EFFAT UNIVERSITY
COLLEGE OF ENGINEERING

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

Techno-Economic Study for Adding Hydrogen Storage to the Photovoltaic Plant in Neom City

A thesis submitted for the requirements of the degree of Master of Science in Energy Engineering

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I hereby declare that this thesis titled " **Techno-Economic Study for Adding Hydrogen Storage to the Photovoltaic Plant in Neom City"** is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that the proposed dissertation has not been previously or concurrently submitted for the award of any degree, at Effat University, any other University or Institution.

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ABSTRACT

The status and future potential of renewable energy in Saudi Arabia for Vision "2030" seeks clean energy, an essential input into most industrial sector production processes. Neom city is 100% dependent on renewable energy to limit climate change caused by increased CO_2 emissions. Hydrogen (H_2) is a clean energy carrier; it can store a large amount of energy. The use of hydrogen as an energy source has gained much attention in recent years. This work aims to study the techno-economic of adding hydrogen storage to a photovoltaic (PV) plant in Neom City and build a mathematical model to simulate metal hydride hydrogen storage. Therefore, this study proposes to create a mathematical model of heat and mass transfer inside a metal hydride hydrogen storage and solve it numerically.

Furthermore, a techno-economics comparison of the two different plants is provided. On the grid, the system has a capacity of 30 MW each year. The first application of PV plants without hydrogen storage and the second application of PV plants with hydrogen storage were compared using the system Advisor model (SAM). To reach the economic-study parameters such as the payback period (PP), intern rate of return IRR), and other economic parameters.

Keywords—*Techno-economic, Hydrogen storage, Metal hydride hydrogen storage, Photovoltaic (PV).*

ملخص الرسالة

ان مكانة الطاقة المتجددة وإمكانياتها المستقبلية في المملكة العربية السعودية بالنسبة لرؤية "2030" تسعى إلى الحصول على الطاقة النظيفة، وهي مُدخل أساسي في معظم عمليات إنتاج القطاع الصناعي. وتعتمد مدينة نيوم بنسبة 100٪ على الطاقة المتجددة للحد من تغير المناخ الناجم عن زيادة انبعاثات ثاني أكسيد الكربون.

الهيدروجين (H_2) هو ناقل للطاقة النظيفة؛ يمكنه تخزين كمية كبيرة من الطاقة. اكتسب استخدام الهيدروجين كمصدر للطاقة اهتمامًا كبيرًا في السنوات الأخيرة. تهدف هذه الدراسة إلى دراسة الاقتصاد التقني لإضافة مخزون الهيدروجين إلى محطة كهروضوئية (PV) في مدينة نيوم. وبناء نموذج رياضي لمحاكاة تخزين الهيدروجين المتهيدر المعدني.

لذلك، تقترح هذه الدراسة إنشاء نموذج رياضي للحرارة وتدفق الكتلة داخل تخزين الهيدروجين المتهيدر المعدني. علاوة على ذلك، يتم توفير مقارنة اقتصادية تقنية بين المحطتين. على الشبكة، تبلغ قدرة النظام 30 ميجاوات كل عام. تمت مقارنة أول محطة للطاقة الكهروضوئية للتطبيق بدون تخزين الهيدروجين والمحطة الكهروضوئية للتطبيق الثاني مع تخزين الهيدروجين باستخدام نموذج (SAM) لمقارنة معلمات الدراسة الاقتصادية مثل فترة الاسترداد (PP) ومعدل العائد الداخلي (IRR)، وغيرها من المعايير الاقتصادية.

الكلمات المفتاحية *— التقنية الاقتصادية، تخزين الهيدروجين ، تخزين الهيدروجين المعدني ، الخلايا الكهروضوئية (PV).*

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List of Abbreviations

AB2	→	Atlantic Bird 2
AB5	→	Atlantic Bird 5
AWE	→	Alkaline Water Electrolyzer
BESS	→	Battery Energy Storage System
CAE	→	Computer-Aided Engineering
CCE	→	Cash and Cash Equivalents
CH4	→	Methane
CFD	→	Computational Fluid Dynamics
CFS	→	Cash Flow Statement
CO2	→	Carbon dioxide
ELs	→	Electrolyzers
EV	→	Electric vehicle
H	→	Hydrogen
H_2	→	Lightest element
HFTO	→	Hydrogen and Fuel Cell Technologies Office
HS	→	Hydrogen Storage
H_2O	→	Water
HRES	→	Hybrid renewable energy system
H/M ratio	→	The ratio between the maximum amplitude
IRR	→	Internal Rate of Return
KSA	→	Kingdom of Saudi Arabia
LaNi5	→	Lanthanum nickel
LaNi5-H_2	→	Lanthanum-nickel alloy hydrogen-storage

LC	→	Levelized Cost
Li-ion	→	Lithium-ion
MG	→	Magnesium
MH	→	Metal hydride
MHT	→	Metal hydride tank
NREP	→	National Renewable Energy Program
NSRDB	→	National Solar Radiation Database (NSRDB)
HRES	→	hybrid renewable energy system
PP	→	Payback period
PV	→	Photovoltaic
PCT	→	Procalcitonin
PEM	→	Polymer Electrolyte Membrane
P_2H	→	Power-to-Hydrogen
RE	→	Renewable energy
RT	→	Room temperature
SAM	→	System advisor model
SCWG	→	Special Collections Working Group
SOFC	→	solid oxide fuel cell

List of Symbols

Activation energy	E_a
Calcium	C_a
Constant	k
Chemical reaction rate	$\dot{m}$
Distance	L
Dynamic viscosity of the fluid	μ
Effective specific heat	C_p
Effective specific heat for gas	C_{pg}
Effective specific heat for solid	C_{ps}
Equilibrium pressure	P_{eq}
Gas constant	R
Gas density	ρ_g
isothermal reaction	ΔH^0
Permeability	K
Porosity	ε
Pressure	P
Pressure drop	Δp

Magnesium	Mg
Radiance	r
Saturated density	ρ_{sat}
Solid density	ρ_s
Temperature	T

Chapter One: Introduction and Background

1.1. Overview

NEOM City is in the Tabuk region, Saudi Arabia, northwest of the country. According to Saudi Arabia's vision 2030, it will be the world's first environmentally friendly city which is 100% dependent on renewable energy, lowering CO_2 emissions and limiting global warming's impacts [1]. Nowadays, the Saudi Energy Procurement Company is competitive, offering renewable and conventional energy projects to keep pace with the growth in energy demand and managing commercial agreements to buy and sell energy from renewable energy projects [2]. With the country's ample area for renewable energy, especially solar energy projects with the rising energy demands and renewable energy projects, battery storage is a big challenge that offers an even stronger case for the government to use hydrogen storage. Green hydrogen, made using renewable electricity to split water, is the most environmentally friendly form. Hydrogen considers being one of the high technologies with zero carbon emission. Hydrogen storage is considered one of the advanced technologies if integrated with future renewable energy [3]. Moreover, by 2025, its first green hydrogen facility in Neom city would only produce 240,000 tons per year [4]. Therefore, it is possible to use hydrogen storage systems effectively because of the extended lifetime storage period and high energy density. The hydrogen is produced from water electrolysis using renewable energy.

This research offers to build and simulate a mathematical model of heat and mass transfer inside hydrogen storage. In addition, a techno-economic comparison of the two applications. The system has a 30 MW capacity per year on the grid. The first application PV plant without hydrogen storage and the second application PV plant with hydrogen storage, by utilizing the System Advisor Model (SAM) to comparing the economic- study such as the payback period (PP) and intern rate of return (IRR) and other financial parameters.

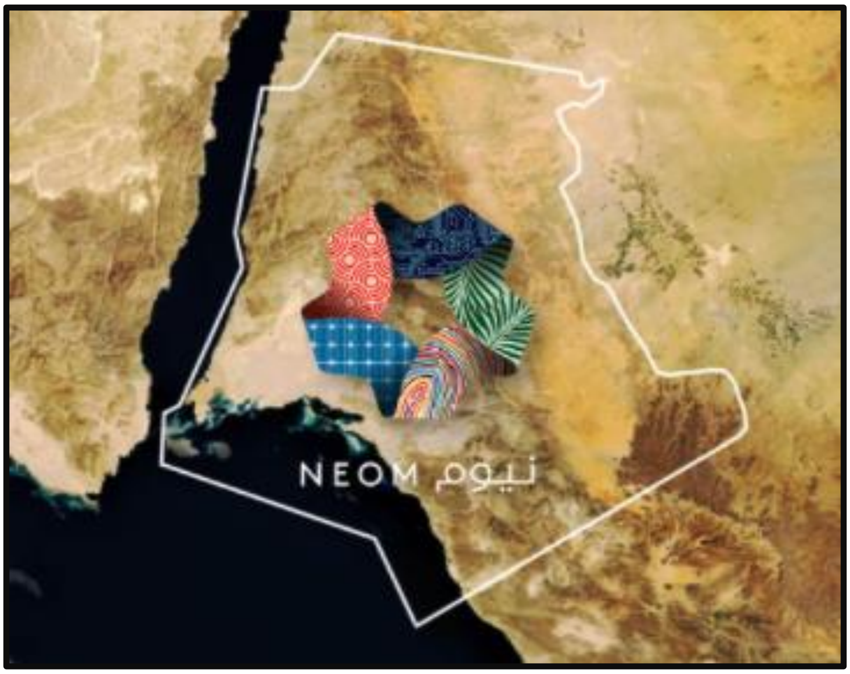

Figure 1.1 Neom City [5].

1.2. Problem Statement

With the rising energy demands and renewable energy projects, battery storage is a big challenge for any clean energy project.

1.3. Research Objectives

The research's primary target is to build a mathematical model of heat and mass transfer inside hydrogen storage (HS) to increase the efficacy of hydrogen storage because it has a greater energy storage density. This research's other goal includes comparing the economics study of two PV plants without and with hydrogen storage. The other goals of this research include:

- Research and understand hydrogen storage and its mathematical modeling.
- Provide literature research of previous use of simulated hydrogen storage and a techno-economic study.
- The analysis obtained economic study such as IRR, PP, and other economics parameters results using system advisor model (SAM) software.

- Build a mathematical model of heat and mass transfer inside metal hydride hydrogen storage.
- The mathematical model should clearly describe the complicated physics such as absorbent, flow in porous media, and the hydrogen extracted from the absorbent material.

1.4. Significant of the Study and Constraints

Nowadays, hydrogen can be considered as one of the solutions for future energy transition if produced by green energy such as using solar power which is one of the most renewable energy sources in KSA. A growing body of research shows that hydrogen storage is an appealing alternative for the deep decarbonization of global energy systems. Recent cost and performance improvements point to economic feasibility. In addition, the National Renewable Energy Program (NREP) is a strategic effort started at His Majesty the King's command as part of vision 2030 to increase the Kingdom's proportion of renewable energy projects and lowering carbon dioxide emissions [6] (see Figure 1.2). The expansion of renewable energy, especially solar energy projects in Saudi Arabia, gives a new opportunity to establish a new renewable energy technology industry.

Neom is taking serious steps to get involved in the global hydrogen market for energy production [7]. Therefore, hydrogen storage may play a role in providing power, heat, industry, transportation, and energy storage in a low-carbon energy system and an appraisal of hydrogen's current state of readiness to fulfill that potential in Neom city.

The research thesis's primary contribution is building a mathematical model of heat and mass transfer inside hydrogen storage (HS) and comparing the economics parameters results between two application PV plant without and with hydrogen storage.

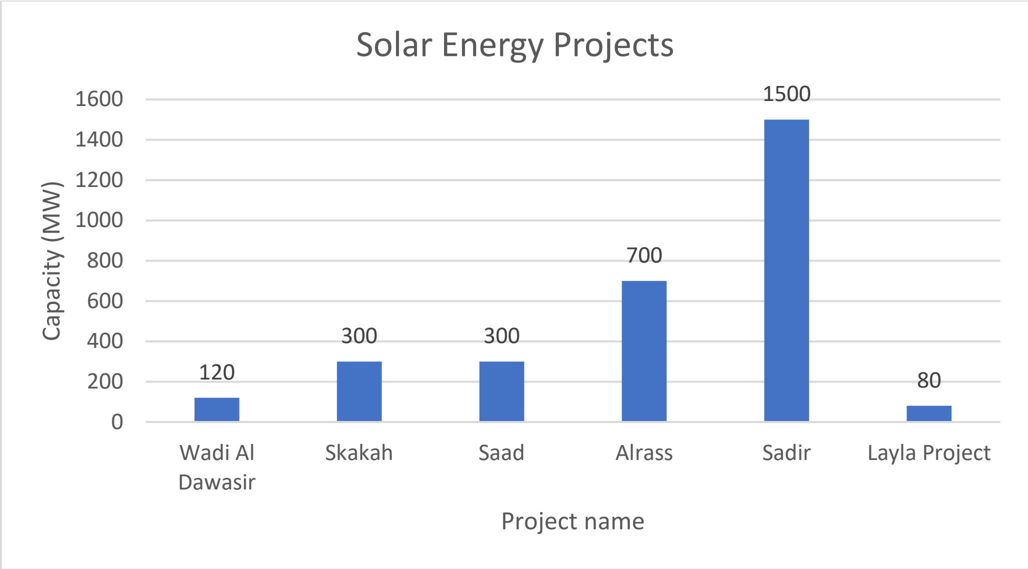

Figure 1.2: Solar projects under the National Renewable Energy Program (NREP) [8].

1.5. Outline of the Thesis

The overall research methodology structure is displayed below in Figure 1.3. This figure explains the main phases of the thesis research.

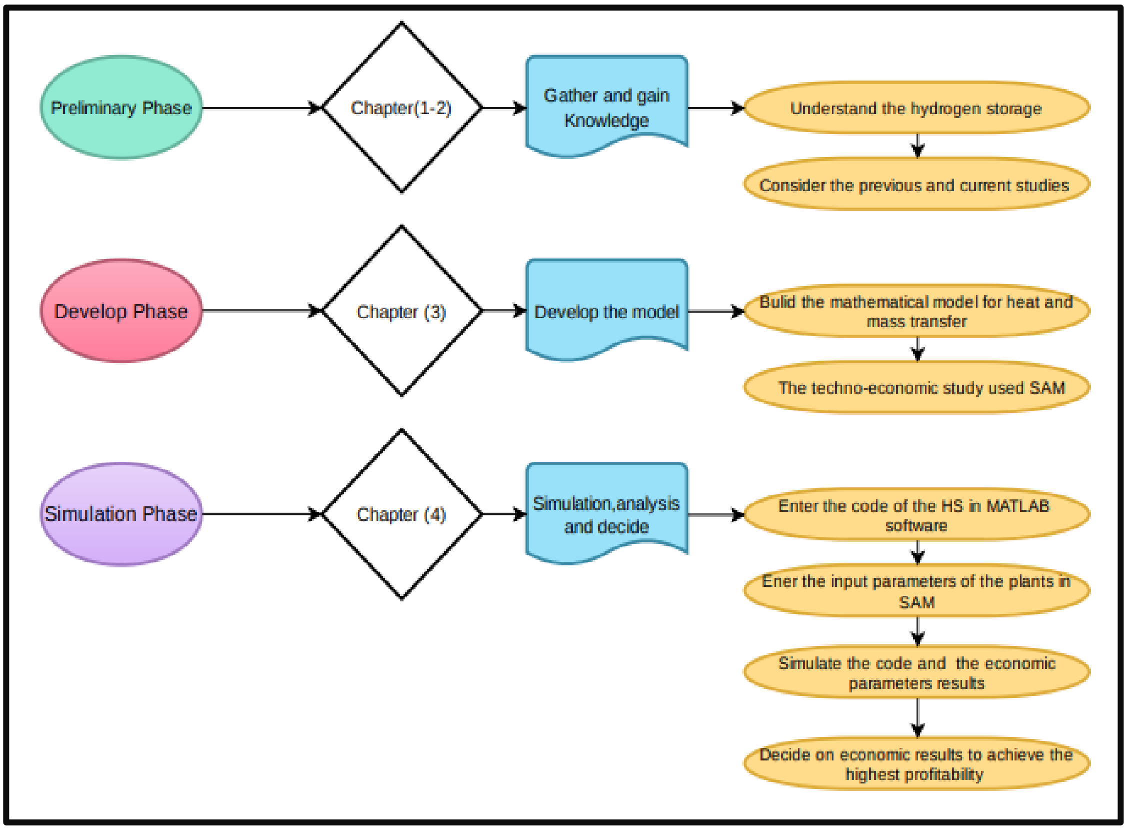

Figure 1.3: Thesis research structure.

