Thermodynamic Analysis of a Solar-Driven CCHP System Powered by Photovoltaic Thermal Collector and Organic Rankine Cycle

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Copyright Statement

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I would dedicate this work to my parents and then my sisters. Without their love and support, reaching this point would not have been possible.

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Nomenclature

PVT	Photo voltaic Thermal
PTC	Parabolic Through Collector
ORC	Organic Rankine Cycle
$VCRC$	Vapour Compression Refrigeration Cycle
$LCOE$	Levelized Cost of Energy
TES	Thermal Energy Stage
HTF	Heat Transfer Fluid
CHP	Combined Heat Power
CCHP	Combined Cooling Heating Power
CSP	Concentrated Solar Power
$F\dot{P}C$	Flat Plate Collectors
$\dot{Q}$	Heat Transfer Rate (W)
$\dot{m}$	Mass flow rate
U_L	Overall loss heat transfer coefficient (W/m^2 K)
U_{tf}	Overall heat coefficient from glass to water through ($W/m^2.K$)
L	Length (m)
K	Thermal conductivity (W/m.K)
ins	Insulation
h_{conv}	Convection heat transfer coefficient
A_c	Collector area
F_R	Heat Removal Factor
K	Thermal conductivity (W/m.K)
$C_{p,w}$	Heat Capacity of water
T_{c}	Cell Temperature

A_r	Receiver Area
A_g	Glass cover area
$h_\mathrm{r,r-c}$	Lineraized radiation coefficient between glass and receiver
h_w	Convective (wind) heat transfer coefficient
k_std	Thermal conductivity at standard temperature
λ	Mean free path between collisions
D_g	Inside Glass cover Diameter
D_t	Outside receiver pipe diameter
$h_\mathrm{c,c-a}$	Convective heat transfer coefficient of glass
ε_g	Glass cover emissivity
T_g	Glass cover temperature
T_a	Ambient Temperature
h_f	Convective heat transfer coefficient inside the receiver tube
F'	Collector efficiency Factor
U_o	Overall Heat Transfer coefficient
C	Concentration Ratio
Q_s	Rate of energy stored in Tank
Q_l	Rate of energy removed from Tank to load
Q_tl	Rate of energy loss from Tank
$T_\mathrm{s-n}$	New Storage Tank Temperature
T_s	Storage Tank Temperature
$(UA)_\mathrm{s}$	Storage Tank loss coefficient and area product (W/°C)

Subscript

i	Input
o	Output
Net	Produced – Consumed
el.	Electrical
st.	Storage
G	Solar Irradiation
Ref.	Reference
Sub.	Sub cooler
T	Transmittance
Th	Thermal
PP	Pitch Point

Greek Letters

h	Enthalpy (KJ/Kg)
s	Entropy (KJ/Kg. K)
η	Thermal Efficiency
α	Absorptance
β	Power Transfer Coefficient.

Abstract

Global energy demands are spurring explorations into diverse renewable resources, spanning solar, geothermal, and biomass reserves. Around the world, researchers are intensifying their focus within these domains to unearth the most fitting solutions. A notable avenue in this endeavor lies in the advancement of CCHP (Combined Cooling, Heating, and Power) systems, epitomizing the concept of polygene-ration. The nucleus of this study revolves around an intricate investigation into a specific CCHP system, a nucleus of innovation in itself. Within this system, the synergy of solar energy finds resonance through a dual-pronged approach. The cooperative prowess of a PVT (Photovoltaic Thermal Collector) and a PTC (Parabolic Trough Collector) intertwines, magnifying their individual capabilities. This union gains momentum as the stage welcomes ORC (Organic Rankine Cycle), converting heat into work seamlessly. Three key factors - mass flow rates, refrigerant choice, and solar radiation levels - drive our experiments. These variables create a complex landscape, revealing profound insights. Notably, increasing the mass flow rate in the PVT system from 0.01 to 0.01583 causes a 2.9% efficiency drop, sparking interest in optimizing performance. We then explore refrigerants, with R600 shining brighter than R123 in this intricate tapestry. This dichotomy in performance ushers forth a pivotal crossroads, channelling an inevitable divergence toward the efficiency prowess encapsulated within R600.

In synthesis, this report propels us into the intricate dynamics of complex systems. It beckons us to recalibrate our understanding of mass flow dynamics, celebrate the ascendancy of specific refrigerants, and ultimately invites us to grasp the symphony that is the CCHP system—an intricate overture to the grand symphony of sustainable energy. As the trajectory of research unfolds, it unfurls a panorama of possibilities, poised to reshape the landscape of energy polygene-ration.

Keywords: *Poly-generation–CCHP, Storage Tanks, Vapour Compression Refrigeration Cycle ,Organic Rankine Cycle ,Photovoltaic Thermal Collectors, Parabolic Trough Collector ,Engineering Equation Solver ,Solar Irradiation ,Mass flow rate*

Chapter 1. Introduction

1.1. Overview

Global warming, depletion of the natural resources, ozone depletion are global issues not hidden by any one of us. Much of the work has been done over decades and the research is still going on to make use of renewable energy sources, waste energy to make sustainable green systems. One such solution to address this problem is the implementation of polygene ration systems like: Combines Heating, Cooling, Power generation and combined heating and power generation. It aims to fulfil different energy needs while maximising energy efficiency and minimising environmental effects by using poly-generation systems in the building sector. A promising approach to meeting the many energy requirements of buildings is the production of heating, cooling, electricity, and other important outputs in a single integrated system, which promotes higher sustainability and resource optimisation. [1,2]. Wide-ranging uses for poly-generation can be found in the utility industry, large buildings, district heating and cooling systems, and several industrial fields like pulp, paper, plastic, rubber, steel, chemical, and food.

Sustainable energy systems must be developed using renewable energy sources, such as solar, hydro, biomass energy and wind. A poly-generation facility can run on both biomass and fossil fuels.[3]

Renewable or non-renewable energy sources may be used as inputs for poly-generation, which produces primarily electricity, heat, cooling, chemicals, liquid or gaseous fuels, drinkable water, etc. Poly-generation can be configured in many different ways. It primarily depends on the input and output energy sources. Different energy conversion devices can be used to convert primary energy to secondary energy, and they are chosen based on configurations, as well as technological and socio-economical viewpoints. [4].

1.2. Purpose of the Thesis

The need to utilise renewable resources with unprecedented effectiveness has become clear in the face of rising global energy demands and growing environmental concerns. There has been a noticeable uptick in efforts in this area over the past few decades, which has resulted in an urgent need for creative solutions. The introduction of poly-generation systems, which epitomise multimodal energy optimisation, is one glorious solution to this loud call. A fundamental understanding of solar energy's limitless potential is at the core of this paradigm shift. These systems act as illustrative beacons, skilfully combining the sounds of various solar sources to create an array of cooling, electricity, and power. These output spectrum, carefully honed with creativity, are a monument to their usefulness, clearly indicating a path towards self-sufficiency.

Ensuring a reliable water supply, the very essence of domestic life, stands as a fundamental pillar of comfort and convenience. This aspect holds an essential place, extending beyond the realm of machinery and measurements. Herein lies the significance of a well-designed storage tank—an ingenious reservoir, purposefully crafted to stand as a sentinel guardian. Within its confines rests a bounty of sustenance, adeptly catering to the elemental needs of households.

The goal of this study, in conclusion, has the potential to be transformational. In a subtle interaction between use and conservation, it promises to unfold a tapestry where sustainable development and renewable energy dance in harmony. The exploration canvas opens up a world that not only satisfies urgent wants but also creates a road to a more peaceful cohabitation with the resources of our earth.

R600 stands out as a shining protagonist inside this refrigerant tapestry, unfolding a tapestry of higher performance in comparison to R123. This performance split revolves around a crucial junction, causing an unavoidable divergence in the direction of R600 as the model of efficiency. In conclusion, this paper propels us into the world of complex system dynamics. In the end, it encourages us to comprehend the symphony that is the CCHP system—an elaborate prelude to the symphony of sustainable energy.

It calls for us to revaluate our understanding of mass flow dynamics, rejoice the triumph of particular refrigerants, and finally grasp the symphony that is the CCHP system. The future unfolds before us, ripe with opportunity, as our research prepares the ground for ground-breaking developments in the field of energy polygene-ration.

1.3. Thesis Lay-out

This thesis contains the following chapters in mentioned order. The order has been kept in such a way to make it self-explanatory for the reader.

- **Chapter 1 – Introduction:** Chapter one highpoints the reason why this study needs to be carried out and what problem is being targeted in this thesis.

- **Chapter 2 – Literature Review:** This section talks about the past work that has already been done and how this thesis differs from those previously completed studies.
- **Chapter 3 – System Description:** The system under consideration is explained in detail along with schematic diagram of plant.
- **Chapter 4 – Analysis:** This chapter discusses the procedures and equations used for carrying out the thermodynamic analysis and predictive modelling of the power plant.
- **Chapter 5 – Results-and-Discussions:** This chapters talks about the results obtained from the analysis and how this data is interpreted.
- **Chapter 6 – Conclusion:** This chapter provides a brief summary of the whole study.
- **Chapter 7 – Future Work:** This chapter will highlight limitations and/or constraints in this study that should be avoided or improved upon in future studies.

Chapter 2. Literature review

In addition to examining the various system integrations of the Polygene ration/CCHP (Combined Cooling, Heating, and Power) systems, this chapter will highlight the advancements in this subject and provide insight into the work done by many researchers. This particular section seeks to delve into the extraordinary developments in this field, illuminating the cutting edge of innovation and providing a thorough overview of the multifarious projects carried out by various researchers. It will also meticulously examine the different complex configurations by which the idea of polygene ration / CCHP (Combined Cooling, Heating, and Power) systems is cleverly used to actual applications.

Throughout this chapter, a meticulous exploration of the advancements that have transpired in this specialized field will be undertaken. By delving into the vanguard of technological evolution, a panoramic view of the remarkable strides taken will be elucidated, signifying the evolving landscape in which profound contributions are being made. The numerous research projects conducted by a variety of researchers, each with their own distinct perspectives and cutting-edge approaches, will also be meticulously examined in this chapter. This kaleidoscope analysis will provide a comprehensive view of the various routes taken, unravelling the intellectual web built by these specialists in their quest to advance CCHP and polygene ratio systems. The careful examination of several integrative paradigms that support the practical implementation of polygene ratio and CCHP systems is a key focus of this work. These intricately designed and multipurpose integrations are proof of the fusion of many engineering approaches and sustainable energy principles. We'll go into detail about the basic principles of these integrative frameworks to provide you a detailed understanding of how cooling, heating, and electricity generating operate together in unison. In summary, by highlighting the efforts of both researchers and practitioners, this chapter serves as a beacon lighting the way forward in this dynamic subject. It serves as a cornerstone for understanding the complex history of polygene ratio and CCHP systems' evolution and use through an unmatched investigation of advancements and a thorough deconstruction of system integrations.

2.1. Solar Collectors

2.1.1. Parabolic Trough Collector

Over time, there has been an exponential rise in the use of solar energy. Researchers have created numerous methods to maximise the utilisation of solar energy, which may subsequently be transformed into useful heat or power, due to their abundance. [4]

Solar collectors are designed to capture incident solar radiation and convert it into two distinct forms of energy: thermal energy (referred to as thermal collectors) and electrical energy, generated by photovoltaic panels (PV). However, there exists a category of collectors that possesses the unique capability to simultaneously produce both heat and electricity, a technology commonly referred to as thermal photovoltaics (PVT). These collector systems can be broadly classified into two main categories: concentrating collectors, which typically operate at higher temperatures, and non-concentrating collectors, often known as flat collectors. Concentrating collectors are frequently integrated with various thermal devices to enhance their efficiency.

