

**ENERGY, EXERGY AND TECHNOECONOMIC
ANALYSIS OF GREEN HYDROGEN PRODUCTION
USING CONCENTRATING SOLAR TECHNOLOGY**

BY

TERUNGWA ANTHONY TIVFA

A Thesis Presented to the
COLLEGE OF GRADUATE AND INTERDISCIPLINARY STUDIES
KING FAHD UNIVERSITY OF PETROLEUM & MINERALS
DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE
In
MECHANICAL ENGINEERING

MAY 2025

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **TERUNGWA ANTHONY TIVFA** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree **MASTER OF SCIENCE IN MECHANICAL ENGINEERING**.



Dr. Mohamed A. Antar
Department Chairman



Dr. Suliman S. Al-Homidan
Dean of Graduate Studies

Date



Dr. Obaidallah Munteshari
(Advisor)



Dr. Hussein A. Mohammed
(Member)



Dr. Awad Alquaity
(Member)



©Terungwa Anthony Tivfa
2025

I dedicate this thesis to God, to my parents Mr./Mrs. Tivfa Thaddeus Azever, and to Mr. Jude Yange.

ACKNOWLEDGMENTS

I would like to thank the Almighty God for the graces and strength he has sustained me with throughout my thesis work. I would like to express my deepest appreciation to my advisor Dr. Obaidallah M. Munteshari for his continuous support, mentorship and motivation. My immense gratitude also goes to my committee members Dr. Hussein A. Mohammed and Dr. Awad S. Alquaity whose feedback and recommendations improved the quality of this work. I am as well grateful to Abdullahi Sani Shuaibu and Kamalluddeen Mahmud Usman for their help and support in regard to the optimization aspect of this thesis. I also want to thank the Deanship of Graduate Studies for the scholarship that enabled me to study at King Fahd University of Petroleum and Minerals. I am grateful to the Chairman of Mechanical Engineering Department, Dr. Mohamed A. Antar, and the whole faculty members and staff of the department for providing a conducive environment for my studies and for the impacted knowledge without which this thesis wouldn't have been a success. Finally, I am immensely grateful to my relatives and friends especially my parents whose prayers, love and support has made it possible for me to get this far in my academic journey.

Contents

ACKNOWLEDGMENTS	v
LIST OF TABLES	viii
LIST OF FIGURES	ix
LIST OF SYMBOLS	xii
LIST OF ABBREVIATIONS	xvi
ABSTRACT (ENGLISH)	xviii
ABSTRACT (ARABIC)	xx
CHAPTER 1 INTRODUCTION	1
1.1 Motivation	3
1.2 Aims and Objectives	4
CHAPTER 2 LITERATURE REVIEW	6
2.1 Steam Rankine Cycle (SRC)	7
2.2 Organic Rankine Cycle (ORC)	8
2.3 Supercritical Brayton Cycle	9
2.4 Combine Cycle Configurations	11
2.5 Cost and Optimization	13
2.6 Summary	14
CHAPTER 3 METHODOLOGY	15
3.1 System Description	15

3.2	Thermodynamic Modeling	18
3.2.1	Energy and Exergy Assessments	18
3.2.2	Solar Tower Model	23
3.2.3	PTC Model	23
3.2.4	Electrolyzer	25
3.3	Cost Analysis	29
3.4	Optimization	33
3.4.1	Brute-Force Optimization Algorithm	34
3.5	Validation	38
CHAPTER 4 RESULTS AND DISCUSSION		39
4.1	Thermodynamic Modeling Results	39
4.1.1	Thermodynamic Parametric Analysis	42
4.2	Cost Assessment Results	54
4.2.1	Cost Parametric Analysis	57
4.2.2	Sensitivity Analysis	64
4.3	Optimization result	65
CHAPTER 5 CONCLUSIONS, CHALLENGES AND RECOM-		
MENDATIONS		68
5.1	Conclusions	68
5.2	Challenges	71
5.3	Recommendations	71
REFERENCES		73
VITAE		87

List of Tables

Table 3.1:	Energy and Exergy Balances for the MSRC-SCBC-ORC configuration [1]	20
Table 3.2:	Standard chemical exergy Values [2]	22
Table 3.3:	Solar tower model [3].	23
Table 3.4:	Input Parameters for the Integrated Power Cycle	24
Table 3.5:	PTC Model [4].	25
Table 3.6:	Equipment Capital Cost	31
Table 3.7:	Economic Assumptions [5].	32
Table 3.8:	Decision variables for optimization	35
Table 4.1:	Efficiency values for different cycle configurations	40
Table 4.2:	The hydrogen cost for 3MW electrolyzer capacity.	55
Table 4.3:	Total PEC values for different power cycles	57
Table 4.4:	Optimization results for the SPT-powered configurations . . .	67

List of Figures

Figure 1.1:	Hydrogen cost by technology [6].	4
Figure 3.1:	Integrated Cycle Configurations: (a) The MSRC-SCBC-ORC Cycle Configuration. (b) The MSRC-SCBC Cycle Configuration. (c) The MSRC-ORC Cycle Configuration. (d) The SCBC-ORC Cycle Configuration.	16
Figure 3.2:	Process diagram for the brute-force algorithm.	37
Figure 3.3:	Electrolyzer model validation showing the variation of electrolyzer voltage with electrolyzer current density for experiment work and current work.	38
Figure 4.1:	Comparison of the total power output from SPT and PTC cycle configurations.	42
Figure 4.2:	Variation of hydrogen production and electrolyzer's efficiency with current density of the electrolyzer.	43
Figure 4.3:	Variation of hydrogen and total power output with solar irradiation	45
Figure 4.4:	Variation of hydrogen and total power output with total area of the solar collector	46
Figure 4.5:	Variation of solar-to-electricity energy and exergy efficiencies with the exit temperature of the solar receiver.	47

Figure 4.6:	Variation of solar-to-electricity exergy efficiency and hydrogen production rate with the inlet pressure of the HPT: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.	50
Figure 4.7:	Variation of solar-to-electricity energy efficiency and the power output of the MSRC with the inlet pressure of the LPT: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.	51
Figure 4.8:	Variation of solar-to-electricity energy efficiency and SCBC power output with the pressure ratio of the SCBC: (a) the system's response when SCBC is the top cycle and (b) the system's response when SCBC is a bottoming cycle.	52
Figure 4.9:	Variation of solar-to-electricity exergy efficiency and hydrogen production rate with the inlet pressure of the ORC turbine: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.	53
Figure 4.10:	The variation of levelized cost of hydrogen with solar irradiation.	58
Figure 4.11:	The variation of levelized cost of hydrogen with number of solar collectors.	59
Figure 4.12:	The variation of levelized cost of hydrogen with the exit temperature of the solar receiver.	60
Figure 4.13:	The variation of levelized cost of hydrogen with the inlet pressure of the HPT.	61
Figure 4.14:	The variation of levelized cost of hydrogen with the inlet pressure of the ORC.	62
Figure 4.15:	The variation of levelized cost of hydrogen with pressure ratio of the SCBC.	63

Figure 4.16: The variation of levelized cost of hydrogen with capacity factor of the system.	63
Figure 4.17: Pareto frontier for the optimization result of the four SPT-powered configurations: (a) MSRC-SCBC-ORC configuration, (b) MSRC-SCBC configuration, (c) MSRC-ORC configuration and (d) SCBC-ORC configuration.	66

LIST OF SYMBOLS

A	Area (m ²)
C	Concentration ratio
C_p	Specific heat capacity (KJ/kg.K)
$\dot{C}$	Cost rate (\$/s)
D	Diameter, thickness (m)
E_{act}	Activation energy (kJ/kmol)
e^{ph}	Specific physical exergy (kJ/kg)
e^{ch}	Specific chemical exergy (kJ/kmol)
F	Faraday's constant (C/mol)
F_1	Efficiency factor
F_R	Heat removal factor
G_b	Solar irradiation (W/m ²)
h	flow enthalpy (kJ/kg)
h_{fi}	Internal heat transfer coefficient (W/m ² .°C)
J	Current density (A/m ²)
k	Thermal conductivity (W/m.°C)
L	Length (m)

$\dot{m}$	Mass flow rate (kg/s)
$\dot{n}$	Molar rate (mol/s)
N_{cs}	Number of solar collectors in series
N_{cp}	Number of solar collectors in parallel
$\dot{Q}$	Heat rate (kW)
R	Universal gas constant (kJ/kg.K), resistance (ohms)
s	Specific entropy (kJ/kg.K)
S	Absorbed solar radiation (W/m ²)
T	Temperature (°C)
U_L	Heat loss coefficient (W/m ² .°C)
V	Voltage (V)
W	Width (m)
$\dot{W}$	Work rate (kW)
x	Mass fraction, membrane space
$\dot{X}$	Exergy rate
Z_k	Purchase of equipment cost for kth component (\$)
$\dot{Z}_k$	Equipment cost rate (\$/s)
α_r	Receiver's absorptivity
η	Efficiency
γ	Activity coefficient, correction factor
λ	Water content
τ_c	Transmissivity of cover glazing

τ_p	Effective transmissivity
ΔG	Gibb's energy (kJ/kmol)
ΔH	Enthalpy change (kJ/kmol)
ΔS	Entropy change (kJ/kmol)

Subscripts

a	Ambient, anode
Apt	Aperture
c	Solar collector, cathode
D	Destroyed
e	Electrolyzer
ex	Exergy
$field$	Solar field
gen	Generator
i	inner, ith state
j	jth state
ms	Molten salt
o	Outer, standard state
$O\&M$	Operation and maintenance
ohm	Ohms
Q	Heat
r	Receiver
STE	Solar-to-electricity

STH	Solar-to-hydrogen
th	Thermal
u	useful
W	Work

LIST OF ABBREVIATIONS

CELF	constant escalation leveling factor
CO ₂	Carbon dioxide
CRF	capital recovery factor
EES	Engineering Equation Solver
FWH	feed water heater
HEX	heat exchanger
HPT	high pressure turbine
HTF	heat transfer fluid
LCOE	levelized cost of electricity
LCOH	levelized cost of hydrogen
LPT	low pressure turbine
MSRC	modified steam Rankine cycle
ORC	Organic Rankine Cycle
PDC	parabolic dish collector
PEC	purchase of equipment cost
PEM	Proton Exchange Membrane

PTC	parabolic trough collector
PV	Photovoltaic
SCBC	Supercritical Carbon dioxide Brayton Cycle
SOEC	solid oxide electrolyzer cell
SPT	solar power tower
SRC	Steam Rankine Cycle

THESIS ABSTRACT

NAME: Terungwa Anthony Tivfa

TITLE OF STUDY: Energy, Exergy, and Technoeconomic Analysis of Green Hydrogen Production Using Concentrating Solar Technology

MAJOR FIELD: Mechanical Engineering

DATE OF DEGREE: May 2025

Globally, there is a huge increase in energy demand while there are serious concerns over the negative impact of climate change that results from the use of fossil fuels which are the main source of global emissions. While decarbonization of carbondioxide emitting industries is a pathway to a carbon-free economy, there are industries that are difficult to decarbonize via the conventional way of using renewable energy resources. This requires a shift to sustainable fuels that can burn without emitting carbondioxide. Hydrogen is currently the best sustainable fuel. Nevertheless, when it is produced using fossil fuels, the whole aim of decarbonization is defeated. To overcome this, a detailed thermodynamic and cost analysis of solar-powered hydrogen production using a Proton Exchange Membrane (PEM) electrolyzer was performed for different

system configurations using solar power tower (SPT) and parabolic trough collector (PTC). A Modified Steam Rankine cycle, supercritical carbondioxide Brayton cycle, and organic Rankine cycle were combined in different ways to form four configurations of integrated power cycles: MSRC-SCBC-ORC, MSRC-ORC, MSRC-SCBC, SCBC-ORC configurations. Among the four, the SPT-powered MSRC-ORC configuration achieved the best thermodynamic performance, with a thermal efficiency of 42.36%, solar-to-electricity energy and exergy efficiencies of 28.59% and 30.15%, respectively, a hydrogen production rate of 63.04 kg/hr, and an oxygen production rate of 504 kg/hr at a solar-to-hydrogen efficiency of 20.43%. However, the PTC-powered MSRC-ORC gave the least levelized cost of hydrogen (LCOH) of 7.78 \$/kg. Parametric analysis of the systems revealed that the solar field area and the solar irradiation had the greatest influence on hydrogen yield while the capacity factor of the system had the highest impact on the LCOH. Furthermore, an optimization of the systems using the brute force method showed that the brute force method was a good way for deciding optimal operating conditions for hydrogen systems. For instance, the optimal solution for the SPT-MSRC-ORC configuration was a thermal efficiency of 44.97% and LCOH of 9.5 \$/kg which improved the efficiency (from 42.36%) at a slight increase in cost (from 9.11 \$/kg). The analysis of this work showed that using PTC could be more profitable for green hydrogen production.

ملخص الرسالة

الاسم: تيرونغوا أنتوني تيفا

عنوان الدراسة: التحليل الطاقوي والاقتصادي التقني لإنتاج الهيدروجين الأخضر باستخدام تقنيات الطاقة الشمسية المركزة

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: مايو 2025

على الصعيد العالمي، يشهد الطلب على الطاقة ارتفاعًا كبيرًا، في وقتٍ تتزايد فيه المخاوف بشأن الآثار السلبية لتغيّر المناخ الناجمة عن استخدام الوقود الأحفوري، الذي يُعد المصدر الرئيسي لانبعاثات الغازات الدفيئة. وفي حين تُعد إزالة الكربون من الصناعات المُصدرة لثاني أكسيد الكربون مسارًا محوريًا نحو اقتصاد خالٍ من الكربون، تظل هناك قطاعات صناعية يصعب إزالة الكربون منها باستخدام أساليب الطاقة المتجددة التقليدية. ويستلزم ذلك التوجّه نحو أنواع وقود مستدامة قادرة على الاحتراق دون انبعاثات كربونية، ويُعد الهيدروجين في الوقت الراهن الخيار الأنسب من بين هذه الأنواع. إلا أن إنتاج الهيدروجين باستخدام مصادر أحفورية يُفقد عملية إزالة الكربون هدفها الأساسي. من هذا المنطلق، أُجري تحليل ديناميكي حراري واقتصادي مفصّل لإنتاج الهيدروجين باستخدام الطاقة الشمسية عبر محلل كهربائي من نوع PEM، وذلك ضمن تكوينات مختلفة للنظام تعتمد على تقنيتي تركيز الطاقة الشمسية: الأبراج الشمسية (SPT) والمجمعات القطعية المكافئة (PTC). وقد جرى دمج دورة رانكن المعدّلة بالبخار (MSRC)، ودورة برايتون بثاني أكسيد الكربون فوق الحرج (SCBC)، ودورة رانكن العضوية (ORC) بأشكال متعددة لتشكيل أربع تكوينات من دورات طاقة مدمجة: MSRC-SCBC-ORC، MSRC-SCBC، MSRC-ORC، و SCBC-ORC. ومن بين هذه التكوينات، حقق النظام MSRC-ORC المعتمد على تقنية SPT أفضل أداء ديناميكي حراري، إذ بلغ معدل الكفاءة الحرارية 42.36 %، وكفاءتا تحويل الطاقة الشمسية إلى كهرباء وإلى إكسبرجي 28.59 % و 30.15 % على التوالي، في حين بلغ معدل إنتاج الهيدروجين 63.04 كغ/ساعة، والأكسجين 504

كغ/ساعة، بكفاءة تحويل من الشمس إلى الهيدروجين بلغت 20.43 %.

أما النظام MSRC-ORC المعتمد على تقنية PTC فقد سجل أدنى تكلفة لإنتاج الهيدروجين (LCOH) بقيمة 78.7 دولار أمريكي لكل كيلوغرام. وقد أظهر التحليل البارامتري أن كلاً من مساحة الحقل الشمسي وشدة الإشعاع الشمسي يمثلان العوامل الأكثر تأثيراً على كمية إنتاج الهيدروجين، بينما تبين أن عامل السعة هو الأكثر تأثيراً على تكلفة الإنتاج. فضلاً عن ذلك، أظهرت نتائج تحسين الأنظمة باستخدام أسلوب "القوة الغاشمة" فعاليته في تحديد ظروف التشغيل المثلى لإنتاج الهيدروجين. ويُستنتج من هذا التحليل أن استخدام تقنية PTC قد يكون الخيار الأكثر جدوى اقتصادياً لإنتاج الهيدروجين الأخضر.

CHAPTER 1

INTRODUCTION

With the global warming crisis and the burgeoning energy demands across the globe, there is a need to adopt sustainable energy resources that do not emit greenhouse gases. The greatest contributor to global warming is Carbon dioxide (CO_2), which is a key product in the combustion of fossil fuels that constitute the major source of energy supply today. One way to combat this is through the electrification of day-to-day processes. If everything can be electrified and powered by electricity from only renewable energy sources, CO_2 emissions into the atmosphere can be significantly cut down. Many processes essential for human life have already been electrified, such as mobile phones, lighting, etc.

Several policies and fundings across the globe have also been geared towards moving to renewable energy resources such as solar, wind, hydro, and so on. As of 2023, the total investment in renewable energy was about 619 billion U.S Dollars [7]. The Kingdom of Saudi Arabia, in particular, has set a very ambitious goal to generate 50% of the country's electricity from renewable energy by 2030 geared towards achieving the country's vision 2030 [8]. However, certain industries, like the transportation sec-

tor, remain challenging to electrify. In industries like this, sustainable fuels are needed to be able to cope with the increasing energy demands and that is where hydrogen comes in.

Hydrogen is a good sustainable fuel because it has high energy density and burns without emitting CO₂, the only products of hydrogen combustion are water and heat. Hydrogen is a naturally occurring element but often needs to be extracted before use. There are different methods of producing hydrogen and each method determines the color of hydrogen which shows how much CO₂ is emitted in the process. The dirtiest form of hydrogen is brown or black hydrogen, which is produced through coal gasification. The most common type of hydrogen is grey hydrogen, which is produced from steam methane reforming, while the cleanest form is green hydrogen, which is produced via water electrolysis using sustainable energy. Apart from green and blue hydrogen, any other color of hydrogen used as a fuel defeats the aim of combating carbon emissions as these emissions occur in its production process. According to International Energy Agency's 2022 hydrogen review, global hydrogen consumption had reached 97 Mt in 2022 while about 38 Mt of low-emission hydrogen was projected to be produced in 2030 [9]. Also, as of 2022, there were 439 green hydrogen plants in the top 10 countries with the highest number of green hydrogen production facilities, with Australia having the highest number of 96 plants [10]. This underscores the need for improved hydrogen production technology.

While green hydrogen offers a clean source of energy, the cost that comes with it is huge when compared to other colors of hydrogen. This is due to the high cost of low-carbon electricity that is used for green hydrogen production as well as the high cost of

electrolyzers. According to the International Energy Agency, between 2019 and 2050, the cost of hydrogen produced by natural gas through steam methane reforming (SMR) could be as low as 0.7 - 1.6 \$/kg while that of low-carbon electricity towers at 3.2 - 7.7 \$/kg [6]. Figure 1.1 shows the cost of hydrogen by technology. A more specific report by the Department of Energy (DOE) gives the cost of green hydrogen per technology to be 5.5-7.9 \$/kg for hydropower, 5.2-7.5 \$/kg for land-based wind power and 4.4-6.0 \$/kg for hybrid-wind-Photovoltaic (PV) [11]. The DOE's report was based on PEM electrolyzer cost ranging from 1500 \$/kW to 2500 \$/kW with low-carbon electricity cost of 0.03 \$/kWh and capacity factors of 50% to 75%. This was a reasonable estimate by the DOE because in 2023 (which was just a year after the DOE's report) the prices of renewable energy electricity were reported by the International Renewable Energy Agency (IREA) to be 0.044 \$/kWh for utility-scale solar power and 0.033 \$/kg for onshore wind power [12]. To enhance the adaptability of hydrogen as a source of energy, low-cost systems have to be produced for the production of green hydrogen. This work aims to perform a comparative analysis of green hydrogen using concentrating solar technologies based on cost and system efficiency, and to optimize the systems in order to determine the best operating parameters for low-cost hydrogen production.