This thesis includes five chapters and two appendices. The first chapter introduces the research background, this research purposes, and the thesis research methodology structure.

The second chapter presents a literature review that summarizes previous and current uses for green hydrogen storage, metal hydride hydrogen storage, and economic analysis studies of integrated hydrogen storage to renewable energy. Besides, it reviews several economic research reports on hydrogen storage adding to renewable energy plants.

Chapter three explains the structure of building the mathematical model of heat and mass transfer inside the metal hydride hydrogen storage. Then, the system advisor model (SAM) was used for the techno-economic study to calculate the payback (PP), Intern rate of return (IRR), and other economic parameters.

Chapter four presents and discusses the relevant results of the simulation. The results for heat and mass transfer inside metal hydride and techno-economic results for PV without hydrogen storage and hydrogen storage are organized and explained in the two different sections of chapter four.

Chapter five presents the limitation and the suggested improvements for the future work. In addition, it offers the conclusion of this study.

Lastly, a list of references used in this research and a section of appendices are provided. There are two appendices, Appendix “A”, Appendix “B”. Where appendix “A” presents certificate of participation in the 3rd African International conference entitled "Techno-economic study of adding hydrogen storage to PV plant in Neom city". Appendix “B” displays a sample result of the system advisor model (SAM) report.

1.6. Background for hydrogen storage

a) Hydrogen:

Hydrogen has been utilized in the refining and chemical manufacturing industries for many decades. However, its application as an energy source has just recently gained popularity. As interest and end-use expand, so will demand hydrogen, which is predicted to use at a compound annual growth of 5.48 percent from 2019 to 2025 [9]. Hydrogen is the lightest element (H_2). Most of the hydrogen is abundant on earth. It is usually found as part of another chemical, such as water (H_2O) or methane (CH_4) and must be split into pure hydrogen. Furthermore, hydrogen is a sort of energy that can be obtained from various sources. It is also a cleaner alternative to methane, which is generally referred to as natural gas. It is the most abundant chemical element, accounting for around 75% of the universe's mass [10].

b) Hydrogen types and Productions:

The diatomic molecule of hydrogen is a colorless gas. Hydrogen is now classified in color code in grey, blue, and green. This color code descriptor was created to distinguish the hydrogen's source, specifically to distinguish non-renewable fossil-based hydrogen from renewable hydrogen [11]. The three primary colors are shown in Table 1.

Table 1: Hydrogen Production Types [11].

GREY	BLUE	GREEN
Hydrogen is produced from fossil fuels, using thermal processes like steam -methane reformation and partial oxidation. Emission s of greenhouse gases occur.	The reforming of natural gas produces hydrogen into carbon dioxide (CO2) and hydrogen. In combination with carbon capture and storage (CCS).	Hydrogen is produced from water electrolysis using renewable energy like solar and wind as a power source.

Hydrogen is primarily employed in the chemical sector, but it will soon become a necessary fuel. The creation of hydrogen can be done in a variety of ways. Hydrogen is found in various "colors," the most common of which are blue and green, each of which corresponds to how it is created. To begin with, blue hydrogen is carbon created by steam reforming that is caught and stored underground using fossil fuels. Green hydrogen, often known as "clean hydrogen," is produced by splitting water into two hydrogen atoms and one oxygen atom using clean energy from excess renewable energy sources, such as solar or wind power, through electrolysis [12]. There's also pink hydrogen. It is made by electrolysis of water, just as green hydrogen. However, it is driven by nuclear energy rather than renewables.

Nuclear reactors' high temperatures could be used for alternative types of hydrogen synthesis, such as creating steam for more efficient electrolysis. Meanwhile, yellow hydrogen is a word that refers to hydrogen produced by the electrolysis of water using solar electricity. Other people use it to refer to hydrogen produced by electrolysis of water with various sources, depending on what is available. Biomass can also be used to generate hydrogen, depending on the type of biomass used [13]. Figure 1.4 below depicts the two most common hydrogen production methods in detail: blue and green.

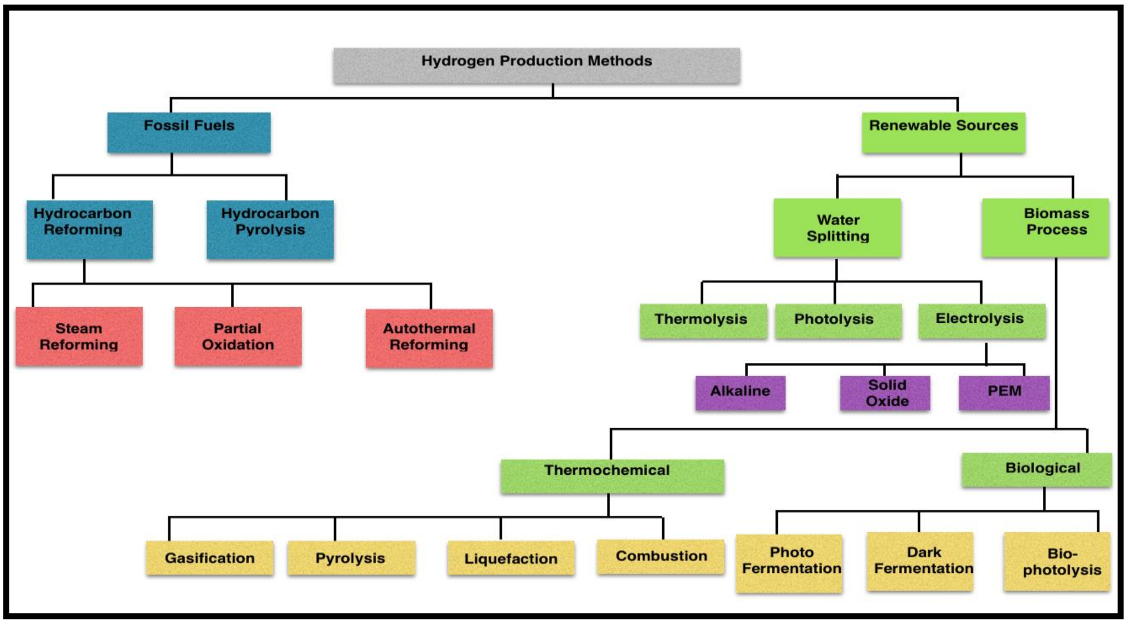

Figure 1.4: Hydrogen Production Method.

c) Hydrogen Storage:

Hydrogen storage can be stored in three different ways gas under high pressures, liquid form under cryogenic temperatures, and on the surface of or within solid and liquid materials. Each of these storage techniques has its requirements [14]. These are considered physical hydrogen storage.

Under high pressures, hydrogen gas is compressed and kept in a gaseous state. This process storage tanks with pressures ranging from 350-700 bar (5000-10,000 psi)

[14]. The hydrogen in liquid forms a cryogenically stored at low temperatures of -252.8°C. Although liquid hydrogen has a higher energy density than gaseous hydrogen, getting it to the needed temperatures can be expensive. In addition, cryogenic liquid hydrogen storage tanks and facilities must be insulated to prevent the liquid hydrogen from boiling and escaping as a gas. Despite these difficulties, liquid hydrogen is in considerable demand for applications that require a high purity [14].

On the other hand, hydrogen can be compressed as gas or stored as a liquid utilizing materials. There are three types of hydrogen storage materials: those store hydrogen on the surface of the material, those that store hydrogen within the material, and hydride storage, which employs a combination of solid and liquid materials. The third of these hydrogen material storage technologies, hydride storage, can exploit the reaction of hydrogen-containing materials with water or other liquid molecules, such as alcohols [14]. In general, these chemical compounds have a high hydrogen absorption capability this research thesis focus on metal hydrides hydrogen storage under chemical hydride.

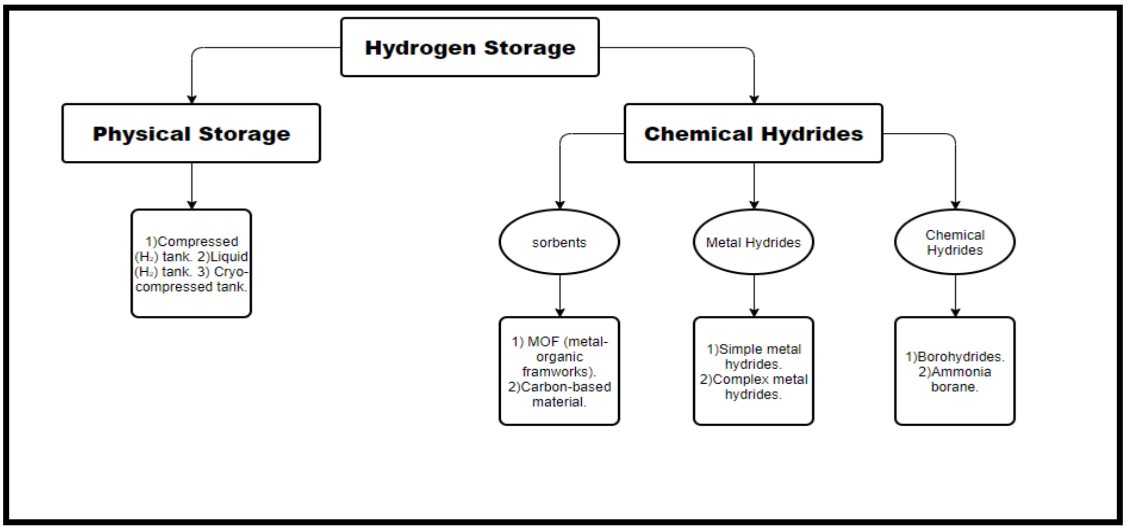

Figure 1.5: Hydrogen storage.

d) Metal Hydride Hydrogen storage:

The metal hydride hydrogen storage is made up of many tubes and filters. Those are evenly distributed inside a cylindrical shell. The reaction bed, which houses the cooling pipes and filters, is formed by hydrogen storage material packed within the cylindrical storage tank. Heat transfer fluid is pumped via the cooling tubes to remove the reaction heat created during the sorption process. The filters aim to distribute hydrogen uniformly over the bed [15]. The store is shown in Figure 1.5. An exterior container with radius 'r1' and cooling tubes with radius 'r2' are arranged in a triangle shape. Filters with a radius of 'r3' are positioned in the center of each triangle configuration [15].

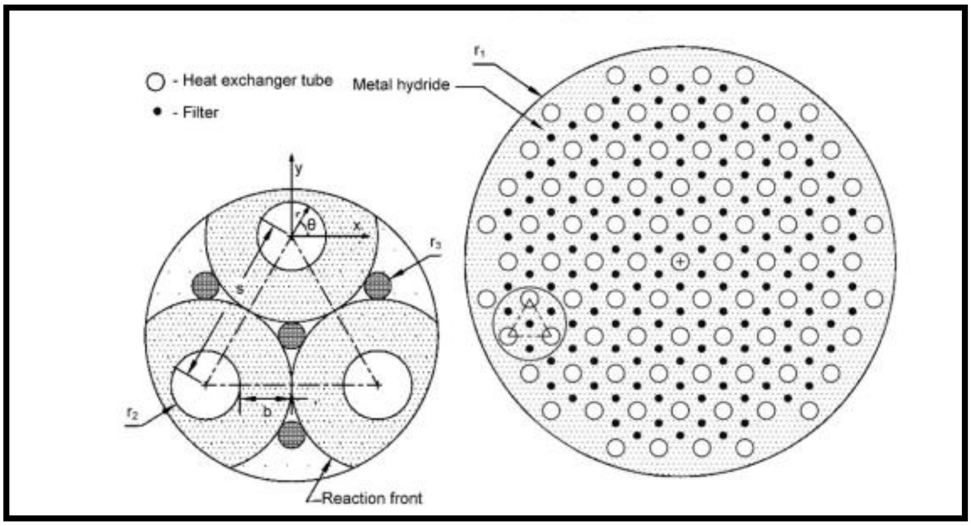

Figure 1.6: Schematic diagram of metal hydride reactor [15].

e) The Advantages of Green Hydrogen:

Green hydrogen is a cost-effective and risk-free solution for storing extra clean energy like wind and solar energy [16]. The following points are some advantages of green hydrogen storage:

- It is entirely sustainable because it emits no damaging gases during combustion or manufacture.
- It is easily stored, allowing it to be used later for various purposes.
- It is versatile since it can be converted into energy or synthetic gas and used for home, commercial, industrial, or transportation applications.
- Transportable: it can be combined with natural gas at a 20% ratio.1.7.6 The heat transfer and cooling.

f) The heat transfer:

The concept of heat (thermal energy) induced by temperature differences and the subsequent temperature distribution and variations is described by the idea of heat transfer [17]. The fundamental laws of heat transfer (conduction, convection, and radiation), the thermo-physical properties of materials, fluids such as the density (kg·m–3), heat capacity (J·kg–1·K –1), thermal conductivity (W·m–1·K–1) and the cooling techniques such as conduction, radiation are required in the design of cooling systems [18]. Furthermore, thermal conduction is a heat transmission without mass transfer in solids. The graph below shows the link between the heat flow density and the temperature gradient.

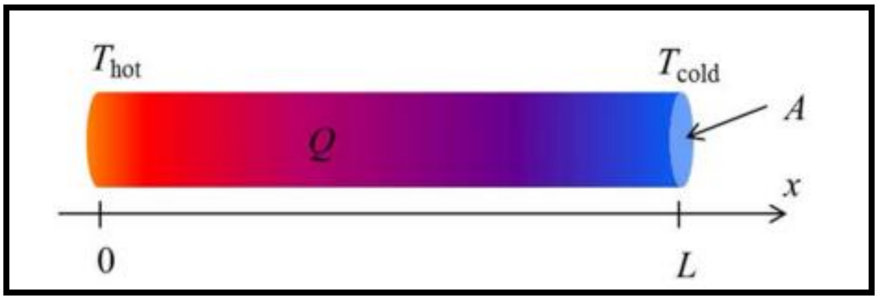

Figure 1.7: The definition of heat flux in a one-dimensional domain [18].

g) The porous media:

Hydrogen storage of porous media is an efficient and long-term energy storage technique for balancing renewable energy supply and seasonal demand. Porous media hydrogen storage could be a viable alternative for mitigating renewable energy supply bottlenecks [19].