The Figure 1 Illustrates collectors employed in the poly-generation systems. Due to its inexpensive cost and decades-long use, FPCs are the most popular and widely used solar collectors. They work well for residential hot water applications and space heating and can withstand temperatures of up to 100 Celsius. But they operate at lower temperatures and provide lower overall system efficiencies. It, therefore, is recommended that they be paired with other renewable sources to provide higher system efficiencies. A model comprising solar collectors (FPCs), thermal storage tanks, biomass boilers and cogeneration units was developed and studied for different weather conditions in Spain. The scheme was able to cater for 50% of the urban thermal energy demands, analyzed from results [5]. Another research investigation examined the effectiveness of a hybrid solar-assisted tri-generation system designed to fulfill the energy requirements of a three-story building. This integrated system included evacuated tube collectors, a micro combined heat and power unit powered by natural gas, two storage tanks, an absorption heat pump, and an auxiliary heating component. The solar fraction achieved its highest point at 53.5%, signifying the proportion of energy derived from solar sources, while the solar collector itself demonstrated an impressive net efficiency of 49%. [6]. But there aren't many studies that use evacuated tube collectors that can be found within the literature. A multitude of studies has been done on the use of parabolic trough collectors in poly-generation systems, primarily because of their capacity to operate at temperatures between 400 and 500 degrees Celsius. The PTC essentially comprises an evacuated tube receiver and a linear parabolic shape concentrator and typically uses only the beam sun irradiation. For the objective of combining cooling, power, and desalination, a hybrid solar-biomass system is created and assessed by adjusting numerous parameters. PTCs are utilized to supply the system with primary heat, whilst biomass boilers are employed to supply secondary heat input. The system as a whole had a 49.35% efficiency [7].

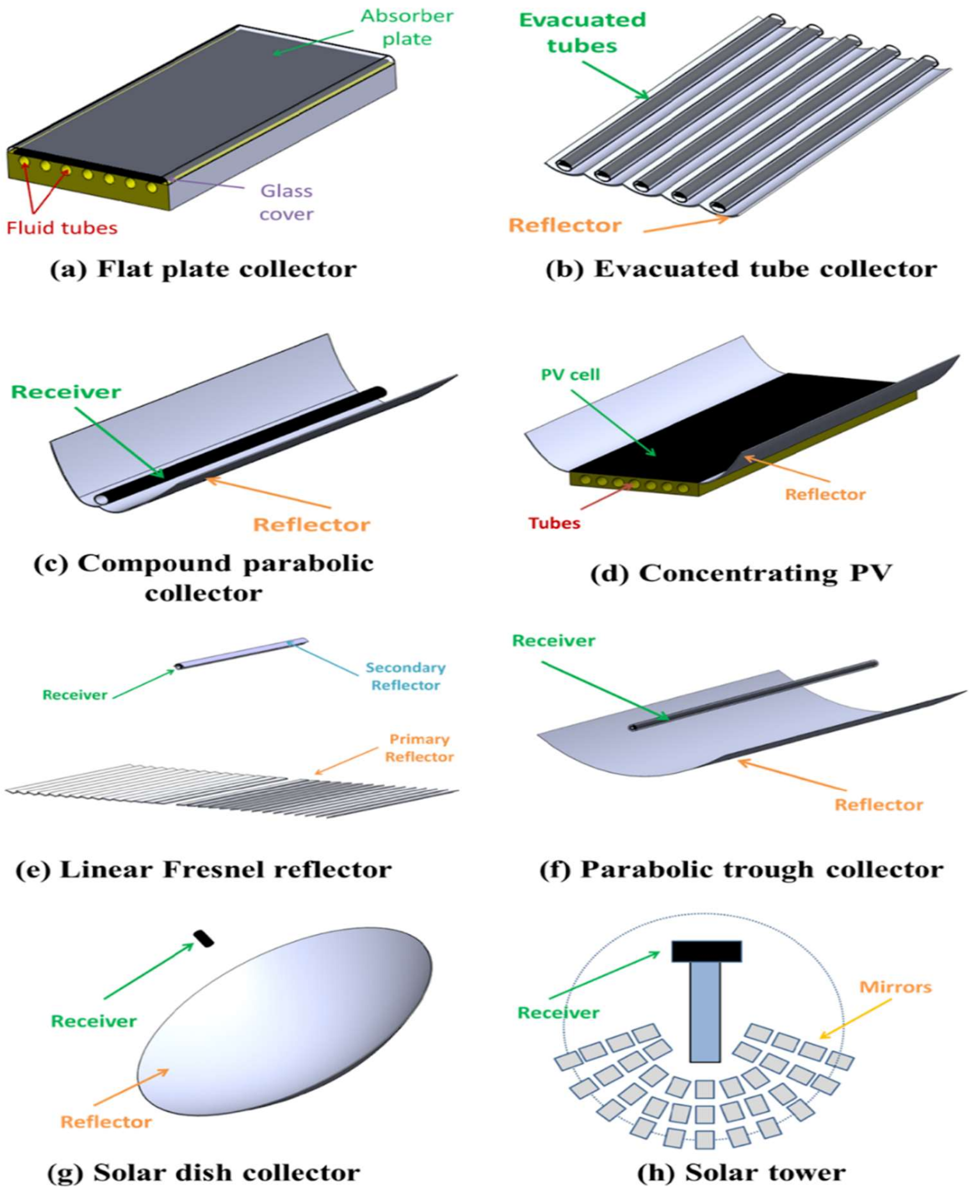

Figure 1.Solar Collectors Types

Three operating modes of a CCHP system are analyzed: solar, solar with storage, and storage. Storage tanks, ORCs, and PTCs made up the model. In the solar mode, the system offered maximum electrical and energy efficiency of 15% and 94%. Therminol-66 is chosen as the fluid in the solar subsystem, a commercial oil suitable for thermal solar systems and thermal storage tanks. Therminol-66 has an operating temperature range of 0-345°C and low relative pressure. The solar subsystem includes two thermal storage tanks, one for hot oil, used as the heat input to the ORC ad after cooling down, it is stored as cold oil [8].

Another investigation was carried out to produce hydrogen and generate power using parabolic solar dishes and troughs integrated separately with Rankine cycles and electrolyzes. According to the comparison study's findings, parabolic dish solar collectors perform better than parabolic trough collectors, with a rate of hydrogen reduction of 0.0322 g/s compared to 0.02454 g/s for PTCs. Improved solar dish collector performance is also implied by the usage of Nano fluids [9]. These results are also supported by [10], who found that employing Nano fluids as the working fluids increased the thermal efficiency of solar collectors by 5%.

To achieve optimal efficiency and a rapid return on capital investment, advanced solar energy utilization technologies demand high-quality energy sources. Concentrated Solar Power (CSP) technology emerges as a versatile solution capable of meeting both thermal and electrical energy demands. The integration of CSP technology with a parabolic trough collector (PTC) system offers several benefits, including a favorable return on investment, well-established technology, and ease of integration with fossil fuels or other renewable energy sources.

This study started out by discussing the PTC system's theoretical foundation for CSP technology. The original full derivation procedure of the PTC's maximum theoretical concentration ratio was then provided. The capabilities of several different kinds of heat transfer fluids in tube receivers were examined.

Also discussed were new advancements in heat transfer improvement techniques for CSP technology with PTC systems. The techniques of thermal deformation and strain for tube receivers were also studied because it was commonly noticed that glass coverings ruptured during application. Worldwide commercial CSP plants with PTC systems that we represented, whether they are operational, under construction, or have just been announced. Last but not least, potential future advancements of CSP plants using PTC systems were shown. Additionally, recommendations for future research were offered, along with application instructions. [31]

In 2012, Kalogirou conducted a study involving the use of a reflective sheet shaped into a parabolic trough to create a solar collector. This collector featured a black metal pipe covered by a glass tube to reduce heat loss. Solar radiation concentrated along the focal line heated the fluid flowing through the receiver tube. The study included a detailed thermal model of this collector, considering all heat transfer methods, such as convection, conduction, and radiation. This model was created using the Engineering Equation Solver (EES) and validated against established collector performance data. It was subsequently used to analyse a collector to be installed at the Archimedes Solar Energy Laboratory, Cyprus University of Technology. [32]

According to study conducted in 2018 by Kasaeian and his colleagues, of all photovoltaic thermal units that have recently been produced, photovoltaic thermal systems are of great interest. In the context of concentrating devices, trough collectors and Fresnel lenses—both of which are successful linear parabolic collectors—are more important. Numerous articles regarding these collectors have been published, demonstrating their value in the effective cogeneration of heat and power. Therefore, it is intriguing to compile and discuss all the relevant research articles in one piece in order to demonstrate the history and most recent advancements in this area.

Trough- and Fresnel-based photovoltaic thermal systems are critically examined in this study. Trough and Fresnel lens chapters are divided into three sections: experimental, hybrid research, and analytical-simulation works. For each of the aforementioned categories, specific tables for the experimental works are provided. The survey comes to a close with some gaps found and suggestions for further research. [33]

Companies are commercializing Linear Fresnel Collector (LFC) technology for solar thermal power plants. This study compares LFC and Parabolic Trough Collectors (PTC) costs for direct steam generation, with PTC as the industry standard. LFC lacks cost data for typical CSP plants. Break-even cost, matching PTC power generation costs, varies between 78 and 216 €/m2 for LFC solar fields, depending on assumptions. LFC's horizontal mirror setup reduces aperture-linked optical efficiency but requires a lower cost per m2 than PTC. The potential cost savings make LFC an attractive collector, pending meeting outlined cost and performance targets. [34]

2.1.2. Photovoltaic Thermal Collector

Other solar devices used in poly-generation systems are photovoltaic thermal collectors. Photovoltaic modules use solar energy to produce electricity, whereas photovoltaic/thermal collectors generate both electricity and usable heat. The improvement of electrical and thermal efficiency is one of the key objectives of photovoltaic collectors and photovoltaic/thermal collectors. These collectors could be coupled with other power generation equipment to boost overall efficiency and solve the aforementioned problem.

A new hybrid system was devised for producing hydrogen, power, cooling, and heating was examined, utilizing solar PVT modules for heating, water heating, and hydrogen production, while geothermal energy was used for power, cooling, and hydrogen production, and the system was tested for a residential area. Different parameters were varied (ambient temperature, pressure, mass flow rates, solar irradiance and working fluids) to determine the overall performance of the system. The highest system efficiency was 10.8% for a water temperature of 210 Celsius, for geothermal [11]. The author conducted another study comprising an integrated system of PVT, ORC, and absorption chiller, geothermal well, heat pump and thermal energy storage, which showed an energy efficiency of 11% [14].

An analysis of a poly-generation system composed of an ORC, PVT, RO desalination unit, a water heater, and an absorption chiller was reported in another study. The findings showed that solar radiation intensity, condenser temperature, PV/T collector length, PV/T collector width, PV/T inlet air mass flow rate, and evaporator pinch point temperature difference have a significant impact on system performance [12]. To provide space heating, cooling, electricity, and domestic hot water for a modest residential building, a model that included heat pumps and adsorption chillers and was powered by photovoltaic thermal collectors was simulated in TRNSYS. PVTs were able to achieve 49% energy efficiency. The study's conclusions also showed that places with higher sun irradiation can achieve higher system performance, and solar-assisted heat pumps are enough for the required space heating [13]. Another study using PVTs, ICE, storage tanks, and absorption chillers was conducted with the same goal of providing power, cooling, and domestic hot water. The system indicated 56 tonnes of CO2 emissions reduced and an energy cost reduction of 35 to 58% [15].

Hybrid PV-T collectors were the subject of research by Herrando et al. (2023), who provided a thorough assessment of both their existing condition and future prospective uses. The study highlights opportunities for performance enhancement and innovation by addressing both experimental and computational elements.

