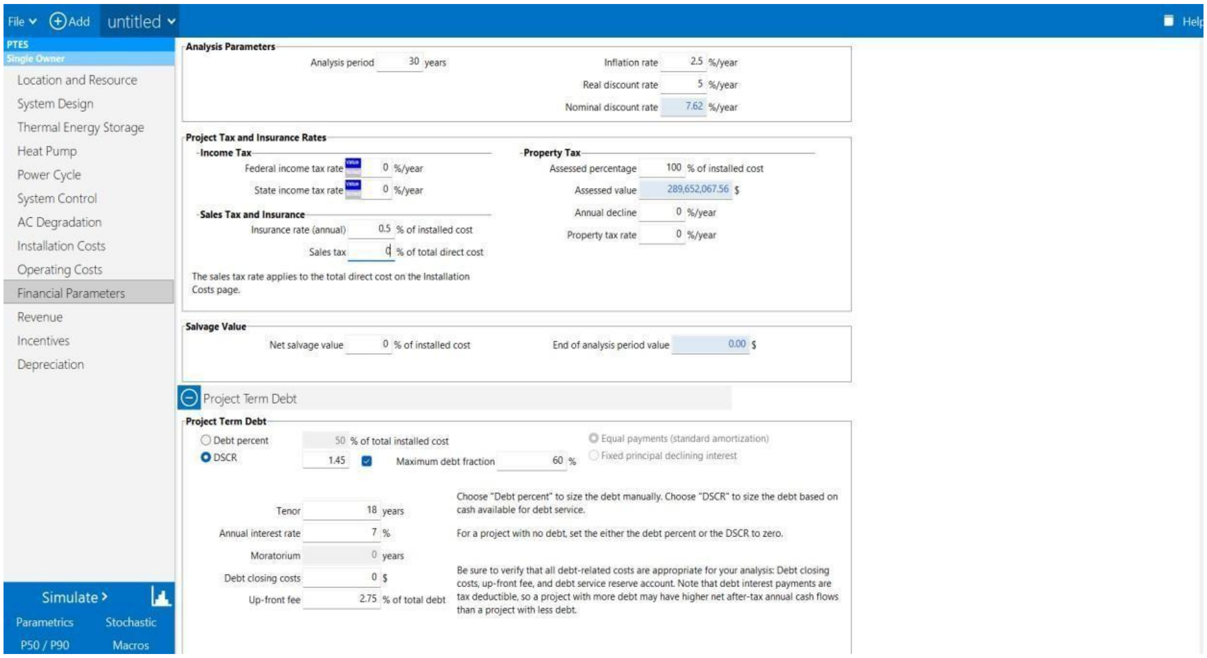

Figure 9 Financial Parameters Page

Input Parameters

Parameter	Value
Rated cycle power	100 MWe
Storage duration	10 h
Hot storage temperature	794 °C
Cold storage temperature range	-70 to 25 °C
Hot storage medium	Solar Salt (60% $NaNO_3$–40% KNO_3)
Cold storage medium	Methanol
Hot TES capacity	2306.3 MWhth
Cold TES capacity	539.0 MWhth
Analysis period	30 years
Real discount rate	5 %

Table 2 Main Input Parameters in PTES system simulation under AIN TEMOUCHENT-Algeria weather conditions.

IV.4 Conclusion

SAM begins by collecting and inputting all necessary data, including site conditions, climate data (temperature and wind speed), system specifications, and economic parameters.

Once this information has been entered into the model, SAM calculates how the energy system is expected to operate under various conditions.

After the model setup is completed, SAM runs simulations to generate expected performance metrics, such as the amount of energy produced and the amount of energy lost.

In addition to generating performance metrics, SAM can also be used to evaluate how system performance is affected by changes in design and operational configurations.

Chapter V
Results and Discussion

Chapter V: Results and Discussion

V.1 Introduction

The subsequent stage, following the modeling and simulation of the system, is the examination and interpretation of the output results of the modeled system.

This is necessary to evaluate the technical and economic performance of the Pumped Thermal Energy Storage (PTES) system under the specified operating conditions.

This chapter discusses and compares all simulation results and explicitly outlines the main Key Performance Indicators (KPIs) for PTES, such as round-trip efficiency (RTE), energy storage capacity, thermal performance, and economic performance.

Additionally, the financial performance will be assessed using metrics such as the Levelized Cost of Storage (LCOS) to examine the feasibility and competitiveness of the PTES system compared with other long-duration energy storage solutions. This evaluation will help determine the potential of PTES as a long-duration energy storage technology and provide insight into its suitability for large-scale renewable energy integration.

V.2 Results and Interpretations

V.2.1 Weather

Previous studies indicate that the performance of a system is affected by three main factors

- Climate type of location
- Chosen storage medium
- Size of the facility.

  Comparing performance between cold and hot climates revealed that the former creates a much better thermodynamic (efficiency) and economic (cost) performance than the latter.

Figure-1 represents the annual variation of dry bulb temperature and Wind speed for the city of AIN TEMOUCHENT-Algeria.

The temperature profile is characterized by a clear seasonal pattern. Lower values can be observed during winter (December–February), with temperatures gradually increasing toward summer and reaching their maximum values in July and August.

In terms of wind speed, significant fluctuations are observed throughout the year without a clear seasonal trend.

For the study region of Ain TEMOUCHENT, Algeria, it can be observed that the dry-bulb temperature reaches a maximum value of 36°C in August, whereas the wind speed reaches a peak of approximately 15 m/s.