1.1 Motivation

To decarbonize industries where it is difficult to use renewable energy resources, sustainable fuels like hydrogen are used. However, the low resource-to-hydrogen con-

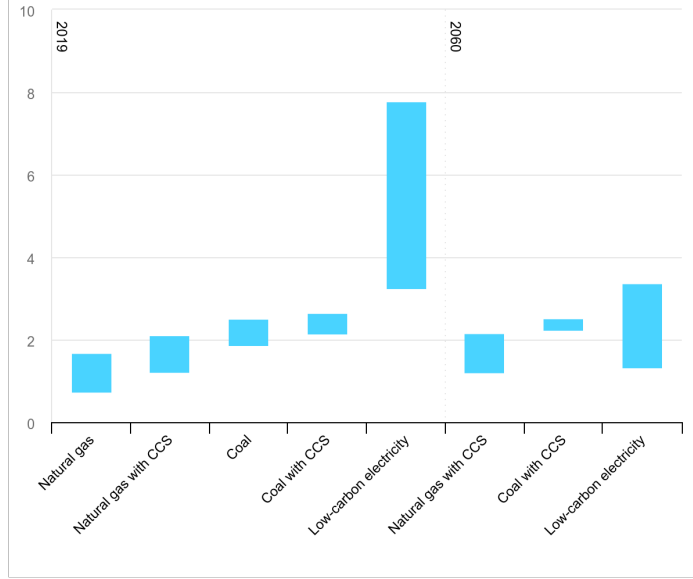


Figure 1.1: Hydrogen cost by technology [6].

version efficiency and high cost of hydrogen pose a big challenge to the adoption of hydrogen as a sustainable fuel. This work seeks to solve this problem by analyzing different integrated cycle configurations to improve the conversion efficiency and optimize the best system for reduced cost of hydrogen.

1.2 Aims and Objectives

The aim of this work is to perform a detailed thermodynamic and technoeconomic analysis of green hydrogen production using various configurations of combined Steam Rankine Cycle (SRC), Supercritical Carbon dioxide Brayton Cycle (SCBC), and Organic Rankine Cycle (ORC) integrated with a PEM electrolyzer and either a PTC or an SPT for comparative analysis. This will be accomplished through the following objectives:

- I. To perform thermodynamic analysis of the PTC and SPT systems using Engi-

neering Equation Solver (EES).

- II. To conduct technoeconomic analysis of the systems powered by PTC and SPT to determine which one is more economically viable.
- III. To carry out multi-objective optimization of the best system to improve the overall system's performance.

CHAPTER 2

LITERATURE REVIEW

The conventional way of producing green hydrogen is through the use of electrolyzers. Three kinds of electrolyzers are used for green hydrogen production, namely, alkaline electrolyzers, solid oxide electrolyzers, and PEM electrolyzers. While alkaline electrolyzers are cost-effective and long-lasting, they have low efficiency and are not best fitted for intermittent power supply, which is what renewable forms of energy often offer. Solid oxide electrolyzers are highly efficient and highly productive due to the high operating temperatures and low cell voltage. However, they require a very high energy supply, high maintenance, and manufacturing cost [13]. PEM electrolyzers, on the other hand, are expensive but highly efficient and can work well with transient power supply. For these reasons, PEM electrolyzers are more common in applications that involve the use of renewable energy. Solid oxide electrolyzers can also be considered when the energy source is at a high temperature, like in SPTs [14]. Numerous studies have explored green hydrogen production. Many researchers have concentrated on green hydrogen as part of a multi-generation system utilizing sustainable energy technologies such as PTCs [15], SPTs [16], photovoltaic-thermal (PV-T) [17], Parabolic

dish [18], hydro plants [19], or a combination of any of these technologies [4]. While others focused on green hydrogen alone [14], [20], [21]. Among all these technologies, concentrated solar technologies are the most widely used technologies to produce green hydrogen. The major challenge with these types of technologies is their expensive nature and the low resource-to-hydrogen efficiency. Different power cycles have been used with these technologies to produce hydrogen such as SRC [21], ORC [20], SCBC [22], or a combination of any of these cycles [3].

2.1 Steam Rankine Cycle (SRC)

For SRCs, not much research has been done on integrating only steam Rankine cycle with renewable energy resources for the purpose of hydrogen production. However, SRC is the simplest and most widely used power cycle in power generation. Recently, Soni and Reddy [23] studied the use of a SRC for hydrogen production with two different energy conversion systems: PTC and parabolic dish collector (PDC). The system was designed to produce 5.5 MW of electricity at an energy efficiency of 15.06% for the PTC and 18.8% for the PDC. Technoeconomic analysis of the system revealed that incorporating ternary salts in the PTC resulted in a 22.7% decrease in capital cost and a 7.8% shorter payback period when compared with the PDC. Sun et al. [24] did a comparative analysis of a supercritical reheating Rankine cycle with an SCBC and their results showed that at supercritical level and with the reheat process, the supercritical Rankine cycle performed better than the SCBC.

2.2 Organic Rankine Cycle (ORC)

ORCs are good for low temperature heat sources like geothermal energy or waste heat from other power cycles like SRC and SCBC. Wang et al. [25] conducted an analysis of a hydrogen generation system powered by a solar tower integrated with a gas-steam turbine and an ORC. The total electricity from the system was 103.9 MW with a hydrogen output of 62.2 kg/day. The system achieved an electrical efficiency of 41.3%, with the combustion chamber and solar receiver accounting for the highest exergy destruction. In a separate study, Cao et al. [26] conducted a thermodynamic and exergoeconomic analysis of a geothermal power plant to generate hydrogen using PEM electrolyzer and a two-stage ORC. Their optimization and parametric analysis showed that the R123 and isopentane were the best and second-best ORC working fluids, respectively. Khouya [27] utilized a dual-loop ORC powered by a PTC to generate hydrogen and ammonia in his analysis. The analysis revealed that the efficiency of the combined system ranged from 15% to 20.28%, which is considered high for ORC systems. Yuksel [28] in his work modified an ORC to include a feedwater heater and then integrated this with a PTC, an absorption cooling cycle, and a PEM electrolyzer to generate hydrogen and cooling. Parametric analysis indicated that solar radiation was the most significant factor influencing the system's exergy efficiency and hydrogen output. Similarly, Derbal-Mokrane et al. [20] studied the production of hydrogen through an ORC powered by a PTC under the Algerian Sahara climate. They performed their analysis using SAM (System Advisor Module) and EES for three different cities and eight different ORC working fluids. Their results showed that benzene gave

the best system efficiency, which was recorded in July with hydrogen output, power output and efficiency of 847 Nm³, 8.74 kW and 21.65% respectively. To investigate the impact of mixed refrigerants on hydrogen production rate of a geothermal-powered ORC, Ganjehsarabi [29] combined pentane, butane and iso-pentane to serve as the system's working fluid. The result showed that the hydrogen production rate of the system improved due to the glide match profiles of heat exchangers' temperatures. In a different approach, Nassar and Hassan [30] studied the performance of PEM electrolyzer and solid oxide electrolyzer cell (SOEC) powered with the same energy from waste heat. The waste heat was utilized to power an ORC for electricity generation to run the PEM electrolyzer and to produce high-temperature steam required for the SOEC. Their analysis showed that the SOEC outperformed the PEM electrolyzer in terms of hydrogen production yielding 36.9 kg/h at a system efficiency of 23.8% and 27.4 kg/h at a system efficiency of 14.45% respectively.

2.3 Supercritical Brayton Cycle

Supercritical Brayton cycles are single phase cycles that work in the supercritical state. The common heat transfer fluids for supercritical Brayton cycles are helium and carbon dioxide but SCBC is the most used supercritical Brayton cycle in the analysis of power systems for green hydrogen production. Supercritical carbon dioxide cycles have many advantages over the conventional Rankine cycles. They are highly efficient at moderate temperatures (450°C – 700°C), operate at lower critical pressure than water, are compact in design due to the high fluid density, give room for pinch point

elimination in heat exchangers due to the single-phase operation, and are suitable for air cooling thereby reducing environmental impact that is caused by water-cooled systems [31]. Abid et al. [18] conducted an analysis to compare two SCBC configurations for hydrogen production via a solar dish technology. The two configurations were a recompression Brayton cycle with reheat and one without reheat. The system's energy and exergy analysis revealed that the SCBC with recompression and reheat performed better than the one without reheat, yielding 0.0125 g/s, 3177 kW, 30.37%, and 32.7% hydrogen rate, power output, energy and exergy efficiency respectively. The system optimization resulted in a levelized electricity cost of \$0.2831 per kilowatts and a payback period of 9.5 years.

Similarly, Liu et al. [32] conducted an analysis to compare four configurations of SCBCs integrated with a fluoride cooled high temperature reactor. The four configurations were single-stage regenerative SCBC, main pressure intercooling SCBC, recompression SCBC, and a reheat recompression SCBC. Their analysis showed that the recompression SCBC gave the best results with a system efficiency in the range of 42% to 44% at a minimum system temperature of 20°C to 40°C and a core outlet temperature of 700°C. Al-Sulaiman and Atif [33] did the same analysis as Liu's group but instead of a high temperature reactor and four-cycle configurations, they used solar power tower and five cycle configurations which were a simple SCBC, regenerative SCBC, recompression SCBC, pre-compression Brayton SCBC, and a split expansion SCBC. However, their results were similar to that obtained by Liu's group, the best performing cycle configuration was the recompression SCBC with an integrated cycle efficiency of 40%.

2.4 Combine Cycle Configurations

All the cycles discussed above have their own challenges, ORCs are best suited for heat sources with low temperatures. SCBC outperforms conventional steam Rankine cycles only at temperatures above 500°C [34], while steam Rankine cycles rely heavily on water for cooling among other challenges. Therefore, many research works focused on combining more than one power cycle to improve energy efficiency and system design. Hai et al. [3] conducted techno-economic optimization of a supercritical Brayton cycle (with helium as the heat transfer fluid) combined with an ORC and an SPT to produce green hydrogen. Their analysis showed that under optimum operating conditions, the integrated supercritical Brayton cycle and ORC performed better than the supercritical Brayton cycle-based system. The combined cycle produced 15.8% more hydrogen and reduced the hydrogen cost by 4.2%. Yang et al. [34] studied the performance of an SCBC cycle bottomed by an SRC for power production through an SPT, with the incorporation of a large thermal storage to take care of solar radiation fluctuations. Their analysis revealed that the electricity output of the combined cycle was 9.5% better than a simple SCBC.

Tong et al. [35] did the same analysis as Yang’s group and gave the same conclusion that the integrated cycle had a significant improvement in system performance when compared to the simple SCBC. In a different approach, Singh and Mishra [36] analyzed an SCBC bottomed by an ORC for power production via a PTC. Eight different ORC heat transfer fluids were studied and their results revealed that R123 gave the best performance for the combined cycle with thermal and exergy efficiency

of 73.4% and 40.89% respectively. Recently, Das and Reddy [37] studied hydrogen and electricity production via a nuclear reactor coupled with an SCBC bottomed by an ORC, and a PEM electrolyzer. The energy and exergy analysis revealed system efficiencies of 42.13% and 58.32%, respectively, along with a levelized energy cost of \$0.063 per kilowatts-hour. In another study, Ajaj et al. [38] studied green hydrogen production from biomass waste heat by using an SRC bottomed by an ORC. Eight system configurations and heat transfer fluids were considered, and the best system performance was for the SRC regenerative cycle bottomed by an ORC with a recuperator and R245fa as a heat transfer fluid. This configuration's hydrogen yield was 94.65 tons/year with a levelized hydrogen cost of 1.724 \$/kg and carbon credit gain of \$37527.

Balta et al. [39] studied the production of hydrogen by a solar-assisted Brayton cycle combined with SRC and an ORC for high-temperature steam electrolysis. The energy efficiency for the system power generation was 24.79% while the exergy efficiency was 22.36%. The hydrogen production block had energy efficiency of 87% and exergy efficiency of 88%. At 230°C, the system produced 0.057 kg/s hydrogen and consumed 1.98 kWhe. Bentoumi et al. [40] did the analysis of an SRC bottomed by an ORC integrated with an SPT for hydrogen generation using different electrolyzers. In their analysis, the SOE gave the best performance, followed by the PEM electrolyzer while the alkaline electrolyzer ranked lowest in terms of hydrogen yield.

2.5 Cost and Optimization

As discussed in Chapter 5, the cost of green hydrogen is very high which makes the adoption of hydrogen as a source of clean energy difficult, among other factors. The cost of green hydrogen is influenced by the type of electrolyzer as well as the type of power cycle deployed. Cheaper power cycles for installation translate to cheaper levelized cost of electricity (LCOE) which greatly influences the cost of green hydrogen [41]. The installation cost of using popular cycles like ORC and SCBC can range from 1800\$/kW to 3000\$/kW for ORCs [42], and 3000\$/kW to 5000\$/kW for SCBCs [43]. Xu et al [44] did a comparative cost analysis of SCBC and an advanced SRC for a coal-fired system and their results revealed that while the SCBC outperformed the advanced SRC in terms of efficiency, the advanced SRC was 1.32% cheaper than the SCBC which had an LCOE of 0.06056\$/kW.

Abdesselem et al [45] studied the cost of integrating an ORC, SRC and Kalina cycle with an SPT and reported that the ORC offered the cheapest LCOE of 0.163\$/kWh while the Kalina cycle was the most expensive with 0.1745\$/kWh. Recently, Muhammad et al [46] studied the impact of electrolyzer type on the cost of green hydrogen by doing an analysis of hydrogen production using different electrolyzers. Their results showed that the alkaline electrolyzer gave the cheapest LCOH of 7.86\$/kg while the PEM electrolyzer was the most expensive with an LCOH of 14.44\$/kg. In a different approach, Razmi et al [47] performed technoeconomic analysis of hydrogen production using methane pyrolysis and SOEC, both powered by solar energy. Their analysis revealed that the methane pyrolysis was a cheaper way of producing hydrogen (at a cost

of 2.31\$/kg) when compared to SOEC (which had a cost of 5.19\$/kg).

There are different optimization algorithms that are used for energy optimization analysis but the popular ones are genetic algorithm [48] and particle swarm algorithm [49]. Optimization processes are used in the production [50], storage [51] and transportation [52] and usage [53] of hydrogen to improve efficiency and decrease cost.

2.6 Summary

It can be seen from the literature review that many works have been done on the analysis of green hydrogen production using concentrating solar technologies such as PTC and SPT as well as different electrolyzer types such as PEM, SOEC and alkaline electrolyzers. These different works have also used different cycles which include SMR, SCBC and ORC. However, there is no work that has compared SPT and PTC technologies for the purpose of green hydrogen production using energy, exergy and technoeconomic analysis of various configurations of these three power cycles: SMR, SCBC and ORC. Moreover, there is no work that uses the modified version of SMR in this work in combination with SCBC. Furthermore, the novel cycle configuration comprising of all three power cycles that is used in this work for analysis has not been used in the literature before. This work therefore aims to analyze eight (8) different configurations of SMR, SCBC and ORC powered by either PTC or SPT for the purpose of green hydrogen production in order to determine the best system with the highest efficiency and least cost of hydrogen.

CHAPTER 3

METHODOLOGY

This section describes working principle of the system and the thermodynamic and cost models that were used in the analyzing the systems.

3.1 System Description

Figure 3.1 shows the new integrated power system proposed in this paper for the production of green hydrogen using SPT, PTC, PEM electrolyzer and different configurations of thermodynamic cycles. Figure 3.1(a) shows the first cycle configuration, the MSRC-SCBC-ORC configuration, which consists of a solar tower, a modified steam Rankine cycle (MSRC) bottomed by an SCBC, an ORC, and an electrolyzer. In this setup, reflected solar radiation from the heliostats heats the heat transfer fluid (HTF), which is molten salt, in the solar tower receiver. The heated HTF transfers its energy to water in the MSRC through heat exchanger (HEX) I, converting the water into superheated steam. The steam is then directed to the high pressure turbine (HPT), where it expands to generate power. A portion of the steam is extracted

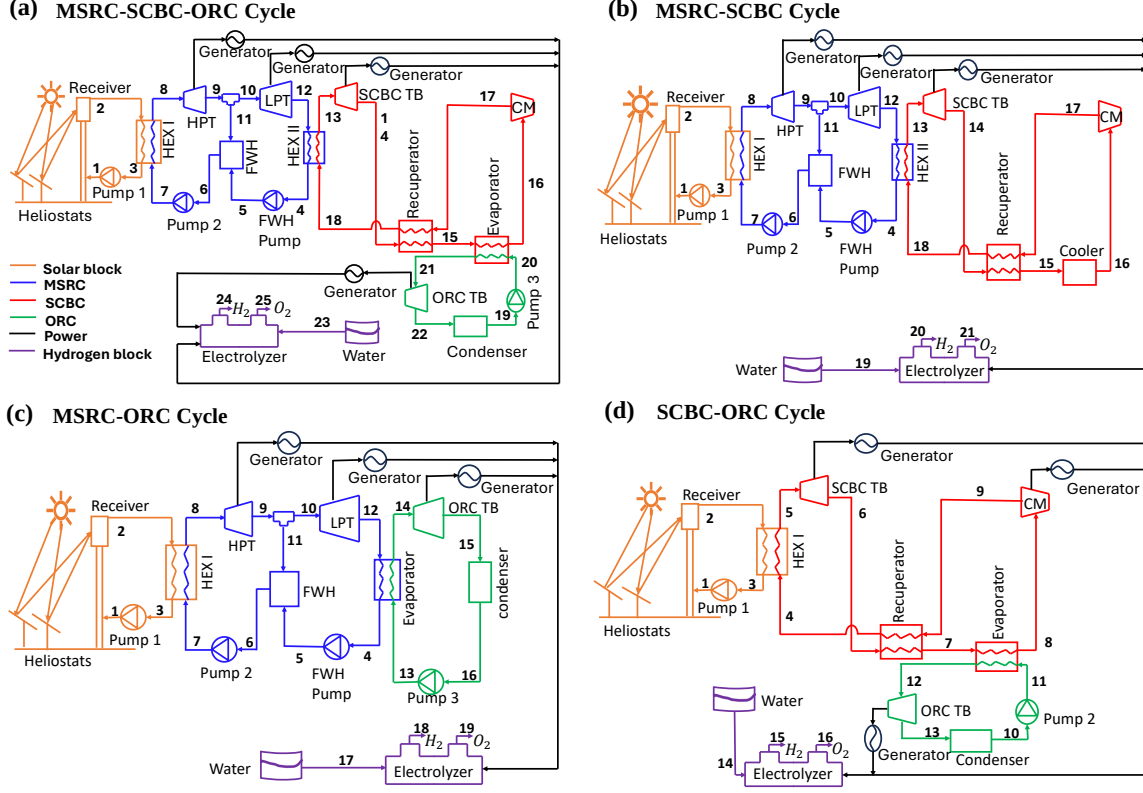


Figure 3.1: Integrated Cycle Configurations: (a) The MSRC-SCBC-ORC Cycle Configuration. (b) The MSRC-SCBC Cycle Configuration. (c) The MSRC-ORC Cycle Configuration. (d) The SCBC-ORC Cycle Configuration.

at state 11 in the HPT and routed to the feed water heater (FWH) to preheat the water entering HEX I. The remaining steam goes to the low pressure turbine (LPT) where it expands again to produce more power. The exhaust of the LPT is used to heat supercritical CO₂ in the SCBC through HEX II. The heated supercritical CO₂ is expanded in the SCBC turbine before it goes to the recuperator for energy recovery. After the recuperator, the supercritical CO₂ is used to provide heat to the ORC via the evaporator. From the evaporator, CO₂ is compressed and sent to the recuperator where it is preheated before being sent to HEX II to restart the SCBC. In the ORC, R600a gains energy from the evaporator and vaporizes to expand in the ORC turbine before it passes to the condenser where it is cooled and pumped back to the evaporator

to begin the ORC again. The electricity produced from the four turbines is sent to the electrolyzer to produce hydrogen and oxygen. The electrolyzer receives electricity and water and gives out hydrogen and oxygen as useful products. Figure 3.1(b) shows the second configuration, the MSRC-SCBC configuration, which consists of a solar tower, an MSRC, an SCBC and an electrolyzer. The difference between the MSRC-SCBC-ORC and MSRC-SCBC configurations is the absence of the ORC in the MSRC-SCBC configuration. Every other thing remains the same. Figure 3.1(c) shows the third cycle configuration, the MSRC-ORC configuration, which consists of a solar tower, an MSRC, an ORC and an electrolyzer. The MSRC-ORC configuration is also similar to the MSRC-SCBC-ORC configuration but without an SCBC. In the MSRC-ORC, the steam that leaves the LPT is used to heat the HTF in the ORC through the evaporator instead of CO₂ through HEX II as in the case of MSRC-SCBC-ORC. The electricity produced from the MSRC and the ORC is fed to the electrolyzer for the production of hydrogen and oxygen. Figure 3.1(d) shows the last configuration, the SCBC-ORC configuration, which consists of a solar tower, an SCBC, an ORC and an electrolyzer. In this configuration, the heat from the solar receiver's HTF is used to heat supercritical CO₂ in the SCBC which expands in the SCBC turbine to produce power. After the SCBC turbine, the supercritical CO₂ undergoes heat recovery in the recuperator and then supplies heat to the ORC via the evaporator before it is finally compressed. The electricity generated from the SCBC and ORC is as usual fed to the electrolyzer for hydrogen and oxygen production.