The classification and reviews of a variety of PV-T collector types, including air-based, liquid-based, dual air-water, heat-pipe, integrated, and concentrated collectors. Design improvements, advanced PV cell technology, coatings, spectrum splitting, and Nano fluids are investigated as performance boosters. The discussion of PV-T systems' larger uses includes solar combined heat and power, cooling, desalination, drying, and hydrogen generation, as well as tips on managing and storing thermal energy. With expanded use of solar PV-T technologies, the research predicts a possible decrease in emissions of 16% by 2030 from the REmap baseline emission curve. Also covered are obstacles and suggestions for adopting PV-T. [40]

Researchers F. Calise, M. D. d'Accadia, and L. Vanoli investigated a solar heating and cooling (SHC) system in 2012. This system combined photovoltaic and thermal (PVT) collectors to provide energy, space heating and cooling, and domestic hot water in a novel poly-generation arrangement. There were PVT collectors that could operate up to 80 °C. A case study using a university building in Naples, Italy was the research's main emphasis. PVT collectors, a single-stage LiBr-H2O absorption chiller, storage tanks, auxiliary heaters, and other parts including heat exchangers, pumps, controllers, and cooling towers were all included in the system. The PVT system produced heat for the absorption chiller in addition to producing energy for building usage and grid sales. A zero-dimensional transient simulation model created with TRNSYS was used in the study to examine system performance while taking both energy and economic factors into account. Economic results showed viability with suitable financing strategies, and overall results matched those of systems described in the literature that were similar to them. [41].A concentrating photovoltaic/thermal (CPVT) system was presented by Mittelman, Kribus, and Dayan in 2007. This system produces both electrical and high-grade thermal energy at temperatures over 100 °C. Processes like desalination, steam generation, and refrigeration may all be powered by this thermal energy. They thoroughly investigated a CPVT system with single-effect absorption cooling. According to the results, combined solar cooling and electricity generation might frequently outperform traditional choices under various economic circumstances. The research admits that its assessments are dependent on variables like site selection and regional economy.

The choice of site significantly influences yearly insolation, affecting solar capacity and fraction. Economic changes also have an impact on the rivalry with conventional energy, as shown by the difference between high energy costs of $3.25/Wp and low energy prices of $1/Wp and $1.5/Wp.[42]

Global interest in solar energy as a renewable resource was highlighted by Shan et al. (2014). They divided solar energy consumption into photovoltaic and thermal systems. Normally, they are distinct, but a hybrid technology called a photovoltaic-thermal collector (PV/T) combines both to do away with the need for traditional power. The performance of PV/T collectors and applications such as heat pump configurations and integrated systems were evaluated by the researchers. They evaluated variables influencing system properties. [43]

2.2. Organic Rankine Cycle

The Organic Rankine Cycle (ORC) is a valuable method for generating electricity at temperatures up to 400°C, with outputs of up to 10 MW. Its compatibility with the working temperatures of solar thermal collector technologies makes it a feasible choice for harnessing solar irradiation to power an ORC, offering a renewable energy solution. Essentially, an ORC is similar to a steam Rankine cycle, but it uses an organic fluid with a lower boiling point to operate efficiently with lower-temperature heat sources. Notably, for smaller systems, typically those under a few MW in size, ORC systems exhibit higher efficiency compared to steam turbines. [16]. The ORC is an emerging technology that is mostly used in China, Japan, Europe, and the USA [17]. In 2021, Loni et al. conducted research highlighting the organic Rankine cycle (ORC) as a reliable method for generating electricity up to 400 °C and capacities of 10 MWel. Solar thermal collector compatibility with the cycle's temperature requirements establishes solar-ORC as a promising renewable energy solution. This review provides an overview of different solar-ORC systems investigated in academic literature. These systems encompass a range of designs, such as flat plate, evacuated tube, compound parabolic, parabolic trough, linear Fresnel, dish concentrators, and solar towers.Various solar thermal technologies are studied for ORC power generation, encompassing simulations and experiments. Heat storage methods and hybrid systems are thoroughly explored. Additionally, ORC-based systems demonstrate high sustainability indices, offering cooling, heating, and freshwater. The paper also identifies research gaps and advocates for trigeneration and poly-generation systems to advance solar-ORC technology and broader sustainable energy systems, more than 37% of the publications taken into consideration dealt with this type of integration, making PTCs the most often used collectors for powering ORC systems. PTCs performed better than other types of collectors in the majority of situations [19].

Toluene produced the best results when compared to n-octane, MDM, and cyclohexane in the examination of a solar tri-generation system consisting of Nano fluids based on ptcS, orc, and an absorption heat pump [18].

A new CCHP-ST-ORC system that includes a normal CCHP system, a ST subsystem, and an ORC subsystem was suggested in 2019 by Wu, D., Zuo, J., Liu, Z., Han, Z., Zhang, Y., Wang, Q., and Li, P. Additionally, the thermodynamic performance of the three systems—CCHP, CCHP-ST-ORC, and CCHP-ST—based on a 100 kW GICE—was compared. It was suggested and accepted in a residential building to operate the CCHP-ST-ORC system in a novel way that offers superior thermodynamic efficiency than the CCHP-ST system. In comparison to the other two systems, the CCHP-ST-ORC system could generate 5.1 kW more electricity at the price of 39.3 kW more heat.The maximum power generation might be increased to 108 kW. According to the example study, the CCHP-ST-ORC system's main energy ratio is 60.2% as opposed to the CCHP-ST system's 37.6%. The CCHP-ST-ORC system, which uses 12.4% less energy than the CCHP-ST system, utilizes 9.81 104 m3/year of natural gas, according to the data. Therefore, these results can encourage the long-term creation of novel energy use models, particularly the coupling CCHP system.[35]

Organic Rankine cycles and supercritical Rankine cycles were examined for low-grade heat conversion into electricity in a research study carried out in 2010 by Chen, H., Goswami, D. Y., and Stefanakos, E. K. A supercritical Rankine cycle, which often requires greater operating pressures, has a better thermal match with its heat sources than an organic Rankine cycle.[36]

Han, Z., Li, P., Jia, Y., Fan, W., et al. based on the characteristic properties of the

working fluid and criteria for working fluid selection, analysis of the thermodynamic performance of the organic Rankine cycle (ORC) was studied. Conversion and Management of Energy found that

- Tcr significantly affects 'x' in the heat-addition phase. 'x' values of low TCR fluids with high limiting temperatures difference is higher than high TCR fluids with small limits.
- T1 and T2 are impacted by key parameters. 'x' and 'T1' show opposite trends at low 'Tg,out', but align at high 'Tg,out'. Tz, limiting temp. diff., and Tcra majorly affect T1; T2 and B display opposing patterns.
- Optimal working fluid criteria: Type I for low 'Tg,out; low Tcr with 'Tz' > 'Tsmax; and small limiting temp. diff. Type II: Tz' > 'Tsmax' with high values for limiting temp. diff. and B. Type III for high 'Tg,out; medium or high Tcr with 'Tz' > 'Tsmax; and high values for limiting temp. diff. and B.
- Proposed criterion distinguishes working fluid types based on heat source temp. Type I excels at low 'Tg,out'; Type III excels at high 'Tg,out'.

- 'T' influences ORC performance during heat addition, while 'T2' impacts efficiency more at higher 'Tg,out'. 'Tcr' has limitations in assessing 'T2s influence on ORC performance.[37]

Mahmoudi and their cliques studied and discussed that Critical environmental issues including acid rain, air pollution, and climate change are the result of increasing fossil fuel usage. Heat is a major source of energy loss worldwide. This wasted heat might be recovered to increase system performance while reducing fuel use and CO2 emissions. The organic Rankine cycle (ORC), which effectively transforms low- to medium-temperature sources into electricity, has long been seen as a potential technique for recovering waste heat.

Numerous studies examine ORC technology in diverse situations. The goal of this paper is to summarize recent theoretical and practical ORC research for waste heat recovery, with a focus on the performance impacts of cycle design, working fluid choice, and operating circumstances. This evaluation covers the previous four years, and it concludes with a comparison of statistics pertaining to system setup, working fluid, and heat source.

- In contemporary scholarly work on waste heat recovery, gas turbines, internal combustion engines, and diesel engines predominate as common heat sources.
- Due to multi-grade waste heat recovery, diesel engines mainly use regenerative twin loop ORCs, whereas internal combustion engines and gas turbines prefer regenerative single loops.
- Critical state, sensible heat, and vaporization latent heat ratio are essential thermophysical properties for working fluids. Fluids are improved by mixing, and combinations frequently perform better than pure fluids overall. However, fluid compositions have a significant influence on cycle performance, calling for optimization in the design of ORC plants.
- Different factors, including heat source kinds, operating circumstances, and temperature ranges, have an impact on cycle performance. While greater condensation temperatures have a detrimental influence on ORC performance, higher heat source temperatures have the opposite effect. In order to establish the best operating parameters for each cycle based on thermodynamic and economic criteria, optimization often requires a multi-objective approach.[38]

2.3. Storage Tanks

In recent times, there has been a notable surge in the integration of thermal energy storage tanks within Combined Cooling, Heating, and Power (CCHP) systems. This strategic incorporation serves a vital role in bridging the divergence between thermal energy demand and supply, all the while upholding the overarching performance metrics of the system. This alignment of thermal energy storage with CCHP systems reflects a progressive approach to addressing the dynamic interplay between energy requirements and availability.

The deliberate inclusion of storage tanks introduces a temporal buffer that optimally synchronizes thermal energy supply with the fluctuating demands of the CCHP system. This synergy effectively mitigates disparities between energy production and consumption, fostering a harmonious equilibrium that enhances overall system efficiency and resilience. By orchestrating the marriage of thermal energy storage tanks and CCHP systems, an intricate dance between sustainability, reliability, and performance emerges, delineating a pathway towards energy optimization in the face of ever-evolving demand patterns. [20] Forecasts indicate that the implementation of such systems holds the potential to yield a substantial reduction in CO2 emissions, estimated at approximately 5.5%. This projection underscores the pivotal role that these integrated approaches can play in advancing environmental sustainability and curtailing the carbon footprint. By harnessing the synergies inherent in these systems, a tangible and quantifiable contribution towards mitigating the adverse impacts of greenhouse gas emissions emerges. This prospective CO2 reduction, while encompassing a numerical value, resonates on a broader scale as a step forward in the global effort to combat climate change. The envisaged reduction not only underscores the efficacy of these systems but also underscores their potential significance in aligning with emission reduction goals and fostering a more sustainable energy landscape. [21]

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these systems but also underscores their potential significance in aligning with emission reduction goals and fostering a more sustainable energy landscape. [22, 23].

Starting with Aquifer system, these are long term underground storage tanks, made up of rock and containing ground water which can be extracted from wells, and have a capacity ranging from 100kW to 30MW. However, the main problem with these systems is their application in densely populated areas. [24].

To combat the escalating environmental issue of CO2 emissions, the globe is adopting renewable energy options at an astounding rate. Because they don't emit any greenhouse gases or other harmful pollutants, renewable energy sources have a huge potential to reduce carbon emissions. However, the RES is dependent on generating energy from natural sources like sunshine, wind, water, and geothermal, which are frequently erratic and dependent on the time of year, season, and weather. Renewable energy can be stored using a variety of methods, and then used consistently and under control as necessary to adjust for these erratic patterns. Over the past century, numerous scientists from all over the world have made significant contributions to the creation of cutting-edge energy storage techniques that are effective enough to keep up with the rising demand for energy and technological advancements. This review aims to offer a critical analysis of the developments in energy storage systems from 1850 to 2022, covering their development, classification, underlying concepts, and comparison. [25]

The study encompasses hermetic Thermal Energy Storage (TES) methods, including sensible, latent, and thermochemical storage. It addresses applications in solar farms and industries, focusing on Phase Change Materials (PCMs) for sensible and latent heat storage, particularly in high-temperature scenarios. Thermochemical storage potential is indicated. The article underscores the relevance of storage medium temperature and TES's role in reducing renewable energy costs. Containment options for storage materials are explored, proposing particle suspensions as Heat Transfer Fluids (HTFs). Innovations like encapsulation techniques, powder circulation loops, improved PCM conductivity, and lithium salt utilization are discussed. The review merges novel concepts with established knowledge, highlighting TES's importance for efficient, lasting energy storage the analysis identifies key research goals: (i) advancing PCMs and associated enhancement techniques; (ii) testing nanoparticle-encapsulated PCMs; (iii) scaling up and confirming TCS storage methods, focusing on endothermic/exothermic reversibility; and (iv) large-scale testing of appropriate PCM/TCS systems. Furthermore, the study emphasizes the significance of analyzing entropy generation in optimizing system design and operational parameters. [26]

District heating systems effectively supply heat to residential, tertiary, and industrial clients. Typically, CHP (combined heat and power) facilities fulfill the base thermal load, accounting for roughly 40-50% of maximum capacity, while the remainder is managed by boilers. By integrating storage tanks, the operational window of CHP plants could be extended. This involves generating heat during periods of low demand, like nighttime, storing it, and releasing it during high-demand times. Boilers are also utilized, leading to a partially diminished thermal load and a steady thermal load pattern. The potential impact on power generation varies based on the specific CHP plant type, a particularly crucial consideration in a competitive electricity market. This study introduces a comprehensive storage tank model suitable for evaluating storage system performance over the heating season, predicting its effects on primary energy consumption, and anticipating financial outcomes. The district heating system in Turin serves as a practical case study. The findings suggest the potential to reduce primary energy consumption by up to 12% and overall costs by approximately 5%. [27]

In the year 2000, Nordell, B. O., and Hellström, G. conducted an initial investigation into a low-temperature space-heating system powered by solar energy and featuring seasonal ground storage. They utilized the DST ground storage module and simulation models TRNSYS and MINSUN to evaluate the system's performance. The research aimed to propose a financially feasible design for a total annual heat demand of 2500 MWh. The primary focus was on Anneberg, a planned community consisting of 90 single-family homes with a combined heat requirement of 1080 MWh. The suggested heating setup incorporated 3000 m^2 of solar collectors and electric heaters, contributing to a 60% solar fraction to achieve peak heating capacity. The floor heating system was designed with a target supply temperature of 30°C.