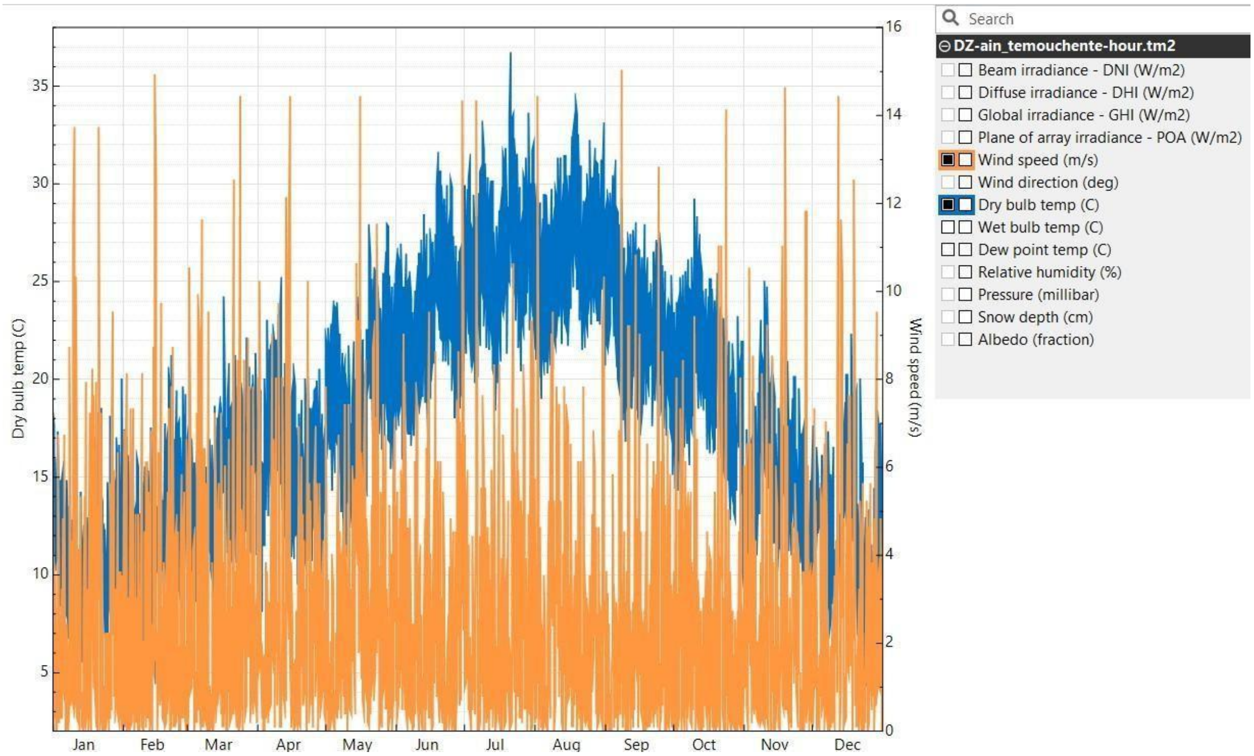

Figure 1 Wind Speed and Dry bulb temperature curves

This combination of the two trends (high summer temperatures and moderate wind conditions) clearly represents suitable environmental conditions for the implementation of the proposed PTES system.

IV.2.2 Technical Results

Technical performance Indicators

An annual simulation was done by System Advisor Model SAM to assess the operational act and performance of Pumped Thermal Energy Storage.

The obtained results are presented in tables and graphs containing all the required data.

The system achieved a thermodynamic efficiency of 42.3%, a thermodynamic round-trip efficiency of 56.5%, and a net round-trip efficiency of 52.5%.

The charging operation consumed 184.98 kW of electrical power, whereas the discharging process delivered 97.31 MW of net electrical power.

IV.2.2.a System Power Generated

The simulation provides hourly results throughout the entire year, allowing the charging and discharging operations of the storage system to be assessed under realistic operating conditions.

These results are used to evaluate the energy exchange between the system and the electric grid, while also demonstrating the effectiveness of the storage operation.

One of the basic indicators used to explain the overall operation of the PTES system is the system power generation profile.

Positive values indicate electricity consumption during the charging operation, whereas negative values indicate electricity generation during the discharging process.

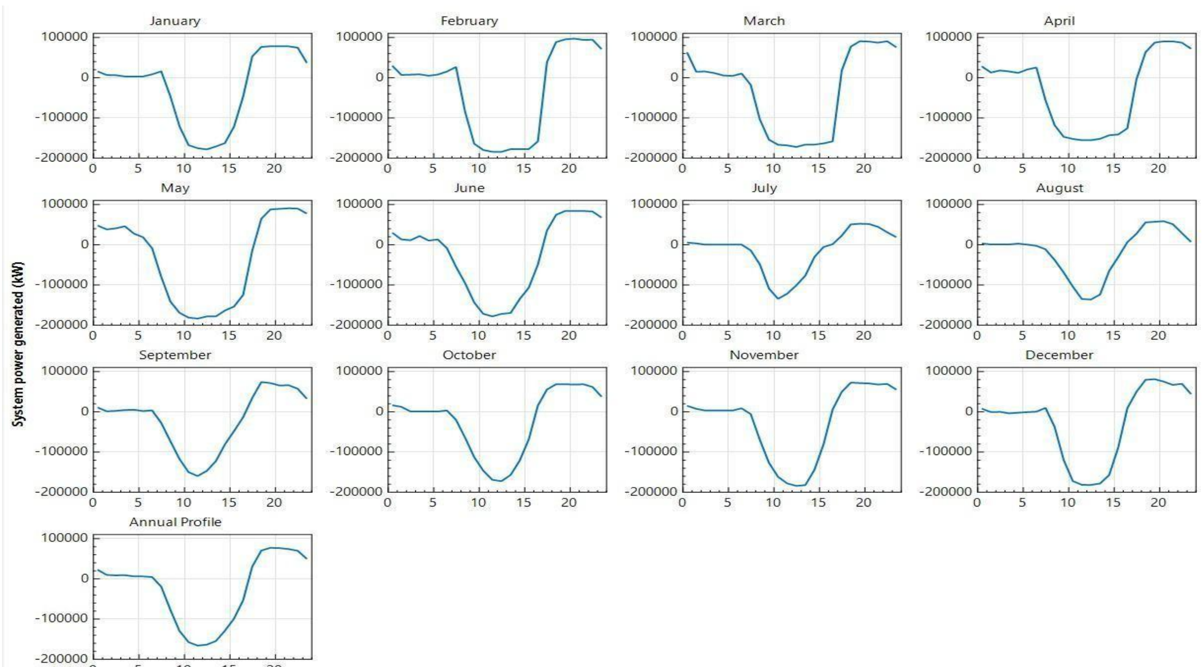

Figure 2 System power generated profile of the PTES system

As **Figure-2** illustrates, the PTES system exhibits a clear daily operating pattern.

During the off-peak hours, the system consumes electricity from the grid to charge the thermal storage tanks, which is represented by negative power values.

During the peak demand periods, the stored thermal energy is converted back into electricity, which is represented by positive power values that are exported to the grid.

IV.2.2.c Electricity from Grid to the system

In this part of the simulation, the total electricity imported to the system is presented as data.

The electricity imported to the system represents the energy required to operate the heat pump during the charging operation.

The results illustrate that electricity consumption mainly occurs during low-demand periods, when the system stores energy in the thermal storage tanks for later use.