Darcy's law is an equation that describes the flow of a fluid through a porous media. Darcy's law is used to analyze water flow through an aquifer; must the conservation of mass equation and, simplifying the groundwater flow equation, one of the primary hydrogeological relationships. The porous media concept applies to a wide range of single-phase by including viscosity in Darcy's single (fluid) phase equation and a multiphase flow of water, oil, and gas in the porous media of a petroleum reservoir [20].

Therefore, in the absence of gravitational forces and in a homogeneously porous media, Darcy's law is given by a simple proportionality connection between the instantaneous flux q=Q/A through a porous media, in the form of:

$$Q = -\frac{K}{\mu L} = \Delta p \qquad (1.1)$$

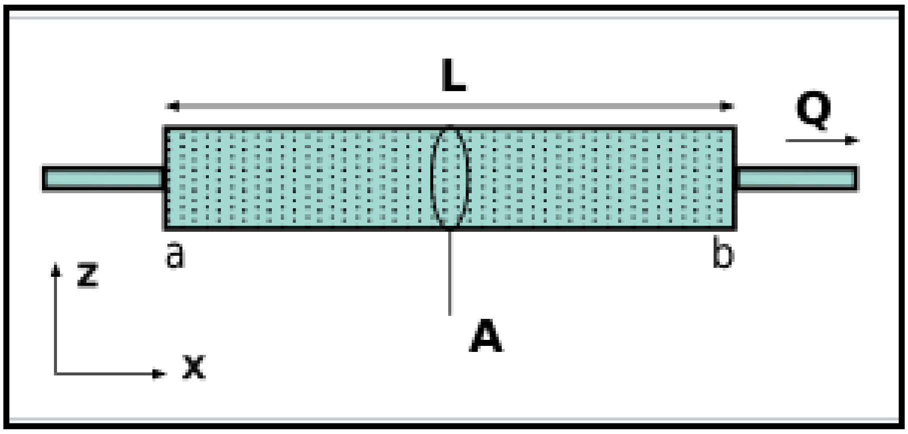

Figure 1.8: The definitions and directions for Darcy's law [20].

Chapter Two: Literature Review

2.1. What is a Literature Review?

The purpose of the literature review is to produce a comprehensive research work. It is essential to consider what other researchers have achieved in the past or are currently doing. This chapter summarizes the current and previous research on the techno-economic study of adding hydrogen storage. The category of the literature review is recognized into three parts: the using of green hydrogen storage, metal hydride hydrogen storage, and techno-economic study. Some of these works will be explored in detail, and some will be examined generally. Finally, Table 2. below groups the literature on metal hydride hydrogen storage and Technical Papers.

Table 2: Literature grouping for metal hydride hydrogen storage and Technical Papers

Author	**Purpose**
Metal hydride hydrogen storage	
Züttel [23]	Hydrogen Storage.
Züttel [24]	Hydrogen Storage.
Ströbel et al. [25]	Overview of experimental work.
Sakintuna et al. [26]	Studied Extensively for Hydrogen Storage.
Chen & Zhu [27]	Features of Common Metal Hydrides.
Askri et al .[28]	Optimizing Hydrogen Storage.
Wang et al.[29]	Hydrogen Storage Efficiency.
Nam et al. [30]	Developed a Three-Dimensional.
Chung et al.[31]	Computational Fluid Dynamics (CFD).
Niaz et al. [32]	Reviewed Hydrogen Storage.
Atef et al. [33]	A numerical analysis on solid-state hydrogen storage.
Barthelemy et al.[34]	An overview of hydrogen storage methods.
Chibani et al.[35]	stimulation of hydrogen absorption/desorption.
Tarasov et al. [36]	Selection of metal hydride materials.
Naruki Endo et al. [37]	operate metal hydride tanks (MHT).

Prasad et al. [38].	The absorption and desorption characteristics.
Techno-Economic Papers	
Becherif et al. [39]	Techno-economic study.
Alshehri et al. [40]	Techno-economic evaluation.
Ran et al. [41]	Economic dispatch.
Silva et al.. [42]	Techno-economic analysis.
Touili et al. [43]	Techno-economic comparison.
Z. Abedin et al. [44]	Techno-economic analysis.
Yu Gua et al. [45]	A comparative techno-economic study.
Naoto Takatsu et al. [46]	Techno-economic analysis.
Nasiraghdam et al. [47]	Techno-economic assessment.
Haider Niaz [48]	Adding hydrogen storage to integrate a plan.

2.2. The use of green hydrogen storage

In Japan by Hidaka & Kawahara [21] were studied the modeling and operating strategy of a hybrid system of photovoltaic (PV) and fuel cells. The proposed plan includes PV arrays, fuel cell stacks, electrolyzers (ELs), hydrogen storage tanks, and power conversion devices. The fuel cell system works in conjunction with the utility grid to make up for power shortages caused by the solar system. If the PV system generates excess electricity, the (EL) system uses it to create hydrogen from water. A programming tool, MATLAB/Simulink, makes modeling and simulation simple for programmers. Also, Rathode et al. [22] presented the necessity of using hydrogen, a future crisis of fossil fuels (traditional energy sources) will arise, necessitating developing an alternative option for them. This new energy-generating source has become an alternative and choice to conventional energy sources in terms of generation, transmission, and consumption. The authors explored the use of solar cells linked to the grid and equipped with a solid oxide fuel cell (SOFC) as a backup power source in a grid outage or malfunction.

2.3. A metal hydride hydrogen storage

Züttel [23] had examined hydrogen storage, which was a material science challenge because all six storage techniques now being investigated require materials with either a strong interaction with hydrogen or no reaction with hydrogen. The six primary hydrogen storage technologies require high pressure to store hydrogen as a gas. The most prevalent storage system used compressed gas in lightweight composite cylinders and operated at a maximum pressure of 20 MPa (tensile strength of the material is 2000 MPa) [23]. Liquid hydrogen is maintained in cryogenic tanks at 21.2 K at atmospheric pressure. Because hydrogen had a low critical temperature of 33 K, it can only be kept in liquid form in open systems because there was no liquid phase above that temperature. A closed storage system's pressure might reach 104 bar at room temperature (RT).

Physisorption of hydrogen at the surface of a solid, on the other hand, occurs when a gas molecule interacts with several atoms. The interaction comprises two terms: an attractive period that decreases to the power of -6 as the distance between the molecule and the surface increases. With space to the power of -12, a disagreeable phrase becomes less repulsive. As a result, at roughly one molecular radius from the adsorbate, the molecule's potential energy achieves a minimum. At high temperatures, hydrogen reacts with a variety of transition metals and alloys to produce hydrides. The same author had previously studied in hydrogen storage systems, highlighting their potential for advancement as well as their physical constraints [24].

And, Strobel et al. [25] offered an overview of experimental work on such systems as well as an outline of theoretical research conducted to determine the realistic limitations to the amount of hydrogen that might be stored per unit weight. A critical review of metal hydride materials for solid hydrogen storage was presented by Sakituna et al. [26] magnesium and related alloys are being studied extensively for hydrogen storage due to their high capacity and high-quality functional features.

In addition, Chen et al. [27] listed the features of common metal hydrides in Table 3. metals with differing hydrogen affinities can be used together to change the characteristics of ternary hydrides, and this was an essential alloying guideline for metal hydrides. For example, (LaNi5) and (ZrV2) alloys were employed to increase the electrochemical hydrogen storage capabilities. Furthermore, various alloys offer blew a variety of properties that help to improve the quality of hydrogen storage.

Table 3: Structure and Hydrogen Storage Properties of Typical Metal Hydrides [27]

Type	**Metal**	**Hydrides**	**Structure**	**Mass %**	***P* eq T**
AB5	LaNi5	LaNi5H6	Hexagonal	1.4	2 bar, 298K
AB3	CaNi3	CaNi3H4.4	Hexagonal	1.8	0.5 bar, 298K
AB2	ZrV2	ZrV2H5.5	Hexagonal	3.0	10^{-8}bar, 323K
AB	TiFe	TiFeH1.8	Cubic	1.9	5 bar, 303 K
A2 B	Mg2Ni	Mg2NiH4	Cubic	3.6	1 bar, 555 K
Solid solution	Ti-V-based	Ti-V-H4	Cubic	2.6	1 bar, 298 K
Elemental	Mg	MgH2	Hexagonal	7.6	1 bar, 573 K

F. Askri et al. [28] provided mathematical models for optimizing hydrogen storage in metal-hydride tanks. The model was first used to assess the effect of the thermal mass of the tank wall on the hydrating process. The results reveal that there was no substantial difference in hydrogen storage duration between steel and brass walls. Then, the installed model was used to study the dynamic behavior inside various designs of MHTs: (a cylindrical tank, b) a cylindrical tank with external fins, c) a cylindrical tank with a center tube filled with sequence cooling fluid, and d) a cylindrical tank with a concentric tube equipped with fins. Optimization results indicated that almost 80% improve. Figure 2.1. described the schematic of MHTs used in simulations.

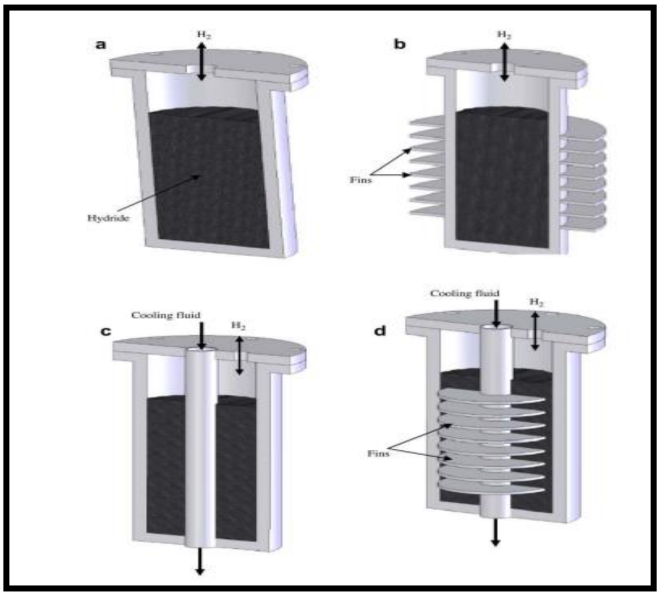

Figure 2.1: Schematic of MHTs used in simulations [28].

Hui Wang et al. [29] investigated hydrogen storage efficiency using hydride materials with increased thermal conductivity, quantifying the effect of these variables. In (Ansys Fluent 12.1), a mathematical model was created an axisymmetric to evaluate the transient heat transfer and mass transfer in a cylindrical metal hydride tank. And to anticipate the transient temperatures and mass of hydrogen stored as a function of the improved hydride material's thermal conductivity, the cylindrical tank's aspect ratio, and the thermal boundary conditions. The model was confirmed by comparing the transient temperature at various locations within the storage tank to concurrent experiments conducted with ($LaNi_5$) material. Figure 2.2. shows the axisymmetric model used in Ansys Fluent.

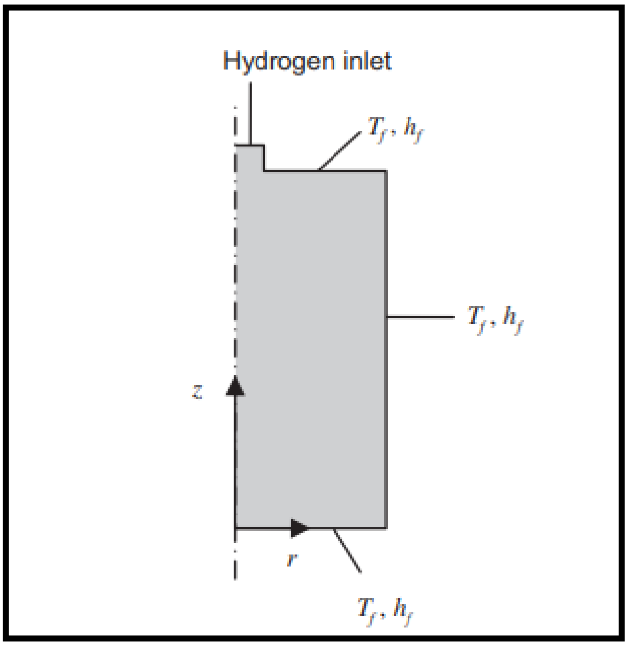

Figure 2.2: Axisymmetric model used in Ansys Fluent [29].

Nam et al. [30] developed a three-dimensional hydrogen absorption model to precisely simulate the hydrogen absorption reaction and the resulting heat and mass transport phenomena in metal hydride hydrogen storage containers. Thorough 3D simulation findings demonstrate that the vessel temperature and H/M ratio distributions ware uniform throughout the vessel during the initial absorption stage, indicating that hydrogen absorption was very efficient early in the hydrating process; consequently, the local cooling effect was unimportant. Chung et al. [31] investigated the computational fluid dynamics (CFD) on performance enhancement of the metal hydride hydrogen storage vessels using heat pipes. That showed a mathematical model for predicting the thermal-fluid behavior of heat pipes embedded in metal hydride beds. Computational fluid dynamics (CFD) simulations were carried out utilizing a commercial program Ansys Fluent and (LaNi5) as the storage medium.

Niaz et al. [32] reviewed hydrogen storage: materials, methods, and perspective to focus on various hydrogen produced and storing methods employed to create a hydrogen economy. The latest advancements that have been made on different hydrogen storing materials and hydrogen storing technologies have proven useful both on a gravimetric and volumetric bases have been highlighted. Moreover, Atef et al. [33] published a numerical analysis on solid-state hydrogen storage and destocking in a concentric triple-tube heat exchanger using lanthanum-nickel (LaNi5-H2). For determined the terms of mass and energy equations, the fluid parameters were considered: kinetics of hydrogen absorption/desorption, chemical processes, enthalpy of fusion, equilibrium pressure, hydrogen concentration, and storage capacity. Barthelemy et al.[34] provided an overview of hydrogen storage methods and their implications for the industry. The behavior of materials in hydrogen at conditions that ware representative of hydrogen energy applications. It was without a doubt, necessary for the development of long-term applications. Chibani et al.[35] investigated the stimulation of hydrogen absorption/desorption on metal hydride (LaNi5-H2): Mass and heat transfer with special emphasis on the mass and heat transfer during these processes. The mathematical model was validated and found that the storage of H2 was a fast exothermic process that generates rapid elevation of the metal hydride temperature.