For seasonal storage, a 60,000 m^3 borehole array embedded in crystalline rock was utilized, maintaining temperatures between 30°C and 45°C throughout the year. The study analyzed the overall yearly heating costs for three different systems: solar heating (1000 SEK MWh), small-scale district heating (1100 SEK MWh), and individual ground-coupled heat pumps (920 SEK MWh). These costs encompassed all expenses, including capital investment, energy consumption, maintenance, and more, associated with the heating system.

Notably, approximately 42% of the captured solar energy was lost as heat in the Anneberg storage system. To address this loss, an instance was examined wherein the projected size of the solar heating system was tripled, as this could potentially mitigate heat loss in a larger storage system. [28]

Kuravi, Goswami, Y., Stefanakos, E. K., Ram, M., Jotshi, C., Pendyala, S.,... & Krakow, point out that thermal energy storage is essential for dealing with the cyclical nature of concentrating solar thermal power (CSP) plants. It helps cut down the levelized cost of energy (LCOE) by extending the power block's operational time. They explain that heat can be stored in different ways, like sensible heat, latent heat, or through chemical processes. The article focuses on USF's latent heat storage method. Such systems hold more energy but face slow charging due to low thermal conductivity in most phase change materials (PCMs). USF's innovation involves enclosing PCMs in small capsules and boosting heat transfer through liquid immersion. USF's unique method caters to high-temperature PCMs, which are valuable for thermal energy storage (TES) in CSP facilities. This innovation could significantly cut system costs compared to existing options. By using an inventive electro less deposition process, the encapsulation becomes affordable. The article covers the factors considered for optimizing this process, presenting initial outcomes. [29]

A tri-generation system based on parabolic trough solar collectors and a thermal energy storage tank was developed in 2021 by Xi, Z., Eshaghi, S., and Sardari, F. for the simultaneous production of power, heating, and freshwater. The suggested system is examined from the perspectives of energy, exergy, and exergy economics. Additionally, a parametric analysis was used to assess how several fundamental thermodynamic parameters affected cycle performance. Additionally, the multi-objective genetic algorithm is used in conjunction with the LINMAP decision-making technique to determine the system's optimal performance in two optimisation situations. The system could provide freshwater rates of 1.34kg/s, 2423 kW of heating capacity, and 370.1 kW of net output power, according to the data. The calculated values for the product's energy and exergy efficiencies, coefficient of performance, and total cost rate are 34.78%, 13.42%, 0.49, and 176.73 $/h, respectively. Additionally, it is discovered that 56% of all energy is destroyed by the solar component. The parametric investigation shown that raising the RORC evaporator's pinch point temperature leads in higher product costs overall as well as decreased energy and energy efficiency. Additionally, for the second optimisation scenario, the final optimal solution chosen by the LINMAP approach has a minimum cost rate of 157.7 a SD/h and a maximum energy efficiency of 19.87%. and found that a new hybrid system based on thermal energy and solar energy is developed for producing freshwater, power, and heating.[30]

Chapter 3. System Description

3.1. System Description of CCPP

The work presented in this research gives a complete insight of a CCHP system integrated with a storage tank, which is capable of handling the hot water requirements of a household. The system components consist of photovoltaic thermal collectors, vapour compression refrigeration cycle, parabolic trough collectors, and organic Rankine cycle and storage tank. The Figure 2 below illustrates the schematic of the system. Thermodynamic analysis is carried out in the Engineering Equation Solver (EES) to assess the performance of the system.

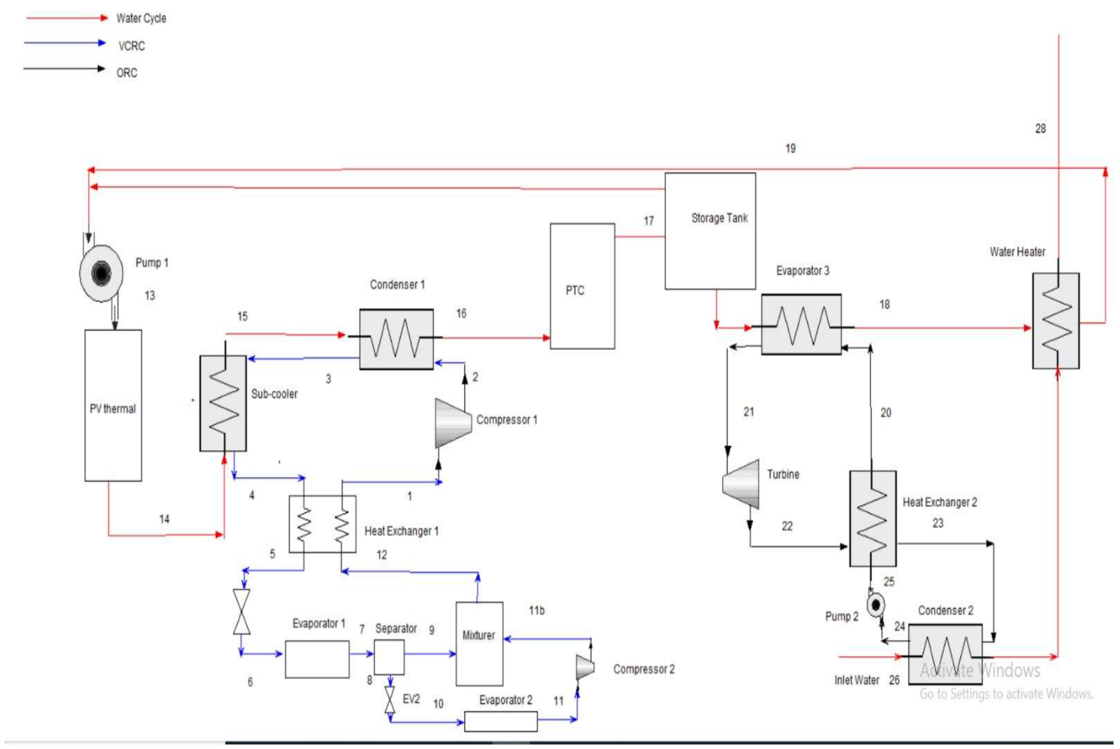

Figure 2.Block Diagram of System

The sunlight incident on the PVT collectors gets absorbed by the individual cells of the solar panel, some of which is then converted into electrical energy using the photovoltaic effect and the rest of of it is used to heat up the fluid passing through them. This heated up fluid passes through the vapor compression cycle and parabolic trough collectors. In the vapor compression cycle, the hot fluid first passes through the sub-cooler which helps to further lower down the temperature of the refrigerant coming from the condenser, thus increasing the overall outputs of the system. The refrigerant then passes through the heat exchanger, cooling the refrigerant further, and then through the throttle valve, which helps in pressure reduction of the refrigerant.

This refrigerant then passes through both the evaporators, separator, and mixing chamber. The purpose of both these evaporators is to produce different cooling outputs, to meet the cooling demand. The cycle is then completed by making the fluid pass first through the compressor, then heat exchanger and then again through the compressor. These three stages help in raising the pressure of the refrigerant flowing through the cycle to a great extent, before then entering the condenser.

The parabolic trough collector is designed in such a manner as to collect and focus all the sun rays onto the receiver tube which then absorbs the heat coming from the sun. This receiver tube has a fluid flowing through it which is heated up, and in this case by double means – solar radiation coming in direct contact and the hot fluid which is also coming from the photovoltaic thermal collectors. This helps in raising the temperature of the output fluid to a greater degree. This output fluid is then transferred to a thermal storage tank and the rest flows through the organic Rankine cycle. The insulated storage tank collects the hot water at a slower rate over a time span of 12 hours. The collected amount of water is enough to cater for the needs of a household. In the organic Rankine cycle, the working organic fluid is in liquid state which passes through the evaporator causing a change of state from liquid to vapor. Then it passes through the turbine where the converted mechanical energy rotates the turbine blades and then the fluid passes through the heat exchanger which transfers the heat between the condenser and the turbine fluid. The pump is used to pressure the fluid moving through the cycle ensuring a continuous flow throughout.

3.1. System Analysis

The major equations used for the system analysis are listed down: [44-51]

3.1.1. PVT Collectors:

$$\eta_{el,PV} = \eta_{el,ref}\left[1 - \beta_{ref}\left(T_{PV} - T_{PV,ref}\right)\right] \qquad (1)$$

$$\dot{W}_{PVT} = GA_{PV}\eta_{el,PV} \qquad (2)$$

$$T_c = T_{in} + \frac{Q_u}{F_R U_L A_c}(1 - F_R) \tag{3}$$

$$Q_u = \dot{m}_w c_{p,w}(T_{out} - T_{\mathrm{in}}) = A_c F_R\left[(\alpha\tau)_{eff} G - U_L(T_{\mathrm{in}} - T_{amb})\right] \tag{4}$$

$$U_L = U_{tf} + (L_{\mathrm{ins}}/K_{\mathrm{ins}} + 1/h_{\mathrm{conv}})^{-1} \tag{5}$$

$$\eta_{th} = \frac{Q_u}{A_{PV} G} \tag{6}$$

$$T_{14} = T_{13} + \frac{Q_u}{m_w C_{p,w}} \tag{7}$$

$$\eta_{PV} = \frac{P_{PV}}{A_{PV} G} = \eta_{PV,R}[1 - \beta_R(T_{\mathrm{cell}} - T_{amb})] \tag{8}$$