The four cycle configurations discussed thus far are all powered by a solar tower. These same configurations are used for the PTC and the only difference is the re-

placement of the solar tower with the PTC in the cycle diagram. The HTF for the PTC is Therminol_VP1.

3.2 Thermodynamic Modeling

The different cycle configurations were modeled in EES for the two major energy sources, PTC and SPT. In the modeling, more emphasis was given to the PTC model, the SPT model and the electrolyzer model. Other components of the systems were analyzed on the basis of energy and exergy balances. To model the systems, some assumptions were made which include:

- The systems are modeled under steady state conditions and pressure drop along pipes and heat exchangers is negligible.
- Kinetic and potential energy variations were ignored.
- The isentropic efficiencies of turbines, pumps, and compressors were respectively 0.85, 0.9, and 0.85.
- The condenser exit is considered to be saturated liquid while the evaporator exit is considered to be saturated vapor.

3.2.1 Energy and Exergy Assessments

The system was modeled as a control volume and therefore the energy balances used were those of a control volume. The mass and energy balances of a control volume are given by equations (3.1) and (3.2), respectively [54]:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (3.1)$$

$$\dot{Q} - \dot{W} = \sum (\dot{m}h)_{out} - \sum (\dot{m}h)_{in} \quad (3.2)$$

Where $\dot{m}_{in}$ and $\dot{m}_{out}$ are the inlet and outlet mass flow rates, h is the flow enthalpy, $\dot{Q}$ is heat rate and $\dot{W}$ is power. The energy balance equations for the MSRC-SCBC-ORC configuration are given in Table 3.1 and these equations apply to the rest of the configurations. The thermal efficiency, the solar-to-electricity efficiency and the solar-to-hydrogen efficiency are given by equations (3.3), (3.4) and (3.5) respectively [3], [35].

$$\eta_{th} = \frac{\dot{W}_{total}}{\dot{Q}_u} \quad (3.3)$$

$$\eta_{STE} = \frac{\dot{W}_{total}\eta_{gen}}{\dot{Q}_{solar}} \quad (3.4)$$

$$\eta_{STH} = \frac{\dot{m}_{H_2}LHV_{H_2}}{\dot{Q}_{solar}} \quad (3.5)$$

Where $\dot{m}_{H_2}$ is the mass flow rate of hydrogen, LHV_{H_2} is the lower heating value of hydrogen, $\dot{Q}_{solar}$ is the solar energy received by the solar collectors, $\dot{Q}_u$ is the thermal energy absorbed in the solar receiver and $\dot{W}_{total}$ is the total power output from the integrated cycle. η_{gen} , η_{th} , η_{STE} and η_{STH} are generator efficiency, thermal efficiency, solar-to-electricity efficiency and solar-to-hydrogen efficiency respectively.

Exergy can be defined as the work potential of a system relative to a defined dead state, indicating the amount of work that can be performed. Unlike energy, which simply denotes the total work potential contained in a system, exergy explicitly

Table 3.1: Energy and Exergy Balances for the MSRC-SCBC-ORC configuration [1]

Component	Energy Balance	Exergy Balance
Solar field	$\dot{Q}_u = \dot{m}_{solar}(h_2 - h_1)$	$\dot{X}_{D,SF} = \dot{X}_{sun} + \dot{X}_1 - \dot{X}_2$
HEX I	$\dot{m}_{solar}(h_2 - h_3) = \dot{m}_{SR}(h_8 - h_7)$	$\dot{X}_{D,HEXI} = \dot{X}_2 + \dot{X}_7 - \dot{X}_3 - \dot{X}_8$
Pump 1	$\dot{W}_{P1} = \dot{m}_{solar}(h_1 - h_3); \eta_{P1}(h_1 - h_3) = v_3(P_1 - P_3)$	$\dot{X}_{D,P1} = \dot{X}_3 - \dot{X}_1 + \dot{W}_{P1}$
HPT	$\dot{W}_{HPT} = \dot{m}_{SR}(h_8 - h_9); \eta_{HPT}(h_8 - h_{9s}) = h_8 - h_9$	$\dot{X}_{D,HPT} = \dot{X}_8 - \dot{X}_9 - \dot{W}_{HPT}$
LPT	$\dot{W}_{LPT} = \dot{m}_{SR}(h_{10} - h_{12});$	$\dot{X}_{D,LPT} = \dot{X}_{10} - \dot{X}_{12} - \dot{W}_{LPT}$
FWH	$\dot{m}_5 h_5 + \dot{m}_{11} h_{11} = \dot{m}_6 h_6$	$\dot{X}_{D,FWH} = \dot{X}_5 + \dot{X}_{11} - \dot{X}_6$
Pump 2	$\dot{W}_{P2} = \dot{m}_{solar}(h_7 - h_6); \eta_{P2}(h_7 - h_6) = v_6(P_7 - P_6)$	$\dot{X}_{D,P2} = \dot{X}_6 - \dot{X}_7 + \dot{W}_{P2}$
FWH Pump	$\dot{W}_{FWP} = \dot{m}_4(h_5 - h_4); \eta_{FWP}(h_5 - h_4) = v_4(P_5 - P_4)$	$\dot{X}_{D,FWH} = \dot{X}_4 - \dot{X}_5 + \dot{W}_{FWP}$
HEX II	$\dot{m}_{SR}(h_{12} - h_4) = \dot{m}_{CO_2}(h_{13} - h_{18})$	$\dot{X}_{D,HEXII} = \dot{X}_{12} + \dot{X}_{18} - \dot{X}_{13} - \dot{X}_4$
SCBC Turbine	$\dot{W}_{SBT} = \dot{m}_{CO_2}(h_{13} - h_{14}); \eta_{SBT}(h_{13} - h_{14s}) = h_{13} - h_{14}$	$\dot{X}_{D,SBT} = \dot{X}_{13} - \dot{X}_{14} - \dot{W}_{SBT}$
Compressor	$\dot{W}_{CM} = \dot{m}_{CO_2}(h_{17} - h_{16}); \eta_{CM}(h_{17} - h_{16}) = h_{17s} - h_{16}$	$\dot{X}_{D,CM} = \dot{X}_{16} - \dot{X}_{17} + \dot{W}_{CM}$
Recuperator	$h_{14} - h_{15} = h_{18} - h_{17}; \epsilon_{REC} = (T_{14} - T_{15}) / (T_{14} - T_{17})$	$\dot{X}_{D,REC} = \dot{X}_{17} + \dot{X}_{14} - \dot{X}_{15} - \dot{X}_{18}$
Evaporator	$\dot{m}_{CO_2}(h_{15} - h_{16}) = \dot{m}_{ORC}(h_{21} - h_{20})$	$\dot{X}_{D,Eva} = \dot{X}_{15} + \dot{X}_{20} - \dot{X}_{21} - \dot{X}_{16}$
ORC Turbine	$\dot{W}_{ORT} = \dot{m}_{ORC}(h_{21} - h_{22}); \eta_{ORT}(h_{21} - h_{22s}) = h_{21} - h_{22}$	$\dot{X}_{D,ORT} = \dot{X}_{21} - \dot{X}_{22} - \dot{W}_{ORT}$
Pump 3	$\dot{W}_{P3} = \dot{m}_{ORC}(h_{20} - h_{19}); \eta_{P3}(h_{20} - h_{19}) = v_{19}(P_{20} - P_{19})$	$\dot{X}_{D,P3} = \dot{X}_{19} - \dot{X}_{20} + \dot{W}_{P3}$
Condenser	$\dot{Q}_{con} = \dot{m}_{ORC}(h_{22} - h_{19})$	$\dot{X}_{D,con} = \dot{X}_{22} - \dot{X}_{19} - \dot{Q}_{con}(1 - T_o/T_{con})$

considers the system's reference to a dead state. There are physical, chemical, kinetic and potential exergies. Only physical and chemical exergies were considered in the analysis of the integrated power cycles. The exergy balance of a control volume is given by equation (3.6) [54]. The total exergy flow of a substance at a given state is expressed by equation (3.7) [55]. Where $\dot{X}$ stands for exergy rate and the subscripts Q and w stand for heat and work respectively, while $\dot{X}_D$ stands for the exergy destroyed or irreversibility. e^{ph} is physical exergy, e^{ch} is chemical exergy and $\dot{m}$ is the mass flow rate of the substance.

$$\dot{X}_Q + \sum \dot{X}_{\text{in}} = \sum \dot{X}_{\text{out}} + \dot{X}_w + \dot{X}_D \quad (3.6)$$

$$\dot{X} = \dot{m} (e^{ph} + e^{ch}) \quad (3.7)$$

Equation (3.8) gives the physical exergy while equation (3.9) gives the molar chemical exergy of a mixture as a function of its constituents [56].

$$e^{ph} = h - h_o - T_o(s - s_o) \quad (3.8)$$

$$e^{ch} = \sum_j x_j e_{o,j} + RT_o \sum_j x_j \ln \gamma_j x_j \quad (3.9)$$

In equation (3.8) and (3.9), h_o is standard enthalpy while s and s_o are flow and standard entropies respectively. $e_{o,j}$ is the standard molar chemical exergy, x_j is the mass fraction and γ_j is the activity coefficient of the j th constituent of a mixture. R and T_o are the universal gas constant and the standard temperature respectively. The chemical exergy of the HTFs in the solar tower, the MSRC, the SCBC and the ORC are considered to be constant throughout the cycle since there is no change in their chemical composition during the cycle. The standard chemical exergy of some substances is given in Table 3.2 [2]. The exergy balances for the MSRC-SCBC-ORC configuration are given in Table 3.1. The exergy balances for the other cycle configurations are the same with this configuration except for the numbering. The thermal exergy efficiency is given by equation (3.10) while the solar-to-electricity and solar-to-hydrogen exergy efficiencies are given by equation (3.11) and (3.12) respectively [3].

$$\eta_{ex} = \frac{\dot{W}_{total}}{\dot{Q}_u(1 - T_o/T_r)} \quad (3.10)$$

$$\eta_{ex,STE} = \frac{\dot{W}_{total}\eta_{gen}}{\dot{X}_{solar}} \quad (3.11)$$

$$\eta_{ex,STH} = \frac{\dot{m}_{H_2}e_{H_2}^{ch}}{\dot{X}_{solar}} \quad (3.12)$$

Where $e_{H_2}^{ch}$ is the chemical exergy of hydrogen, T_r is the temperature of the solar receiver, and $\dot{X}_{solar}$ is the solar exergy supplied to the system which is a function of the solar energy received by the solar collectors. η_{ex} , $\eta_{ex,STE}$ and $\eta_{ex,STH}$ are thermal exergy efficiency, solar-to-electricity exergy efficiency and solar-to-hydrogen exergy efficiency respectively. The solar exergy is given by equation (3.13), where T_{sun} is the temperature of the sun.

$$\dot{X}_{solar} = \dot{Q}_{solar} \left(1 - \frac{T_o}{T_{sun}} \right) \quad (3.13)$$

Table 3.2: Standard chemical exergy Values [2]

Substance	Standard chemical exergy (kJ/kmol)
Oxygen (g)	3970
Hydrogen (g)	238490
Water (l)	3120
Water (g)	11710

3.2.2 Solar Tower Model

The solar tower model adopted in this work is the one used by Hai et al [3] as presented in Table 3.3. Where A_{field} is total area of the heliostat field, G_b is solar irradiation, η_{field} is optical efficiency of the heliostat field, η_{Rec} is receiver's efficiency, A_{Rec} is receiver surface area, C is concentration ratio and A_{Apt} is receiver's aperture area. h_2 and h_1 are the flow enthalpies at the exit and inlet of the solar receiver respectively. The input values for the solar tower plant are given in Table 3.4.

Table 3.3: Solar tower model [3].

Parameter	Equation
Total energy received on the heliostats, $\dot{Q}_{solar}$	$\dot{Q}_{solar} = A_{field}G_b$
Energy concentrated on the receiver by the heliostats, $\dot{Q}_{Rec}$	$\dot{Q}_{REC} = \eta_{field}\dot{Q}_{solar}$
Useful heat absorbed by the molten salt in the receiver, $\dot{Q}_u$	$\dot{Q}_u = \eta_{Rec}\dot{Q}_{Rec}$
Mass flow rate of molten salt in the receiver, $\dot{m}_{ms}$	$\dot{m}_{ms} = \dot{Q}_u / (h_2 - h_1)$
Receiver surface area, A_{Rec}	$A_{Rec} = A_{field} / CF_r$
Concentration ratio, C	$C = A_{field} / A_{Apt}$
View factor, F_r	$F_r = A_{Apt} / A_{Rec}$

3.2.3 PTC Model

The PTC model used in this work is the one adopted by Alirahmi et al. [4] as presented in Table 3.5. Where N_{cp} is the number of PTCs in parallel, N_{cs} is the number of PTCs in series, A_r is the area of the receiver in the PTC, T_{ri} is the receiver's inlet temper-

Table 3.4: Input Parameters for the Integrated Power Cycle

	Parameter	Value	Reference
SPT	G_b	850 W/m ²	[3]
	$A_{helio\,stat}$	9.45×12.8 m ²	[3]
	η_{field}	0.75	[3]
	η_{Rec}	0.90	[3]
PTC	W	5.76 m	[4]
	L	12.27 m	[4]
	$D_{o,r}$	0.07 m	[4]
	$D_{i,r}$	0.066 m	[4]
	U_L	3.82 W/m ² .°C	[4]
	h_{fi}	300 W/m ² .°C	[4]
	k	16 W/m.°C	[4]
	τ_c	0.96	[4]
	τ_p	0.94	[4]
	α_r	0.96	[4]
	γ	0.95	[4]
PEM	T_{PEM}	353 K	[57]
	$E_{act,a}$	76×10^3 kJ/kmol	[57]
	$E_{act,c}$	18×10^3 kJ/kmol	[57]
	λ_a	14	[57]
	λ_c	10	[57]
	D	1×10^4 m	[57]
	J_{ref}^a	1.7×10^5 A/m ²	[58]
	J_{ref}^c	4.6×10^3 A/m ²	[58]
	F	96485 C/mol	[4]

ature, T_a is the ambient temperature, γ is the correction factor for diffuse radiation, τ_c is the transmissivity of the cover glazing, τ_p is the PTC effective transmissivity, α_r is the receiver's absorptivity, U_L is the total heat loss coefficient, L is the length of the collector, W is the width of the collector, $D_{i,r}$ and $D_{o,r}$ are the inner and outer diameters of the receiver, h_{fi} is the internal fluid heat transfer coefficient, k is thermal conductivity, $C_{p,c}$ is the specific heat capacity of PTC's HTF and $\dot{m}_c$ is the mass flow rate of the HTF in the PTC. The HTF for the PTC is Therminol_VP1. The input parameters for the PTC are given in Table 3.4.

Table 3.5: PTC Model [4].

Parameter	Equation
Useful heat absorbed by PTC HTF, $\dot{Q}_u$	$\dot{Q}_u = N_{cp}N_{cs}F_R[SA_a - A_rU_L(T_{ri} - T_a)]$
Absorbed solar radiation by receiver, S	$S = G_b\eta_r$
Efficiency of the PTC receiver, η_r	$\eta_r = \gamma\tau_c\tau_p\alpha_r$
Heat removal factor F_R	$F_R = \frac{\dot{m}_c C_{p,c}}{A_r U_L} \left[1 - \exp\left(\frac{-A_r U_L F_1}{\dot{m}_c C_{p,c}}\right) \right]$
Collector's efficiency factor, F_1	$F_1 = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_{o,r}}{h_{fi}} + \left(\frac{D_{o,r}}{2k} + \ln \frac{D_{o,r}}{D_{i,r}}\right)}$
Aperture area of the collector, A_{apt}	$A_{apt} = L(W - D_{o,r})$

3.2.4 Electrolyzer

Electrolyzers are used to produce hydrogen, and they are of different types as discussed earlier in the introduction. For this work a PEM electrolyzer was used. PEM electrolyzers operate at very high efficiencies (80% - 90%) with high hydrogen purity

(> 99.99%) [59]. They use electricity to split water into hydrogen and oxygen. A solid polymer membrane acts as the electrolyte, allowing only protons to pass through while blocking gases. Water enters the anode, where it splits into protons, electrons, and oxygen. Protons move through the membrane to the cathode, where they combine with electrons to form hydrogen gas while oxygen gas is released at the anode as a by product. The basic reactions in a PEM electrolyzer are the oxidation reaction at the anode, (I), and the reduction reaction at the cathode, (II). Two moles of water are electrolyzed using electricity to produce two moles of hydrogen and one mole of oxygen as shown in reaction (III), where ΔH signifies the total energy required to split water into hydrogen and oxygen.



The total energy demand of a PEM electrolyzer is expressed in equation (3.14) [60]. Where $T\Delta S$ is the thermal energy demand in the electrolyzer, and ΔG is the Gibb's energy.

$$\Delta H = \Delta G + T\Delta S \quad (3.14)$$

The molar rate of hydrogen and oxygen produced per unit area is given by equations (3.15) and (3.16) respectively, while the power per unit unit area of the elec-

trolyzer is given by equation (3.17).

$$\dot{n}_{H_2} = \frac{J_e}{2F} \quad (3.15)$$

$$\dot{n}_{O_2} = \frac{J_e}{4F} \quad (3.16)$$

$$\dot{W}_e = J_e V \quad (3.17)$$

In equation (3.15) and (3.17), $\dot{n}_{H_2}$ is the molar rate of hydrogen, J_e is the current density of the electrolyzer, F is Faraday's constant, V is the cell voltage and $\dot{W}_e$ is the electrolyzer's power. The reversible voltage and the losses in form of activation overpotentials and ohmic overpotential all sum up to give the cell voltage as expressed in equation (3.18), where V_o is the reversible voltage, $V_{act,a}$ and $V_{act,c}$ are the activation overpotentials at the anode and cathode respectively, and V_{ohm} is the ohmic overpotential. The reversible voltage is a function of the electrolyzer temperature as expressed in equation (3.19) [4] where T_{PEM} is the electrolyzer temperature, while the ohmic overpotential is the product of current density and ohmic resistance, R_{PEM} as expressed in equation (3.20).

$$V = V_o + V_{act,a} + V_{act,c} + V_{ohm} \quad (3.18)$$

$$V_o = 1.229 - 8.5 \times 10^{-4} (T_{PEM} - 298) \quad (3.19)$$

$$V_{ohm} = J_e R_{PEM} \quad (3.20)$$

The local ionic conductivity of PEM membrane, σ_{PEM} is given by equation (3.21)

where x is the membrane space calculated out of the cathode membrane contact and $\lambda(x)$ is the content of water at position x . $\lambda(x)$ is given by equation (3.22) where D is the membrane thickness while λ_a and λ_c are respectively the content of water at the anode and cathode interfaces [4].

$$\sigma_{PEM}[\lambda(x)] = [0.5139\lambda(x) - 0.326] \exp \left[1268 \left(\frac{1}{303} - \frac{1}{T_{PEM}} \right) \right] \quad (3.21)$$

$$\lambda(x) = \frac{\lambda_a - \lambda_c}{D}x + \lambda_c \quad (3.22)$$

The activation overpotential is given by equation (3.23) [61] where $i = a, c$, R is the universal gas constant and $J_{o,i}$ is the exchange current density which is given by equation (3.24).

$$V_{act,i} = \frac{RT}{F} \sinh^{-1} \left(\frac{J_e}{2J_{o,i}} \right) \quad (3.23)$$

$$J_{o,i} = J_{ref}^i \exp \left(\frac{E_{act,i}}{RT_{PEM}} \right) \quad (3.24)$$

In equation (3.24), $E_{act,i}$ is the activation energy for anode and cathode and J_{ref}^i is the pre-exponential factor. The PEM resistance is given by equation (3.25). The input parameters for PEM electrolyzer are given in Table 3.4.