On the other hand, a brief overview of literature data on metal hydride hydrogen storage and compression systems for energy storage technologies presented by Tarasov et al. [36] The emphasis was on the proper selection of metal hydride materials for hydrogen storage and compression applications based on examining (PCT) properties of the materials in systems containing hydrogen gas, using AB5- and AB2-type intermetallic complexes. Thermal management and power-saving activities for better energy efficiency within a renewable hydrogen energy system utilizing metal hydride hydrogen storage were researched by Naruki Endo et al. [37]. These principles were followed to operate metal hydride tanks (MHT) in the (HydroQ – BiCTM) bench-scale hydrogen system. Which included photovoltaic panels 20 kW, an electrolyze 5 Nm3 /h, (MHT) containing a (TiFe) based (MH) 40 Nm3, fuel cells FC; 3.5 kW power /2.5 kW heat, and Li-ion batteries 20 kW/20 kWh. In Figure 2.3. below shows the schematic of the renewable hydrogen energy system.

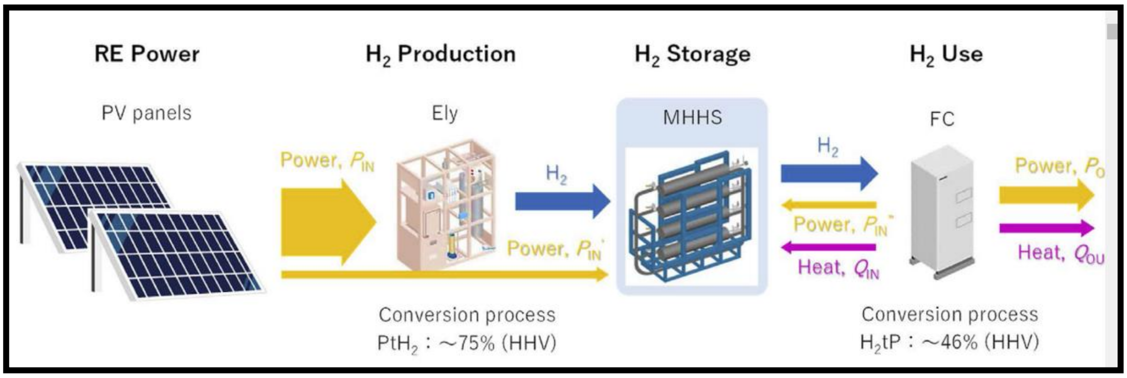

Figure 2.3: Schematic of the renewable H2 energy system [37].

Design and performance studies of an annular metal hydride reactor for large-scale hydrogen storage applications were given by Prasad et al. [38]. The absorption and desorption characteristics of the planned annular metal hydride reactor were studied using a computer model. The weight ratio (i.e., the mass of the metal hydride alloy to the reactor's mass) of three annular metal hydride reactor topologies is examined. The primary goal of the three configurations was to see how much the reaction rate and outlet temperature had improved. The second design increased the peak outflow temperature by 3.6 C, according to the results.

2.4. Techno-Economic Study

Hydrogen storage systems have matured as viable for power system stabilization during generation-demand mismatches and for generating economic rewards from excess hydrogen and oxygen production. Becherif et al. [39] used hydrogen energy storage as a new techno-economic emergence solution analysis. It drew attention to the novel hydrogen generation and storage technology, its efficacy, and the regulatory context's impact on its development. The techno-economic aspects of hydrogen production and storage were discussed. For a power system rated at 70 kW, MATLAB-Simulink was used. Hydrogen storage systems have matured as viable for power system stabilization during generation-demand mismatches and for generating economic rewards from excess hydrogen and oxygen production. Figure 2.4. below shows the System under study.

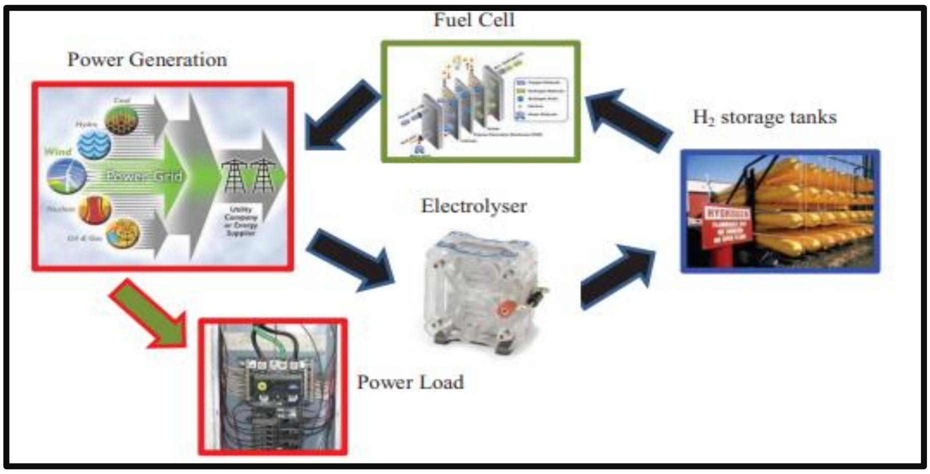

Figure 2.4: System under study [39].

Previous study have reported [40] about the Middle East and North Africa (MENA) area was endowed with energy from the sun may be captured from the MENA and stored as hydrogen, which is gaining popularity as a supplementary energy source. The authors looked at cost-efficient of the hydrogen generation and storage. Hydrogen may be produced using photovoltaic solar power and electrolysis devices. Most of the cost of the PV and electrolyzing systems must be paid upfront to produce hydrogen from solar electricity. Because of this, capital efficiency was the essential element to consider.

A techno-economic review was carried out by Ran et al.[41] the major materials of an off-grid solar panel generating model with hybrid power storage were built as mathematical systems. Depending on the material requirements, self-wastage, and system capacity affects. The authors examined the values and developed a modeling framework for an off-grid PV microgrid with hybrid energy storage using MATLAB software. The storage battery, electrolyzer, compressor, hydrogen tank, and fuel cell were all modelled in MATLAB/Simulink. They built a modeling framework for off-grid solar power generation with hybrid energy storage, using the power management method.

A techno-economic evaluation was conducted in Sri Lanka to the reliability and economic viability of putting in place hydrogen production, storage, and solar photovoltaic systems Diesel generators were used to power the sites for the communications [42]. The scientists analyzed data from 3039 telecom base station sites in order to create and store hydrogen gas by electrolyzing water using solar energy collected. HOMER Grid was utilized to determine the best system composition. Their study's findings indicated that low-demand sites were appropriate for this design, and as the demand increased, more than one point in the system was required.

Also, an economic analysis was conducted to assess solar hydrogen generation in Morocco between Morocco and Southern Europe via the water electrolysis [43] The authors studied the economy from 2014 to 2016 to model and create hydrogen from a 100 MWp PV power plant system was linked to a polymer electrolyte membrane (PEM). The study's findings highlight hydrogen's solar energy potential generation, providing policymakers and investors with important information to promote them. The findings demonstrated that the suggested idea was technically and economically viable in the majority of situations, but, in some scenarios with higher power consumption, an optimized variant of the standard design was shown to be still economically viable.

Moreover, Abdin and Mérida [44] investigated a techno-economic analysis of hybrid energy systems for off-grid power supply and hydrogen synthesis based on renewable energy to investigate power generation and hydrogen production via renewable energy resources (mainly solar and wind) to produce synthetic fuels by capturing CO2 from the atmosphere in five different global locations; Squamish, Canada; Los Angeles and Golden, USA; and Brisbane and Adelaide, Australia. Figure 2.5. below shows the Generic renewable hybrid energy system. The findings of this study imply that hydrogen has a lower cost of energy storage than batteries in off-grid energy systems.

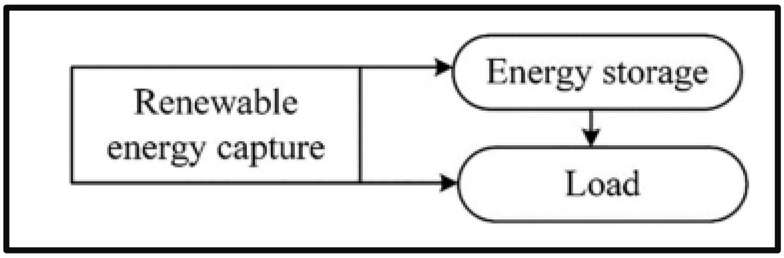

Figure 2.5: Generic renewable hybrid energy system [44].

Gu et al. [45] identifies a comparative techno-economic study of solar energy integrated hydrogen supply pathways for hydrogen refueling stations in China. It was determined the economic, energy, and environmental elements of prospective solar-integrated green hydrogen supply routes in China, including cross-regional and onsite possibilities for hydrogen filling stations. Four solar energy-integrated green hydrogen supply options have been presented. The findings show that solar energy-integrated hydrogen supply channels reduce (CO_2) emissions significantly. When compared to the standard coal gasification for hydrogen production coupled with gas (H_2) transportation to a local filling station pathway.

Takatsu and Farzaneh [46] used techno-economic analysis of a novel Hydrogen-based hybrid renewable energy system for grid-tied and Off-grid power supply in Japan, the case of Fukushima Prefecture. That presented a revolutionary hydrogen-based hybrid renewable energy system (HRES), in which hydrogen fuel can be produced, utilizing solar electrolysis and biomass feedstock (SCWG). In all scenarios, the proposed HRES can generate roughly 47.3 MWh of energy, which is required to meet the external load need in the research region. Figure 2.6. shows the Proposed system configuration.

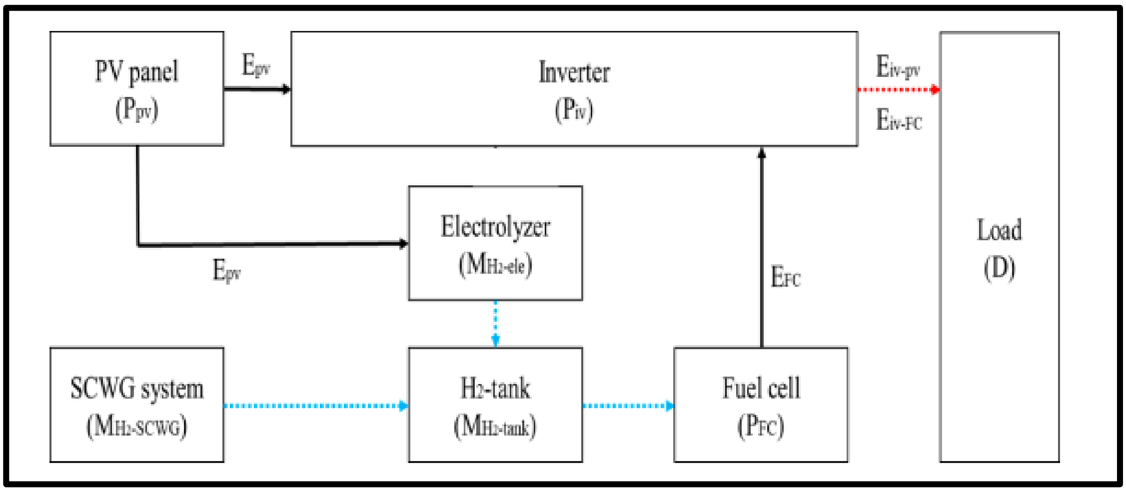

Figure 2.6: Proposed system configuration [46].

Furthermore, Nasiraghdam & Safari [47] discussed a techno-economic assessment of combined power to hydrogen technology and hydrogen storage in optimal bidding strategy of high renewable units penetrated microgrids. Their goal was to develop a novel method for finding the best bidding strategies for magnesium (MG) modified by renewable resources in the day-ahead energy and spinning reserve markets, taking advantage of the capabilities of power to hydrogen (P2H) and hydrogen storage (HS) technology. It used the power to hydrogen (P2H) and hydrogen storage (HS) technologies' capabilities. In addition, the unscented transformation has been employed to efficiently simulate the uncertainty in the entity's renewable resources, load consumption, and electricity. The cost of operating the system without energy storage is 779 dollars but utilizing an energy storage system (ESS) reduces the cost to 741 dollars, a savings of 4%. Furthermore, by employing (ESS) as both energy and reserve suppliers, the operational cost drops to 640$, a savings of 18%. On the other hand, using the HS system cuts operating costs by as much as 26% and 40% for energy suppliers and energy and reserve suppliers, resulting in 577$ and 487$, respectively.

Also, Haider Niaz [48] investigated adding to demonstrate an alkaline water electrolyzer (AWE) and a battery energy storage device was made to meet the flexible and changeable nature of renewable energy (BESS). An alkaline water electrolyzer and battery energy storage system (BESS) of 4.5 MW were proposed to construct a continuous, environmental hydrogen production system. that evaluated the real economic potential of the suggested models and cost analyses for systems with and without BESS were undertaken. AWE's minimum hydrogen selling price (MHSP) is $3.97/kg with BESS. Control methods efficiently combine ESS and AWE due to renewable energy's dynamic nature, whereas the system without BESS is 4.96 $//kg. Finally, the solar power facilities can be built at the lowest possible cost due to the current weather conditions. Figures 2.7 and 2.8 described the dynamic modelling with and without ESS.

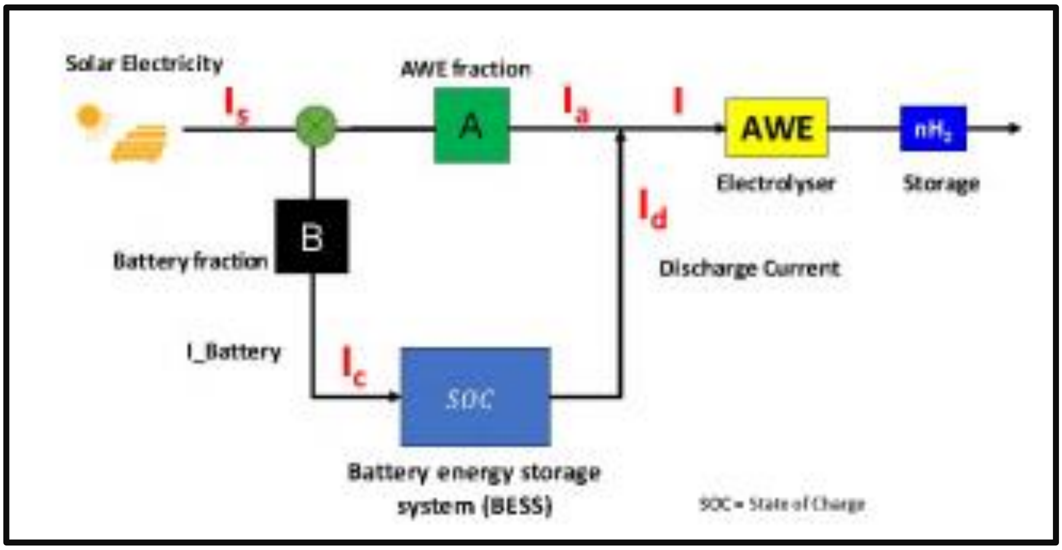

Figure 2.7: The dynamic modelling approach to overcome the dynamic nature of the renewable energy source by coupling with an ESS (energy storage system) [48].