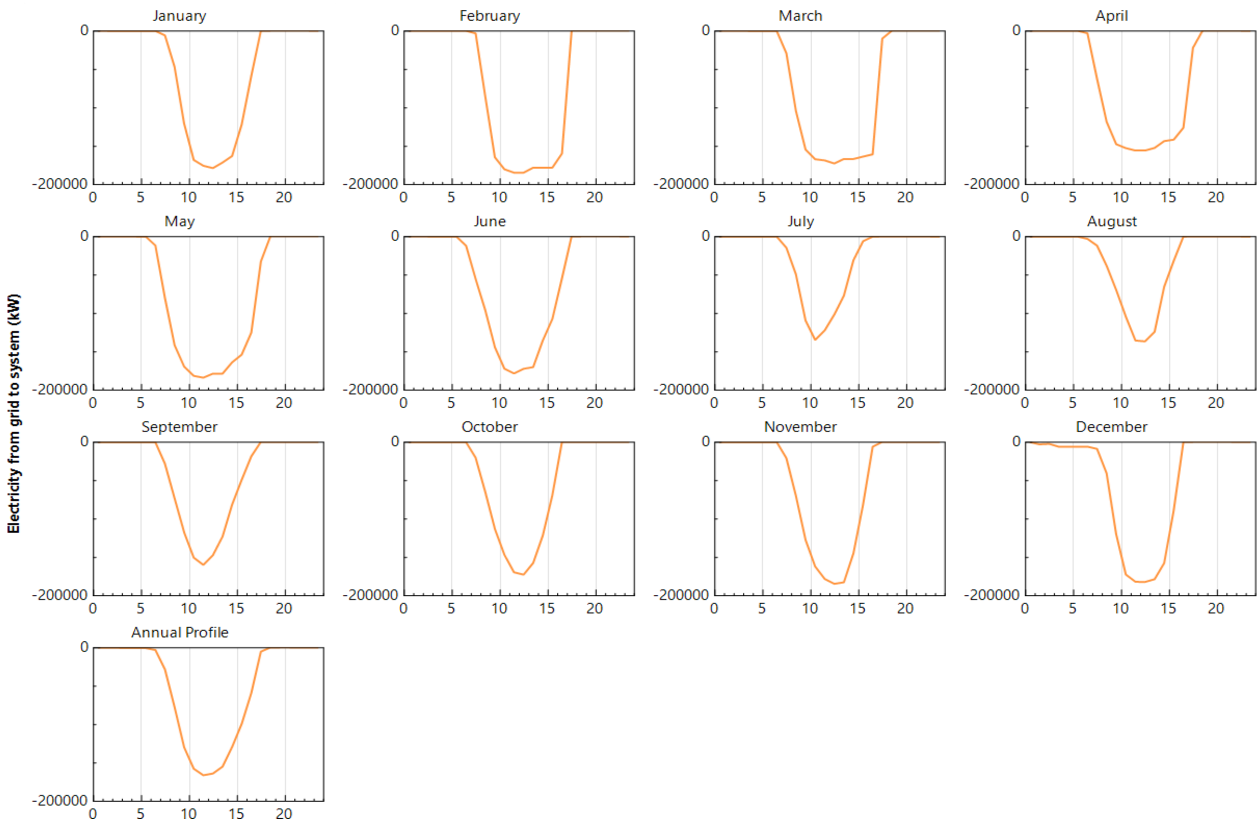

Figure 3 Electricty from grid the system profile of PTES system

It can also be observed that there is a seasonal variation in the charging profile.

The charging demand varies slightly throughout the year, from January to December, due to several factors, such as weather conditions and system operating requirements.

While the overall performance of the system remains stable, the results demonstrate the capability of the PTES system to store electrical energy in the form of heat and recover it later during periods of high demand.

IV.2.2.d System Power Generated Electricity to the Grid

This part of the simulation represents one of the main objectives of the PTES system, where thermal energy is converted into electrical energy during the operating process of the system, as discussed in the previous chapters.

The electricity exported to the grid represents the electrical energy generated by the PTES system during the discharging operation.

During this process, the stored thermal energy is converted back into electricity.

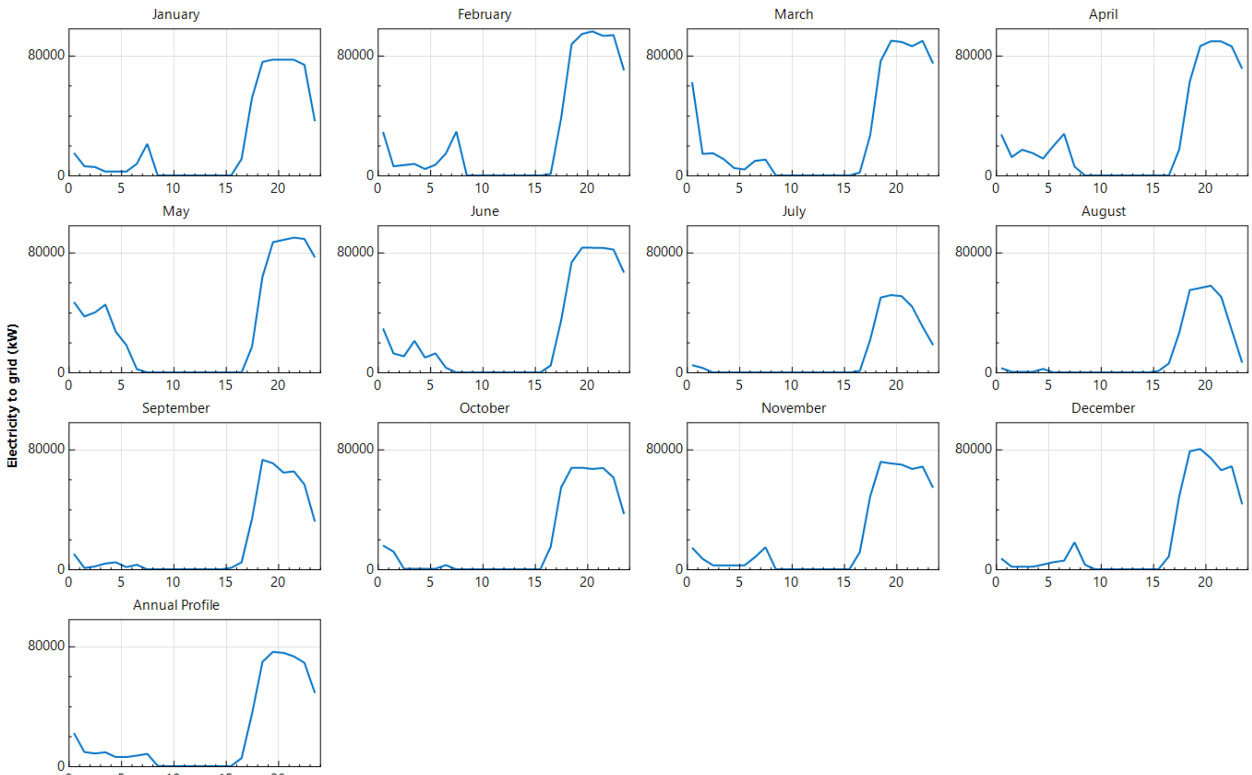

Figure 4 Electricty to grid profile of PTES system

t can also be observed that the discharging profile exhibits moderate variation throughout the year.

The discharging operation varies slightly throughout the year, from January to December, due to several factors, such as weather conditions and system operating requirements.

Despite this variation, the overall performance of the system remains stable, demonstrating the ability of the PTES system to recover and convert the stored thermal energy into electrical energy during periods of high electricity demand.

IV.2.2.e Thermodynamic Performance Analysis

These performance indicators measure how effectively the power cycle and the complete energy storage cycle operate, as well as how the consumption of auxiliary power impacts the overall performance of the system.

Three main thermodynamic performance parameters have been evaluated in this study: cycle net efficiency, thermodynamic round-trip efficiency, and net round-trip efficiency. These parameters were explained in **Chapter-IV**.

Single Values

Cycle net efficiency (-)	0.423557
Net round-trip efficiency considering all parasitics (MWe)	0.525107
Round-trip efficiency of working fluid cycles (MWe)	0.565823

Table 1 Key Performance Indicators

- **Net Round-trip efficiency**

The net round-trip efficiency provides a better estimation of PTES performance than the thermodynamic round-trip efficiency, mainly because it takes into account the impact of auxiliary electricity (used to power auxiliary equipment and auxiliary loads) and parasitic losses (caused by equipment that does not contribute to useful electrical output) on system operation.

According to the SAM (System Advisor Model) simulations, the calculated net round-trip efficiency was 52.51%.

The difference between the calculated thermodynamic round-trip efficiency and the net round-trip efficiency is attributed to auxiliary power requirements, which reduce the amount of useful electrical output generated by the system.

IV.3 Thermal Storage Temperature Analysis

IV.3.1 Hot and Cold Storage Temperature

This section, and especially the thermal storage material temperature inside the tank, plays a crucial role, as it directly affects the performance of the entire system.

The temperature levels of the hot and cold thermal storage tanks were evaluated to assess the stability of PTES system operation throughout the simulation period.

Maintaining stable storage temperatures, as shown in Figure 6, is essential to ensure efficient charging and discharging operations and to keep the thermodynamic conditions of the system under control.