$$R_{PEM} = \int_0^D \frac{dx}{\sigma_{PEM}[\lambda(x)]} \quad (3.25)$$

3.3 Cost Analysis

In the evaluation of engineering systems, different cost analysis methods are used depending on the nature and aims of the cost assessment. In this work, the cost model used by Muhammad et al [5] was deployed to evaluate the LCOH for each cycle configuration. In this cost assessment method, the capital cost of equipment or purchase of equipment cost (PEC), and operation and maintenance cost ($\dot{C}_{O\&M}$) are used. The capital recovery factor (CRF) and life span of the designed system was used to convert the PEC of each component denoted as Z_k into a cost rate denoted as $\dot{Z}_k$. Where the subscript k stands for the component whose cost is being evaluated. The PEC of the system components was gotten from different sources and is presented in Table 3.6. The cost rate, $\dot{Z}_k$ is given by equation (3.26) [5], where H is the annual operating hours and CRF is the capital recovery factor. The annual operating hours can also be expressed as a capacity factor of the system which in this work was taken be 25%. That is, 6 hours of operation per day. The $\dot{C}_{O\&M}$ is given by equation (3.27) where CELF is the constant escalation leveling factor, and θ is the operation and maintenance cost ratio which was taken as a percentage of the initial capital cost. The CRF and constant escalation leveling factor (CELF) are given by equation (3.28) and equation (3.29) respectively. In the equations for CRF and CELF, i_{eff} , k and N stand for effective interest rate, annual escalation rate and economic life span of the system respectively. The annual escalation rate is given by equation (3.30) where r_N is the nominal escalation rate. The economic assumptions used for the cost model are given in Table 3.7 [5]. The total cost rate and the LCOH were then calculated

by equations (3.31) and (3.32) respectively. Where $\dot{m}_{H_2}$ is the rate of production of hydrogen in kg/s.

$$\dot{Z}_k = \sum_i^n Z_k * \left(\frac{CRF}{3600H} \right) \quad (3.26)$$

$$\dot{C}_{O\&M} = \sum_i^n Z_k * \theta * \left(\frac{CELF}{3600H} \right) \quad (3.27)$$

$$CRF = \frac{i_{eff}(1 + i_{eff})^N}{(1 + i_{eff})^N - 1} \quad (3.28)$$

$$CELF = \frac{k(1 - k^N)}{1 - k} * CRF \quad (3.29)$$

$$k = \frac{1 + r_N}{1 + i_{eff}} \quad (3.30)$$

$$\dot{C}_{total} = \dot{Z}_k + \dot{C}_{O\&M} \quad (3.31)$$

$$LCOH = \frac{\dot{C}_{total}}{\dot{m}_{H_2}} \quad (3.32)$$

For the cost functions for the SCBC, there is a temperature correction factor, f_T for each component. That is, $f_{T,turbine}$, $f_{T,HEX}$, $f_{T,CM}$ and $f_{T,Recu} \cdot f_{T,CM}$ is 1 while the other temperature correction factors are given by equations (3.33) - (3.35) [66]. The pressure factor for the cost of the ORC's pump, f_{pw} is also given by equation (3.36) [65].

$$f_{T,turbine} = \begin{cases} 1 & \text{if } T_{max} < 550^\circ C \\ 1 + 1.137 \times 10^{-5}(T_{max} - 550^\circ C) & \text{if } T_{max} \geq 550^\circ C \end{cases} \quad (3.33)$$

Table 3.6: Equipment Capital Cost

	Equipment	Cost Equation	Reference
PTC	Solar field	150 \$/m ²	[62]
	HTF system	60 \$/m ²	[62]
	Site improvements	25 \$/m ²	[62]
SPT	Solar field	140 \$/m ²	[63]
	Tower and solar receiver	152 \$/m ²	[63]
	Site improvement	16 \$/m ²	[63]
MSRC	MSRC turbine	$Z_{T,MSRC} = 3880.5\dot{W}_T^{0.7} \left[1 + \left(\frac{0.05}{1-\eta_T^3} \right)^3 \right] \left[5\exp\left(\frac{T-866}{10.4}\right) \right]$	[64]
	Heat exchanger	$Z_{HEX1} = 130 \left[\frac{A_{HEX1}}{0.093} \right]^{0.78}$	[65]
	Pump	$Z_{P2} = Z_{FWP} = 705.48\dot{W}_p^{0.7} \left[1 + \frac{0.2}{(1-\eta_p)^3} \right]$	[64]
SCBC	SCBC turbine	$Z_{T,SCBC} = 406200\dot{W}_{sh}^{0.8} \times f_{T,turbine}$	[66]
	Heat exchanger	$Z_{HEX2} = 820800\dot{Q}_{in,SCBC}^{0.7327} \times f_{T,HEX}$	[67]
	Compressor	$Z_{CM} = 1.23 \times 10^6 \dot{W}_{sh}^{0.3992} \times f_{T,CM}$	[66]
	Recuperator	$Z_{recu} = 49.45UA^{0.7544} \times f_{T,Recu}$	[67]
ORC	ORC turbine	$Z_{T,ORC} = 2237\dot{W}_{T,ORC}^{0.41}$	[65]
	Pump	$Z_P = (475.3 + 34.95\dot{W}_P - 0.031\dot{W}_P^2)f_{pw}$	[65]
	Evaporator	$Z_{eva} = 235\dot{Q}_{eva}^{0.75}$	[68]
	Condenser	$Z_{con} = 43\dot{Q}_L^{0.68}$	[65]
	PEM	$1000\dot{W}_{PEM}$	[69]

$$f_{T,HEX} = \begin{cases} 1 & \text{if } T_{max} < 550^\circ C \\ 1 + 5.4 \times 10^{-4}(T_{max} - 550^\circ C) & \text{if } T_{max} \geq 550^\circ C \end{cases} \quad (3.34)$$

Table 3.7: Economic Assumptions [5].

Parameter	Value
Effective interest rate (i_{eff})	6.0%
Economic lifetime (N)	20 years
Operation and maintenance cost ratio (θ)	6.0%
Nominal escalation rate (r_N)	2.5%

$$f_{T,Recu} = \begin{cases} 1 & \text{if } T_{max} < 550^\circ C \\ 1 + 0.02141(T_{max} - 550^\circ C) & \text{if } T_{max} \geq 550^\circ C \end{cases} \quad (3.35)$$

$$f_{pw} = \begin{cases} 1 & \text{if } 1 < P < 1.03 MPa \\ 1.62 & \text{if } 1.03 < P < 3.45 MPa \\ 2.12 & \text{if } P > 3.45 MPa \end{cases} \quad (3.36)$$

The area for the heat exchangers, A_{HEX} in the MSRC and SCBC was modeled using equation (3.37) [70]. Where $\dot{Q}$ is the heat transfered across the heat exchanger area, U is the heat transfer coefficient of the heat exchanger material and $\Delta(T_m)_{ln}$ is the logarithmic temperature difference which is calculated using equation (3.38) [70]. In equation (3.38), T is temperature of the HTF in the heat exchanger. The subscripts h and c stand for hot and cold flows while i and o stand for inlet and outlet flows respectively. U for the heat exchanger in the MSRC and SCBC is taken to be 0.3 kW/m²K and 1.6 kW/m²K respectively, [70].

$$A_{HEX} = \frac{\dot{Q}}{U \Delta(T_m)_{ln}} \quad (3.37)$$

$$\Delta(T_m)_{ln} = \frac{(T_{h,i} - T_{c,o}) - (T_{h,o} - T_{c,i})}{\ln \left(\frac{T_{h,i} - T_{c,o}}{T_{h,o} - T_{c,i}} \right)} \quad (3.38)$$

3.4 Optimization

An optimization of the system configurations was done for the SPT powered configurations using brute force algorithm in Python. CoolProp was used for the evaluation of the thermodynamic properties of water, carbondioxide and R600a. However, for the molten salt in the SPT, the correlation for specific heat capacity of molten salt as given by equation (3.39) [71] was used to evaluate the enthalpy and entropy of molten salt using equation (3.40) and (3.41) [1] respectively. Where T , h , s and C_p stand for temperature specific enthalpy, specific entropy and specific heat capacity respectively. The subscripts ms and ref stand for molten salt and reference state respectively. The reference temperature used for the calculation of molten salt properties in python was 533K. The values gotten in Python using the correlations were then validated with the values from EES with negligible errors.

$$C_{p,ms} = 1443 + 0.172(T - 273.15); 533K < T < 873K \quad (3.39)$$

$$h_{ms} = h_{ref} + \int_{T_{ref}}^T C_p(T) dT \quad (3.40)$$

$$s_{ms} = S_{ref} + \int_{T_{ref}}^T C_p(T) \frac{dT}{T} \quad (3.41)$$

3.4.1 Brute-Force Optimization Algorithm

Optimization in multi-domain thermodynamic systems often presents challenges related to non-convexity, discontinuities, and complex interdependencies among decision variables and performance metrics. For these reasons, a brute-force grid search method was employed in this study. Unlike gradient-based techniques or heuristic algorithms, the brute-force method guarantees global optima within the sampled parameter space and does not rely on assumptions of smoothness or continuity in the objective functions. This makes it particularly robust and reliable for systems governed by non-linear thermodynamic equations and hard physical constraints [72].

The brute-force method evaluates a large number of configurations by discretizing each decision variable over a fixed interval. For each variable x_i , a set of N_i values is defined over its feasible range. The complete input space, $\mathcal{X}$, is then formed by taking the Cartesian product of these discretized sets as given in equation (3.42)

$$\mathcal{X} = \{x_1^{(1)}, \dots, x_1^{(N_1)}\} \times \dots \times \{x_n^{(1)}, \dots, x_n^{(N_n)}\} \quad (3.42)$$

This usually results in $N_{\text{total}} = \prod_{i=1}^n N_i$ total configurations to evaluate. The decision variables for the optimization of the SPT-powered configurations are given in Table 3.8 where NC is number of collectors and PR is pressure ratio. Each configuration $\mathbf{x} \in \mathbb{R}^n$ is passed through a high-fidelity simulation model which returns one or more objective functions. These typically include LCOH, energy efficiency, exergy efficiency, fuel consumption, or carbon intensity depending on the system under study. In this study, the objective functions were LCOH, denoted $f_1(\mathbf{x})$, measured in dollars

per kilogram (\$/kg), and the thermal efficiency, denoted $f_2(\mathbf{x}) = \eta_{\text{th}}(\mathbf{x})$, expressed as a percentage.

Table 3.8: Decision variables for optimization

Decision variables	Range			
	MSRC-SCBC-ORC	MSRC-SCBC	MSRC-ORC	SCBC-ORC
T_2 ($^{\circ}\text{C}$)	540-565	540-565	540-565	540-565
NC	100-10000	100-5100	100-10000	100 - 5100
P_8 (MPa)	10-15	10-15	10-15	-
P_9 (MPa)	5.5-7.0	5.5-7.5	1.5-3.5	-
P_{21} (MPa)	0.8-1.2	-	1.0-1.5	1.0-2.5
PR	2.5-3.5	2.5-3.5	-	2.5-3.5

Only configurations that meet a set of predefined physical and thermodynamic constraints are considered valid. These constraints can include bounds on temperatures, pressures, phase quality, and pressure ratios. In this work, the most critical constraints were related to exergy destruction. For each system component or subsystem j , the exergy destruction rate $\dot{X}_{D,j}(\mathbf{x})$ was required to be non-negative, ensuring that no component violates the second law of thermodynamics [73]. That is:

$$\forall j, \quad \dot{X}_{D,j}(\mathbf{x}) \geq 0$$

Configurations that violated any such constraints were discarded as physically infeasible.

To evaluate trade-offs between the competing goals of minimizing cost and maximizing efficiency, a scalarized composite objective function was defined as given in equation (3.43) where w_1 and w_2 are weighting coefficients.

$$J(\mathbf{x}) = w_1 \cdot f_1(\mathbf{x}) + w_2 \cdot (1 - f_2(\mathbf{x})) \quad (3.43)$$

The first term, f_1 in equation (3.43) represents the cost objective (LCOH), which is to be minimized. The second term, $1 - f_2$, represents inefficiency, which should also be minimized. This structure ensures that the function $J(\mathbf{x})$ increases with both higher cost and lower efficiency. In this study, the weights were selected as $w_1 = 1$ and $w_2 = 10$, giving greater emphasis to improving efficiency while still accounting for cost.

The optimization results included the identification of the following:

1. The minimum levelized cost of hydrogen (LCOH) observed among feasible designs, in \$/kg.
2. The maximum thermal efficiency achieved, in percent.
3. The configuration that minimized the composite objective $J(\mathbf{x})$, indicating a compromise between cost and efficiency.

The overall procedure of the brute-force optimization algorithm is outlined in Figure 3.2, which illustrates the sequential steps: from grid generation, through simulation and constraint filtering, to the storage and analysis of valid results.

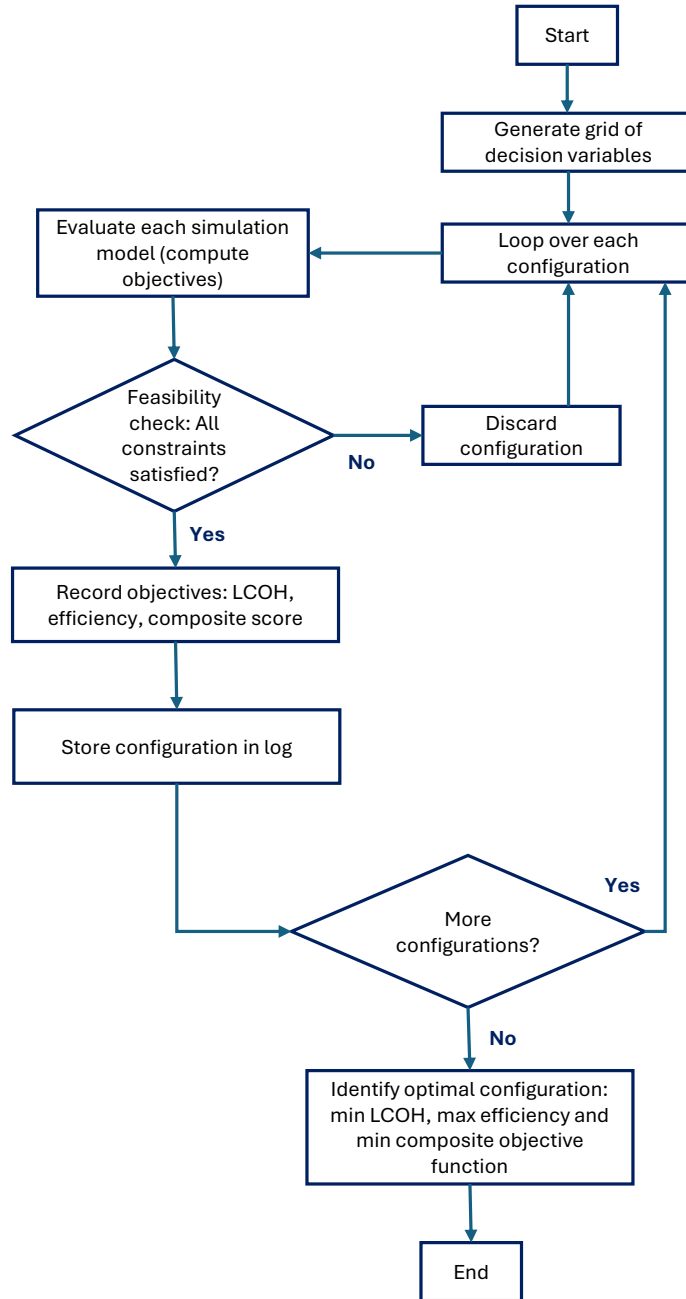


Figure 3.2: Process diagram for the brute-force algorithm.

This method is particularly advantageous when the objective functions are non-differentiable, or when the simulation model is a black box, as is often the case in thermodynamic systems. Moreover, the dense sampling provides a rich dataset suit-

able for downstream tasks such as surrogate modeling, regression analysis, or machine learning-based decision support. Despite its computational expense, the brute-force approach provides a robust foundation for comparative studies and a baseline against which more sophisticated algorithms can be benchmarked. After the optimization was done, the Pareto frontier curve for all the cycle configurations were plotted to see the decision boundaries between feasible and non-feasible reasons.

3.5 Validation

Figure 3.3 shows the validation of the electrolyzer model with experimental work by Ioroi et al. [74], a consistency was observed between the experimental work and the current numerical study.

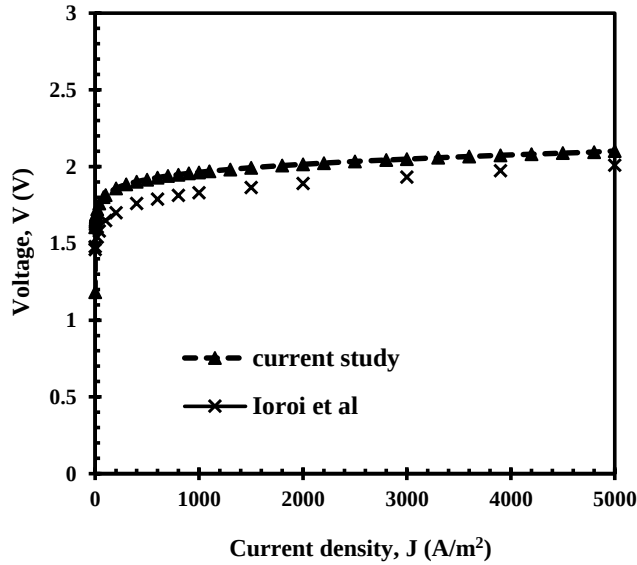


Figure 3.3: Electrolyzer model validation showing the variation of electrolyzer voltage with electrolyzer current density for experiment work and current work.

CHAPTER 4

RESULTS AND DISCUSSION

This section describes the results of both thermodynamic and economic analysis of the different cycle configurations as well as the optimization of the SPT-powered cycle configurations in Python.

4.1 Thermodynamic Modeling Results

The different power cycle configurations were simulated with the same amount of solar irradiation at 850 W/m^2 and 100 solar collectors each for PTC and SPT-powered configurations. Subsequently, a parametric analysis was carried out to see the impact of some input parameters on the performance of the system. For the SPT-powered configurations, the outlet temperature of the receiver was set at 527°C while the receiver's outlet temperature for the PTC-powered configurations was 380°C . These outlets temperatures were set based on the temperature range for Therminol_VP1, 12°C to 400°C , for PTC [75], and the values used by Ratlamwala et al. [76] for SPT analysis. The results showed that the MSRC-ORC configuration gave the best results

for both PTC and SPT configurations while the MSRC-SCBC configuration was the least performing configuration for both PTC and SPT configurations as shown in Table 4.1. The MSRC-SCBC-ORC was the second best configuration and the SCBC-ORC was the third best configuration.

Table 4.1: Efficiency values for different cycle configurations

Cycle Configuration		η_{th}	η_{STE}	η_{STH}	η_{ex}	$\eta_{ex,STE}$	$\eta_{ex,STH}$
MSRC-SCBC	SPT	34.54	23.32	16.77	36.42	24.58	17.68
	PTC	24.90	20.06	14.49	26.26	21.15	15.28
MSRC-SCBC-ORC	SPT	40.65	27.44	19.63	42.86	28.93	20.70
	PTC	30.54	24.60	17.66	32.20	25.94	18.86
MSRC-ORC	SPT	42.36	28.59	20.43	44.66	30.15	21.54
	PTC	34.54	27.82	19.90	36.42	29.33	20.98
SCBC-ORC	SPT	35.94	24.26	17.42	37.89	25.58	18.37
	PTC	27.88	22.45	16.17	29.40	23.68	17.05

For the SPT integrated power cycles, the MSRC-ORC configuration produced a total power output of 2939 kW at a thermal efficiency of 42.36%, a solar-to-electricity efficiency of 28.59% and a solar-to-hydrogen efficiency of 20.43%, with a hydrogen and oxygen yield of 63.04 kg/hr and 504 kg/hr respectively. The thermal exergy efficiency, solar-to-electricity exergy efficiency and solar-to-hydrogen exergy efficiency for this configuration were 44.66%, 30.15% and 21.54% respectively. These values were lesser for the PTC-powered MSRC-ORC configuration because of the lower out-

let temperature of the receiver in the PTC. The MSRC-ORC for the PTC gave a total power output of 1651 kW at a thermal efficiency of 34.54%, solar-to-electricity efficiency of 27.82% and solar-to-hydrogen efficiency of 19.90%, with a hydrogen and oxygen production of 36 kg/hr and 288 kg/hr respectively. Interestingly, the MSRC-SCBC-ORC did not outperform the MSRC-ORC in any of the concentrating solar technologies. However, it outperformed the other two configurations. This means that using three power cycles did not give the best result at the temperature ranges for which the integrated cycles were simulated. The decreased system performance when SCBC was added to the MSRC-ORC configuration was due to the reduced performance of the MSRC when the SCBC was added. The MSRC in the MSRC-ORC configuration was operated at low exit pressure for the LPT ensuring maximum power was harnessed in the MSRC turbines but in the MSRC-SCBC-ORC configuration a low exit pressure in the LPT of the MSRC was not feasible because it also resulted to a low exit temperature that was not feasible for transferring enough heat to the SCBC.