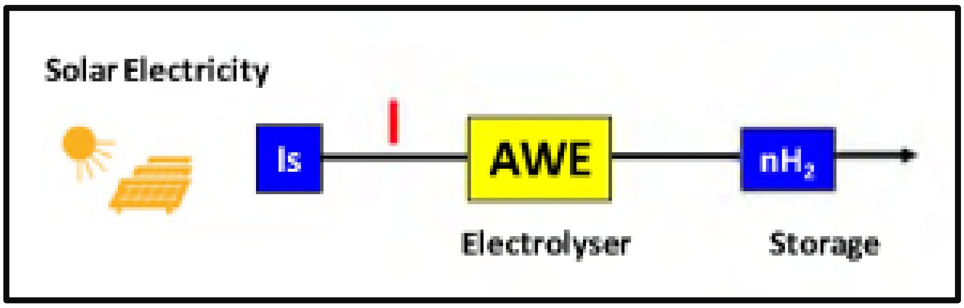

Figure 2.8: Schematic for the dynamic modelling approach without ESS (energy storage system) [48].

Chapter Three: Research Methodology

3.1. Describing the Methodology Used in the Study

The background of hydrogen and the literature review assisted in gathering the necessary data and information for the techno-economic study of adding hydrogen storage to a PV plant. This chapter creates the mathematical model of heat and mass transfer inside metal hydride hydrogen storage (MHHS) to simulate the heat and mass transfer using MATLAB software. The capacity of the PV plant is 30 MW per year on the grid located in Neom city, Tabuk region, Saudi Arabia, northwest of the country. On the other hand, the techno-economic study for two PV plants: the first is a PV system with an inverter connected to the grid (Figure 3.1), and the second is a PV plant connected to the inverter and an electrolyze, compressor, and hydrogen storage, followed by a fuel cell connected to the grid (Figure 3.2). This chapter gives the details steps of utilizing System Advisor Model (SAM) software to get the payback period (PP), the intern rate of return (IRR), and other economic parameters for the PV plant located in Neom city, Tabuk region, Saudi Arabia.

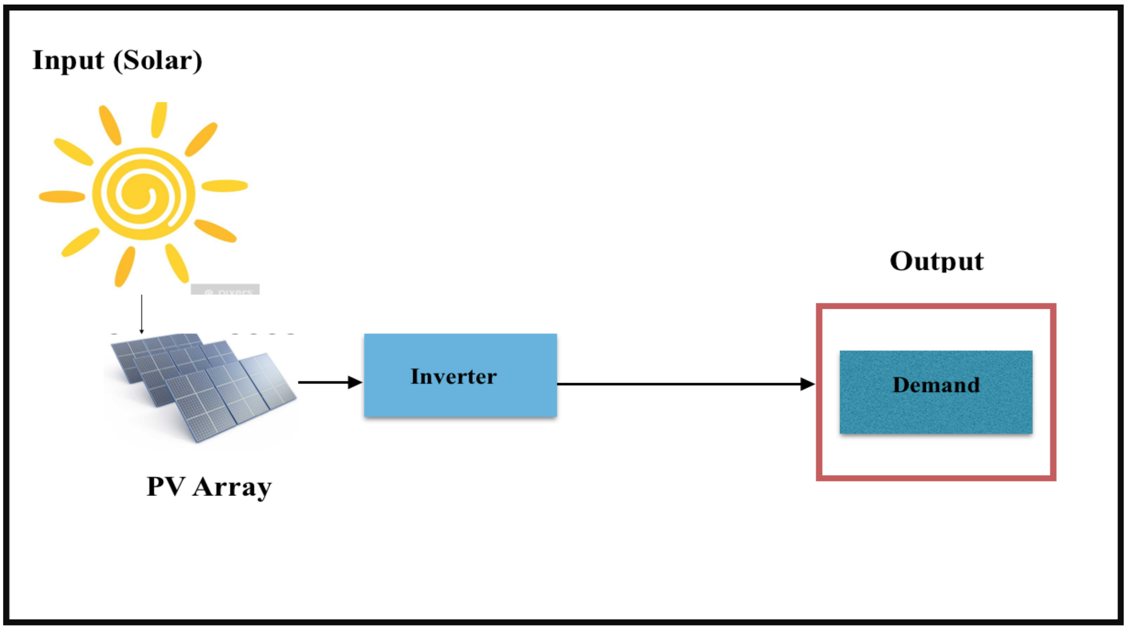

Figure 3.1: PV system without hydrogen storage.

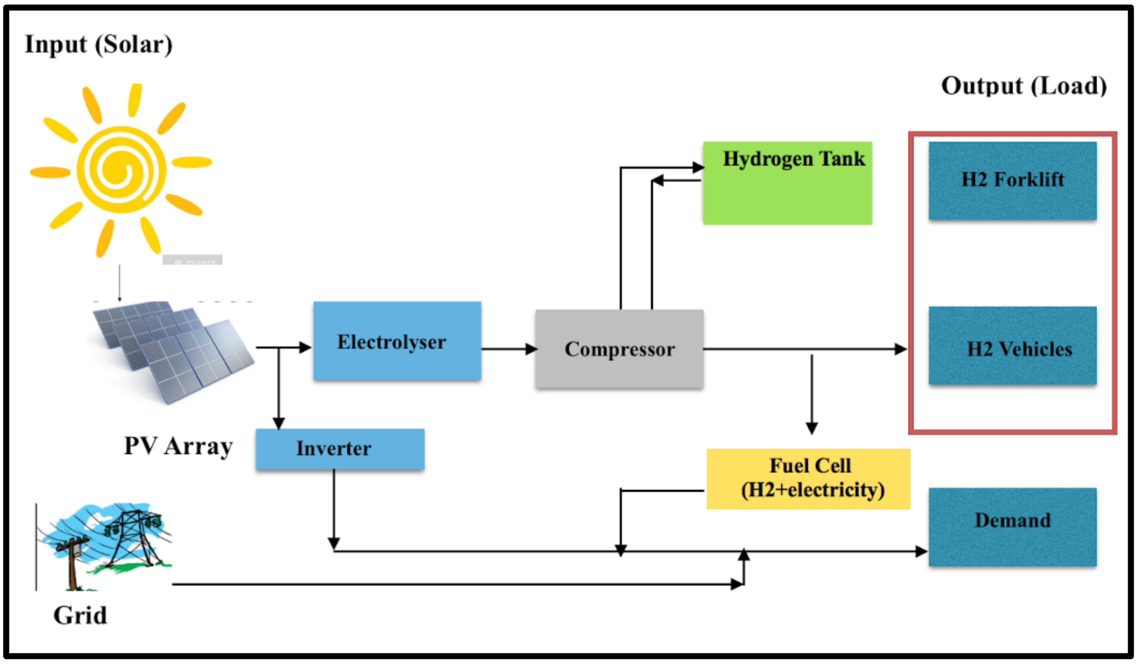

Figure 3.2: PV system with hydrogen storage.

3.2. Modeling of Metal Hydride Hydrogen storage

In this chapter section, the modeling is simulated hydrogen storage added to the PV plant. Build a mathematical model of heat and mass transfer inside (metal hydride hydrogen storage) and solve it using a MATLAB built-in function.

a) The Metal hydride hydrogen storage:

Metal hydride storage is appropriate for scenarios in which hydrogen is produced on-site using renewable electrolysis and stored for long periods. When power is required, it can be recovered instantaneously as hydrogen gas or in the form of electric or thermal energy using a fuel cell [49]. A hydrogen storage alloy powered, heat exchanger pieces, and gas transit components are loaded into a metal hydride tank. The container's body is aluminum alloy and filled with commercial LaNi5 grains. The metal hydride is a more compact and safer. alternative than other storage types [50].

Figure 3.3: Metal hydride hydrogen storage [50].

b) Mathematical modeling:

The process of constructing mathematical models for heat and mass transfer to and from the metal hydride hydrogen storage reactor bed. The e main assumptions considered in developing the metal hydride hydrogen storage are the following:

1. The hydrogen is assumed to be an ideal gas as the pressure within the bed is moderate.
2. The solid phase is isotropic and has a uniform porosity.
3. The equilibrium gas pressure is calculated by the Van’t Hoff Equation.
4. Thermal–physical properties are constant.

In the mass balance equation, the hydrogen enters through the alloy bed, the metal hydride, through the filter. The metal powders absorb hydrogen to form metal hydrides associated with changes in density. This change in hydride density produces both absorption reaction and diffusive movement due to variation in the hydride concentration, where the porosity and diffusion movement coefficient will be constant. Eq 3.1 expresses the mass conversion for the reactor's solid phase in polar coordinates:

$$(1-\varepsilon)\frac{\partial \rho_s}{\partial t} = \dot{m} + (1-\varepsilon)D\,\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial \rho_s}{\partial r}\right) + (1-\varepsilon)\,D\frac{1}{r^2}\,\frac{\partial}{\partial \theta}\left(\frac{\partial \rho_s}{\partial \theta}\right) \qquad (3.1)$$

Where are:

- $\boldsymbol{\varepsilon}$ is the porosity.

- $\dot{m}$ is the chemical reaction rate.
- ρ_s is the solid density.
- r is the radiance.

The mass of hydrogen absorbed due to the reaction is known as the chemical reaction term:

$$\dot{m} = -C_a \exp\left(-\frac{E_a}{RT}\right) \ln\left(\frac{P}{P_{eq}}\right) (\rho_{sat} - \rho_s) \tag{3.2}$$

Where are:

- C_a is the calcium.
- ρ_{sat} is the saturated density.
- E_a is the activation energy.
- R is the gas constant.
- T is the temperature.
- P is the pressure.
- P_{eq} is equilibrium pressure.

The Van't Hoff relationship, to determines the equilibrium pressure, where A and B are van't Hoff constants.:

$$P_{eq} = A - \frac{B}{T} \tag{3.3}$$

The hydrogen flow through a porous media is described by Darcy law. Where ρ_g is gas density, $\vec{u}$ is dynamic viscosity of the fluid and M_g is magnesium.

$$\varepsilon \frac{\partial \rho_g}{\partial t} + \nabla.(\vec{u}\,\rho_g) = -(1-\epsilon)\,\frac{\partial \rho_s}{\partial t} \tag{3.4}$$

$$\rho_g = \frac{M_g P}{RT} \tag{3.5}$$

$$\vec{u} = -\frac{K}{\mu_g}\nabla p \tag{3.6}$$

$$K = \frac{d_p^2\ \epsilon^3}{150\,.(1-\epsilon)^2} \tag{3.7}$$

$$\frac{\partial \rho_s}{\partial t} = C_a \exp\left(-\frac{E_a}{RT}\right) \text{In}\left(\frac{P}{P_{eq}}\right) (\rho_{sat} - \rho_s) \quad (3.8)$$

Substituted by $\vec{u}$,where k is constant in the Eq (3.9):

$$\varepsilon \frac{\partial \rho_g}{\partial t} + \varepsilon \left(\frac{-k}{\mu_g}\right) \frac{1}{r} \frac{\partial}{\partial r} \left[r\rho_g \quad \frac{\partial p}{\partial r} \right] + \varepsilon \left(\frac{-k}{\mu_g}\right) \frac{1}{r^2} \frac{\partial}{\partial \theta} \left[\rho_g \quad \frac{\partial p}{\partial \theta} \right] = -\dot{m} \quad (3.9)$$

The heat generated due to exothermic reaction requires energy, the alloy bed's energy conservation; where C_p is effective specific heat, k_e is constant and ΔH^0 is the isothermal reaction. The Eq 3.10 could be represented as follows:

$$(\rho C_p)_e \ \frac{\partial T}{\partial t} = k_e \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + k_e \frac{1}{r^2} \frac{\partial}{\partial \theta} \left(\frac{\partial T}{\partial \theta} \right) - \dot{m}\Delta H^0 \quad (3.10)$$

The Eq 3.11 is how effective volumetric heat capacity is expressed below:

$$(\rho C_p)_e = (\varepsilon \rho_g C_{pg} + (1 - \varepsilon) C_{ps} \quad (3.11)$$

Where are:

- C_{pg} is effective specific heat for gas.
- C_{ps} is effective specific heat for solid.

The effective thermal conductivity is provided in Eq 3.12:

$$k_e = \varepsilon k_g + (1 - \varepsilon) k_s \quad (3.12)$$

The initial and boundary conditions for the pressure and temperature of reactor bed as summed to be uniform:

$$p = p_0 \ ; \ T = T_0 \ ; \ \rho = \rho_0 \ \text{ at } t = 0.$$

The boundary walls of reactor are assumed to be impermeable and adiabatic.

$$\frac{\partial p}{\partial r} = 0; \frac{\partial T}{\partial r} = 0 \text{ at } t > 0. \quad (3.13)$$

Cooling tube wall at r = r_2 :

$$\frac{\partial p}{\partial r} = 0; \quad -k \frac{\partial T}{\partial r} = h_f (T_f - T) \quad \text{at } t > 0 \quad (3.14)$$

Filter wall at r=r_3:

$$p= p_{in} : \frac{\partial T}{\partial r} \quad \text{at } t > 0. \tag{3.15}$$

c) One-dimensional Model

The 1D mass balance equation in (r) has this form:

$$(1-\varepsilon)\frac{\partial \rho_s}{\partial t} = \dot{m} \; + (1-\varepsilon)D\,\frac{1}{r}\,\frac{\partial}{\partial r}\left(r\frac{\partial \rho_s}{\partial r}\right) \tag{3.16}$$

$$\varepsilon\frac{\partial \rho_g}{\partial t} + \varepsilon\left(\frac{-k}{\mu}\right)\frac{1}{r}\frac{\partial}{\partial r}\left[r\rho_g \quad \frac{\partial p}{\partial r}\right] = = -\dot{m} \tag{3.17}$$

$$(\rho C_p)_e \; \frac{\partial T}{\partial t} = \; k_e\frac{1}{r}\,\frac{\partial}{\partial r}\left(r\;\frac{\partial T}{\partial r}\right) \tag{3.18}$$

For the initial and boundary conditions for the pressure and temperature of reactor bed have mentioned in mathematical equations section above.

d) The Simulation Software MATLAB

The software used to simulate the heat and mass transfer is MATLAB. A programming platform created exclusively for engineers and scientists to study and design systems and technologies that will change the world. The MATLAB language, a matrix-based language that allows for the most natural expression of computational mathematics, lies at the heart of MATLAB [51] .

3.3. The Techno-Economic Study

System Advisor Model (SAM) is the software used to compare the techno-economic study of adding hydrogen storage to fixed PV plants on the grid to analyze the economic parameters to get results such as the intern rate of return (IRR) and payback period (PP).

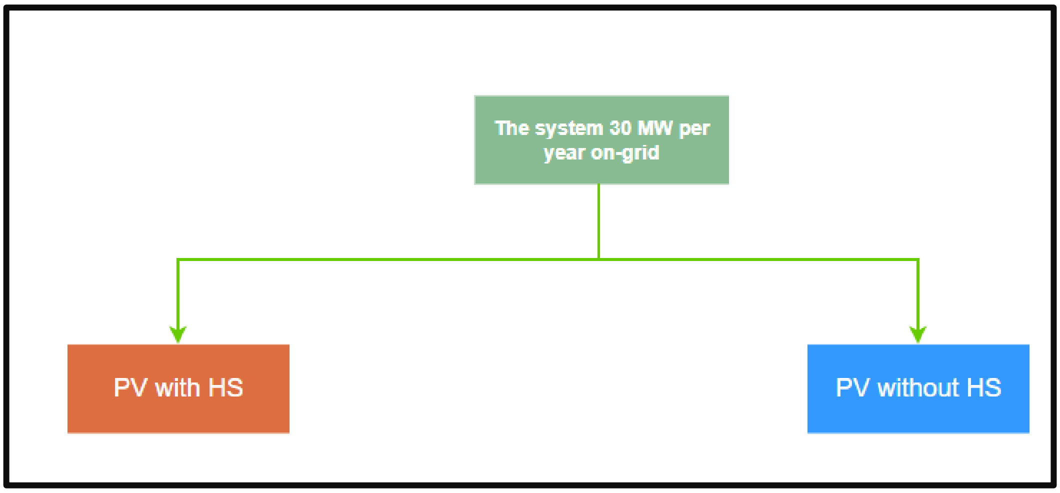

Figure 3.4: The comparative systems.