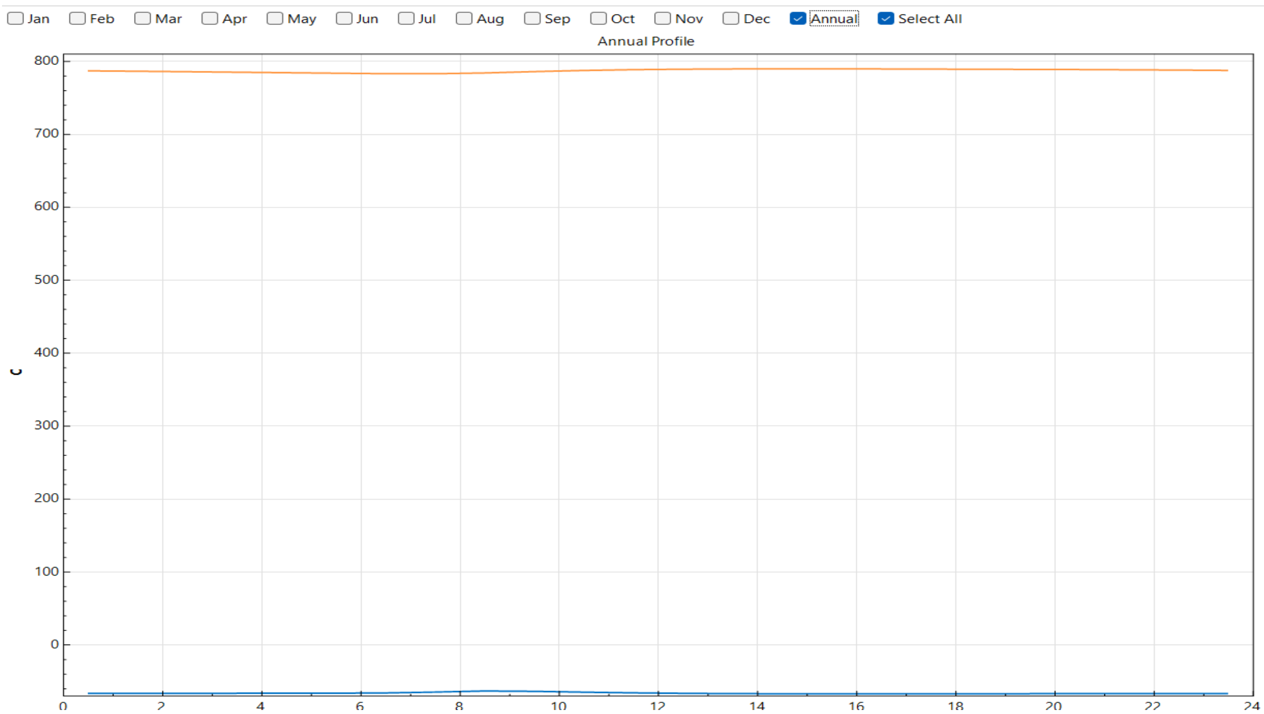

Figure 5 Annual hourly variation of Hot and Cold Storage Temperatures

As shown in **Figure-5**, both tanks maintained steady temperatures, with very little fluctuation in their actual temperature values. The hot storage temperature remained close to its design value of approximately 794°C, while the cold storage temperature remained close to −70°C throughout the simulation period.

This indicates that the charging and discharging processes were highly stable.

The results also indicate that there was minimal loss of thermal energy stored in each tank during the simulation period, as the temperatures of both tanks remained stable

IV.4 Thermal Losses Analysis

One of the key elements affecting the overall performance of a PTES system is thermal losses.

Since electrical energy is stored as thermal energy in this type of system, some of the heat stored in the tanks is lost to the environment through the tanks and associated equipment during operation.

Therefore, understanding the behavior of thermal losses throughout the year is important for evaluating how effectively the thermal energy storage method and thermal management strategy perform within the system.

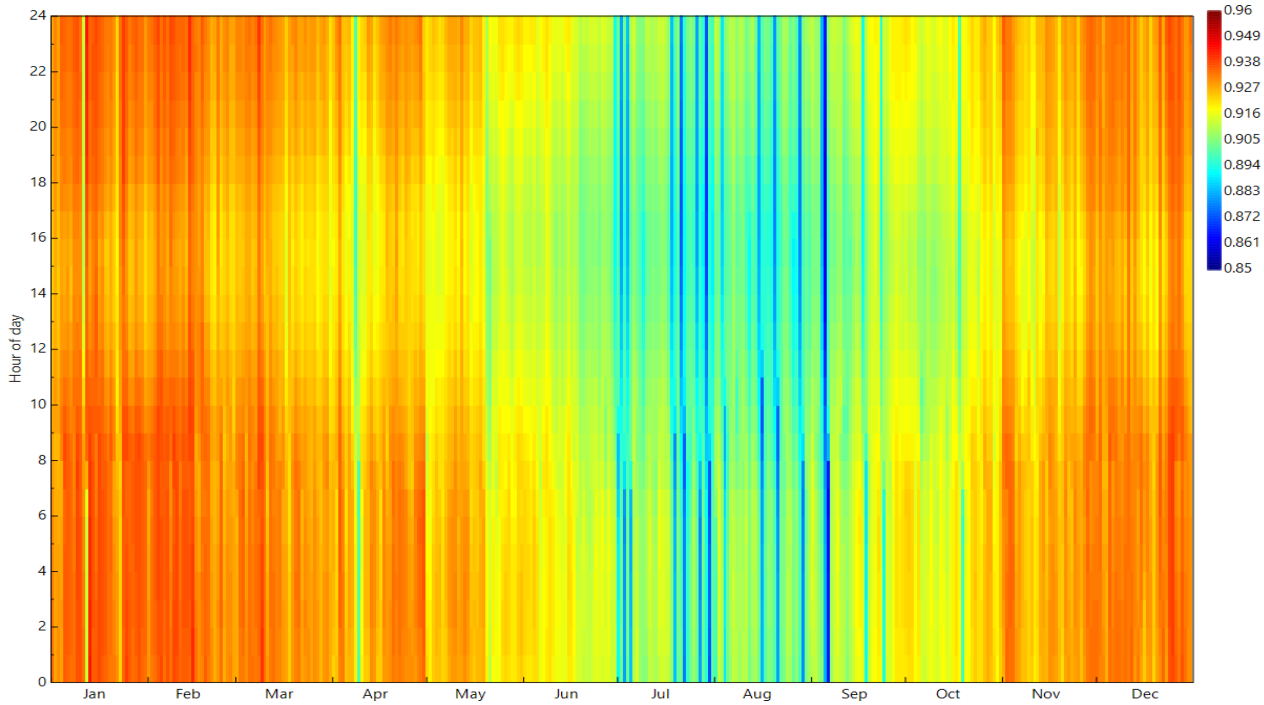

Figure 6 Annual Heat loss Map

It can be seen from **Figure-6** that the thermal loss remains relatively consistent throughout the year, fluctuating between approximately 0.85 MWt and 0.96 MWt.

Higher levels of thermal loss are observed in January and December, with these higher values represented by orange and red colors.

During the summer months, lower levels of thermal loss are observed, represented by green and blue colors.

The greater the temperature differential, the greater the transfer of thermal energy to the surrounding environment, which consequently leads to higher thermal losses.

The thermal loss range of 0.85 MWt to 0.96 MWt is relatively narrow, illustrating that the thermal storage system is capable of providing a good degree of thermal retention.

Furthermore, the use of molten salt as the energy storage medium allows thermal energy to be retained over long periods due to its high heat capacity and thermal stability.

In addition to these factors, the insulation of the thermal storage tanks, along with the use of nitrogen as the working fluid, demonstrates effective thermal management by limiting energy losses to the surrounding environment throughout the year.

Overall, the observed thermal losses remain limited compared with the amount of stored thermal energy. This indicates that the selected configuration is adequate for long-duration energy storage applications.