Figure 4.1 shows the comparison between PTC-powered configurations and SPT-powered configurations. The SPT-powered configurations outperformed the PTC configurations. This was due to the higher solar receiver temperature in the SPT which enabled the supply of heat to the power cycles at elevated temperatures thereby increasing the efficiency of the SPT configurations. In terms of the best performing configuration and the least performing configurations, the trend was the same for SPT-powered and PTC-powered configurations.

This trend is similar with the energy and exergy efficiencies for the different con-

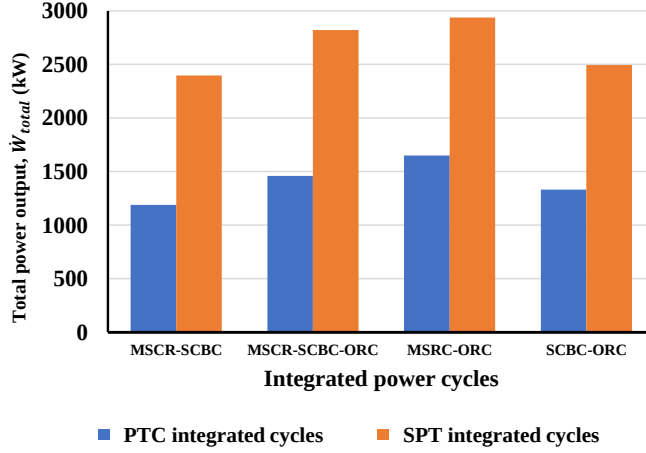


Figure 4.1: Comparison of the total power output from SPT and PTC cycle configurations.

centrating solar technologies as shown in Table 4.1. By extension, the hydrogen yield from the SPT configurations was also higher than that of the PTC configurations. The percentage increase in hydrogen yield for MSRC-SCBC-ORC, MSRC-SCBC, MSRC-ORC, SCBC-ORC configurations powered by SPT as compared to those powered by PTC was 89.6%, 97.4%, 75.1% and 83.9% respectively. For exergy destruction, the highest exergy destruction was recorded in the solar receivers for both the SPT and PTC-powered configurations. The solar receivers accounted for more than 80% of the exergy destruction in all cycle configurations.

4.1.1 Thermodynamic Parametric Analysis

Parametric analysis was carried out to determine the impact of input parameters on the performance of the cycle. An independent parametric study was done for the electrolyzer to study the effect of electrolyzer current density on electrolyzer efficiency and rate of hydrogen production. Figure 4.2 shows the variation of hydrogen production

and electrolyzer's efficiency with current density. It was observed that while the electrolyzer efficiency decreased with increasing current density, the hydrogen production rate constantly increased as the current density was increased.

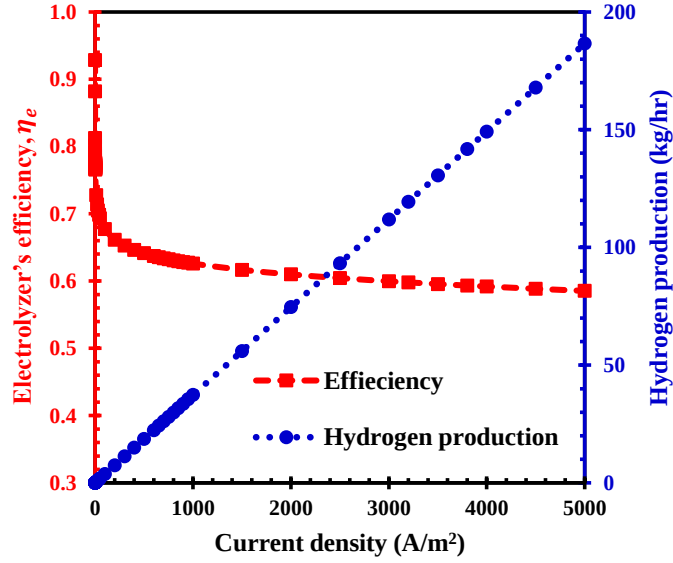


Figure 4.2: Variation of hydrogen production and electrolyzer's efficiency with current density of the electrolyzer.

A non-linear relationship existed between electrolyzer's efficiency and its current density. As the current density increased, the electrolyzer's efficiency decreased to a certain value where an increase in current density did not result to a significant decrease in the electrolyzer efficiency. This is because as the current density increased, electrolyzer losses, primarily due to activation and ohmic overpotentials, also increased, leading to a reduction in the electrolyzer's efficiency. However, higher current density simultaneously resulted in a greater hydrogen output. Eventually, the increase in hydrogen production and the corresponding rise in electrolyzer losses balanced each other, making the effect of current density on the electrolyzer's efficiency negligible. Changing the current density from zero to 20 A/m² resulted to

about 23% decrease in electrolyzer's efficiency while varying it from 20 A/m² to 5000 A/m² only resulted to about 18% decrease in electrolyzer efficiency.

For the integrated power cycles, only the cycle configurations powered by the SPT were used for parametric analysis. This is because the same pattern of system response to varying input parameters was observed for both the SPT and PTC-powered configurations. Figure 4.3 shows the system's response to varying solar irradiation. A study on the effect of solar irradiation on system performance reviewed that changes in solar radiation did not affect the energy or exergy efficiencies of the integrated power cycles but varied directly with hydrogen and power output. This is because the parametric analysis was done at a constant exit temperature for the solar receiver and as such an increase in the solar irradiation only resulted to increased flow rate of the HTF in the solar receiver which increased the amount of heat transferred to the power cycles but at the same temperature. The increase in the heat transferred resulted to increased power output and hydrogen production but the efficiency remained the same due to the constant temperature of the heat source, the solar receiver.

Figure 4.4 shows that a similar pattern was observed in the effect of solar collectors' area on the system's performance. The larger the area of the solar collectors, the more the heat that is concentrated on and absorbed in the solar receiver. However, the increase in absorbed heat only results to an increased flow rate in the solar receiver which by extension results to higher amounts of hydrogen and power output. The correlation between hydrogen and oxygen production was linear, as the amount of hydrogen produced increased so also did the amount of

oxygen produced and vice versa. The impact of solar radiation and solar collector's area on the system was massive as a 100% increase in solar radiation resulted in a 100% increase in the total power output and at least a 75% increase in hydrogen production rate. Similarly, a 100% change in solar collector's area resulted in a 100% change in power output and at least 95% change in hydrogen output.

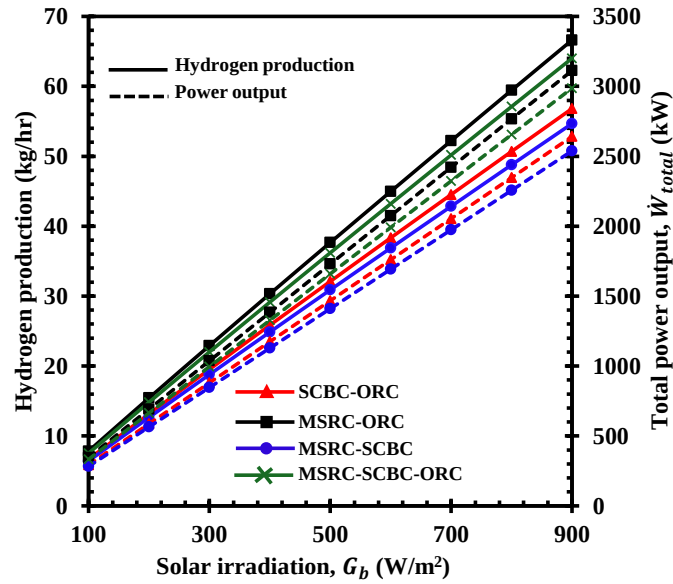


Figure 4.3: Variation of hydrogen and total power output with solar irradiation

Figure 4.5 shows the response of the system's performance to changes in the exit temperature of the solar receiver. In the analysis of the effect of the exit temperature of solar receiver, T_2 , on the system performance it was observed that both the energy and exergy efficiencies of the system increased with increasing T_2 . The solar-to-electricity exergy and energy efficiencies of all the cycle configurations increased. The increased solar-to-electricity energy efficiency also resulted in an increased hydrogen production and solar-to-hydrogen efficiency as well. When T_2

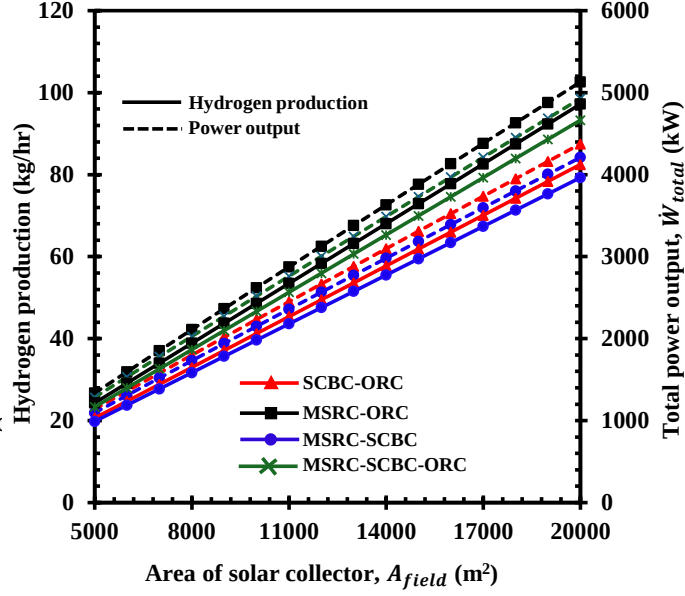


Figure 4.4: Variation of hydrogen and total power output with total area of the solar collector

was varied from 450°C to 550°C , the changes in the solar-to-electricity efficiency for the SCBC-ORC, MSRC-ORC, MSRC-SCBC and MSRC-SCBC-ORC configurations were 8.8%, 2.8%, 18.6% and 13.% respectively. It was observed that the cycle configurations with the SCBC were more sensitive to T_2 changes. The SCBC-ORC configuration with a SCBC as the top cycle was the most sensitive with 18.6% while the MSRC-ORC configuration without an SCBC was the least sensitive with just a 2.8% increase in efficiency. This is because the HTF in the SCBC which was supercritical CO_2 operates at supercritical state where there is no phase change and changes in temperature significantly affect fluid properties. The change in the power output of the cycle configurations with respect to the changes in T_2 was also similar to the change in hydrogen production.

Figure 4.6 shows the system's performance with respect to varying inlet pressure

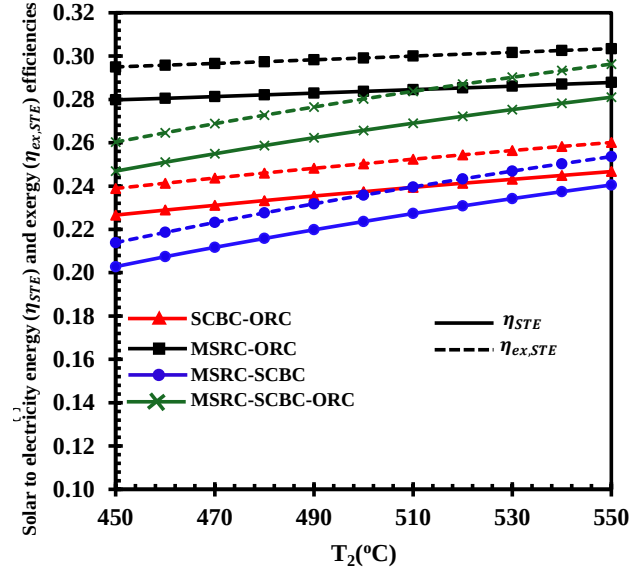


Figure 4.5: Variation of solar-to-electricity energy and exergy efficiencies with the exit temperature of the solar receiver.

of HPT for the MSRC, P_8 . As the top cycle for most of the cycle configurations, P_8 had a significant effect on the performance of the integrated cycle. An increase in P_8 resulted in increased solar-to-electricity exergy efficiency and increased hydrogen production. Changing P_8 from 7000 kPa to 15000 kPa resulted to a continuous increase in solar-to-hydrogen efficiency and hydrogen production for the MSRC-ORC cycle configuration as illustrated in Figure 4.6 (a). However, for the other cycle configurations with SCBC bottoming the MSRC, there was a threshold around 14000 kPa where an increase in P_8 did not result in a significant increase in the performance of the system as shown in Figure 4.6 (b). The increase in solar-to-electricity exergy efficiency was due to the increased power output in the HPT of the MSRC that comes with increasing P_8 which results to higher total power output from the integrated cycle. The increased total power output means more energy is supplied to the electrolyzer thus resulting to increased hydrogen production.

Overall, the effect of P_8 on the system performance was minimal. Increasing P_8 from 7500 kPa to 1500 kPa only resulted to about 3% to 8% changes in the energy and exergy efficiencies as well as hydrogen production across all system configurations.

Figure 4.7 shows the variation of system performance with changing inlet pressure of the LPT (P_9). Unlike P_8 , increasing P_9 led to a decrease in the solar-to-electricity energy efficiency and, consequently, a reduction in the solar-to-electricity exergy efficiency of the MSRC-ORC configuration. This occurred because P_9 represents the pressure at which steam was extracted and sent to the FWH, which was also the exit pressure of the HPT. Therefore, increasing P_9 resulted in lower power generation in the HPT and greater energy extraction with the steam sent to the FWH. This resulted to a decreased power output in the MSRC as shown in Figure 4.7 (a). A decreased power generation in MSRC resulted to a decreased total power output which resulted to the decrease in solar-to-electricity efficiency of the system. Because the total power output was decreased, hydrogen production rate also dropped when P_9 was increased for the MSRC-ORC configuration. For the other cycle configurations with SCBC bottoming the MSRC, there was an increase in system performance as P_9 was increased. However, a peak was reached and then the performance of the system began to decline as shown in Figure 4.7 (b). This is because the presence of the SCBC required high pressures at the exit of the LPT for heat to be supplied to the SCBC at feasible temperatures. Therefore, the reduced power generation in the HPT of the MSRC that came with increasing P_9 was compensated for by the power generated in the SCBC. However, at very high values of P_9 , very little power

was generated in the MSRC and most of the energy was sent to the SCBC which was less efficient than the MSRC at the temperature ranges for which the parametric analysis was done. This caused both the power generated in the MSRC and the solar-to-electricity energy efficiency to drop at very high values of P_9 . Similar to P_8 , the effect of P_9 on the overall system performance was minimal.

Figure 4.8 shows the effect of pressure ratio of the SCBC on the overall system performance. For the SCBC-ORC configuration, increasing the pressure ratio from 1.5 to 4.0 resulted in a sharp increase in system performance from a pressure ratio of 1.5 to 3.0 but after that changes in pressure ratio did not result to significant changes in the performance of the system as shown in Figure 4.8 (a). For the other cycle configurations where SCBC was not the top cycle, the increase in system performance that resulted from increasing the pressure ratio peaked at a pressure ratio of 3.0 after which the performance of the system began to decrease as shown in Figure 4.8 (b).

This is because in the other configurations where SCBC is not the top cycle, the temperature at which heat was supplied to the SCBC subcycle was lower than the temperature at which heat was supplied to the SCBC from the solar receiver in the SCBC-ORC configuration. Therefore, although the system performance continued to improve beyond a pressure ratio of 3.0 in the SCBC-ORC configuration, increasing the pressure ratio beyond this point in the other cycle configurations led to higher energy consumption in the compressor without a corresponding significant increase of power generation in the SCBC turbine. As a result, the net power output of the SCBC decreased, as shown in Figure 4.8 (b). In general, within the pressure ratio range of

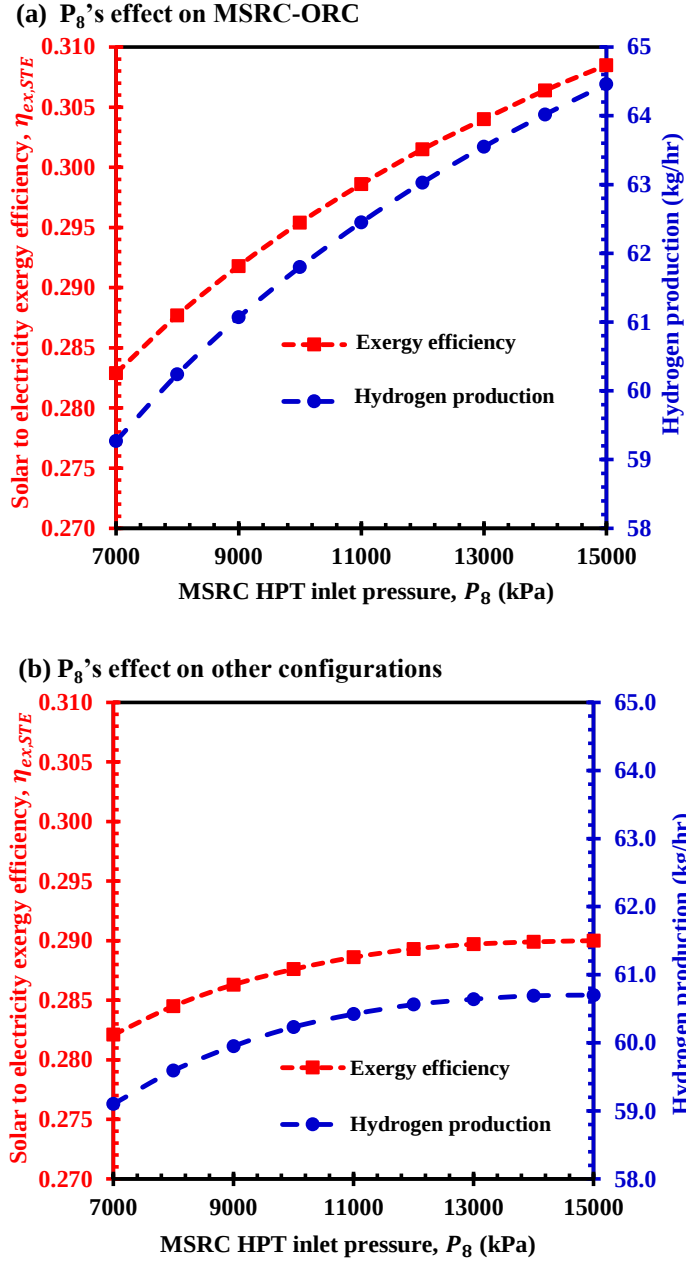


Figure 4.6: Variation of solar-to-electricity exergy efficiency and hydrogen production rate with the inlet pressure of the HPT: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.

1.5 to 3.0, there was an increase in solar-to-electricity energy and exergy efficiencies, along with an increase in total power output and hydrogen production rate across all cycle configurations.

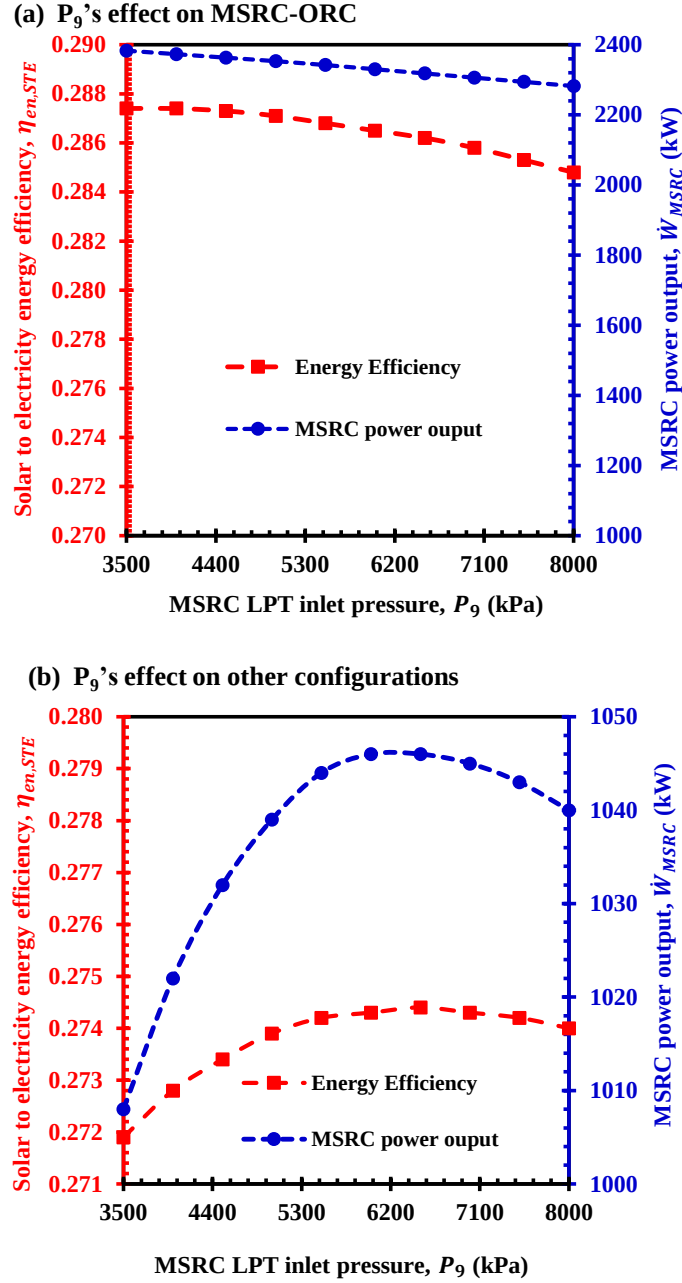


Figure 4.7: Variation of solar-to-electricity energy efficiency and the power output of the MSRC with the inlet pressure of the LPT: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.