The first PV plant without hydrogen storage connected to the grid. The location of the PV plant with the weather data, the model structure, the parameters of the inverter, and the system design are explained in detail.

On the other hand, the second system adds hydrogen storage to the PV plant adding hydrogen storage. In this section, it is explained fuel-cell type and capacity of fuel-cell. A PV system comprises multiple panels, each creating a small amount of energy and connecting the boards to get the needed electrical output of 30 MW per year.

a) The System Advisor Model (SAM)

The System Advisor Model (SAM) is a performance, and financial model meant to help people in the renewable energy business make decisions. In addition, SAM produces performance projections and energy cost estimates for grid-connected power projects based on installation and operating expenses and system design characteristics that you supply as model inputs [52].

b) The payback period (PP)

The Payback Period (PP) refers to the required period to recover the cost of an investment in a potential investment. The simple PP considers only the initial cost and total annual cash flows of a potential investment [53]. It is a widely used economic parameter in the industry for measuring a financial analysis of a possible system, and it considers a safety indicator for an investor. Eq. 3.19 below shows the payback period (PP) equation.

$$\text{Payback Period (PP)} = \text{Initial investment} / \text{Cash flow per year} \quad (3.19)$$

Initial investment: The initial sum of money required to open an account or establish a buy-in relationship [54].

Cash flow: It is a financial statement that summarizes the flow of cash and cash equivalents (CCE) into and out of a business [55].

c) Internal Rate of Return (IRR)

Internal Rate of Return (IRR) considers as a discount rate that leads the net present value (NPV) of a potential investment equal to zero [56] . IRR is a common financial parameter for investigating the profitability of a potential investment. To calculate it, the discount rate should be determined, which leads an NPV equal to zero. If the IRR is equal to or bigger than the required rate of return, then the potential project can be financially accepted. If it is less than the required rate of return, then the potential project is unacceptable [56]. Eq 3.20 below shows the internal rate of return (IRR) equation.

$$\text{Internal Rate of Return (IRR)} = \frac{(\text{Cash flows})}{(1+r)^{i}} - \text{Initial Investment} \quad (3.20)$$

3.4. PV plant without hydrogen storage

a) Location and resources

The weather files for Neom in Tabuk, Saudi Arabia, obtained from the solar resource library, are accessible via the Location and Resource tab. The following information describes the data for Neom in Tabuk, Saudi Arabia, in the highlighted weather file from the Solar Resource collection.

Table 4: The header data from weather file

Latitude	**24.65**
Longitude	46.7
Time zone	GMT 3
Elevation	603 m
Time step	60 minutes
Station ID	2379183
Data Source	NSRDB

For National Solar Radiation Database (NSRDB), the latitude and longitude are shown in the weather file header are the coordinates of the NSROB grid cell and may be different from the values in the file name, which are the coordinates of the requested location.

Table 5: Annual Average Calculated from Weather File Data

Global horizontal	5.88 kWh/$\boldsymbol{m^2}$/day
Direct normal (beam)	5.25 kWh/m^2/day
Diffuse horizontal	2.29 kWh/m^2/day
Average temperature	26.5 C^o
Average wind speed	3.0 m/s

b) Module

Choose a model to show a solar module's performance on the module. Based on the design parameters and incident solar radiation (plane-of-array irradiance) supplied from data in the weather file, the module model calculates the DC electrical output of a single module for each simulation time step. The module type was Jinko Solar Co.Ltd JKMS395M-72L-V-MX3. The reference conditions from model characteristics at reference condonations from the system advisor model. The number of modules is 75,872 units.

Table 6: The solar radiation from weather data and the data sheet for PV cell

Total Irradiance	**1000 W/m2**
Cell temp	25
Nominal efficiency	20.59%
Maximum power (Pmp)	395.370 Wdc
Max power voltage (Vmp)	41.4 Vdc
Max power current (Imp)	9.6 Adc
Open circuit voltage (Voc)	49.5 Vdc
Short circuit current (Isc)	10.2 Adc
The number of modules	75,872 units

Table 7: Temperature Coefficients

-0.402 %C	-1.589 W/C
-0.300	-0.148 V/C
0.050 %C	0.005 A/C

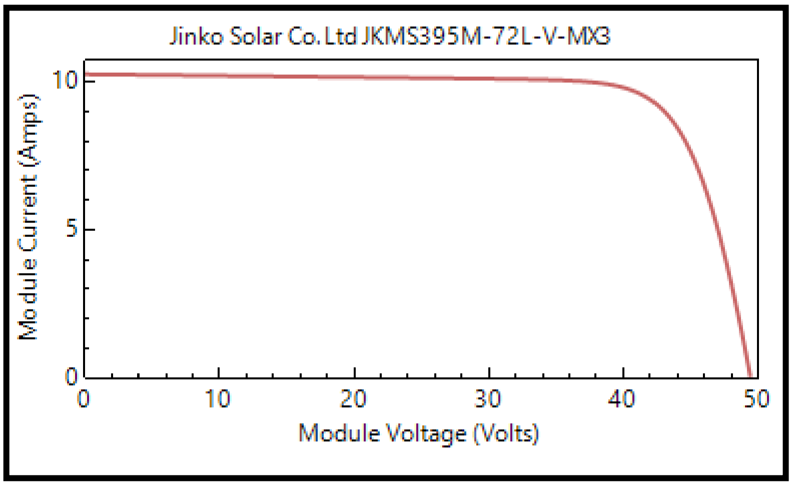

Figure 3.5: PV power.

c) Inverter

According to the performance model and an inverter from a list, we have chosen the inverter. SMA America is the inverter type, SC750CP-US (with ABB EcoDry Ultra transformer). The reference conditions from the efficiency curve and the system advisor model (SAM).

Table 8: Datasheet Parameters

Maximum AC power	770000 Wac
Maximum DC power	791706.4375 Wdc
Power use during operation	2859.504883 Wdc
Power use at night	231 Wac
Nominal AC voltage	0 Vac
Maximum DC voltage	820 Vdc
Maximum DC current	1289.424165 Adc
Minimum MPPT DC voltage	545 Vdc
Nominal DC voltage	614 Vdc
Maximum MPPT DC voltage	820 Vdc

Table 9: Sandia Coefficients

C0	-2.445577e-08 1/Wac
C1	1.200000e05 1/Vdc
C2	1.461000e-03 1/Vdc
C3	-2.030000e-04 1/Vdc

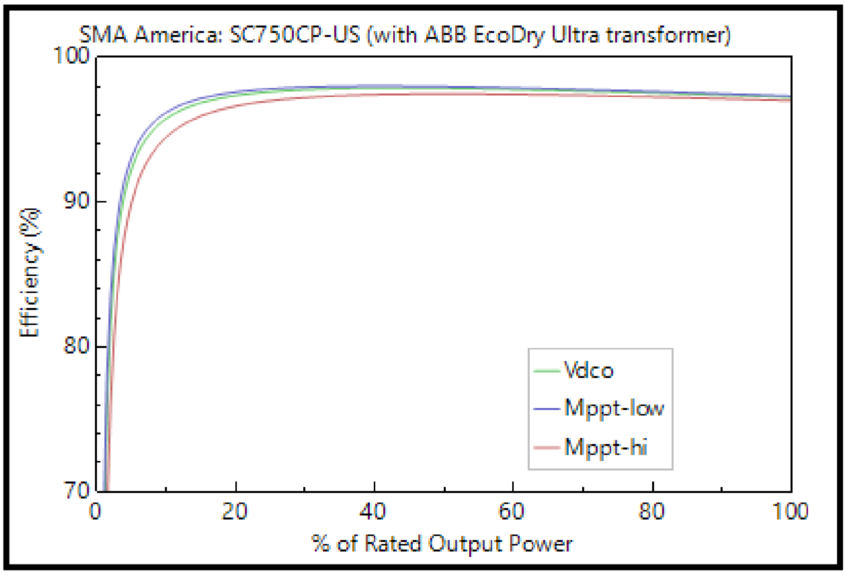

Figure 3.6: Efficiency Curve.

d) System design

The System Design variables are used to size a solar system. The AC Sizing inputs determine the system's AC rating. And, the sizing summary variables below where values SAM calculates based on the inputs you specify.

Table 10: The system design and sizing

Desired array size	30000 KWdc
Desired DC to AC ratio	1.2
Nameplate DC capacity	29,997.513 KWdc
Total AC capacity	24,640.000 kWac
Total inverter DC capacity	25,334.606 KWdc
Number of modules	75,872
Number of strings	4,742
The number of inverters	32 units
Total module area	145,674.240 m^2

Table 11: Electrical configuration

Maximum DC voltage	820.0 Vdc
Minimum MPPT voltage	545.0 Vdc
Maximum MPPT voltage	820.0 Vdc

The tilt and azimuth angles indicated by the values of Tilt and Azimuth are fixed, and the subarray does not follow the sun's movement Figure 3.7.

Table 12: Tracking & Oration

Tilt (deg)	25
Azimuth (deg)	180
Ground coverage ratio (GCR)	0.3

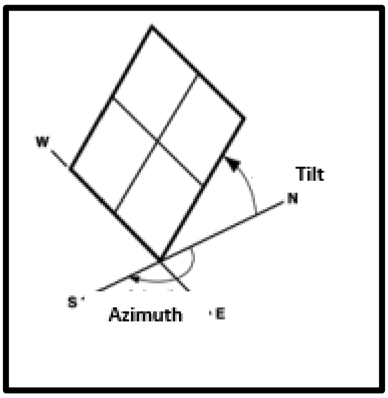

Figure 3.7: PV array facing south at fixed tillt.

Based on the design parameters and incident solar radiation (plane-of-array irradiance) supplied from data in the weather file, the module model calculates the DC electrical output of a single module for each simulation time step. The selected module type is Jinko Solar Co. Ltd JKMS395M-72L-V-MX3. The reference conditions from model characteristics at reference condonations from the system advisor model are shown in (Figure 3.4). The number of modules is 75,872 units. Also, the inverter was chosen according to the performance model and an inverter from a list. SMA America is the inverter type, SC750CP-US with ABB EcoDry Ultra transformer. The reference conditions from efficiency curve and characteristics from the system advisor model are shown in (Figure 3.5).

3.5. PV plant with Hydrogen Storage

This section is designed by adding hydrogen storage to a PV plant capacity of 30 MW on the grid. This design had a divided PV plant with 15 MW and a hydrogen storage capacity of 15 MW.

a) Battery Bank Sizing

The Table 13. below Specify desired values for DC units, the nominal bank capacity, and the power for SAM to calculate the number of cells and strings.

Table 13: Battery Bank Sizing data

The desired bank power	15000 KW
The desired bank capacity	17 hours
the number of strings	1
the number of cells in series	3
the Max C-rate of charge	0.5 per/hour
the Max C-rate of discharge	0.5 per/hour

The cycle degradation and calendar degradation are defined blow:

Table 14: Cycle and Calendar Degradation data

Depth-of-discharge (%)	Cycles Elapsed	Capacity (%)
20	0	100
20	5000	80
20	1000	60
80	0	100
80	1000	80
80	2000	60

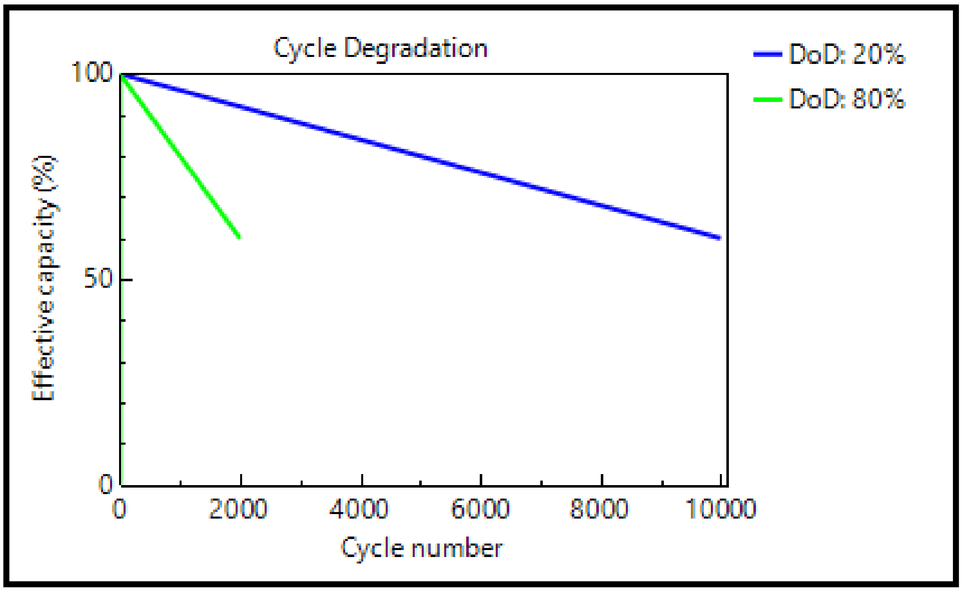

Figure 3.8: The cycle degradation.

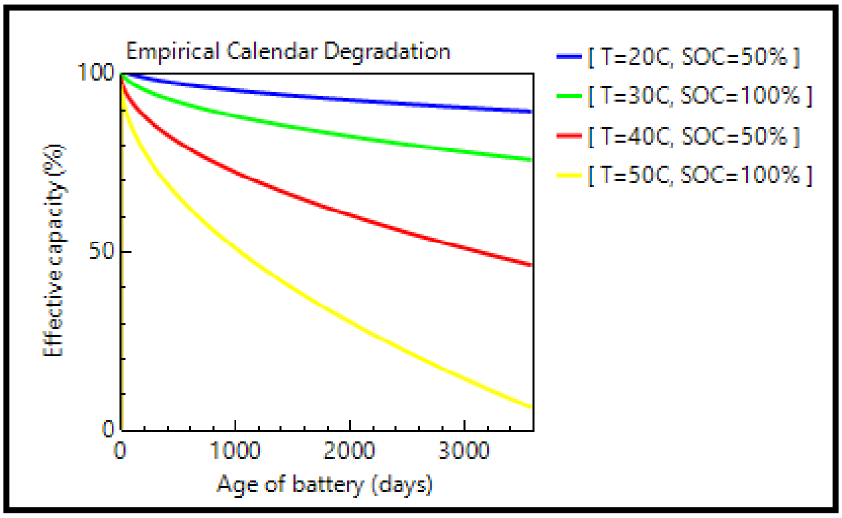

Figure 3.9: The Empirical Calendar degradation.

b) Fuel Cell

The type of fuel cell is a solid oxide fuel cell (SOFC), which operates at a temperature between 650 and 1,000   and can convert a wide range of fossil fuels.