3.1.2. PTC:

$$U_{\mathrm{L}} = \left[\frac{A_{\mathrm{r}}}{\left(h_{\mathrm{w}} + h_{\mathrm{r,c-a}}\right)A_{\mathrm{g}}} + \frac{1}{h_{\mathrm{r,r-c}}}\right]^{-1} \tag{9}$$

$$U_{\mathrm{o}} = \left[\frac{1}{U_{\mathrm{L}}} + \frac{D_{\mathrm{o}}}{h_{\mathrm{fi}} D_{\mathrm{i}}} + \frac{D_{\mathrm{o}} \ln(D_{\mathrm{o}}/D_{\mathrm{i}})}{2k}\right]^{-1} \tag{10}$$

$$Q_{\mathrm{u}} = G_{\mathrm{B}}\eta_{\mathrm{o}}A_{\mathrm{a}} - A_{\mathrm{r}}U_{\mathrm{L}}(T_{\mathrm{r}} - T_{\mathrm{a}}) \tag{11}$$

$$F' = \frac{1/U_{\mathrm{L}}}{\frac{1}{U_{\mathrm{L}}} + \frac{D_{\mathrm{o}}}{h_{\mathrm{f}}D_{\mathrm{i}}} + \left(\frac{D_{\mathrm{o}}}{2k}\ln\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)} = \frac{U_{\mathrm{o}}}{U_{\mathrm{L}}} \tag{12}$$

$$F' = \frac{1/U_{\mathrm{L}}}{\frac{1}{U_{\mathrm{L}}} + \frac{D_{\mathrm{o}}}{h_{\mathrm{f}}D_{\mathrm{i}}} + \left(\frac{D_{\mathrm{o}}}{2k}\ln\frac{D_{\mathrm{o}}}{D_{\mathrm{i}}}\right)} = \frac{U_{\mathrm{o}}}{U_{\mathrm{L}}} \tag{13}$$

$$Q_{\mathrm{u}} = F_{\mathrm{R}}[G_{\mathrm{B}}\eta_{\mathrm{o}}A_{\mathrm{a}} - A_{\mathrm{r}}U_{\mathrm{L}}(T_{\mathrm{i}} - T_{\mathrm{a}})] \tag{14}$$

$$\eta = F_{\mathrm{R}}\left[\eta_{\mathrm{o}} - U_{\mathrm{L}}\left(\frac{T_{\mathrm{i}} - T_{\mathrm{a}}}{G_{\mathrm{B}}C}\right)\right] \tag{14}$$

$$h_{\mathrm{c,c-a}} = h_{\mathrm{w}} = (\mathrm{Nu})k/D_{\mathrm{g}} \tag{15}$$

$$h_{\mathrm{r,c-a}} = \varepsilon_{\mathrm{g}}\sigma\left(T_{\mathrm{g}} + T_{\mathrm{a}}\right)\left(T_{\mathrm{g}}^{2} + T_{\mathrm{a}}^{2}\right) \tag{16}$$

$$h_{\mathrm{c,r-c}} = \frac{k_{\mathrm{std}}}{\frac{D_{\mathrm{t}}}{2\ln\left(\frac{D_{\mathrm{g}}}{D_t}\right)} + b\lambda\left(\frac{D_{\mathrm{t}}}{D_{\mathrm{g}}} + 1\right)} \tag{17}$$

3.1.3. Storage Tank:

$$Q_{\mathrm{s}} = \left(Mc_{\mathrm{p}}\right)_{\mathrm{s}} \Delta T_{\mathrm{s}} \tag{18}$$

$$\left(Mc_{\mathrm{p}}\right)_{\mathrm{s}} \frac{\mathrm{d}T_{\mathrm{s}}}{\mathrm{d}t} = Q_{\mathrm{u}} - Q_{\mathrm{l}} - Q_{\mathrm{tl}} \tag{19}$$

$$Q_{\mathrm{tl}} = (UA)_{\mathrm{s}}(T_{\mathrm{s}} - T_{\mathrm{env}}) \tag{20}$$

$$T_{\mathrm{s-n}} = T_{\mathrm{s}} + \frac{\Delta t}{\left(Mc_{\mathrm{p}}\right)_{\mathrm{s}}}\left[Q_{\mathrm{u}} - Q_{\mathrm{l}} - (UA)_{\mathrm{s}}(T_{\mathrm{s}} - T_{\mathrm{env}})\right] \tag{21}$$

$$\dot{Q}_{\mathrm{st}} = (UA)_{\mathrm{s}}(T_{\mathrm{s}} - T_{\mathrm{env}}) \tag{22}$$

3.2. Work Methodology through EES:

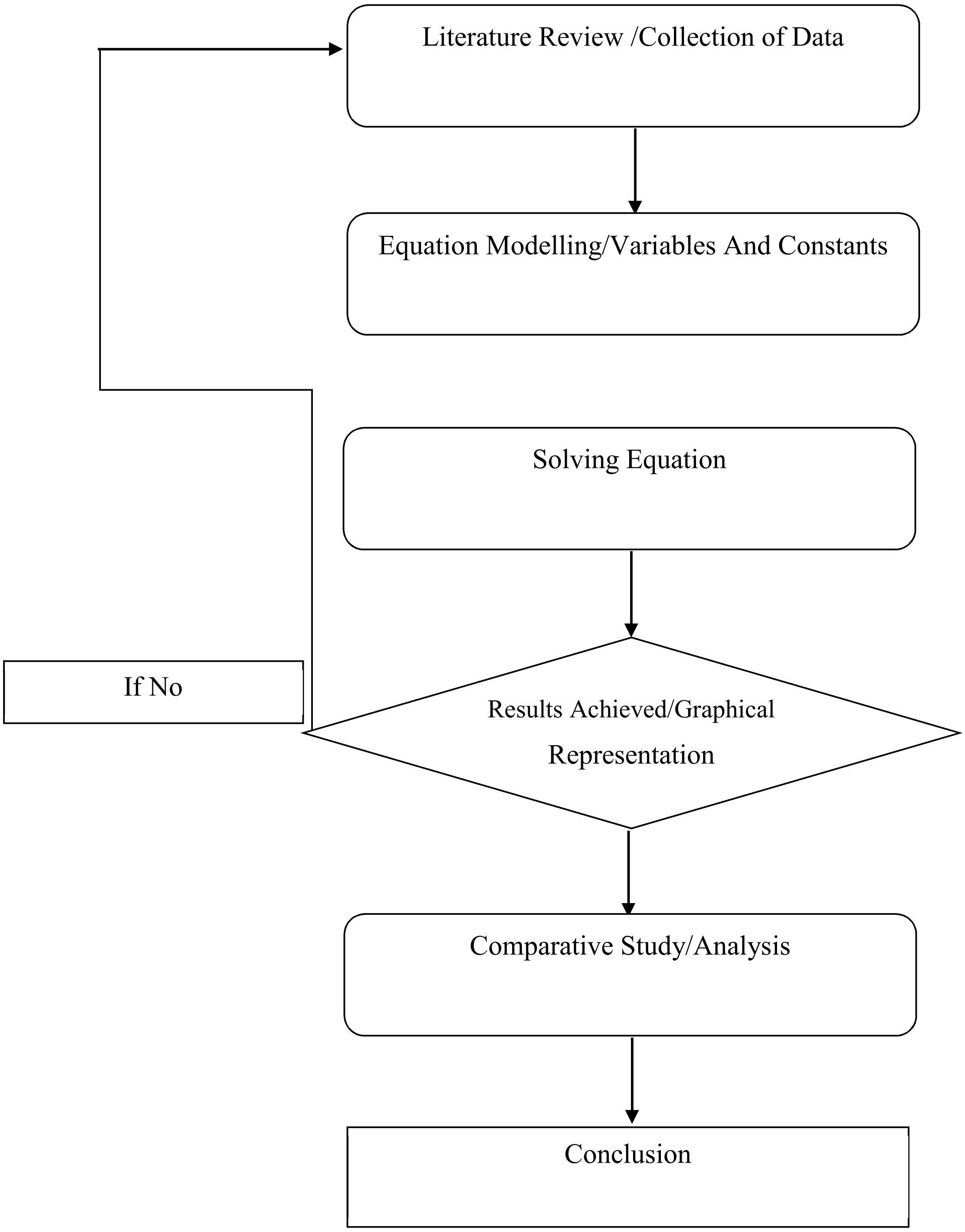

Figure 3.Work Mythology through EES

"Above mentioned Figure 3": This part of the sentence refers to a specific figure, likely Figure 3 in a research paper or report. Figures in research papers typically include graphs, charts, diagrams, or visual representations of data or concepts "The work methodology of EES": Here, it's discussing the methodology used in the research related to EES. Methodology refers to the systematic approach or set of methods and procedures used to conduct the research. In this context, it specifically relates to how EES was studied or applied in the research.

"Engineering Equation Solving": EES stands for Engineering Equation Solving, which is a computational tool or software used in engineering and scientific fields to solve complex equations and simulations. The sentence suggests that the research is related to the application or study of EES."Comparative study done in this research": This part indicates that the research involved a comparative analysis. A comparative study typically involves comparing two or more things, such as methods, systems, or variables, to understand their similarities, differences, advantages, and disadvantages. “Get the conclusion": This part implies that the research aimed to draw conclusions based on the findings. Conclusions in research papers summarize the results and insights gained from the study. In essence, the sentence is likely part of a research paper or report discussing Figure 3, which represents a visual element related to the research on EES. The research involves a methodology for studying EES and includes a comparative analysis of some kind. The objective is to derive conclusions from this study. To provide a more detailed explanation, it would be helpful to have additional context or information about Figure 3 and the specific research being discussed.

Chapter 4. Results and Discussion

4.1. Solar Collectors

Through the modification of many factors, the systematic analysis included a thorough investigation of the system's behaviours. This carefully crafted variation provided as a lens through which to see the complex system dynamics. A mosaic of insights was created by carefully examining each parameter's individuality and thoroughly documenting its influence.

The incorporation of the meteorological data from Karachi was a crucial tenet of our inquiry. The study's authenticity and applicability were enhanced by the setting, which was influenced by solar light and climate changes. A number of graphical representations began to emerge against this background, visually telling the dynamic evolution of the performance of solar collectors. These illustrations highlighted the subtle changes in efficacy and captured the complex link between solar irradiation and temporal progression. Such graphic depictions unlocked the essence of solar collectors' responsiveness and revealed how they interact adaptively with the constantly shifting solar brightness. The analysis revealed the complex relationships between variables, weather patterns, and the use of solar energy, demonstrating the need of careful observation, research, and data documentation.