Overall, the pressure ratio had a remarkable impact on the performance of the integrated power cycles: a 100% increase of pressure ratio from 1.5 to 3.0 resulted in 64.3% increase in the net power output of the SCBC and 38.3% in the

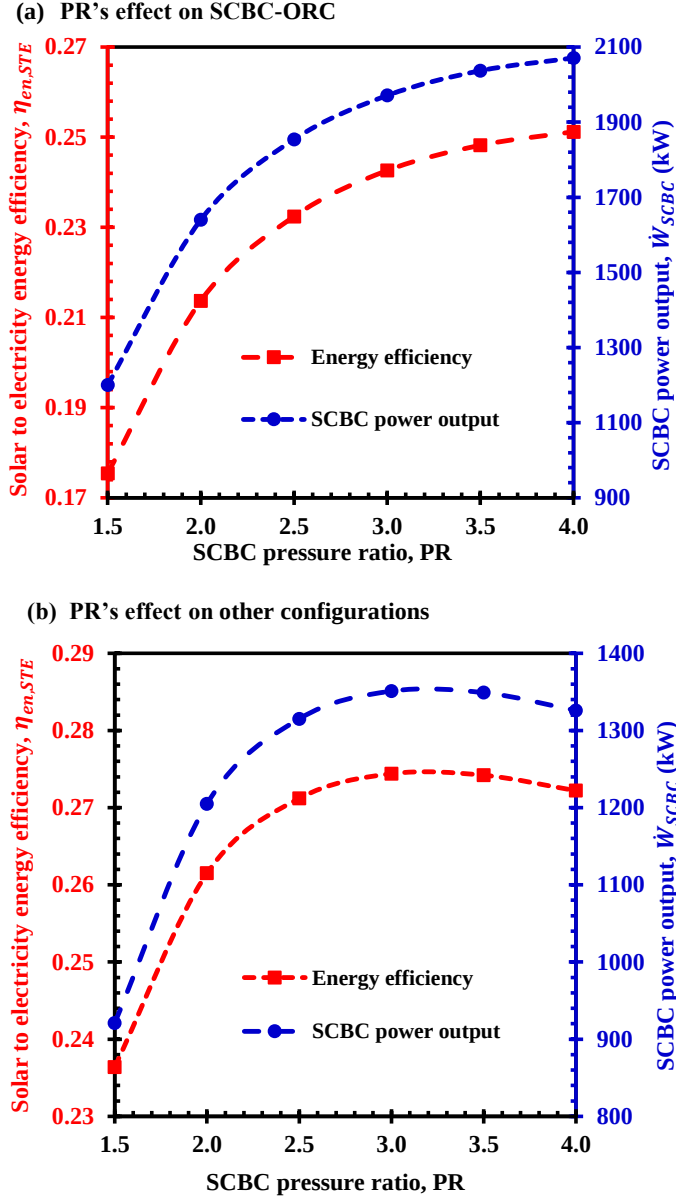


Figure 4.8: Variation of solar-to-electricity energy efficiency and SCBC power output with the pressure ratio of the SCBC: (a) the system's response when SCBC is the top cycle and (b) the system's response when SCBC is a bottoming cycle.

solar-to-electricity efficiency of the overall cycle for the SCBC-ORC configuration.

These figures were 46.7% and 16.1% for the MSRC-SCBC-ORC configuration, and 46.7% and 21.8% for the MSRC-SCBC configuration. The improved system efficiency resulted to higher hydrogen production rate across all configurations.

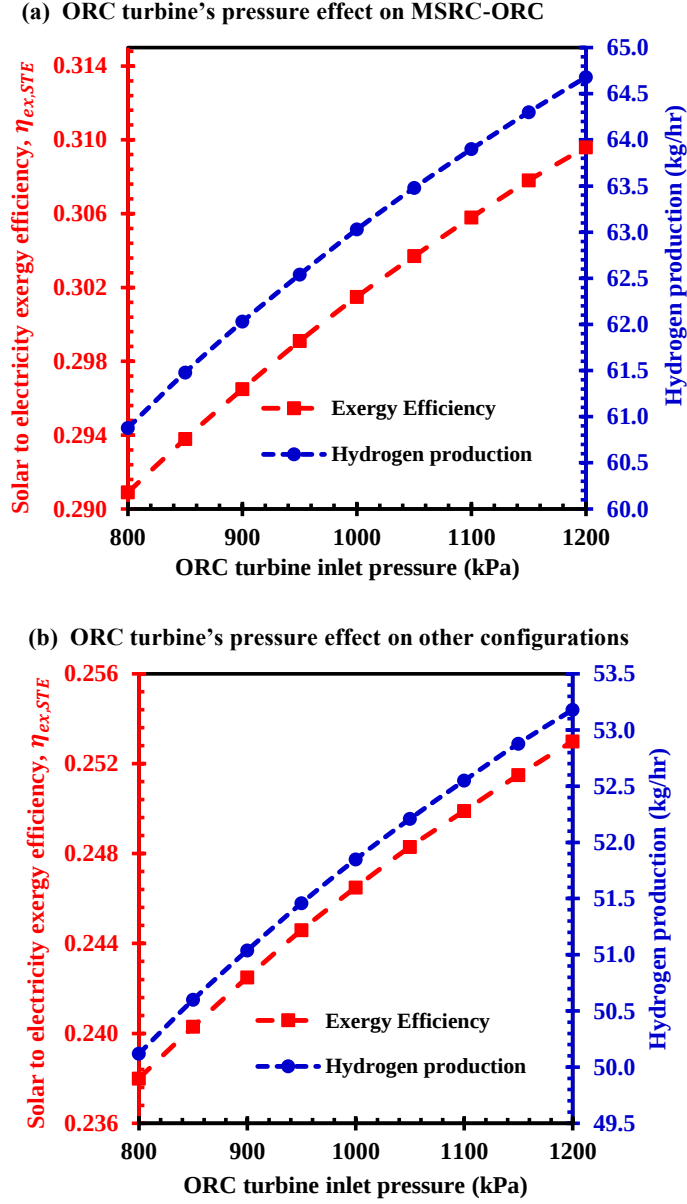


Figure 4.9: Variation of solar-to-electricity exergy efficiency and hydrogen production rate with the inlet pressure of the ORC turbine: (a) The system's response for the MSRC-ORC configuration and (b) the system's response for other cycle configurations with SCBC bottoming the MSRC.

Lastly, Figure 4.9 shows the system's response to inlet pressure of the ORC turbine. In the study on the effect of the inlet turbine pressure for the ORC on the systems performance it was observed that a direct proportionality existed between the per-

formance of the system and the ORC turbine inlet pressure. The solar-to-hydrogen exergy efficiency and the hydrogen production rate both increased as the ORC inlet turbine pressure was increased as shown in Figure 4.9 (a) for MSRC-ORC configuration and Figure 4.9 (b) for the other cycle configurations which has the SCBC. Generally, the effect of this parameter on the system was the same across all cycle configurations. As the exergy efficiency was improved, so also was the total power output and energy efficiency of the cycle.

4.2 Cost Assessment Results

A comparative cost analysis for the different cycle configurations was performed for a 3MW electrolyzer capacity. In the cost analysis, only the major equipment costs were considered. The cost for things such as Engineering and liscensing, civil works, working capital, instrumentation and control, piping and bearings, and other installation accessories were not considered. Therefore the cost presented here is an underestimation of the real cost of the system. The result of the cost analysis showed that the configuration with the highest LCOH was the MSRC-SCBC configuration while the configuration with the lowest LCOH was the MSRC-ORC configuration as shown in Table 4.2. The more efficient configuration was, the lower the LCOH for the configuration given that all other things were equal. The MSRC-SCBC had the highest LCOH because the PEC for both the MSRC and the SCBC were high. Also, because of the low efficiency of the MSRC-SCBC configuration which was lower than other configurations as shown in Table 4.1 in Section 4.1. The difference in the LCOH for the

MSRC-SCBC and the MSRC-SCBC-ORC was not much because the improvement in system efficiency that came with the addition of the ORC also came with more PEC for the ORC. The performance of the SCBC-ORC was similar to that of the MSRC-SCBC in terms of cost. This is because of the low efficiency of the SCBC cycle at low temperature ranges under which the analysis was performed, that is , around 527°C. As explained by Baglietto et al [77], the MSRC and the ORC are most likely to overperform the SCBC at this temperature range. The MSRC-ORC configuration had the lowest LCOH because the CAPEX for the ORC for each configuration was lower than the other power cycles. Therefore, combining it with the MSRC, which was very efficient under the operating temperature, greatly improved the performance of the system at a lower cost thereby lowering the LCOH of the configuration.

Table 4.2: The hydrogen cost for 3MW electrolyzer capacity.

Cycle Configuration		Hydrogen cost (\$/kg)
MSRC-SCBC	SPT	17.02
	PTC	17.76
MSRC-SCBC-ORC	SPT	15.57
	PTC	15.93
MSRC-ORC	SPT	9.11
	PTC	7.78
SCBC-ORC	SPT	16.62
	PTC	16,67

Table 4.3 shows the total PEC for the power cycles under each configuration. It was observed that the total PEC for the SCBC was high but according to the report done by [66], the SCBC total installation cost for this work falls within the range for SCBCs. Moreover, as it will be seen later in the parametric analysis, at higher capacity, the cost per kilowatt for all cycles drops with increased production capacity. The total PEC for MSRC and ORC was very low in all configurations compared to the reports in the literature that give a range of 1800-3000 \$/kW for ORC and a range of 4000-7000 \$/kW for steam power plants [78]. The cost of MSRC and ORC was low because only a few components were considered in the technoeconomic analysis, while in practice, the installation of steam power plants involves many components.

When comparing the SPT and PTC configurations, the SPT configurations just slightly outperformed the PTC configurations except for the MSRC-ORC configuration where the cost for the PTC-MSRC-ORC configuration, 7.78\$/kg was better than that of the SPT-MSRC-ORC configuration, 9.11\$/kg. Given that the operating temperature of the SPT configurations was way higher than the PTC configurations, it was expected that the cost for the SPT configurations would considerably drop when compared to the PTC configurations. However, this was not the case because the PEC for the SPT was higher than that of the PTC thereby compromising the efficiency improvement in the cost equation. In fact, for the MSRC-ORC configuration, the PTC-powered configuration was cheaper because the efficiency improvement that resulted from the increase in operating temperature did not have a great impact on the LCOH as can be later seen in the cost parametric analysis.

Table 4.3: Total PEC values for different power cycles

Configuration		PEC (\$/kW)		
		MSRC	SCBC	ORC
MSRC-ORC	SPT	374.7	-	372.9
	PTC	236.6	-	345.2
MSRC-SCBC	SPT	918.3	3518	-
	PTC	514.9	3879.3	-
MSRC-SCBC-ORC	SPT	959.6	3716	396.5
	PTC	544.3	4151	427.1
SCBC-ORC	SPT	-	2673.1	329.9
	PTC	-	3340	354.5

4.2.1 Cost Parametric Analysis

Parametric analysis was carried out for the SPT-powered configurations to determine the influence of some system parameters on the LCOH. It is good to note that the same pattern was observed with the PTC-powered configurations therefore only the analysis for the SPT-powered configurations is discussed. For the solar field, the influence of solar irradiation, number of collectors and the exit temperature of the receiver, T_2 on the LCOH was studied. Figure 4.10 shows the variation of solar irradiation with LCOH where it can be seen that solar irradiation had a huge impact on the LCOH. In all configurations, increasing the solar radiation drastically reduced the cost of hydrogen. Increasing the solar irradiation from 100 W/m^2 to 900 W/m^2 reduced the cost of

hydrogen from: 41.64 \$/kg to 9.65 \$/kg for the MSRC-ORC configuration, 63.60 \$/kg to 17.13 \$/kg for the MSRC-SCBC configuration, 55.13 \$/kg to 15.35 \$/kg for the MSRC-SCBC-ORC configuration and 60.57 \$/kg to 16.09 \$/kg for the SCBC-ORC configuration. The huge drop in the cost of hydrogen is due to the enormous increase in energy supplied to the power block when solar irradiation is high. As discussed in Section 4.1.1, the solar radiation had a great influence on the amount of power output from the system. And this translate to reduced LCOH when other system costs are fixed.

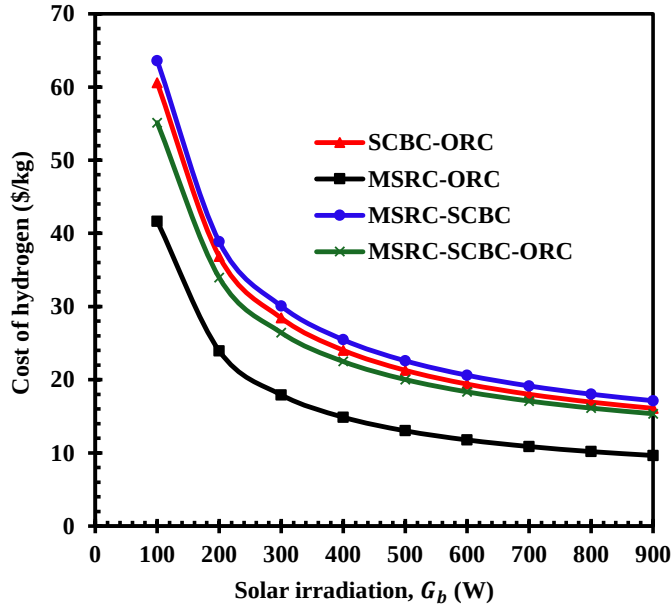


Figure 4.10: The variation of levelized cost of hydrogen with solar irradiation.

Figure 4.11 shows the variation of LCOH with number of collectors. Just like the solar irradiation, the number of solar collectors also had a significant impact on the cost of hydrogen. This is due to the law of economies of scale which states that as the quantity of output increases, the average cost per unit of production decreases [79]. Increasing the number of collectors from 100 to about 500 collectors produced a sharp

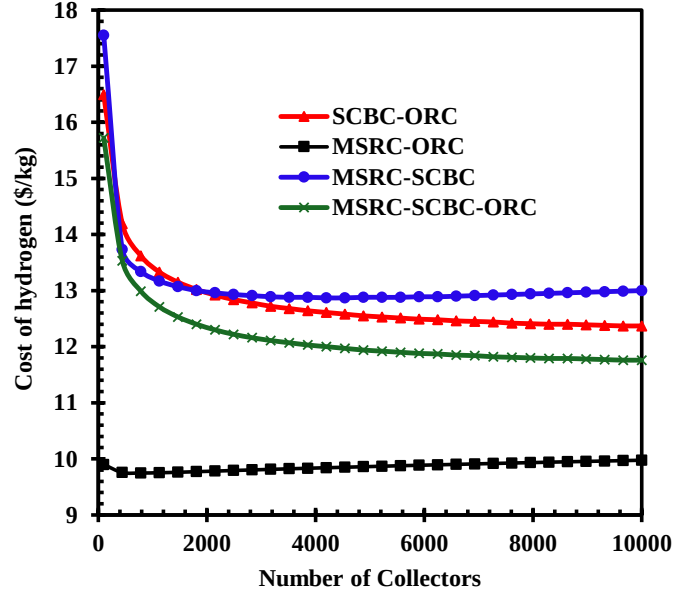


Figure 4.11: The variation of levelized cost of hydrogen with number of solar collectors.

decline of LCOH in all configurations but after that, the decrease in LCOH that came with increasing the number of solar collectors was low and at some point negligible. This is also due to the law of diminishing returns which states that: as additional units of a variable input are added to a fixed input, the marginal output from each additional unit of input will eventually decrease given that all other factors are constant [80].

Figure 4.12 shows the variation of LCOH with T_2 . Just like the other two parameters for the solar field, the LCOH decreased with higher values of T_2 . This is because as T_2 increased, so did the efficiency of the system as discussed in Section 4.1.1. The increased efficiency resulted in increased power output while other cost parameters remained the same thereby reducing the cost of hydrogen. More power means more hydrogen produced and more hydrogen implies lesser LCOH when the total cost is constant as given by equation (3.32). However, the impact of T_2 on the LCOH was not very significant. A 22.22% increase in T_2 only resulted in a 0.64%, 12.58%, 9.54%

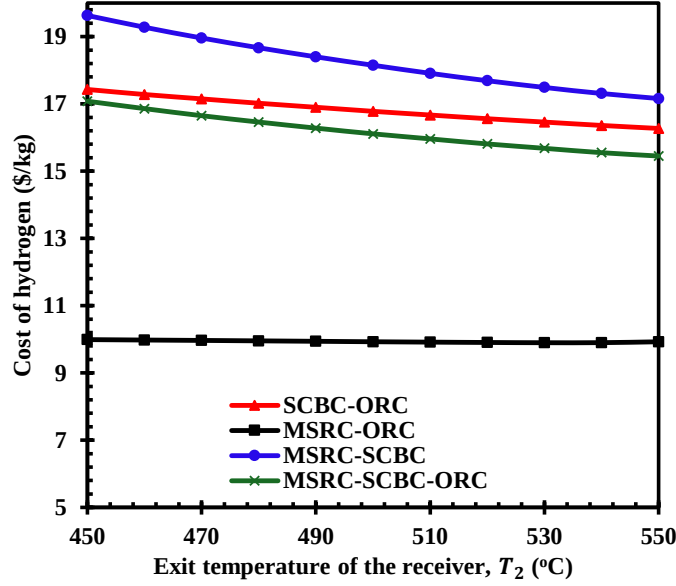


Figure 4.12: The variation of levelized cost of hydrogen with the exit temperature of the solar receiver.

and 6.66% decrease in LCOH for the MSRC-ORC, MSRC-SCBC, MSRC-SCBC-ORC and SCBC-ORC configurations respectively. This little influence of T_2 on system performance could be attributed to the fact that it directly affects heat transfer in a single heat exchanger, which is the heat exchanger for the topping cycle. The heat transfer to the other cycles depends largely on the operating conditions of the topping cycle. For instance, in the MSRC-ORC configuration, no matter the exit temperature of the solar receiver, what determines the amount of heat transferred to the ORC HTF is the outlet pressure of steam in the LPT in the MSRC.

Figure 4.13 shows the variation of LCOH with the inlet pressure of the HPT in the MSRC, P_8 . The P_8 's influence was only studied for 3 configurations as the SCBC-ORC did not have a steam turbine. The impact of P_8 on LCOH was not significant even though LCOH decreased at higher values of P_8 . Increasing P_8 from 7 MPa to 15 MPa only resulted to a 3.83%, 2.18% and 1.69% decrease in LCOH for the MSRC-ORC,

MSRC-SCBC and MSRC-SCBC-ORC configurations respectively. Figure 4.14 shows the variation of LCOH with the inlet pressure of the ORC turbine. Just like P_8 , the inlet pressure of the ORC turbine in all configurations (except for the MSRC-SCBC) had an inverse proportionality with the LCOH but did not significantly affect the cost of hydrogen.