- Efficiency

The electrical efficiency is applied to the power generated, while heat recovery percent determines heat generation. These efficiencies are calculated by the current power output, which can define relative to the original nameplate power or degraded max power.

Table 15: The electrical efficiency

% Power	Electrical Efficiency LHV (%)	Max Heat Recovery (%)
0	3	50
16.1	21	50
25.5	25.2	50
34.8	31.5	50
44.1	37.3	50
53.4	42.6	50
62.7	47.4	49
72	49.9	48
81.4	52	47
90.7	51.8	46
100	50.7	45

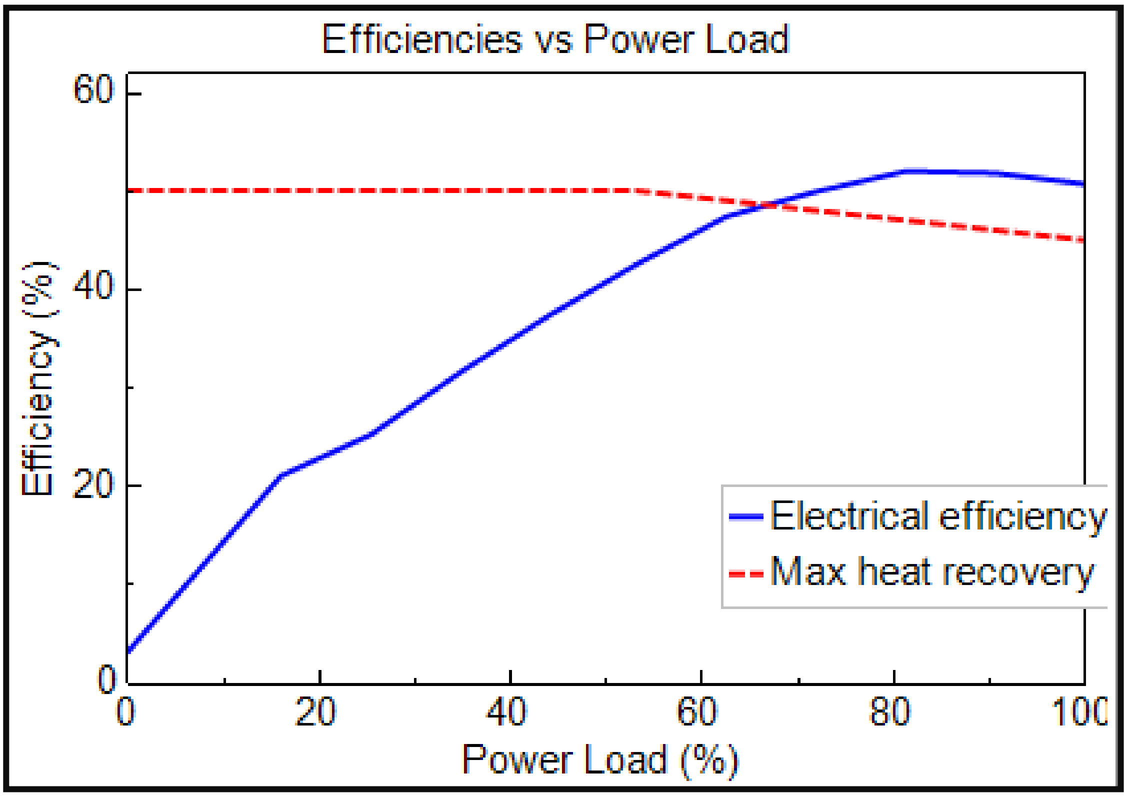

Figure 3.10: The efficiencies Vs power load.

Chapter Four: Results and Discussion

4.1. Introduction

This chapter presents the simulation of heat and mass transfer inside metal hydride hydrogen storage (MHHS) by solving the mathematical governing equation in the MATLAB environment. A MATLAB code has been written to solve the one-dimensional nonlinear partial differential system along with its initial and boundary conditions. Also, this chapter provides the summary result from the system advisor model (SAM), indicating IRR, PP, and other economic parameters. Moreover, the net electricity to the grid for the PV plant.

4.2. Metal hydride Hydrogen Storage Result

The one-dimensional governing equations (3.16) - (3.18) along with the initial and boundary conditions (3.13) - (3.15) has been solved numerically using finite element method in the MATLAB environment. Some of the results are listed and discussed in this section. Figure 4.1 shows the change in hydride density against time with different positions on the storage radius. It is clear from this figure that the metal density has been increased clearly as we go far from the center of the tank. This may be interpreted as the time increases the hydride density increases. Figure 4.2 illustrates the variation in the hydride density against radius at different times. This figure supports the results of Figure 1 and shows clearly that change against is small but increases with time. Figure 4.3 shows the change in the hydrogen density against time with different positions on the storage radius. The hydrogen in the storage decreases with time as it reacts with the metal, and it will be higher far from the center depending on the efficiency of the cooling. Variation in the hydrogen density profiles against radius at different times are plotted in Figure 4.4. The results in this graph support the same finding of Figure 4.3. The cooling process results is represented in Figures 4.5 and 4.6. Figure 4.5 presents the change in temperature against time with different positions on the storage radius. Figure 4.6 introduces the variation in temperature against radius at different times. These figures indicate that the cooling process is working perfectly as it reaches the steady state quickly and keep the storage at low temperature.

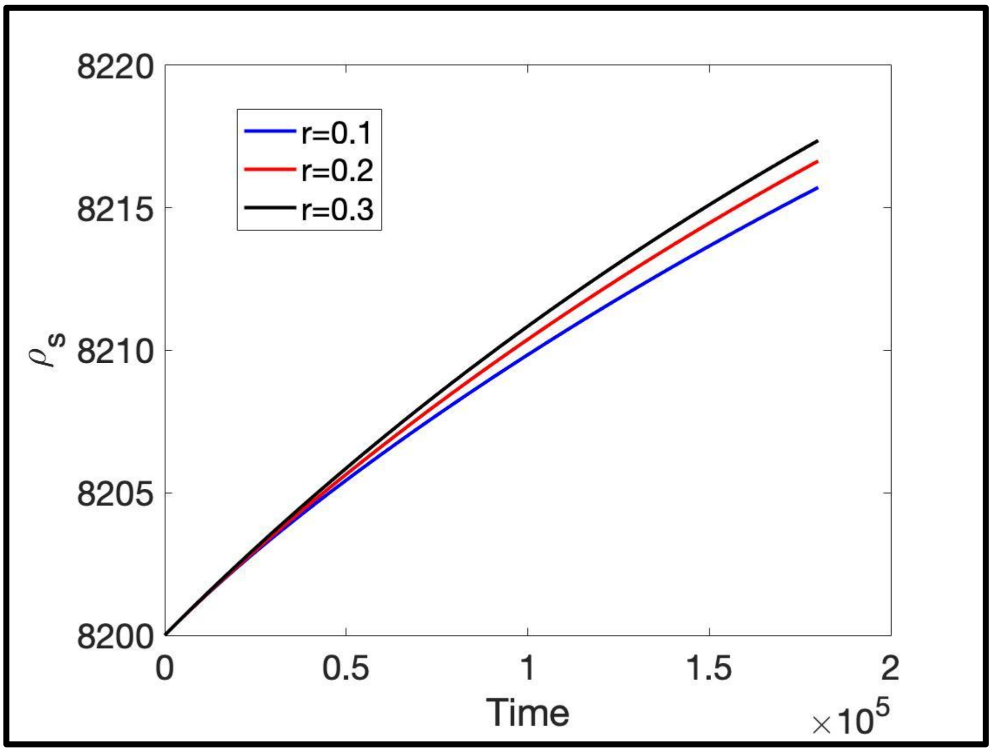

Figure 4.1: Variation in the hydride density against time with different positions on the storage radius.

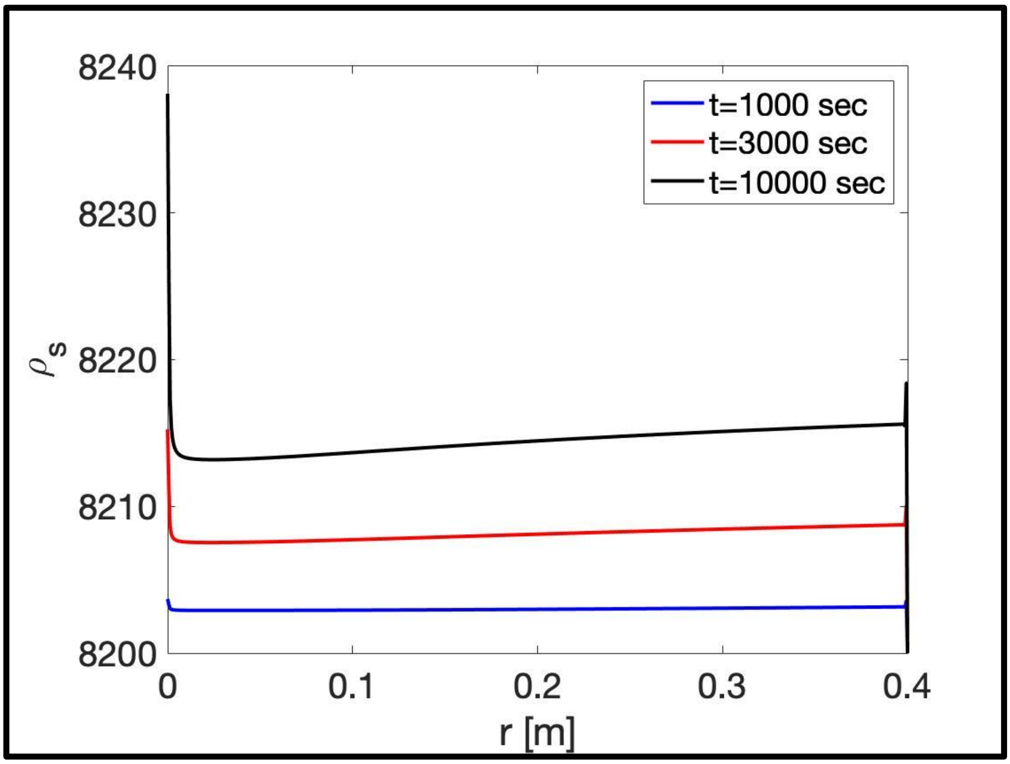

Figure 4.2: Variation in the hydride density against radius at different times.

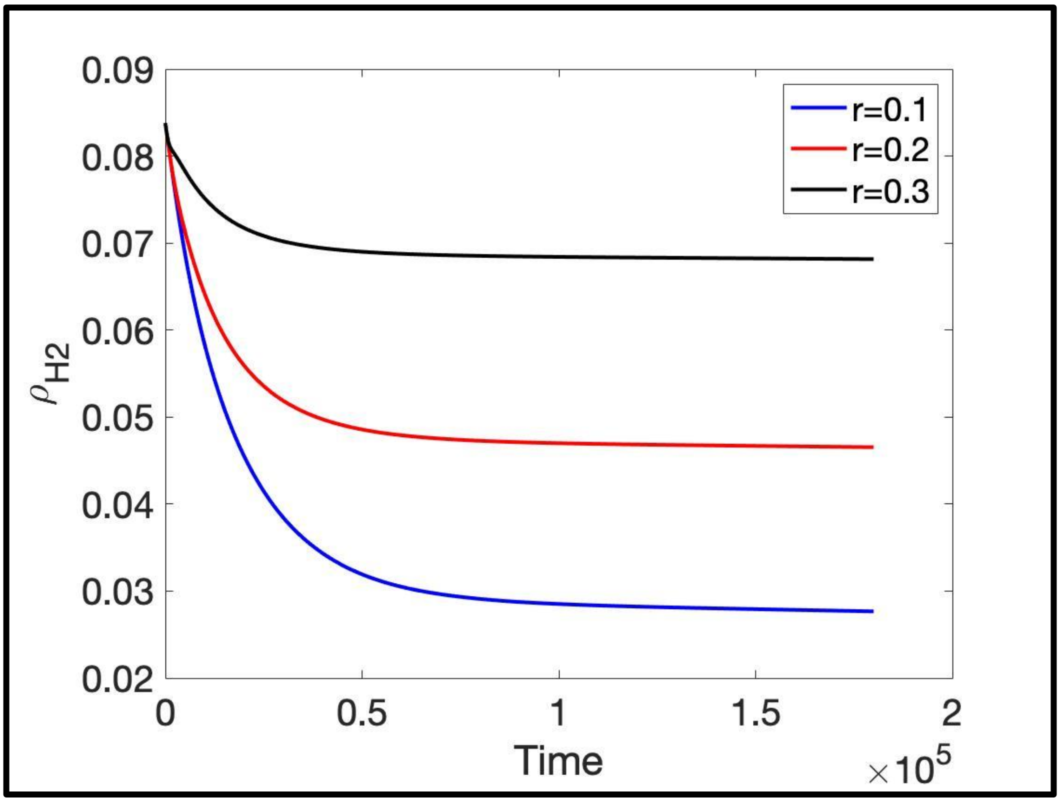

Figure 4.3: Variation in the hydrogen density against time with different positions on the storage radius.

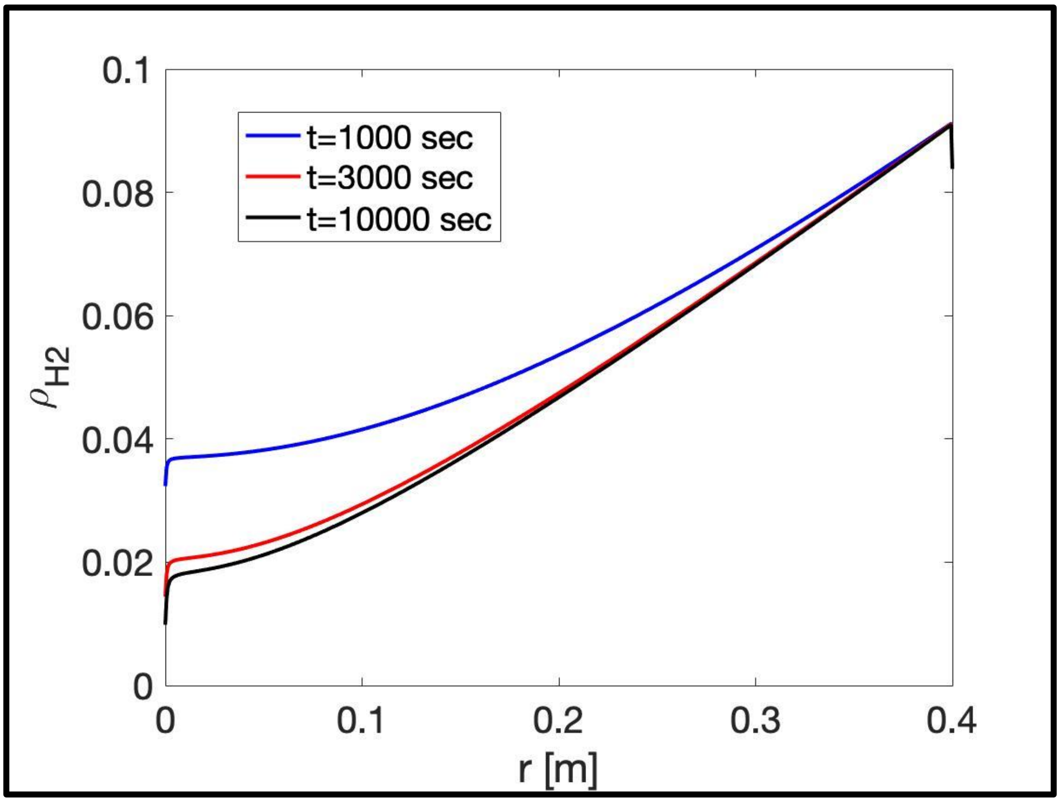

Figure 4.4: Variation in the hydrogen density against radius at different times.