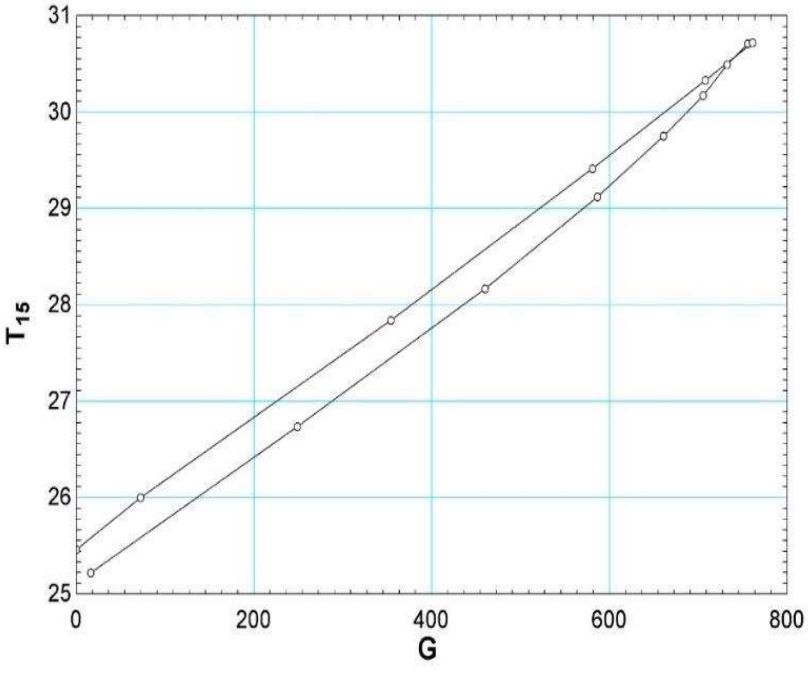

Figure 4.Solar Irradiation v/s PVT Outlet

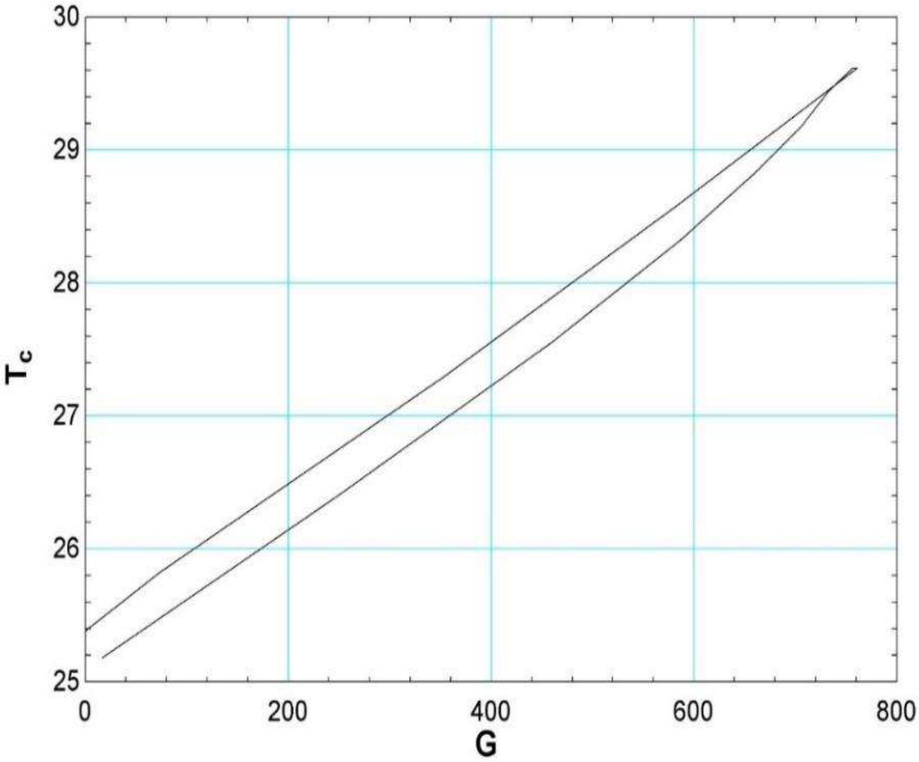

Figure 5.Solar irradiation v/s cell temperature

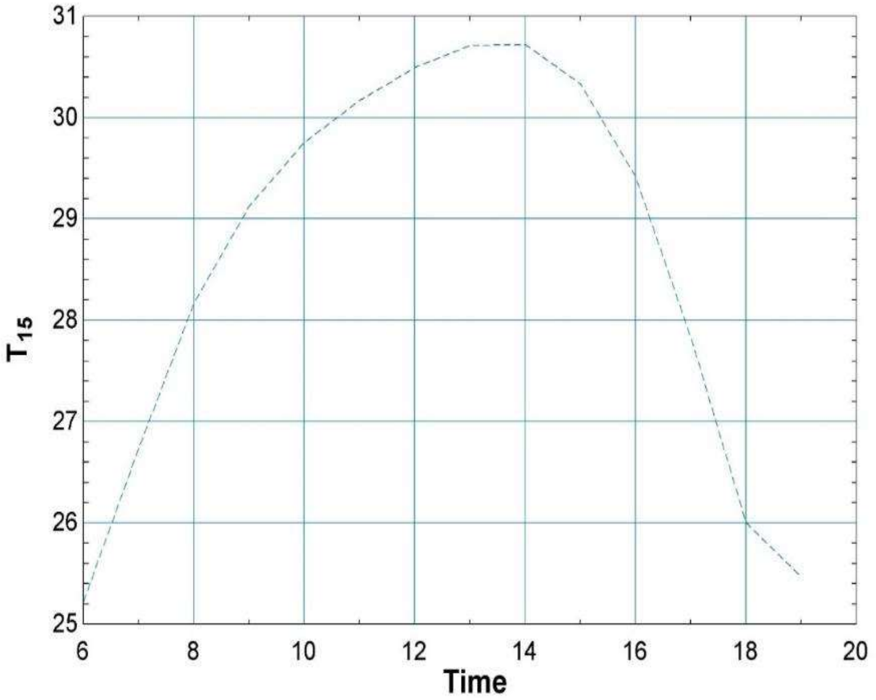

Figure 6.Time v/s PVT outlet temperature

Table 1.The solar irradiation vs time and solar collector outputs

Sr. No	G	T13	T14	T15	Time	Tc	Tamb
1	16.41	25	25.16	25.22	6	25.18	26.15
2	248.6	25	26.27	26.74	7	26.4	27.03
3	460	25	27.32	28.17	8	27.55	28.33
4	586.5	25	28.02	29.12	9	28.32	30.03
5	661.1	25	28.49	29.75	10	28.84	31.68
6	705.3	25	28.8	30.17	11	29.18	33.08
7	732.5	25	29.04	30.5	12	29.44	34.6
8	756.1	25	29.2	30.71	13	29.62	35.25
9	761	25	29.2	30.72	14	29.62	35.05
10	708	25	28.92	30.33	15	29.31	34.45
11	581	25	28.25	29.42	16	28.57	33.17
12	354	25	27.09	27.84	17	27.3	31.38
13	72.55	25	25.75	26	18	25.82	30.3

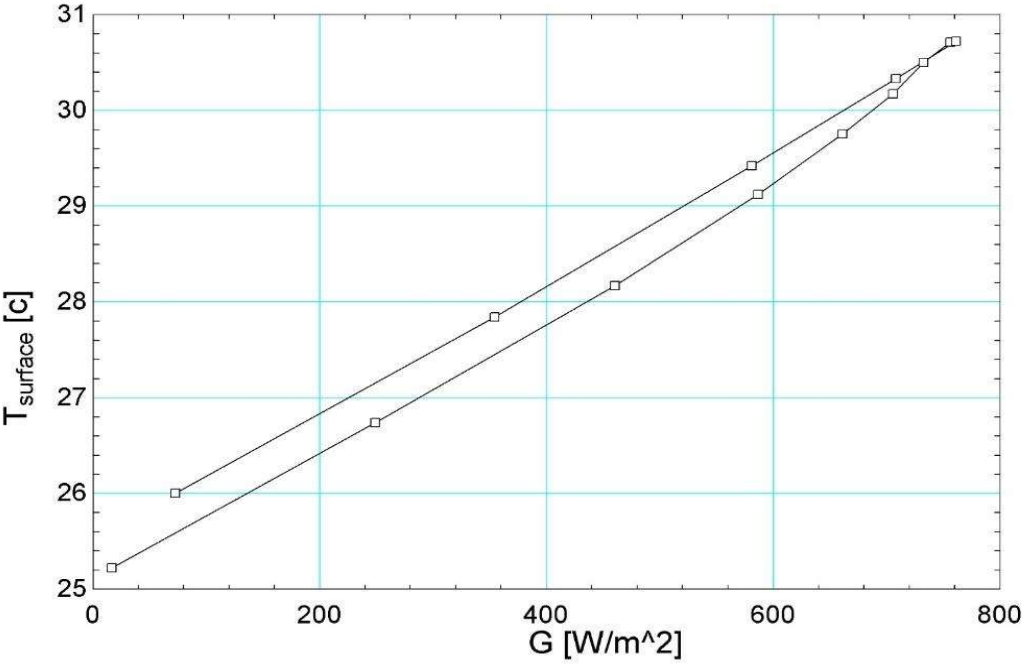

Figure 7.PVT surface temperature variation w.r.t. solar irradiation

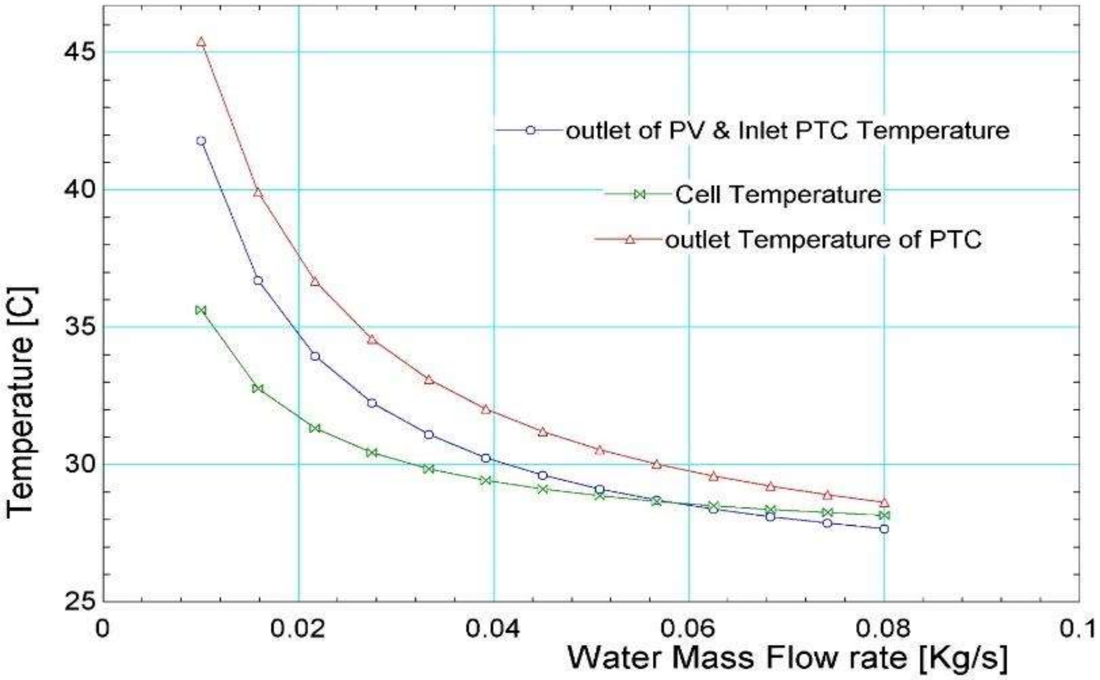

Figure 8.Impact of variable mass flow rate on solar collector temperatures

Solar irradiation plays a crucial role in determining the performance of the collector. Higher solar irradiation means more heat absorption and hence an increased inlet temperature of the PV module. Also, the difference between the inlet and outlet temperatures is linked to the cooling capacity of the system. The lower the difference, the greater the cooling effect. Cell Temperature is another important factor in determining the effectiveness of the collector. An increase in solar irradiation leads to greater cell temperature, which can result in an overall reduction in electrical efficiency. Owing to the above-stated reasons, an increasing trend can be observed in each of the graphs for the inlet, outlet and cell temperature of the photovoltaic thermal collector. The variation in solar irradiation value can also be observed in the above graphs.

The mass flow rate of the fluid passing through the collector directly impacts the performance and efficiency of the collector. Higher flow rates will lead to higher pressure drops, lower outlet temperatures and lower collector efficiency. This is the result of the decrease in the heat absorption time and capacity between the fluid and the surface of the collector. Higher pressure drops will also lead to an increase in the pumping power of the overall system. However, care must be taken to not decrease the mass flow rate to an excessively low rate as this can result in overheating of the collector, along with the reaching of the stagnation point.

4.2. Organic Rankine Cycle

Two essential aspects of the ORC cycle study were the exploration of various working fluids and the adjustment of water and working fluid mass flow rates. This intentional change in the inputs revealed the system's responses and provided a comprehensive knowledge. The investigation's main focus was on changing the mass flow rates of both the working fluid and water. In order to illustrate the intricate dynamics of the ORC cycle, this carefully planned change of the inputs yielded a range of results. Concurrently, exploring various working fluids introduced a new level of exploration. These fluids' distinctive thermodynamic properties made it possible to compare them and show how each one's particular effects on cycle performance differ. The behaviour of the system was visualised via graphics, which showed how changes in input had real-world consequences. These graphic revelations gave sharp peeks into the governing linkages inside the ORC cycle. This analysis highlights the value of thorough investigation, where input modifications and ongoing research work together to shed light on the behaviour of the ORC cycle. The study clarifies the complex mechanisms governing energy conversion inside the ORC framework amid this interaction of parameters and results.