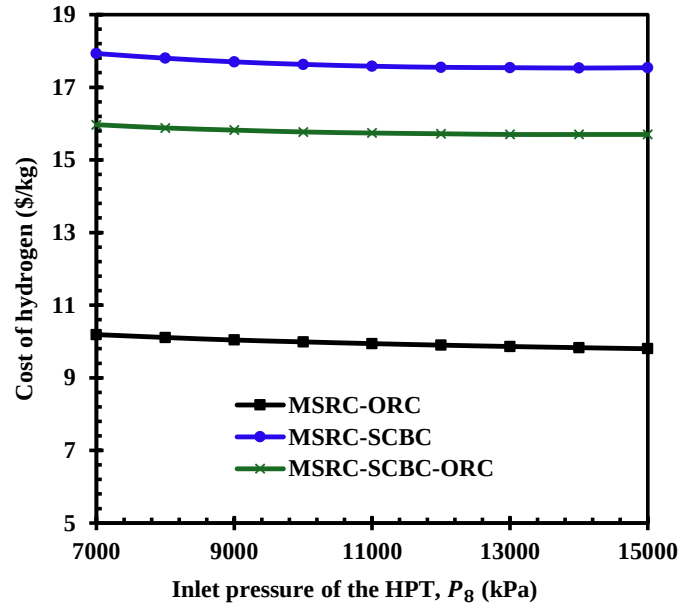


Figure 4.13: The variation of levelized cost of hydrogen with the inlet pressure of the HPT.

Figure 4.15 shows the variation of LCOH with the pressure ratio of the SCBC. The LCOH decreased when the pressure ratio was increased because higher values of the pressure ratio made the SCBC more efficient, thereby increasing the amount of total power output from the system which by extension reduced the cost of hydrogen produced. Unlike P_8 and the ORC turbine inlet pressure, the pressure ratio had a significant impact on the cost of hydrogen. The LCOH had a sharp decline in all configurations when the pressure ratio was increased from 1.5 to 2.5. After that the decrease in LCOH was mild until a pressure ratio of 3.5 when the LCOH started

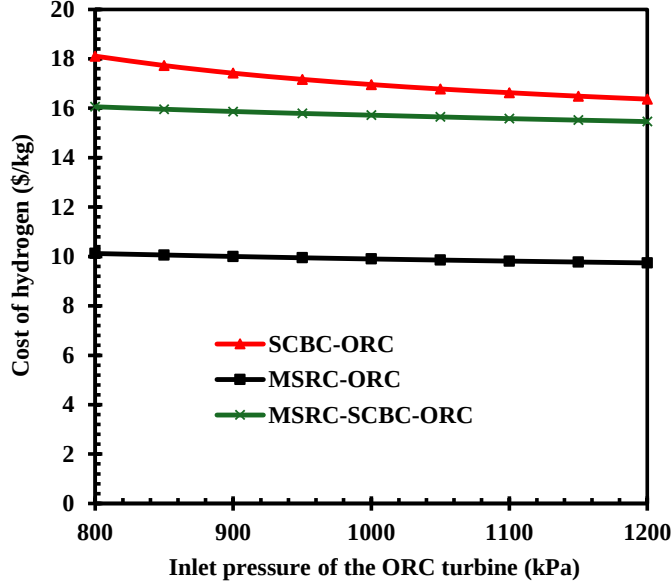


Figure 4.14: The variation of levelized cost of hydrogen with the inlet pressure of the ORC.

increasing with increasing values of pressure for the MSRC-SCBC and MSRC-SCBC-ORC configurations. This behavior was different for the SCBC-ORC configuration where the LCOH continued to decrease gradually till the pressure ratio of 4.0. This discrepancy in the pattern of system response when it comes to pressure ratio was explained in Section 4.1.1 under the parametric analysis for pressure ratio. The effect of pressure ratio on the LCOH was also mild. A 100% increase in the pressure ratio resulted in just 3.71%, 7.12% and 18.14% decrease in the LCOH for the MSRC-SCBC-ORC, MSRC-SCBC and SCBC-ORC configurations respectively.

Figure 4.16 shows the variation of LCOH with the capacity factor of the system. The capacity factor had the greatest impact on the LCOH among all the studied parameters in the parametric analysis. This is because this parameter deals with how effectively a system is utilized over time as compared to its maximum capacity. Apart from the operation and maintenance costs, which are usually a small fraction of the

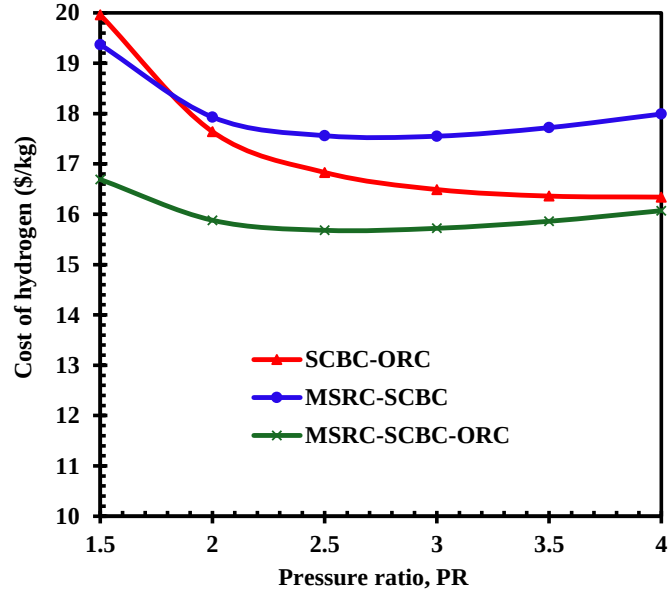


Figure 4.15: The variation of levelized cost of hydrogen with pressure ratio of the SCBC.

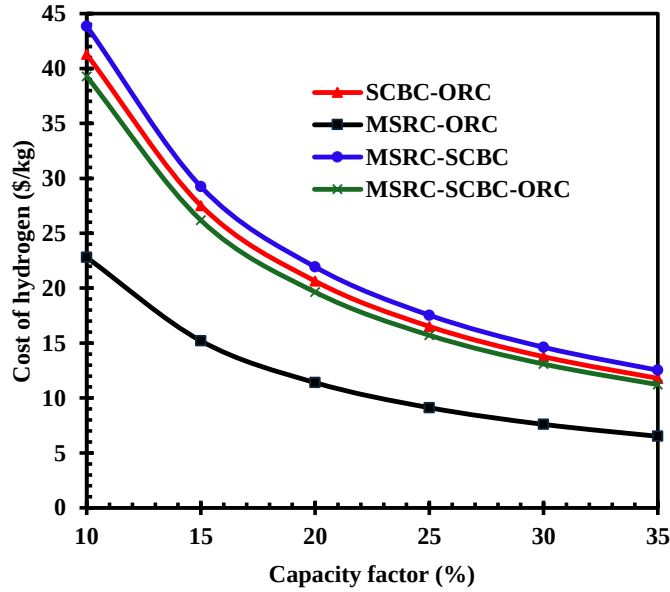


Figure 4.16: The variation of levelized cost of hydrogen with capacity factor of the system.

fixed cost for renewable energy systems, all the fixed cost remain constant regardless of how effective the system is utilized. Therefore, the capacity factor has a huge role to play in the LCOH which accounts for the cost of hydrogen over the entire lifetime

of the hydrogen production system. When the capacity factor was increased from 10% to just 35%, the LCOH reduced from: 22.80 \$/kg to 6.51 \$/kg for the MSRC-ORC configuration, 43.86 \$/kg to 12.53 \$/kg for the MSRC-SCBC configuration, 39.28 \$/kg to 11.22 \$/kg for the MSRC-SCBC-ORC configuration and 41.28 \$/kg to 11.79 \$/kg for the SCBC-ORC configuration. At a capacity factor of 35%, the LCOH for the MSRC-ORC which was 6.51\$/kg was a reasonable price compared to the prices in the literature which are around 5 \$/kg [11]. Considering that 35% capacity factor is roughly 8 hours of system capacity per day, this is a reasonable estimate because in regions with high solar irradiation, 8 hours of solar light is common for most part of the year. This shows that the system designed in this work is competitive in terms of cost with the systems discussed under literature review in Chapter 2 even though it is without storage.

4.2.2 Sensitivity Analysis

A sensitivity analysis was performed on two cost parameters to see their influence on the LCOH. The parameters considered were the effective interest rate and economic lifetime. While the LCOH increased with increase in the effective interest rate, it decreased with increasing economic lifetime. This is because, when the interest rate increases, it makes the upfront investment in hydrogen production systems such as solar collectors, electrolyzers, and power cycles seem more expensive in today's terms. Since most of the costs in green hydrogen production are paid upfront (PEC), a higher interest rate spreads these costs less efficiently over the system's lifetime, resulting in a higher levelized cost of hydrogen. In essence, the project becomes less

economically attractive when money is more expensive to borrow or invest. Similarly, increasing the lifetime of the project means you're producing hydrogen for more years without repeating the large initial investment. Since most of the cost in green hydrogen production is upfront, operating the system longer spreads that cost across more kilograms of hydrogen, making each unit cheaper.

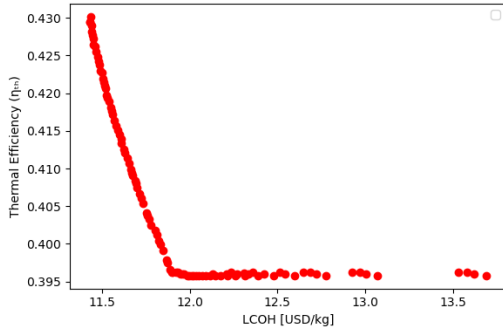
The relationship between LCOH and effective interest rate as well as that of LCOH and economic lifetime was the same across all cycle configurations. For instance, for the configuration with the least hydrogen cost, the PTC-MSRC-ORC configuration, increasing the effective interest rate from 5% to 7% increased the LCOH from 7.45 \$/kg to 8.13 \$/kg. However, increasing the economic lifetime from 15 years to 25 years for the same configuration decreased the LCOH from 8.55 \$/kg to 7.36 \$/kg.

4.3 Optimization result

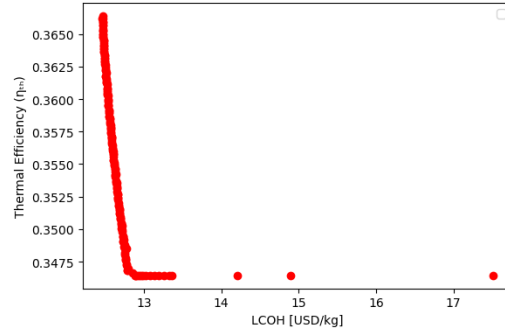
The result of the multiobjective optimization that was carried out on the SPT-powered configurations using brute force optimization method in Python is presented in Table 4.4. When the result in this table is compared with the results in Table 4.2 under Section 4.2 and Table 4.1 under Section 4.1, it can be seen that the optimized system in each configuration was improved in terms of efficiency and cost. Figure 4.17 also shows the Pareto frontier for the configurations. This shows the decision boundary between the feasible region and the infeasible region for the configurations as demonstrated in Figure 4.17 (c). For instance for the MSRC-SCBC-ORC configuration, the Pareto frontier shows that it was impossible to get a system with an LCOH of 11.5 \$/kg and

an efficiency of 40.5%.

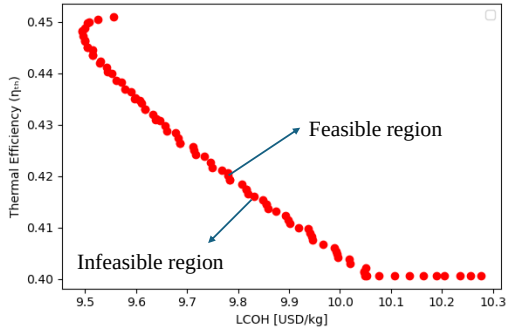
(a) MSRC-SCBC-ORC



(b) MSRC-SCBC



(c) MSRC-ORC



(d) SCBC-ORC

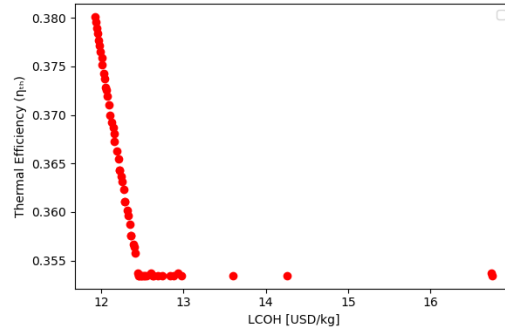


Figure 4.17: Pareto frontier for the optimization result of the four SPT-powered configurations: (a) MSRC-SCBC-ORC configuration, (b) MSRC-SCBC configuration, (c) MSRC-ORC configuration and (d) SCBC-ORC configuration.

Table 4.4: Optimization results for the SPT-powered configurations

Configuration	Best decision variables						Best Objective Function	
	T_2 (°C)	P_8 (MPa)	P_9 (MPa)	OIP (MPa)	PR	NC	LCOH	$\eta_{th}(\%)$
MSRC-ORC	548	15	2.6	1.2	-	1000	9.51	44.97
MSRC-SCBC	565	15	7.5	-	3.2	21000	12.47	36.64
MSRC-SCBC-ORC	565	15	7	1.1	3.4	6000	11.55	43.02
SCBC-ORC	549	-	-	1.5	3.5	18500	11.93	38.01

Note: OIP = ORC turbine's inlet pressure, PR = pressure ratio of the SCBC and NC = number of solar collectors.

CHAPTER 5

CONCLUSIONS, CHALLENGES AND RECOMMENDATIONS

5.1 Conclusions

A novel integrated power cycle configuration comprising an MSRC, an SCBC, and an ORC and other integrated cycle configurations were studied for green hydrogen production using SPT and PTC. The steam Rankine cycle in all the integrated cycle configurations was enhanced with a feedwater heater to have an MSRC for improved cycle efficiency. A comparative and parametric analysis of the system was carried out in terms of energy and exergy analysis. Additionally a cost analysis was also and another parametric analysis based on the LCOH of systems was performed for the SPT-powered configurations. Then an optimization using brute force method was performed in Python on the SPT-powered configuration to determine optimal system parameters. The following observations were made.

- In terms of energy and exergy efficiencies, and hydrogen yield, the SPT-powered MSRC-ORC configuration achieved the best performance, with a thermal efficiency of 42.36%, solar-to-electricity energy and exergy efficiencies of 28.59% and 30.15%, respectively, and a hydrogen production rate of 63.04 kg/hr alongside an oxygen production rate of 504 kg/hr at a solar-to-hydrogen efficiency of 20.43%.
- Adding a third cycle, the SCBC, to the MSRC-ORC did not enhance efficiency in either the SPT or PTC-powered configurations. However, incorporating the ORC improved the efficiency of the MSRC-SCBC configuration. Therefore, for concentrating solar technologies, a two-cycle integrated configuration proved to be the most effective option
- As the current density in the electrolyzer increased, the hydrogen production rate increased, while the electrolyzer's efficiency decreased.
- The solar collector area and solar irradiation had the greatest influence on hydrogen production across all configurations, while the pressure ratio of the SCBC had the most significant impact on the efficiencies of the integrated power cycles incorporating the SCBC.
- The performance of the system was positively correlated with solar irradiation, solar collector area, exit temperature of the solar receiver, inlet pressure of the HPT and inlet pressure of the ORC turbine in all cycle configurations.
- In the MSRC-ORC configuration, system performance varied inversely with the

LPT inlet pressure, whereas in the other configurations, the relationship was nonlinear for the investigated pressure range.

- In terms of hydrogen cost, the PTC-MSRC-ORC had the lowest cost with an LCOH of 7.78 \$/kg while the PTC-MSRC-SCBC had the highest cost with an LCOH of 17.76 \$/kg. Also, all SPT-powered configurations outperformed the PTC-powered configurations except for the MSRC-ORC configuration which was due to how well the MSRC-ORC configuration performed under the low operating temperature of the PTC system.
- Analysis of the total PEC from each subcycle showed that the cost relations for the SCBC did well in predicting the cost of the SCBC cycle while the cost relations for the MSRC and ORC underestimated the PEC for their components. This showed that the cost gotten from the analysis in this work was an underestimation of the real LCOH of a practical system that would operate under the system parameters for which the configurations were analyzed.
- Parametric analysis of the system based on LCOH revealed that the capacity factor had the greatest impact on the LCOH of the configurations. At a capacity factor of 100%, the SPT-MSRC-ORC configuration had an LCOH of just 2.28 \$/kg which was a huge reduction from the LCOH at 10% which was 22.77\$/kg. Additionally, other parameters like solar irradiation and the number of solar collectors also had a significant impact on the LCOH of the system while the rest of studied parameter presented a mild effect on the LCOH of the systems.
- Finally, the optimization of the SPT-powered configurations revealed that the

brute force optimization method was a good method for determining the best decision variables for optimal system performance. The optimal system from the optimization of each configuration showed an improvement in terms of LCOH and thermal efficiency. For instance, the optimal solution for the SPT-MSRC-ORC configuration was a thermal efficiency of 44.97% and LCOH of 9.5 \$/kg. This improved the efficiency (from 42.36%) at a slight increase in cost (from 9.11 \$/kg).

5.2 Challenges

During the process of this thesis, the challenges encountered were:

- The difficulty in getting financial information about the installation cost of the different power cycles.
- Getting cost relations that could correctly predict the cost of the power cycles which is largely due to the uncertainty in the prices of equipment and the assumptions that are made when developing the cost relations.

5.3 Recommendations

The following recommendations are made for further research.

- More research should be done on developing accurate cost relations for different capacities or operating conditions for the MSRC, SCBC and ORC. This will enhance cost analysis and provide a more reliable way of doing cost analysis.

- To improve the system's performance, further research could be done in developing SPT and PTC models with higher efficiency than the one used in this work. This could be done by developing new HTFs with improved heat transfer properties and/or developing solar receiver systems with higher optical efficiencies.
- The configurations analyzed in this work did not have storage because it was not considered wise to add storage to a system that is used strictly for the production of an energy carrier like hydrogen, which is largely used as an energy storage. Further research should focus on producing optimized systems for green hydrogen production that would have additional outputs like fresh water without comprising the energy usage by electrolyzers. This would make the addition of storage a more appealing option.
- Other interesting research areas to improve this work could be in development of electrolyzer materials that could improve PEM electrolyzer efficiency and cost as the cost of the PEM electrolyzer played a huge role in increasing the cost of hydrogen production.
- Finally, this work did not consider the storage, transport and supply chains for hydrogen, a cost analysis incorporating all these aspects of green hydrogen will give a broader understanding of the economics of green hydrogen and how this could be optimized to enhance the adoption a hydrogen economy.

REFERENCES

- [1] Y. A. Cengel and M. A. Boles, “Thermodynamics: an engineering approach,” *Sea*, vol. 1000, no. 8862, pp. 287–93, 2002.
- [2] J. K. Tadeusz, *EXERGY METHOD OF THERMAL PLANT ANALYSIS*. PARAGON PUBLISHING, 2012.
- [3] T. Hai and et al., “Design, modeling and multi-objective techno-economic optimization of an integrated supercritical brayton cycle with solar power tower for efficient hydrogen production,” *Sustainable Energy Technologies and Assessments*, vol. 53, p. 102599, Oct 2022.
- [4] S. M. Alirahmi and E. Assareh, “Energy, exergy, and exergoeconomics (3e) analysis and multi-objective optimization of a multi-generation energy system for day and night time power generation - case study: Dezful city,” *International Journal of Hydrogen Energy*, vol. 45, no. 56, pp. 31 555–31 573, Nov 2020.
- [5] H. A. Muhammad, M. Naseem, J. Kim, S. Kim, Y. Choi, and Y. D. Lee, “Solar hydrogen production: Technoeconomic analysis of a concentrated solar-powered high-temperature electrolysis system,” *Energy*, vol. 298, p. 131284, 2024.