IV.5 Power cycle Thermodynamic efficiency Analysis

The power cycle thermodynamic efficiency provides an indication of how effectively the PTES system converts stored thermal energy into electrical power.

The SAM model calculated a year-long, hourly-based heat map of thermodynamic efficiency to capture different operating conditions and the resulting variations in cycle performance throughout the year.

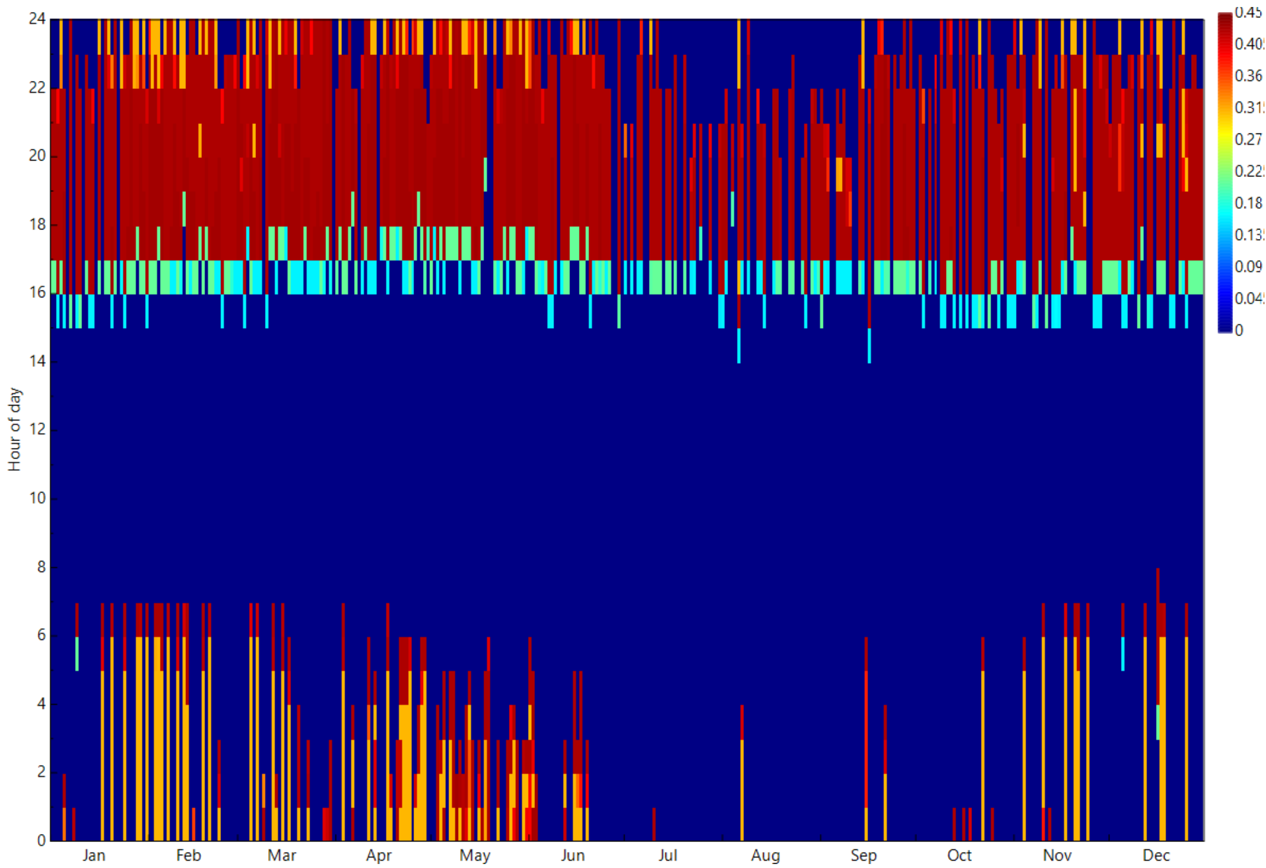

Figure 7 Annual hourly heat map of power cycle thermodynamic efficiency

The annual hourly variation in power cycle thermodynamic efficiency is displayed by the heat map in **Figure V-7.**

The color scale ranges from 0 to 0.45. Dark blue areas signify periods when the power cycle is not operating, while yellow, orange, and red areas signify discharging periods associated with electricity generation, during which the efficiency exceeds the design value of approximately 0.45. These periods typically occur during high-demand hours.

Large blue areas also represent charging periods, during which the heat pump is operating and no electricity is generated. Therefore, the power cycle exhibits nearly zero thermodynamic efficiency during charging.

The heat map shows that high thermodynamic efficiency is achieved repeatedly throughout the year during discharging operations. The Brayton cycle consistently records efficiencies close to the design value due to the use of molten salt as the thermal storage medium, which provides a reliable thermal energy source for the power cycle.

IV.6 Economic Results

The economic assessment of the simulated PTES system was conducted using the financial indicators generated by SAM. The analysis takes into account the capital investment, operational revenue, electricity sales, financing structure, and long-term project performance throughout the system lifespan.

The main economic indicators of the system consist of several factors, such as Net Present Value (NPV), Internal Rate of Return (IRR), and Levelized Cost of Energy (LCOE), which were used to assess the economic viability of the project.

Metric	Value
Net electricity to grid (year 1)	-233,514,272 kWh
PPA price in Year 1	6.00 ¢/kWh
PPA price escalation	1.00 %/year
LPPA Levelized PPA price nominal	10.63 ¢/kWh
LPPA Levelized PPA price real	8.07 ¢/kWh
LCOE Levelized cost of energy nominal	17.46 ¢/kWh
LCOE Levelized cost of energy real	13.25 ¢/kWh
NPV Net present value	$18,944,594
IRR Internal rate of return	6.35 %
Year IRR is achieved	20
IRR at end of project	9.60 %
Net capital cost	$311,895,840
Equity	$136,277,696
Size of debt	$175,618,128
Debt percent	56.31%

Figure 8 Economic performance Indicators

It can be observed from **Figure-8** that the project achieves an Internal Rate of Return (IRR) of 6.35% after approximately 20 years of operation, out of a total project lifespan of 30 years.

The cumulative IRR is expected to continue growing throughout the project lifetime and reach 9.60% at the end of the 30-year operating period, indicating the long-term economic viability and profitability of the system.

IV.6.1 Levelized Cost of Energy

Figure-9 illustrates the Levelized Cost of Electricity (LCOE) for the project.

The LCOE is 17.46 $/kWh (nominal) and 13.25 $/kWh (real), representing the average cost of electricity generated by the system over its lifetime, taking into account capital costs, operation and maintenance costs, and financing assumptions.

The LCOE is competitive with that of other long-duration energy storage technologies, which confirms the economic viability of PTES technology for long-duration energy storage applications.