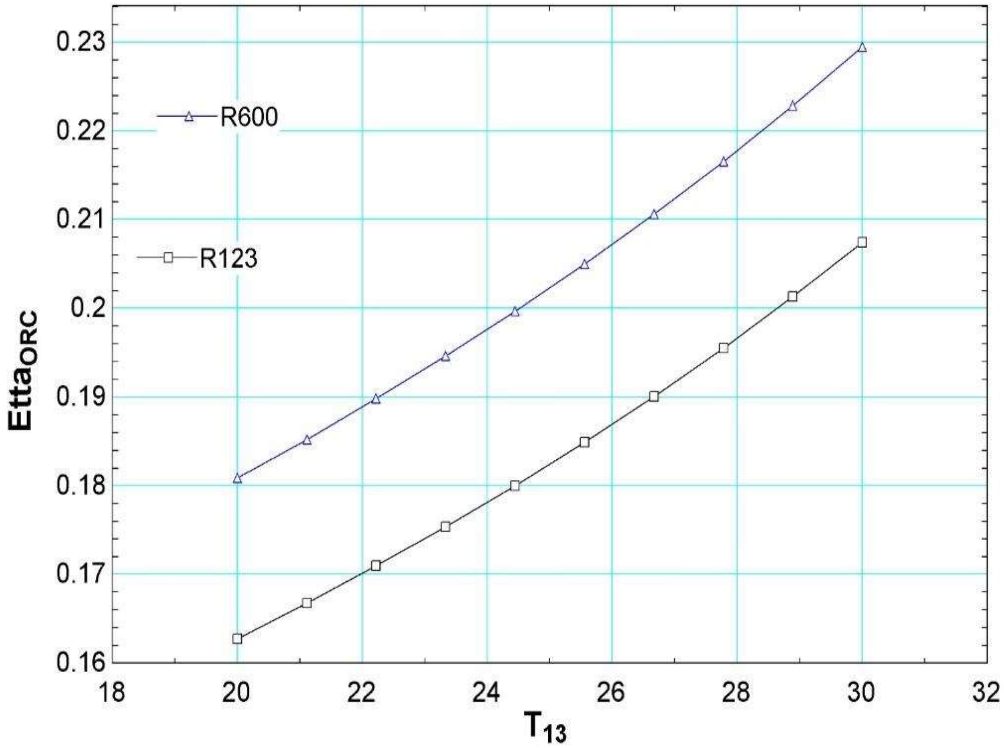

Figure 9.Effect of Outlet temperature of PTC on ORC efficiency

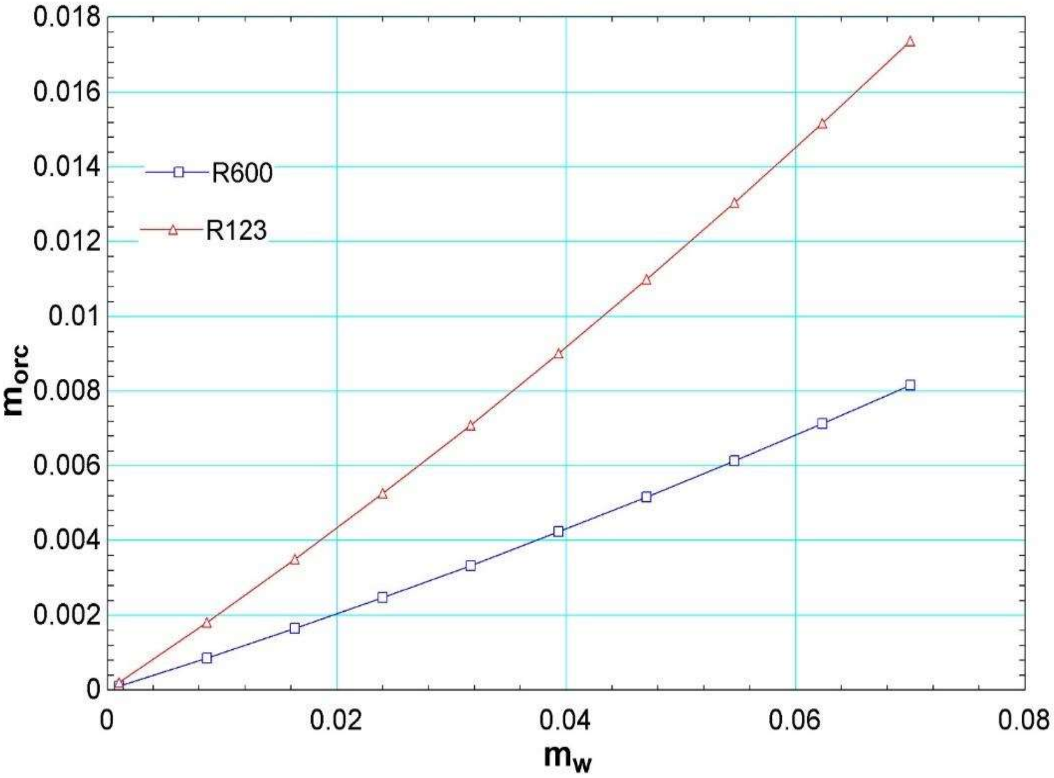

Figure 10.Effect of PVT PTC cycle mass flow rate on organic working fluid.

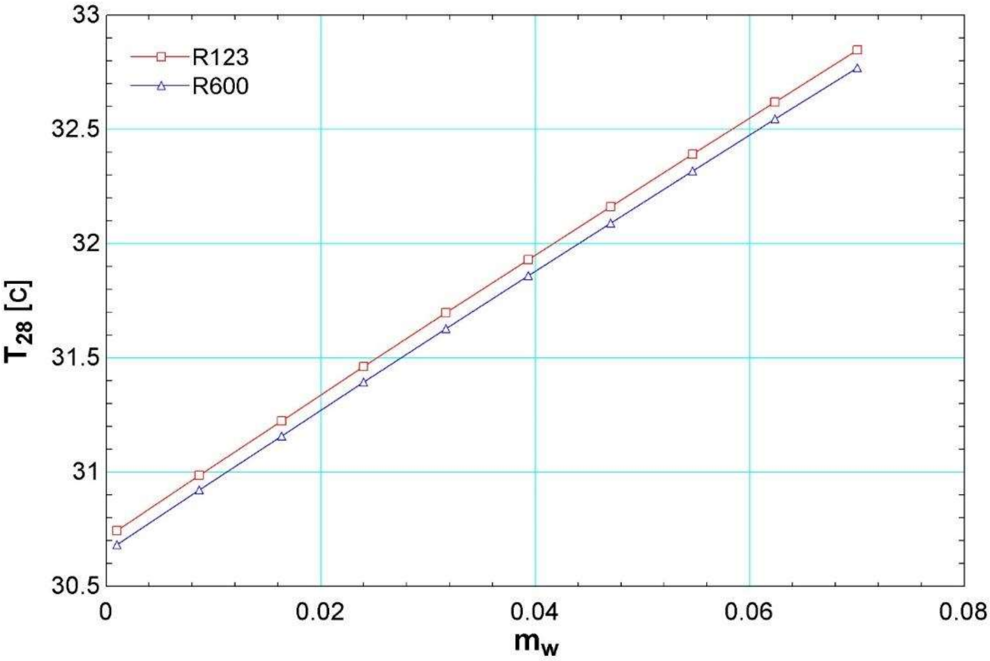

Figure 11.Effetc of mass flow rate of PVT PTC cycle on Outlet temperature of ORC cycle

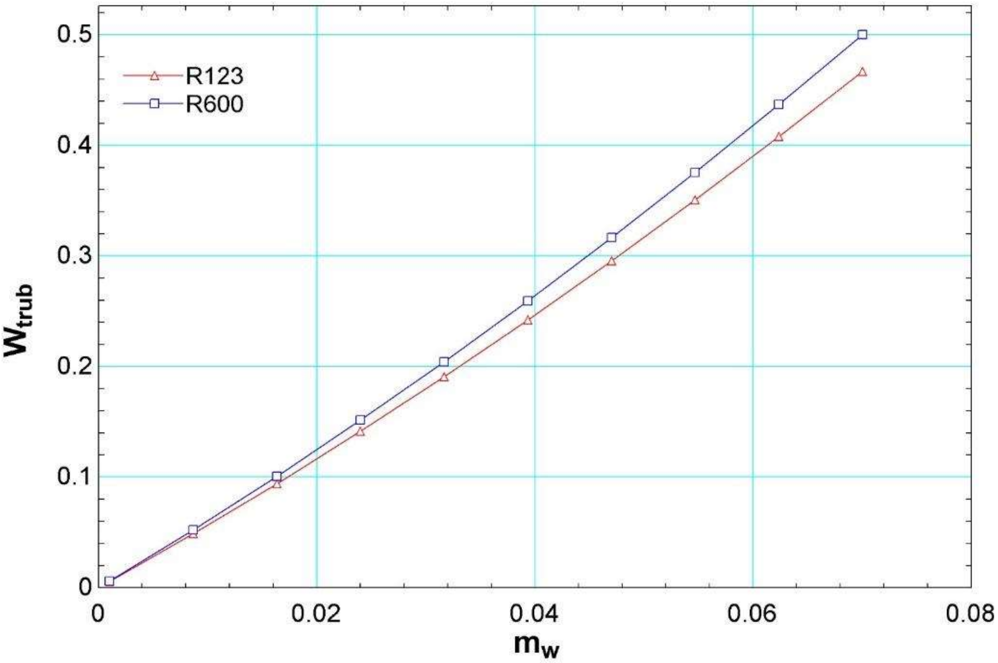

Figure 12.Effetc of mass flow rate of PVT PTC cycle on Work done by Turbine

The mass flow rate of the working fluid and the water mass flow rate between the PVT-PTC circuits are correlated. Increasing one will increase the other as well, as is seen by the increasing trend of the graph. Higher mass flow rate through the system means higher heat transfer amongst the system, leading to increased temperature, turbine output, power output and efficiency of the stated subsystem, but this will also increase the pumping power increasing the overall cost.

4.2.1. Comparative Study

A comparison between two fluids was compared: R600 (Isobutene) and R123 (Di-chloro-tri-fluor-ethane) was carried out. Both fluids show good results but R600 tends to show better results in terms of thermodynamic analysis. The lower boiling point and greater vapour pressure of R600 make it a better choice for low-temperature heat sources, whereas R123 can work best for low and moderate heat source temperatures.

However, if other factors (safety and environmental impact) are taken into account then a difference is observed. R600 has a lower GWP (Global Warming Potential) and zero (ozone depletion potential), making it a more environmentally friendly refrigerant. In contrast, if safety is to be considered then R123 is a better choice owing to its non-flammable nature, but if R600 is to be used then safety measures should be taken.

4.3. Storage Tank

In this study, two various tank positioning locations were assessed. In the first case, the tank was put in place adjacent to the water heater, especially at the ORC's output. The tank was positioned downstream of the PVT-PTC circuit in the second layout, in contrast. Notably, the PVT-PTC circuit-related later design produced better storage results. This finding is supported by the subsequent numerical information and graphic displays. The results unmistakably show a link between increasing solar radiation and mass flow rates and increased energy collection and subsequent transfer to the storage tank. Notably, maintaining a flow rate as low as 0.01 kg/s demonstrates the ability to accumulate storage up to 400 litres in a period of 12 hours. The tank location plan is also shown in the following graphic below.