- [6] International Energy Agency, “Global average levelised cost of hydrogen production by energy source and technology, 2019 and 2050,” 2021, accessed: 2025-04-15. [Online]. Available: <https://www.iea.org/data-and-statistics/charts/global-average-levelised-cost-of-hydrogen-production-by-energy-source-and-technology-2019-and-2050>
- [7] L. Fernandez, “Worldwide investment in renewable energy 2014-2023,” 2023, accessed: 2024-12-27. [Online]. Available: <https://www.statista.com/statistics/186807/worldwide-investment-in-sustainable-energy-since-2004/>
- [8] Q. Hassan, A. Z. Sameen, H. M. Salman, M. Jaszczur, M. Al-Hitmi, and M. Alghoul, “Energy futures and green hydrogen production: Is saudi arabia trend?” *Results in Engineering*, vol. 18, p. 101165, 2023.
- [9] I. E. A. (IEA), “Hydrogen,” 2023, accessed: 2024-12-27. [Online]. Available: <https://www.iea.org/energy-system/low-emission-fuels/hydrogen>
- [10] Statista, “Number of green hydrogen production facilities worldwide as of 2022, by country,” 2022, accessed: 2024-12-27. [Online]. Available: <https://www.statista.com/statistics/1311948/number-of-green-hydrogen-plants-by-country/>
- [11] U.S. Department of Energy, “Clean hydrogen production cost scenarios with pem electrolyzer technology,” U.S. Department of Energy, Tech. Rep. DOE/EE-24005, May 2024, accessed: 2025-04-15. [Online]. Available: <https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24005-clean-hydrogen-production-cost-pem-electrolyzer.pdf>

- [12] International Renewable Energy Agency (IRENA), “Renewable power generation costs in 2023,” International Renewable Energy Agency, Tech. Rep., September 2024, accessed: 2025-04-15. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf
- [13] Y. Xu, S. Cai, B. Chi, and Z. Tu, “Technological limitations and recent developments in a solid oxide electrolyzer cell: A review,” *International journal of hydrogen energy*, vol. 50, pp. 548–591, 2024.
- [14] A. A. AlZahrani and I. Dincer, “Design and analysis of a solar tower based integrated system using high temperature electrolyzer for hydrogen production,” *International Journal of Hydrogen Energy*, vol. 41, no. 19, pp. 8042–8056, May 2016.
- [15] F. Khalid and R. Kumar, “Thermodynamic assessment of a new ptc operated polygeneration system for fresh water, cooling, electricity and hydrogen production for a residential community,” *International Journal of Hydrogen Energy*, vol. 48, no. 99, pp. 38 991–39 001, Dec 2023.
- [16] R. S. El-Emam and I. Dincer, “Development and assessment of a novel solar heliostat-based multigeneration system,” *International Journal of Hydrogen Energy*, vol. 43, no. 5, pp. 2610–2620, Feb 2018.
- [17] A. Atiz, M. Erden, and M. Karakilcik, “Investigation of electricity, and hydrogen generation and economical analysis of pv-t depending on different water flow rates

- and conditions,” *International Journal of Hydrogen Energy*, vol. 48, no. 60, pp. 22 766–22 776, Jul 2023.
- [18] M. Abid, M. S. Khan, and T. A. H. Ratlamwala, “Comparative energy, exergy and exergo-economic analysis of solar driven supercritical carbon dioxide power and hydrogen generation cycle,” *International Journal of Hydrogen Energy*, vol. 45, no. 9, pp. 5653–5667, Feb 2020.
- [19] B. S. Thapa, B. Neupane, H. Yang, and Y.-H. Lee, “Green hydrogen potentials from surplus hydro energy in nepal,” *International Journal of Hydrogen Energy*, vol. 46, no. 43, pp. 22 256–22 267, Jun 2021.
- [20] H. Derbal-Mokrane, F. Amrouche, M. N. Omari, and I. Yahmi, “Hydrogen production through parabolic trough power plant based on the organic rankine cycle implemented in the algerian sahara,” *International Journal of Hydrogen Energy*, vol. 46, no. 65, pp. 32 768–32 782, Sep 2021.
- [21] M. S. Shahin, M. F. Orhan, K. Saka, A. T. Hamada, and F. Uygul, “Energy assessment of an integrated hydrogen production system,” *International Journal of Thermofluids*, vol. 17, Feb 2023.
- [22] X.-R. Zhang, H. Yamaguchi, and Y. Cao, “Hydrogen production from solar energy powered supercritical cycle using carbon dioxide,” *International Journal of Hydrogen Energy*, vol. 35, no. 10, pp. 4925–4932, May 2010.
- [23] N. Soni and K. Reddy, “Techno-economic assessment of concentrated solar power technologies integrated with thermal energy storage system for green hydrogen

- production,” *International Journal of Hydrogen Energy*, vol. 72, pp. 1184–1203, 2024.
- [24] E. Sun, X. Wang, Q. Qian, H. Li, W. Ma, L. Zhang, and J. Xu, “Proposal and application of supercritical steam rankine cycle using supercritical reheating regeneration process and its comparison between s-co₂ brayton cycle,” *Energy Conversion and Management*, vol. 280, p. 116798, 2023.
- [25] G. Wang, D. He, J. Lin, T. Jiang, and Z. Chen, “Exergy estimate of a novel hybrid solar-gas power and organic rankine cycle-based hydrogen-production system,” *Case Studies in Thermal Engineering*, vol. 33, p. 101961, 2022.
- [26] Y. Cao, M. A. Haghghi, M. Shamsaiee, H. Athari, M. Ghaemi, and M. A. Rosen, “Evaluation and optimization of a novel geothermal-driven hydrogen production system using an electrolyser fed by a two-stage organic rankine cycle with different working fluids,” *Journal of Energy Storage*, vol. 32, p. 101766, 2020.
- [27] A. Khouya, “Performance assessment of a dual loop organic rankine cycle powered by a parabolic trough collector for ammonia and hydrogen production purpose,” *International Journal of Ambient Energy*, vol. 43, no. 1, pp. 6149–6166, 2022.
- [28] Y. E. Yüksel, “Thermodynamic assessment of modified organic rankine cycle integrated with parabolic trough collector for hydrogen production,” *International Journal of Hydrogen Energy*, vol. 43, no. 11, pp. 5832–5841, 2018.

- [29] H. Ganjehsarabi, “Mixed refrigerant as working fluid in organic rankine cycle for hydrogen production driven by geothermal energy,” *International Journal of Hydrogen Energy*, vol. 44, no. 34, pp. 18 703–18 711, 2019.
- [30] M. Nasser and H. Hassan, “Assessment of hydrogen production from waste heat using hybrid systems of rankine cycle with proton exchange membrane/solid oxide electrolyzer,” *International Journal of Hydrogen Energy*, vol. 48, no. 20, pp. 7135–7153, 2023.
- [31] Y. Liu, Y. Wang, and D. Huang, “Supercritical co2 brayton cycle: A state-of-the-art review,” *Energy*, vol. 189, p. 115900, 2019.
- [32] X. Liu, Y. Huang, M. Liu, L. Min, T. Zhang, X. Li, and W. Zhuo, “Analysis of the brayton cycle coupled with a small fluoride salt-cooled high-temperature reactor,” *Frontiers in Energy Research*, vol. 10, p. 1097023, 2023.
- [33] F. A. Al-Sulaiman and M. Atif, “Performance comparison of different supercritical carbon dioxide brayton cycles integrated with a solar power tower,” *Energy*, vol. 82, pp. 61–71, 2015.
- [34] H. Yang, J. Li, Q. Wang, L. Wu, M. R. Rodríguez-Sanchez, D. Santana, and G. Pei, “Performance investigation of solar tower system using cascade supercritical carbon dioxide brayton-steam rankine cycle,” *Energy Conversion and Management*, vol. 225, p. 113430, 2020.
- [35] Y. Tong, L. Duan, M. Yang, and Y. Jiang, “Performance analysis and optimization study of a new supercritical co2 solar tower power generation system

- integrated with steam rankine cycle,” *Applied Thermal Engineering*, vol. 232, p. 121050, 2023.
- [36] H. Singh and R. Mishra, “Energy-and exergy-based performance evaluation of solar powered combined cycle (recompression supercritical carbon dioxide cycle/organic rankine cycle),” *Clean Energy*, vol. 2, no. 2, pp. 140–153, 2018.
- [37] M. Das and K. Reddy, “Modelling and optimization of combined supercritical carbon dioxide brayton cycle and organic rankine cycle for electricity and hydrogen production,” *Applied Energy*, vol. 377, p. 124586, 2025.
- [38] Y. Ajaj, A. B. Ali, A. Kumar, D. J. Jasim, C. Mancheno, A. H. Jabbar, S. Islam, A. Lasisi, and R. Zainul, “Innovative biomass waste heat utilization for green hydrogen production: A comparative and optimization study of steam and organic rankine cycles,” *Process Safety and Environmental Protection*, vol. 190, pp. 148–174, 2024.
- [39] M. T. Balta, O. Kizilkan, and F. Yilmaz, “Energy and exergy analyses of integrated hydrogen production system using high temperature steam electrolysis,” *international journal of hydrogen energy*, vol. 41, no. 19, pp. 8032–8041, 2016.
- [40] L. Bentoumi, A. Miles, and Z. Korei, “Green hydrogen production by integrating a solar power plant with a combined cycle in the desert climate of algeria,” *Solar Energy*, vol. 268, p. 112311, 2024.
- [41] M. Awad, A. Said, M. H. Saad, A. Farouk, M. M. Mahmoud, M. S. Alshammari, M. L. Alghaythi, S. H. A. Aleem, A. Y. Abdelaziz, and A. I.

- Omar, “A review of water electrolysis for green hydrogen generation considering pv/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application,” *Alexandria Engineering Journal*, vol. 87, pp. 213–239, 2024.
- [42] P. Arvay, M. R. Muller, V. Ramdeen, and G. Cunningham, “Economic implementation of the organic rankine cycle in industry,” in *ACEEE Summer Study on Energy Efficiency in Industry*, vol. 5, no. 02. Kavanagh, L. and Monroe, R. Niagara Falls, NY, 2011, pp. 12–22.
- [43] C. W. White, W. Shelton, N. Weiland, T. Shultz, J. Plunkett, and D. Gray, “Techno-economic evaluation of utility-scale power plants based on the indirect sco2 brayton cycle-report,” National Energy Technology Laboratory (NETL), Pittsburgh, PA, Morgantown, WV ..., Tech. Rep., 2017.
- [44] J. Xu, X. Wang, E. Sun, and M. Li, “Economic comparison between sco2 power cycle and water-steam rankine cycle for coal-fired power generation system,” *Energy Conversion and Management*, vol. 238, p. 114150, 2021.
- [45] M. E. Abdesselem, T. E. Boukelia, and M. S. Mecibah, “Comparative analysis of integrating different power cycles into a concentrated solar power plant,” *Solar Energy Materials and Solar Cells*, vol. 285, p. 113534, 2025.
- [46] H. A. Muhammad, S. Lim, H. Kim, and Y. D. Lee, “Comparative evaluation of electrolysis methods for solar-assisted green hydrogen production,” *Renewable Energy*, vol. 239, p. 122104, 2025.

- [47] A. R. Razmi, A. R. Hanifi, and M. Shahbakhti, “A comparative techno-economic assessment between solar-based hydrogen production by methane pyrolysis and water electrolysis methods,” *Renewable Energy*, p. 122504, 2025.
- [48] P. Venkatesh and N. Visali, “Application of machine learning to generate a contingency ranking for power system security,” in *2023 Third International Conference on Artificial Intelligence and Smart Energy (ICAIS)*. IEEE, 2023, pp. 590–595.
- [49] J. Xu, Y. Fang, W. Yang, Z. Lu, and X. Wang, “Multi-objective optimal research on low-energy dwellings design based on genetic algorithm in qinba mountain region, china,” *Scientific Reports*, vol. 15, no. 1, p. 6504, 2025.
- [50] O. Obumneme Onyeka, E. Obiajulu Godson, and O. Ann Amalate, “Optimization of hydrogen gas production from flare gas using a genetic algorithm,” *Petroleum Science and Technology*, pp. 1–19, 2025.
- [51] P. Xu, J. Zheng, H. Chen, and P. Liu, “Optimal design of high pressure hydrogen storage vessel using an adaptive genetic algorithm,” *International Journal of Hydrogen Energy*, vol. 35, no. 7, pp. 2840–2846, 2010.
- [52] Y.-B. Woo and B. S. Kim, “A genetic algorithm-based matheuristic for hydrogen supply chain network problem with two transportation modes and replenishment cycles,” *Computers & Industrial Engineering*, vol. 127, pp. 981–997, 2019.
- [53] L. Wang, Y. Zhao, J. Dang, and Z. Yang, “Performance optimization of hydrogen fueled engines based on genetic information fusion algorithm,” *Chemical Engineering Transactions*, vol. 62, pp. 607–612, 2017.

- [54] E. Assareh, S. M. Alirahmi, and P. Ahmadi, “A sustainable model for the integration of solar and geothermal energy boosted with thermoelectric generators (tegs) for electricity, cooling and desalination purpose,” *Geothermics*, vol. 92, p. 102042, May 2021.
- [55] D. Marmolejo-Correa and T. Gundersen, “A comparison of exergy efficiency definitions with focus on low temperature processes,” *Energy*, vol. 44, no. 1, pp. 477–489, 2012.
- [56] B. Caglar, M. Araz, H. G. Ozcan, A. Calisan, and A. Hepbasli, “Energy and exergy analysis of a pv-t integrated ethanol pem electrolyzer,” *International Journal of Hydrogen Energy*, vol. 46, no. 24, pp. 12 615–12 638, 2021.
- [57] M. Ni, M. K. Leung, and D. Y. Leung, “Energy and exergy analysis of hydrogen production by a proton exchange membrane (pem) electrolyzer plant,” *Energy conversion and management*, vol. 49, no. 10, pp. 2748–2756, 2008.
- [58] X. Zhang, R. Zeng, T. Du, Y. He, H. Tian, K. Mu, X. Liu, and H. Li, “Conventional and energy level based exergoeconomic analysis of biomass and natural gas fired polygeneration system integrated with ground source heat pump and pem electrolyzer,” *Energy conversion and management*, vol. 195, pp. 313–327, 2019.
- [59] K. Zhang, X. Liang, L. Wang, K. Sun, Y. Wang, Z. Xie, Q. Wu, X. Bai, M. S. Hamdy, H. Chen *et al.*, “Status and perspectives of key materials for pem electrolyzer,” *Nano Res. Energy*, vol. 1, no. 3, p. e9120032, 2022.

- [60] S. C. Toker, G. Soy Turk, and O. Kizilkan, “Development of a sustainable multi-generation system with re-compression sco₂ brayton cycle for hydrogen generation,” *International Journal of Hydrogen Energy*, vol. 47, no. 45, pp. 19 397–19 410, 2022.
- [61] Z. Mohammadi, P. Ahmadi, and M. Ashjaee, “An innovative transient simulation of a solar energy system with a thermochemical hydrogen production cycle for zero-energy buildings,” *International Journal of Hydrogen Energy*, vol. 76, pp. 62–74, 2024.
- [62] S. Bayoumi, N. Moharram, A. Shehata, M. Imam, and W. El-Maghlany, “A multi-criteria performance assessment of concentrated solar power plants for site and technology selection in egypt,” *International Journal of Environmental Science and Technology*, vol. 21, no. 3, pp. 2989–3004, 2024.
- [63] O. Behar, D. Sbarbaro, and L. Morán, “A practical methodology for the design and cost estimation of solar tower power plants,” *Sustainability*, vol. 12, no. 20, p. 8708, 2020.
- [64] N. Nazari, P. Heidarnejad, and S. Porkhial, “Multi-objective optimization of a combined steam-organic rankine cycle based on exergy and exergo-economic analysis for waste heat recovery application,” *Energy conversion and management*, vol. 127, pp. 366–379, 2016.
- [65] C. G. Gutiérrez-Arriaga, F. Abdelhady, H. S. Bamuffeh, M. Serna-González, M. M. El-Halwagi, and J. M. Ponce-Ortega, “Industrial waste heat recovery and

- cogeneration involving organic rankine cycles,” *Clean Technologies and Environmental Policy*, vol. 17, pp. 767–779, 2015.
- [66] N. T. Weiland, B. W. Lance, and S. R. Pidaparti, “Sco2 power cycle component cost correlations from doe data spanning multiple scales and applications,” in *Turbo Expo: Power for Land, Sea, and Air*, vol. 58721. American Society of Mechanical Engineers, 2019, p. V009T38A008.
- [67] D. Thanganadar, F. Asfand, K. Patchigolla, and P. Turner, “Techno-economic analysis of supercritical carbon dioxide cycle integrated with coal-fired power plant,” *Energy Conversion and Management*, vol. 242, p. 114294, 2021.
- [68] N. Bonyadi, E. Johnson, and D. Baker, “Technoeconomic and exergy analysis of a solar geothermal hybrid electric power plant using a novel combined cycle,” *Energy Conversion and Management*, vol. 156, pp. 542–554, 2018.
- [69] Y. Cao, H. A. Dhahad, K. Sharma, A. El-Shafay, A. N. Ahmed, M. A. Shamseldin, S. F. Almojil, A. I. Almohana, A. F. Alali, and B. Farhang, “Techno-economic evaluation and parametric study of generating green hydrogen from waste heat recovery of efficient solid oxide fuel cell,” *International Journal of Hydrogen Energy*, vol. 47, no. 62, pp. 26 632–26 645, 2022.
- [70] B. Besevli, E. Kayabasi, A. Akroot, W. Talal, A. Alfari, Y. H. Assaf, M. Y. Nawaf, M. Bdaiwi, and J. Khudhur, “Technoeconomic analysis of oxygen-supported combined systems for recovering waste heat in an iron-steel facility,” *Applied Sciences*, vol. 14, no. 6, p. 2563, 2024.

- [71] H. Benoit, L. Spreafico, D. Gauthier, and G. Flamant, “Review of heat transfer fluids in tube-receivers used in concentrating solar thermal systems: Properties and heat transfer coefficients,” *Renewable and Sustainable Energy Reviews*, vol. 55, pp. 298–315, 2016.
- [72] G. G. Wang and S. Shan, “Review of metamodeling techniques in support of engineering design optimization,” in *International design engineering technical conferences and computers and information in engineering conference*, vol. 4255, 2006, pp. 415–426.
- [73] I. Dincer and M. A. Rosen, *Exergy: energy, environment and sustainable development*. Newnes, 2012.
- [74] T. Ioroi, K. Yasuda, Z. Siroma, N. Fujiwara, and Y. Miyazaki, “Thin film electrocatalyst layer for unitized regenerative polymer electrolyte fuel cells,” *Journal of Power sources*, vol. 112, no. 2, pp. 583–587, 2002.
- [75] Eastman Chemical Company, “Therminol VP-1 heat transfer fluid,” <https://www.therminol.com/product/71093459>, accessed: 2025-02-08.
- [76] T. A. H. Ratlamwala, I. Dincer, and M. Aydin, “Energy and exergy analyses and optimization study of an integrated solar heliostat field system for hydrogen production,” *International Journal of Hydrogen Energy*, vol. 37, no. 24, pp. 18 704–18 712, Dec 2012.
- [77] G. Baglietto, S. Maccarini, A. Traverso, and P. Bruttini, “Techno-economic comparison of supercritical co₂, steam, and organic rankine cycles

- for waste heat recovery applications,” *Journal of Engineering for Gas Turbines and Power*, vol. 145, no. 4, p. 041021, 2023. [Online]. Available: <https://doi.org/10.1115/1.4055727>
- [78] U.S. Energy Information Administration, “Capital cost and performance characteristics for utility-scale electric power generating technologies,” U.S. Department of Energy, Washington, DC, Tech. Rep., January 2024, prepared for the Annual Energy Outlook 2025. [Online]. Available: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2025.pdf
- [79] P. A. Samuelson and W. D. Nordhaus, *Economics*, 19th ed. New York: McGraw-Hill Education, 2010.
- [80] N. G. Mankiw, *Principles of Economics*, 9th ed. Boston, MA: Cengage Learning, 2020.

VITAE

- Name: Terungwa Anthony Tivfa
- Nationality: Nigerian
- Date of Birth: 04/12/1991
- Email: *tivfaanthony@gmail.com*
- Permenant Address: St. Winifred's Parish Ihugh, P.O.Box 1102 Gboko, Benue State of Nigeria.
- Bachelor of Engineering in Mechanical Engineering at University of Agriculture, Makurdi, Nigeria - 2016
- Master of Science in Mechanical Engineering at King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia - 2025
- Publication: J. K. Moses, T. A. Tivfa, N. A. Qasem, and A. B. Alquaity, "Combustion characteristics of hydrogen, ammonia, and their blends: A review," *Fuel*, vol. 388, p. 134404, 2025. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0016236125001280>

- Technical skills: Matlab, Python, Machine Learning, Ansys Fluent, Engineering Equation Solver, Homer Energy, Labview, System Advisor Module.
- Scholarships and Awards
 - Deanship of Graduate Studies Scholarship (MSc. Mechanical Engineering)
 - King Fahd University of Petroleum and Minerals, Saudi Arabia. (2023)
 - Graduate Assistantship – University of Northern Iowa, Cedar Falls, USA. (2023)
 - Abay Kunanbayev scholarship (MSc. Mechanical and Aerospace Engineering) – Nazarbayev University Kazakhstan. (2023)
 - African Graduate Fellowship (MSc. Mechanical Engineering) – The American University in Cairo. (2023)
 - Best graduating Student – Department of Mechanical Engineering, University of Agriculture, Makurdi. (2017)