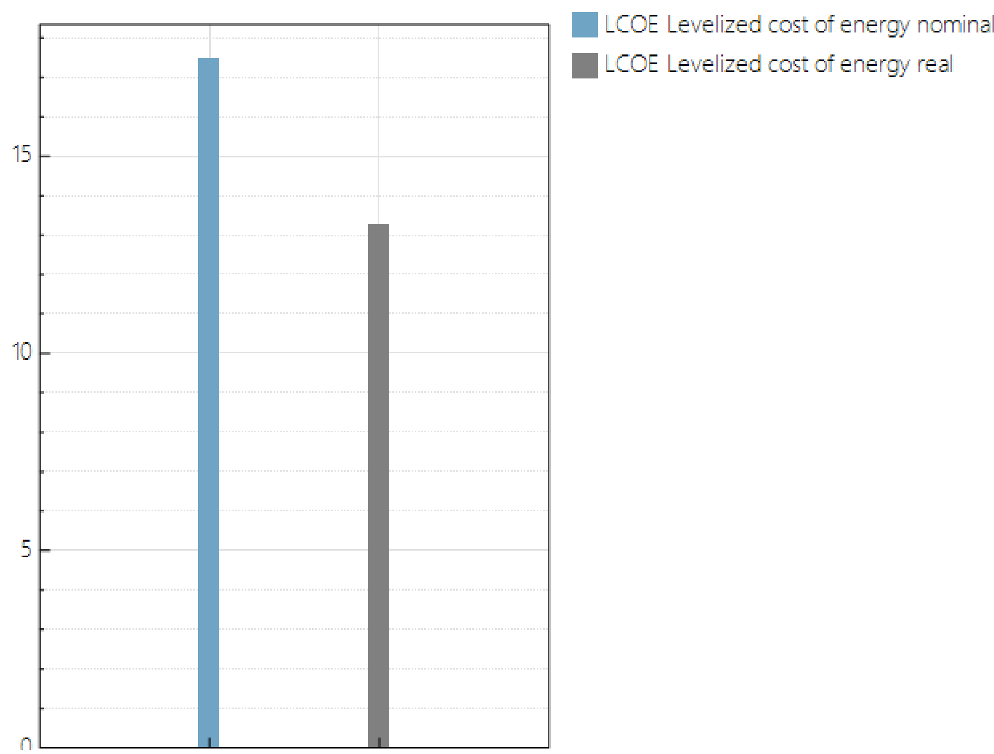

Figure 9 Levelized cost of energy Nominal/Real

The Levelized Cost of Energy (LCOE) was explained in Chapter II, where it is defined as the average cost of producing one unit of electricity over the entire lifespan of a project.

IV.6.2 Internal Rate of Return

This parameter represents the annual percentage return that the project is expected to generate over its lifetime.

Figure-10 illustrates the after-tax cumulative IRR over the project's lifetime.

The graph shows that the cumulative IRR is deeply negative during the first years, reaching approximately -32.3%, and remains below zero from the first year until about year 12. This is due to the high initial investment costs associated with developing the PTES system.

Once revenue from the project begins to accumulate, the cumulative IRR rises toward the payback point.

The cumulative IRR becomes positive after approximately 11 to 12 years, indicating that the project has recovered its capital investment and is generating positive cash flows. Furthermore, the IRR continues to rise steadily throughout the project lifetime.

At the end of the project life, the cumulative IRR reaches approximately 9.6%, indicating that the PTES system is a profitable long-term investment.

The steady increase in cumulative IRR demonstrates that the project generates sufficient revenue to cover both its initial investment and ongoing operating costs, while also providing a positive long-term economic benefit throughout the 30-year analysis period.

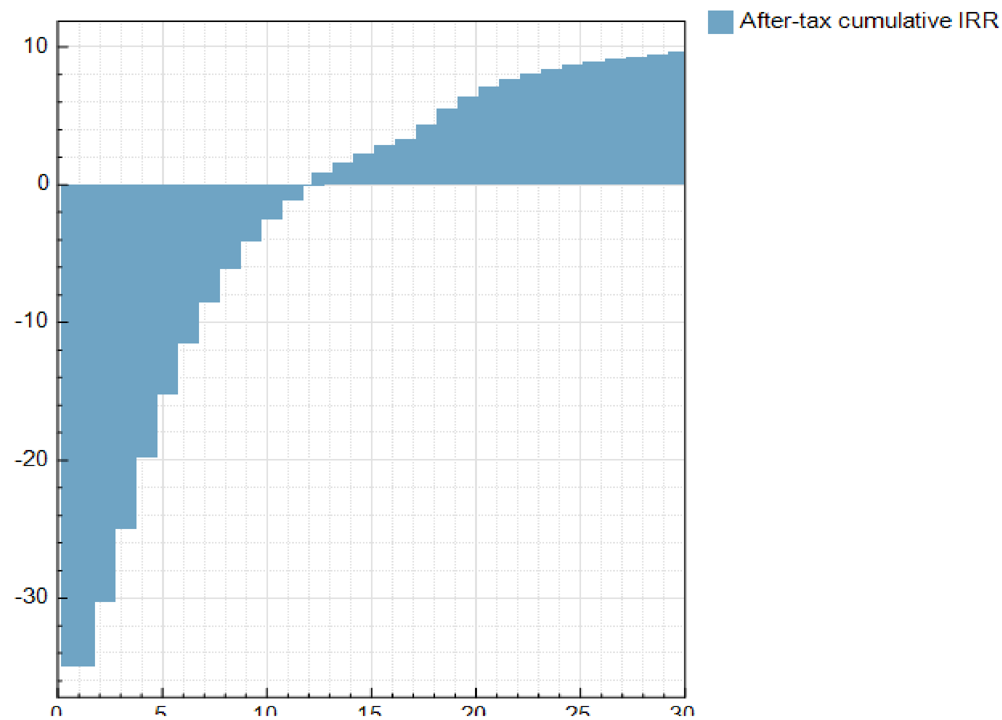

Figure 10 Internal Rate of Return Development

The overall results of the assessment of the proposed PTES system indicate that it has the potential to provide a reasonable return on investment.

The projected Internal Rate of Return (IRR), Levelized Cost of Energy (LCOE), and stable long-term financial performance demonstrate that the PTES system represents an economically and technically viable solution for large-scale energy storage applications.

V.7 Output main parameters

Parameter	Value
Thermodynamic round-trip efficiency	56.6 %
Net round-trip efficiency	52.5 %
Net electrical output	97.13 MWe
Net Capital cost	311.895.840$
Net present value (NPV)	$ 18.94 millions
Internal rate of return (IRR)	6.35 %
Real LCOE	13.25 ¢/kWh
Heat pump COP	1.305
Real LPPA	8.07 ¢/kWh

Table 2 Output main parameter under AIN TEMOUCHENT weather conditions

V.8 Parametric Analysis and Performance optimization

PTES systems can be designed to operate at capacities ranging from a few megawatts to several hundred megawatts.

Although this technology has not yet been widely implemented in real-world applications, mainly due to thermal losses and system irreversibility's, many studies have examined its performance through theoretical models.

These studies have shown promising results in terms of power output, efficiency, energy storage capacity, and charging and discharging times.

Researchers have also investigated different system configurations and design improvements to reduce losses and enhance the overall performance of PTES systems.

In this part of the study, a parametric analysis of the proposed PTES system is carried out using selected input and output parameters.

This analysis provides a clear understanding of the system's performance and behavior under different operating conditions. It also helps identify the most influential parameters, making it possible to improve and optimize the system by adjusting key variables to achieve better performance and overall results.

Table-3 summarizes the main input parameters and key output results of the proposed PTES system, including the thermodynamic, economic, and performance indicators used to evaluate its operation.

Input Parameter	Value	Output Parameter	Value
Rated cycle power	100 MWe	Thermodynamic round-trip efficiency	56.6 %
Storage duration	10 h	Net round-trip efficiency	52.5 %
Hot storage temperature	794 °C	Net electrical output	97.13 MWe
Cold storage temperature range	−70 to 25 °C	Heat pump COP	1.305
Working fluid	Nitrogen (N_2)	Net Capital cost	311.895.840$
Hot storage medium	Solar Salt (60% $NaNO_3$–40% KNO_3)	Net present value (NPV)	$ 18.94 millions
Cold storage medium	Methanol	Internal rate of return (IRR)	6.35 %
Hot TES capacity	2306.3 MWhth	Real LCOE	13.25 ¢/kWh
Cold TES capacity	539.0 MWhth	Real LPPA	8.07 ¢/kWh
Analysis period	30 years	—	—
Real discount rate	5 %	—	—

Table 3 Baseline PTES system parameters and performance indicators.