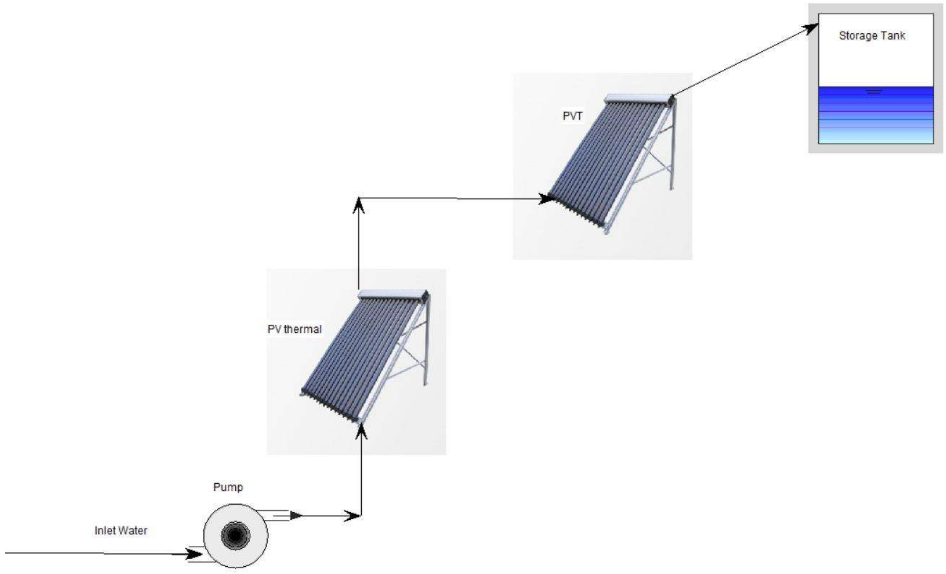

Figure 13.Schematic followed for storing hot water

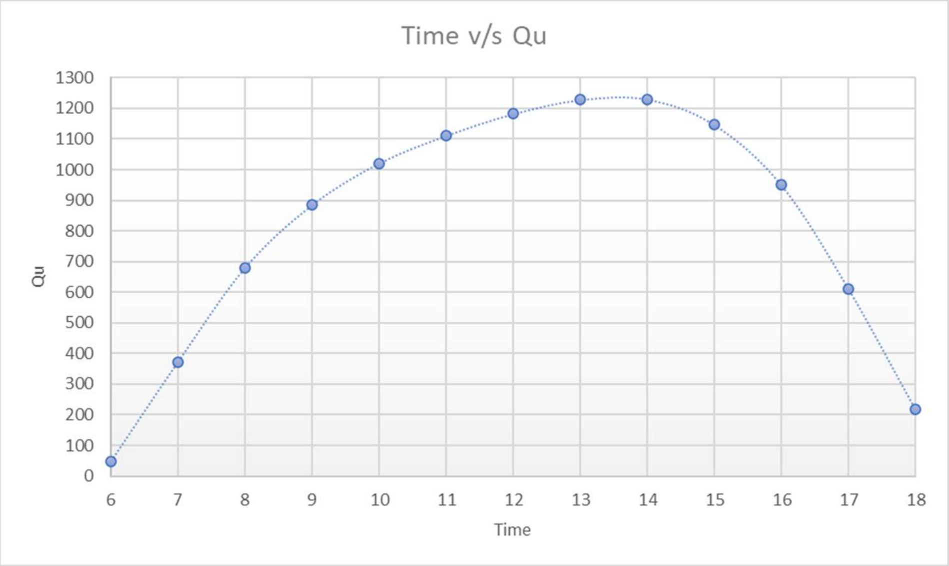

Figure 14.Variation in energy stored w.r.t. to time.

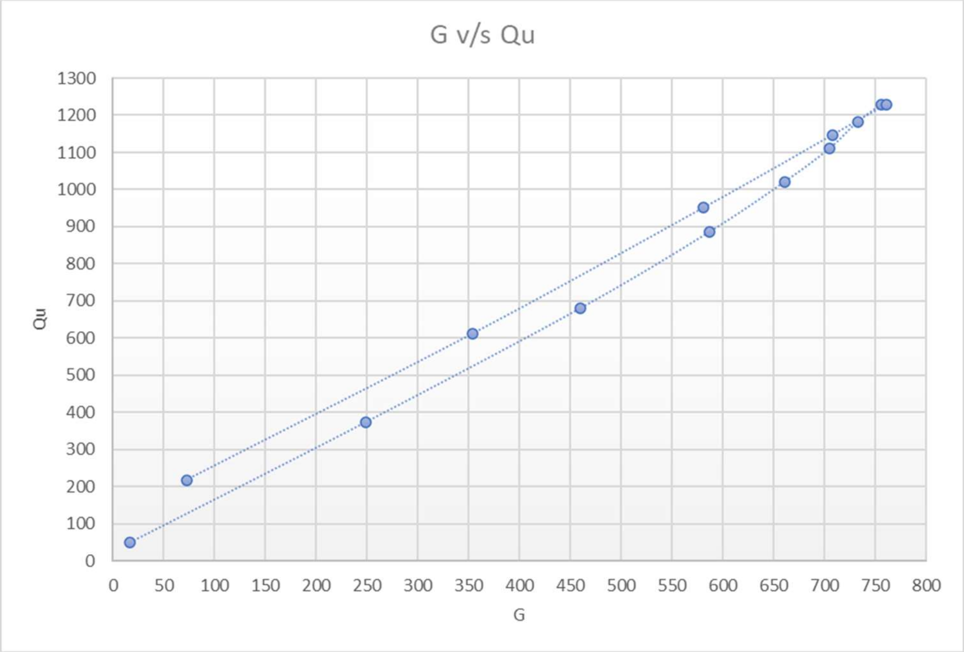

Figure 15.Variation in energy stored w.r.t. to solar irradiation

Table 2.Volume of water stored by varying mass flow rate through PVT-PTC cycle over 12 hour span

Volume	Mass	t	mw
0.4363	432	1	0.01
0.6893	684	1	0.01583
0.9422	936	1	0.02167
1.195	1188	1	0.0275
1.448	1440	1	0.033
1.7	1692	1	0.0392
1.953	1944	1	0.045
2.206	2196	1	0.0508
2.459	2448	1	0.05667
2.711	2700	1	0.0625
2.964	2952	1	0.0683
3.217	3204	1	0.07417
3.47	3456	1	0.08

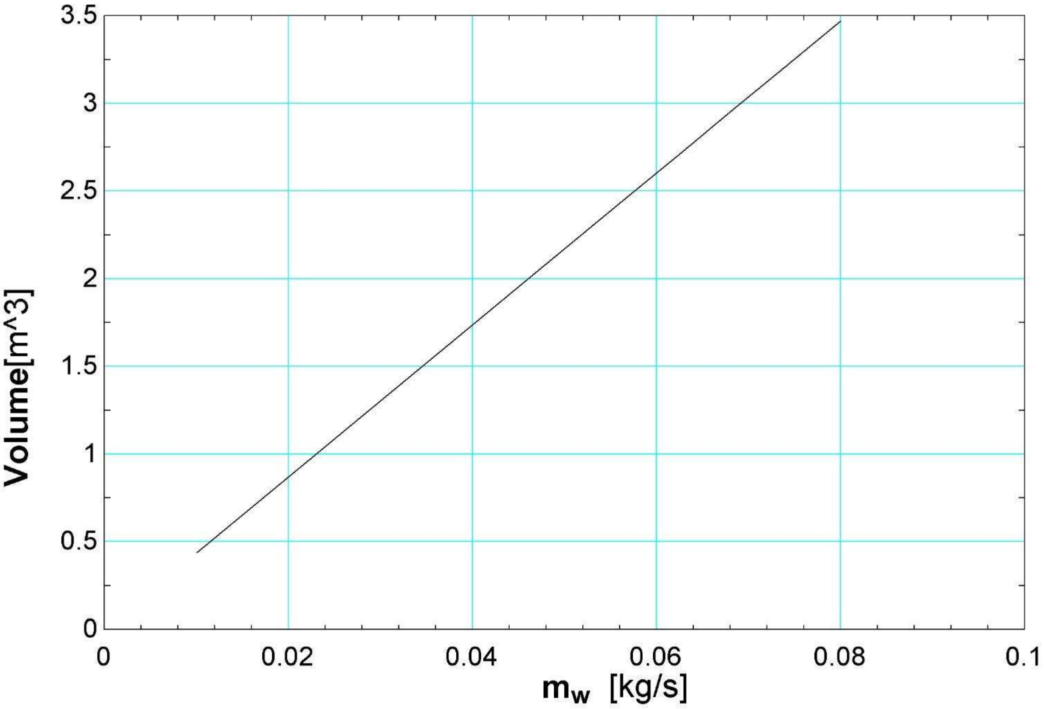

Figure 16.Volume of water stored by varying mass flow rate of water

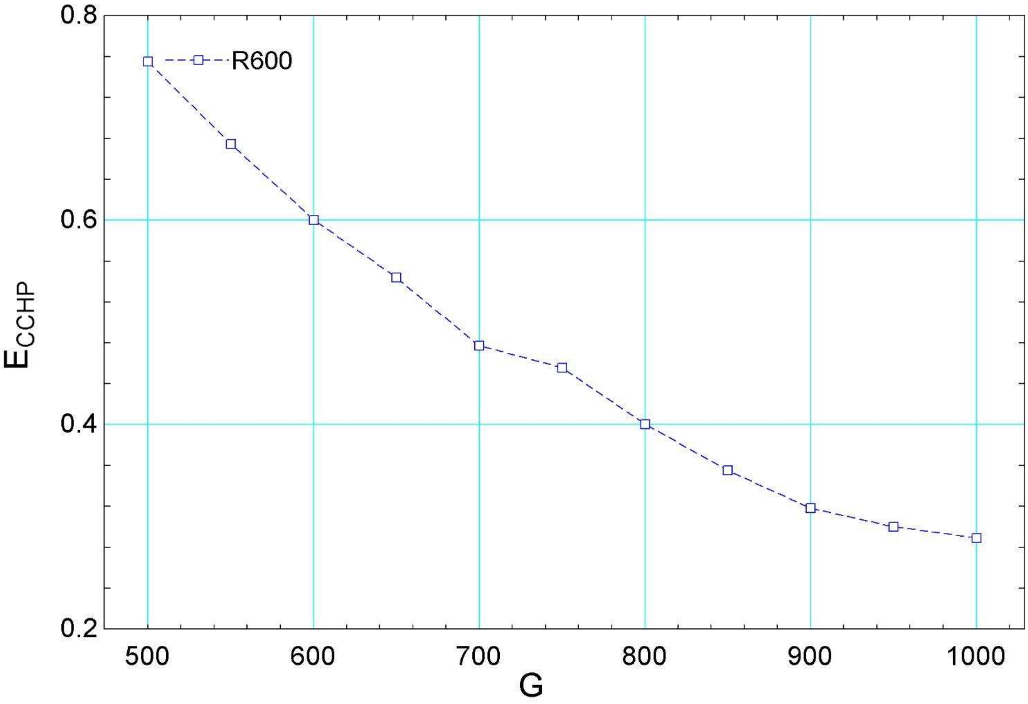

Figure 17.Impact of solar irradiation on overall system efficiency

Chapter 5. Conclusion

The content provided in this report showcases an all-encompassing exploration and examination of an integrated system that combines cooling, heating, and power functionalities while also incorporating a thermal energy storage tank. At the core of this system lies the utilization of a dual solar source, a pivotal input responsible for propelling the entire mechanism. The utilization of Engineering Equation Solver (EES) in our energy analysis has revealed that the system holds the capacity to sufficiently cater to the thermal energy requisites of a household. Succinctly encapsulated in the subsequent passage are the summative outcomes of our investigative endeavor.

Modulating the mass flow rate of water coursing through the system yields discernible impacts on collector efficiencies. Incrementally enhancing the mass flow rate of water from 0.01 to 0.01583 leads to a nominal 2.9% dip in PVT (Photovoltaic Thermal) efficiency, whereas a more substantial elevation from 0.027 to 0.033 engenders a minute 0.065% surge. This concurrent alteration also precipitates an escalation in the overall pumping power requirements. Evidently, maintaining a lower mass flow rate within the system engenders a heightened performance level across the board.

Comparatively evaluating refrigerant options, R600 and R290 demonstrate closely aligned attributes, albeit R600 emerges as the frontrunner in terms of thermodynamic scrutiny. Noteworthy is the tank's proficiency in storing up to 400 liters of water across a 12-hour timeframe, designed to accommodate a mass flow rate of 0.01. This capacity significantly overshoots the daily water consumption needs, signifying potential room for optimization via improved insulation and precision temperature control mechanisms.

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Chapter 6. Future Work

Our research has unveiled insights into an integrated system encompassing cooling, heating, and power functions, emphasizing thermal energy storage and dual solar sources. Opportunities for future research and improvement include:

6.1. Optimal Flow Rate

Investigate the ideal water flow rate through the system to maximize efficiency and performance, considering varying parameters.

6.2. Alternative Refrigerants

Explore alternative refrigerants with improved environmental and thermodynamic properties to enhance system performance.

6.3. Enhanced Thermal Storage

Improve thermal energy storage with enhanced insulation and precision temperature control for greater energy savings.

6.4. Advanced Control Systems

Integrate advanced control systems, such as machine learning, to optimize system operation in real-time.

6.5. Practical Implementation

Field-test and implement the system in real-world settings to validate theoretical findings and performance.

6.6. Sustainability Assessment

Conduct a comprehensive environmental impact assessment, including life cycle analysis, to align the system with sustainability goals.

These avenues offer exciting opportunities for innovation and advancement in integrated energy systems.

Chapter 7. Work Cited

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