V.8.1 Effect of duration Storage on the system

In order to assess the effect of storage duration on the PTES system's performance, a sensitivity analysis was performed by varying the storage duration from 4 to 12 hours.

This analysis evaluated thermodynamic and economic parameters, such as cycle net efficiency, net power produced, heat pump energy consumption, IRR, and NPV.

The data collected for the different storage durations are summarized in **Table-4**.

The thermodynamic indicators (cycle net efficiency, net power produced, and heat pump power consumption) show no significant change regardless of the storage duration.

This indicates that the storage duration has no influence on the thermodynamic performance of the PTES cycle in this configuration.

In contrast, the economic performance indicators show a much wider range of variation with changes in storage duration.

The Internal Rate of Return (IRR) and Net Present Value (NPV) exhibit significant increases when the storage duration is increased from 4 hours to 8 hours. Beyond 8 hours of storage, both the IRR and NPV experience a gradual decline in economic performance.

	Hours of storage (hrs)	Cycle net efficiency (-)	Cycle net power generation (MWe)	Heat pump total power consumption (MWe)	IRR Internal rate of return (%)	NPV Net present value ($)
1	4	0.423557	97.6862	184.429	6.36883	-1.22525e+07
2	6	0.423557	97.6862	184.429	9.12524	1.36059e+07
3	8	0.423557	97.6862	184.429	10.0291	2.17662e+07
4	10	0.423557	97.6862	184.429	9.60087	1.89321e+07
5	12	0.423557	97.6862	184.429	8.85409	1.26123e+07

Table 4 Effect of duration storage on different performance indicators

As shown in **Figure-11,** both IRR and NPV follow a similar trend, increasing as the storage duration rises from 4 hours to 8 hours. At a storage duration of 8 hours, both IRR and NPV reach their maximum values.

At a storage duration of 4 hours, the IRR is approximately 6.36%, while at a storage duration of 8 hours, the IRR reaches approximately 10%.

At the 8-hour storage duration, the NPV of the system reaches its maximum value of approximately $20 million. Therefore, the study findings indicate that the highest level of economic performance is achieved with 8 hours of storage.

Furthermore, the findings indicate that the optimum design point for the PTES system is a storage duration of 8 hours. In other words, the 8-hour storage design represents the most effective trade-off between system cost and rate of return.

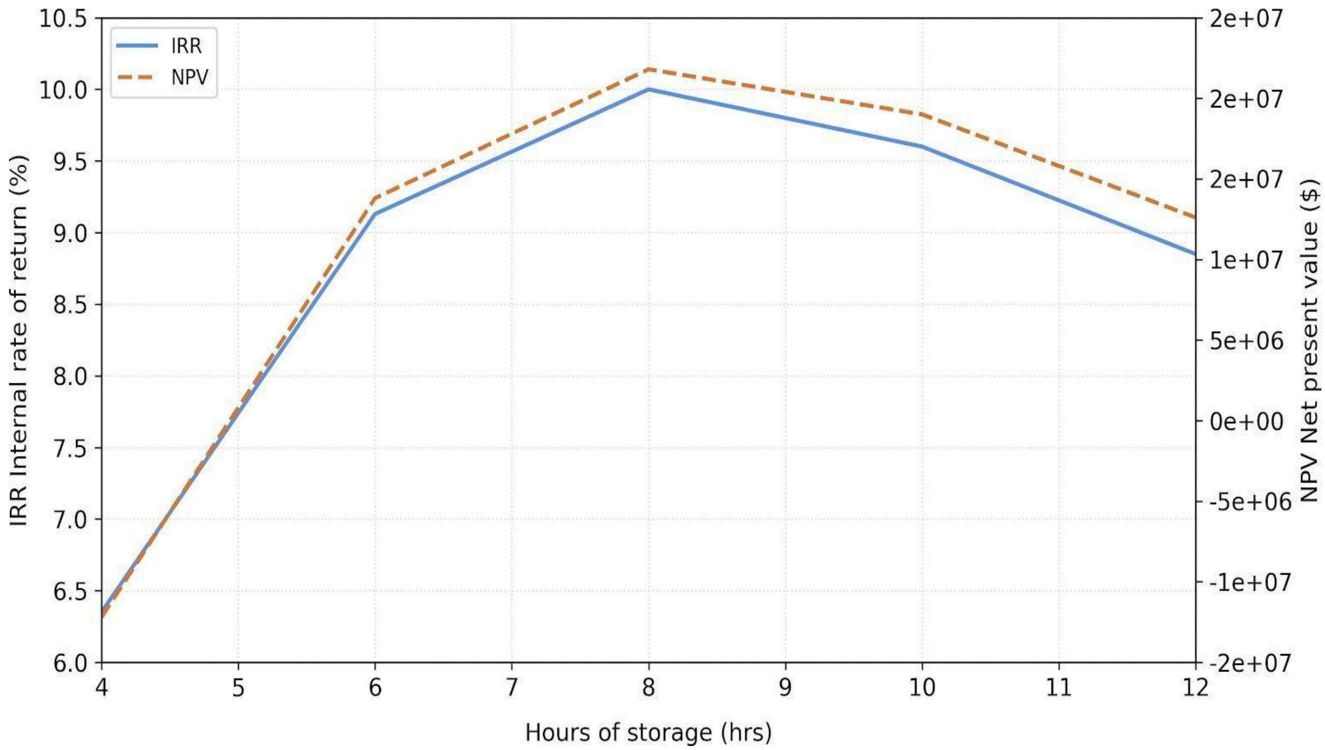

Figure V-11 Variation of IRR and NPV with Storage Duration

V.8.2 Effect of the hot storage hot temperature

In order to assess the effect of hot storage temperature on the PTES system's performance, a sensitivity analysis was performed by varying the hot storage temperature from 450°C to 850°C.

This analysis evaluated thermodynamic and economic parameters, such as cycle net efficiency, net power produced, heat pump energy consumption, IRR, and NPV.

Table V-5 illustrates how various performance indicators are affected by the hot storage temperature.

The results indicate that, as the hot storage temperature increases, there is no significant impact on the thermodynamic performance of the cycle (e.g., cycle net efficiency, cycle net power generated, and heat pump power consumption) for all temperatures investigated.

In contrast, the economic indicators exhibit a strong response. For example, the IRR increases from approximately -0.65% at 450°C to 9.64% at 850°C.

The NPV also improves significantly over the same temperature range, increasing from approximately -$10.92 million at 450°C to approximately $19.19 million at 850°C.

Therefore, it can be concluded that increasing the hot storage temperature, in combination with an appropriate storage system design, can greatly enhance the overall economic feasibility of PTES systems.

	Hot storage hot temperature (°C)	Cycle net efficiency (-)	Cycle net power generation (MWe)	Heat pump total power consumption (MWe)	IRR Internal rate of return (%)	NPV Net present value ($)
1	450	0.423557	97.6862	184.429	-0.649502	-1.09194e+08
2	550	0.423557	97.6862	184.429	9.18698	1.52509e+07
3	650	0.423557	97.6862	184.429	9.42588	1.73921e+07
4	750	0.423557	97.6862	184.429	9.53866	1.83872e+07
5	850	0.423557	97.6862	184.429	9.61045	1.90152e+07

Table 5 Effect of hot storage hot temperature on different performance indicators

Figure V-12 shows that increasing the hot storage temperature from 450°C to 550°C results in significant improvements in both IRR and NPV, with the greatest improvement occurring within this temperature range.

At 450°C, the NPV is approximately −10.92 million , whereas at 550°C it increases to approximately $15.25 million.

Beyond 550°C, both IRR and NPV continue to improve, although the rate of improvement becomes slower. The gradual increase in both indicators provides additional economic benefits as the hot storage temperature increases.

The highest economic performance is achieved at a hot storage temperature of 850°C, where the IRR reaches 9.61% and the NPV is approximately $19.02 million.

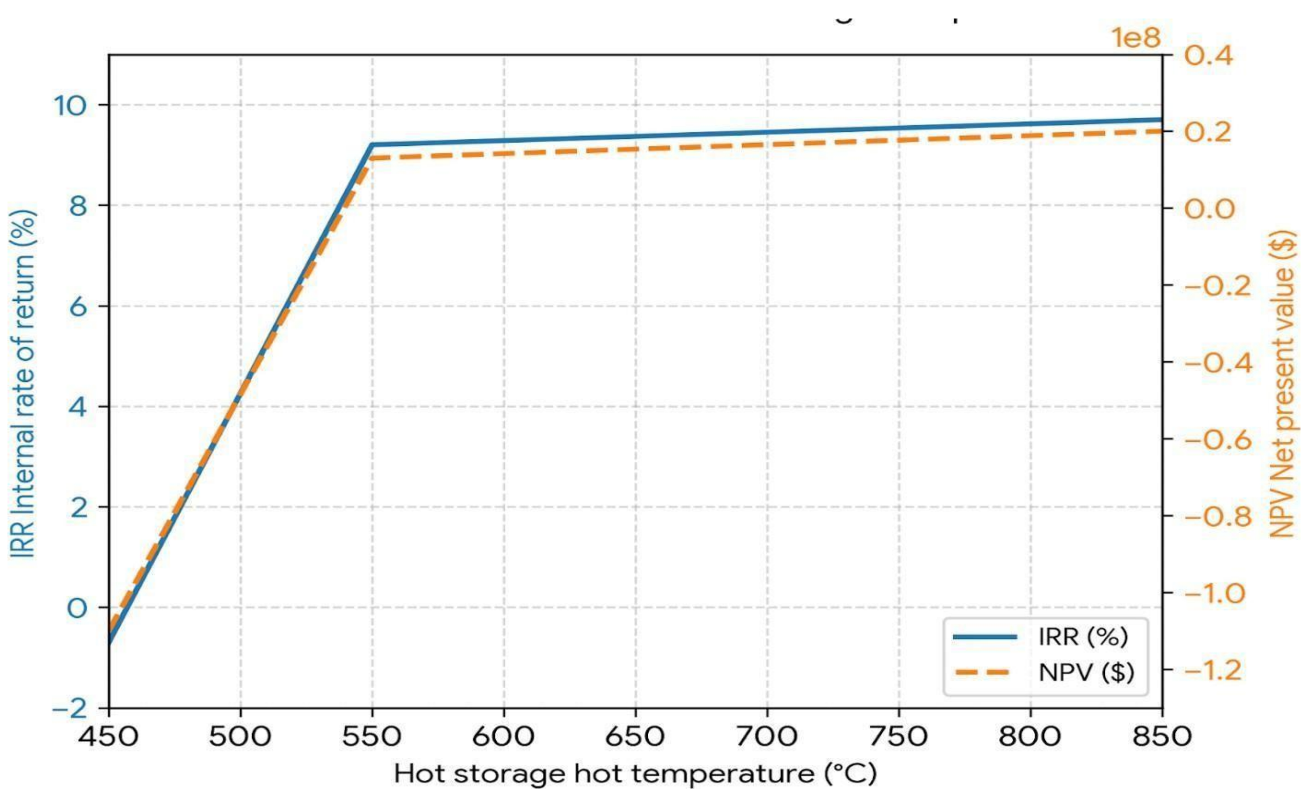

Figure 12 Variation of IRR and NPV with Hot storage hot temperature

Therefore, the improved economic feasibility of the PTES system can be partially attributed to the use of molten salt, specifically Solar Salt (60% $NaNO_3$–40% KNO_3), as the thermal energy storage medium.

Its excellent thermal stability and adequate heat storage properties allow the system to operate at elevated hot storage temperatures, thereby contributing to improved economic performance.

V.9 Conclusion

The performance of the proposed Pumped Thermal Energy Storage (PTES) system was analyzed using the System Advisor Model (SAM), which utilizes a lumped-cycle thermodynamic model suitable for PTES systems operating under the Joule–Brayton (Brayton) cycle.

The working fluid used in this study was nitrogen; the hot storage medium was Solar Salt (60% sodium nitrate–40% potassium nitrate), and the cold storage medium was methanol.

The results of this study indicate that PTES can provide a Long-Duration Energy Storage (LDES) solution for Ain TEMOUCHENT, Algeria, under the climatic conditions of the region. The demonstrated performance characteristics of the PTES system include a thermodynamic round-trip efficiency of 56.6% and a net round-trip efficiency of 52.5%. Furthermore, the PTES system produced a total net electrical energy output of 97.13 MWe while maintaining stable storage temperatures and limiting thermal losses throughout the simulation period.

The estimated capital cost of the PTES project is $311.895.840. The project is expected to achieve a positive NPV ($18,940,000) and IRR (6.35%) over a 30-year period and is projected to recover its capital investment within 11–12 years, with continued positive cash flow thereafter.

Additionally, the results of the parametric analysis indicate that optimizing the storage duration and increasing the hot storage temperature can further improve the economic performance of the PTES system.

Finally, the results demonstrate the technical feasibility and economic potential of PTES for large-scale energy storage and renewable energy integration in Ain TEMOUCHENT, Algeria.

General Conclusion

General Conclusion

The aim of this project was to investigate the potential of Pumped Thermal Energy Storage (PTES) as a large-scale, long-duration energy storage solution capable of supporting the integration of renewable energy into modern power systems through the technical and economic assessment of a Brayton-cycle PTES system in Ain TEMOCHENT, Algeria.

This study began by examining the challenges associated with the energy transition and the increasing penetration of intermittent renewable energy sources, such as solar and wind power. The limitations of conventional energy storage technologies, including Pumped Hydro Storage (PHS) and lithium-ion batteries, were also highlighted, emphasizing the need for alternative energy storage solutions. A comprehensive review of PTES technology was then presented, covering its operating principles, main components, thermodynamic cycles, performance indicators, and economic aspects.

A thermodynamic model of the proposed PTES system was developed based on the principles of mass and energy conservation. Detailed analyses of the charging and discharging processes, thermal storage units, and major system components were subsequently carried out. The System Advisor Model (SAM) was then used to evaluate the technical and economic performance of the proposed system.

The results obtained from this study confirmed that the proposed PTES system is capable of providing effective long-duration energy storage while maintaining satisfactory thermodynamic performance. The simulation results also demonstrated promising economic indicators, further supporting the feasibility of PTES for future renewable energy applications. In addition, the parametric analysis revealed that both storage duration and hot storage temperature have a significant influence on the overall economic performance of the system.

In conclusion, this study demonstrates that PTES is a promising and viable energy storage technology. The results confirm its potential to facilitate the integration of renewable energy sources, enhance grid flexibility, and contribute to the development of more reliable and sustainable electrical power systems in Algeria.

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