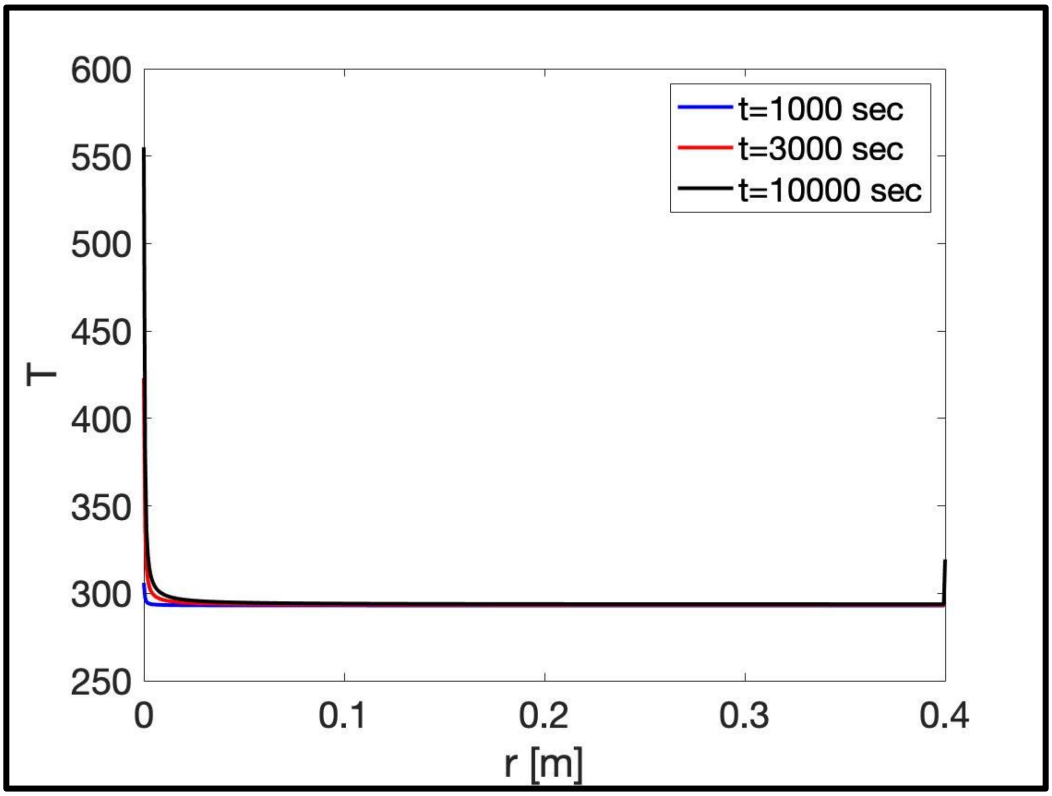

Figure 4.5: Variation in temperature against time with different positions on the storage radius

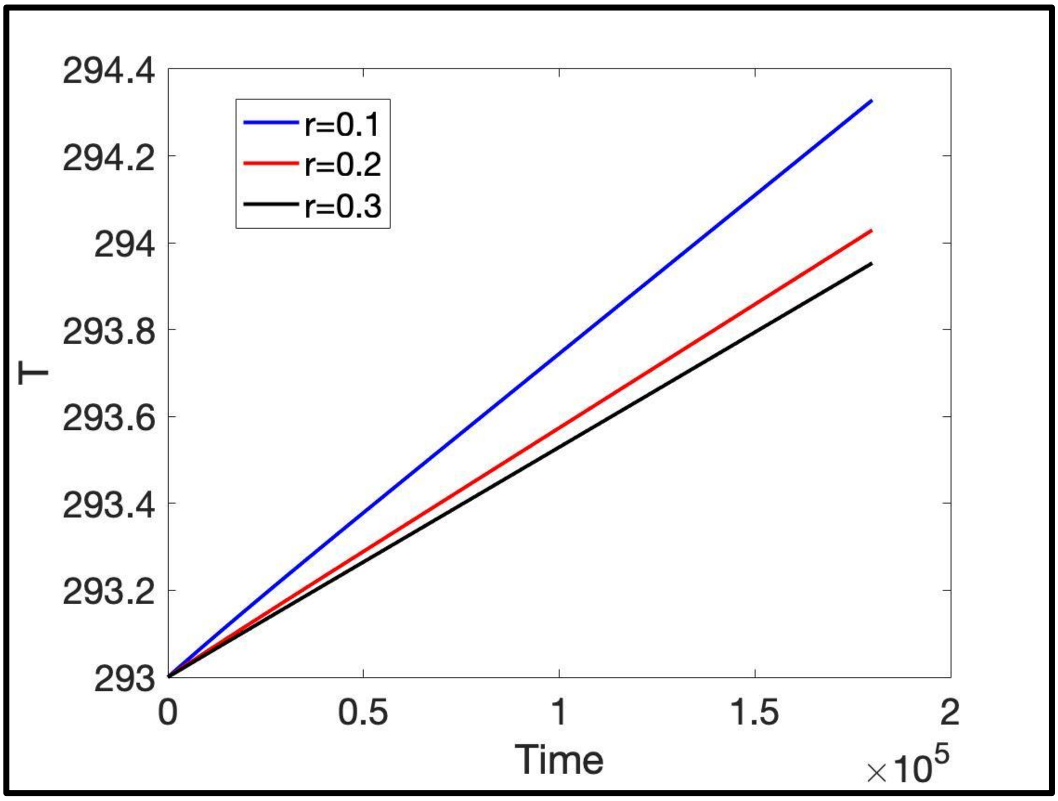

Figure 4.6: Variation in temperature against radius at different times

4.3. Techno-Economic Results

a) Results

According to Tables.16 and 17, the system without hydrogen storage, produces 54,815,952 kWh of annual energy in the first year, with an energy yield of 1,827 kWh/kW. In contrast, the system with hydrogen storage has 60,697,240 kWh of yearly energy in the first year, with an energy yield of 1,971 kWh/kW. As a result, when we compare production costs, the second project outcome is higher.

Furthermore, as shown in Tables 16 and 17, the first without hydrogen storage will sell energy at 5.00 $/kWh for a capital cost of $33,402,842. Still, Project Two with Hydrogen Storage will sell power at 10.54 $/kWh for a capital cost of $62,140,600. As a result, when we evaluate the project from the perspective of the clients and the cost of insulation, the task becomes more appealing.

Also, as indicated in Tables 16 and 17, the project without hydrogen storage has a net present value of $2,014,911. However, the project with hydrogen storage has a net current value of $6,887,662. As a result, the second project incorporates the time value of money from the supplied value.

Similarly, as shown in Tables. 16 and 17, the project without hydrogen storage estimates the profitability of prospective investments at 8.01%, with a year of completion at the end of year 10. While the project with hydrogen storage estimates a possible investment return at 10% and the year of completion at the end of year 8. As a result, from the investor's perspective, project two will earn more money.

Table 16: The system without hydrogen storage

Annual energy (year1)	54,815,952KWh
DC capacity factor (year1)	20.9%
Energy yield	1,827 KWh/KW
Performance ratio (year1)	0.79
PPA price (year1)	5.00 Euro/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	5.40 Euro/kWh
Levelized PPA price (real)	4.31 Euro/kWh
Levelized COE (nominal)	5.01 Euro/kWh
Levelized COE (real)	4.00Euro/kWh

Net present value	$2,014,911
Internal rate of return (IRR)	8.01%
Year IRR is archived	10
IRR at end of the project	13.12%
Net Capital cost	$33,402,842
Equity	$13,409,554
Size of debt	$19,993,288
Debt percent	59,86%

Table 17: The system with hydrogen storage

Annual energy (year1)	60,697,240KWh
DC capacity factor (year1)	22.9%
Energy yield	1,971 KWh/KW
Performance ratio (year1)	0.79
Battery roundtrip efficiency	100.00%
Thermal bill without system (year1)	$-0
Thermal bill with system (year1)	$-0
Net thermal savings with system (year1)	$0
PPA price (year1)	10.54 Euro/kWh
PPA price escalation	1.00%/year
Levelized PPA price (nominal)	11.27 Euro/kWh
Levelized PPA price (real)	9.27 Euro/kWh
Levelized COE (nominal)	9.95 Euro/kWh
Levelized COE (real)	8.18 Euro/kWh
Net present value	$6,887,662
Internal rate of return (IRR)	10.00%
Year IRR is archived	8
IRR at end of the project	19.21%
Net Capital cost	$62,140,600
Equity	$6,935,462
Size of debt	$55,205,140
Debt percent	88.84%

b) Cash Flow

Besides, as shown in Figures 4.7 and 4.8, the cash flow of the project without hydrogen storage is balanced at the end of year 10, whereas the cash flow of the project is suspended at the end of year 8. As a result, the cash flow of the second project is more attractive even when we see a double capital cost.

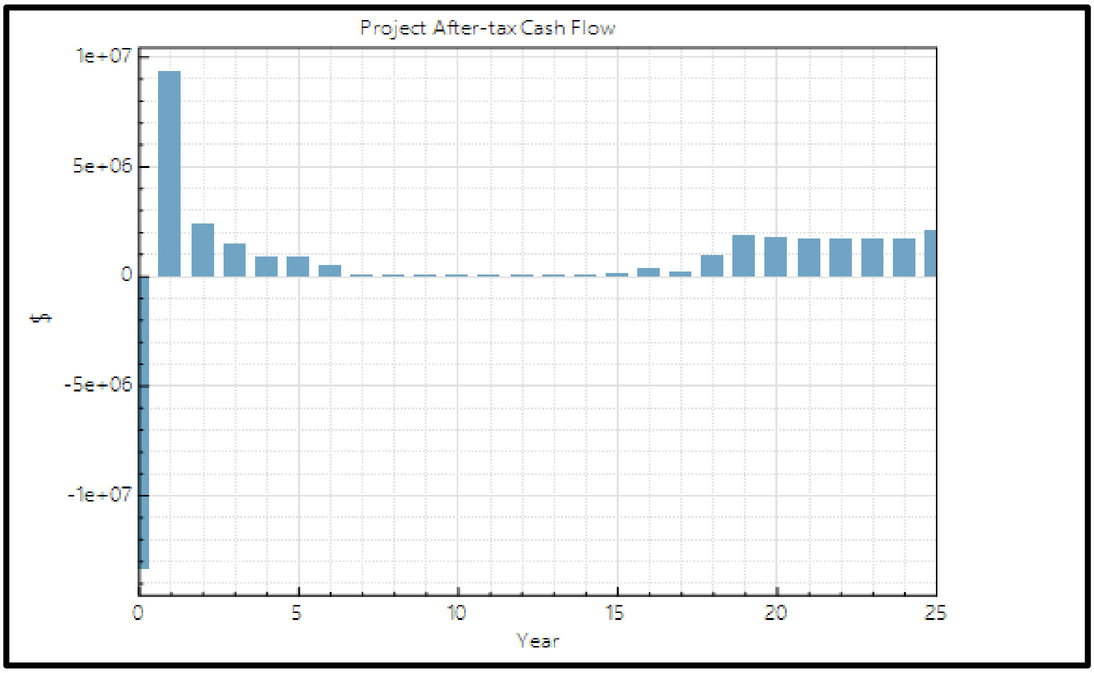

Figure 4.7: The cash flow for system without Hydrogen Storage.

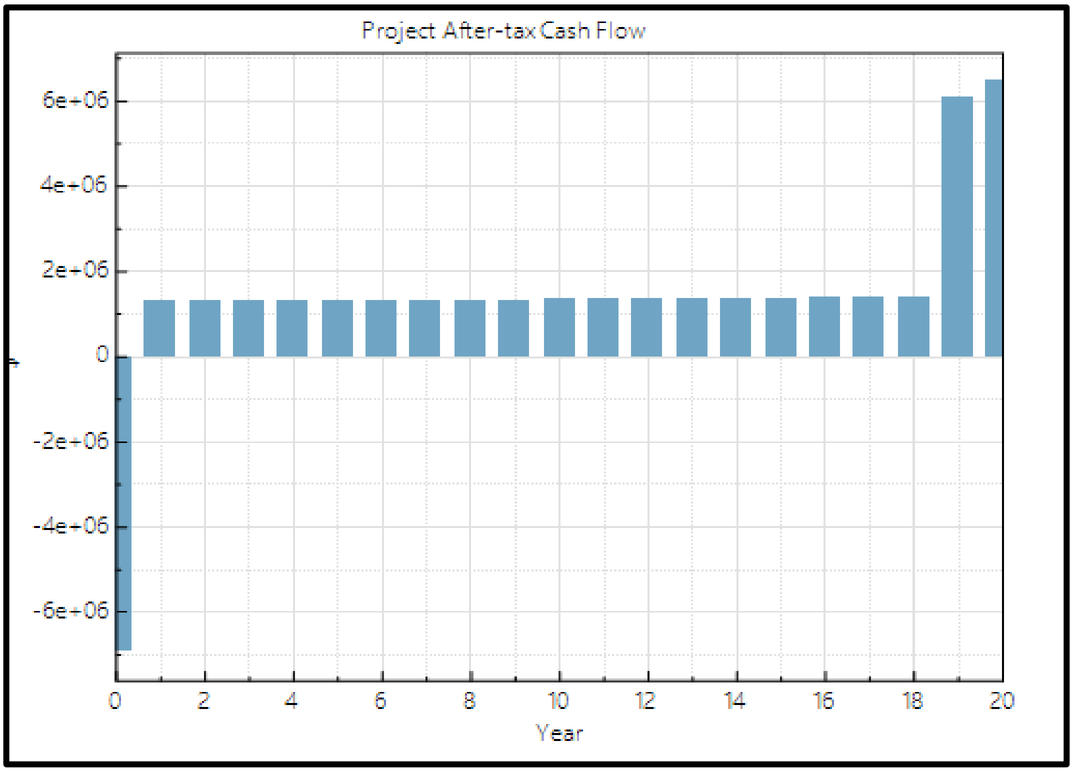

Figure 4.8: The cash flow for system with Hydrogen Storage.

c) The net electricity to grid for PV plant

Figure 4.9 shows the heat map based on the year's season. The x-axis represents the time on days while y-axis in the daily hours. The system generates the amount of power (in KW) over a year (365 days). The system developed a maximum of 24,393.6 KW after 50 to 125 days. The system starts to create electricity between 8 AM and 2 PM hours, with the peak hour around 11 AM.

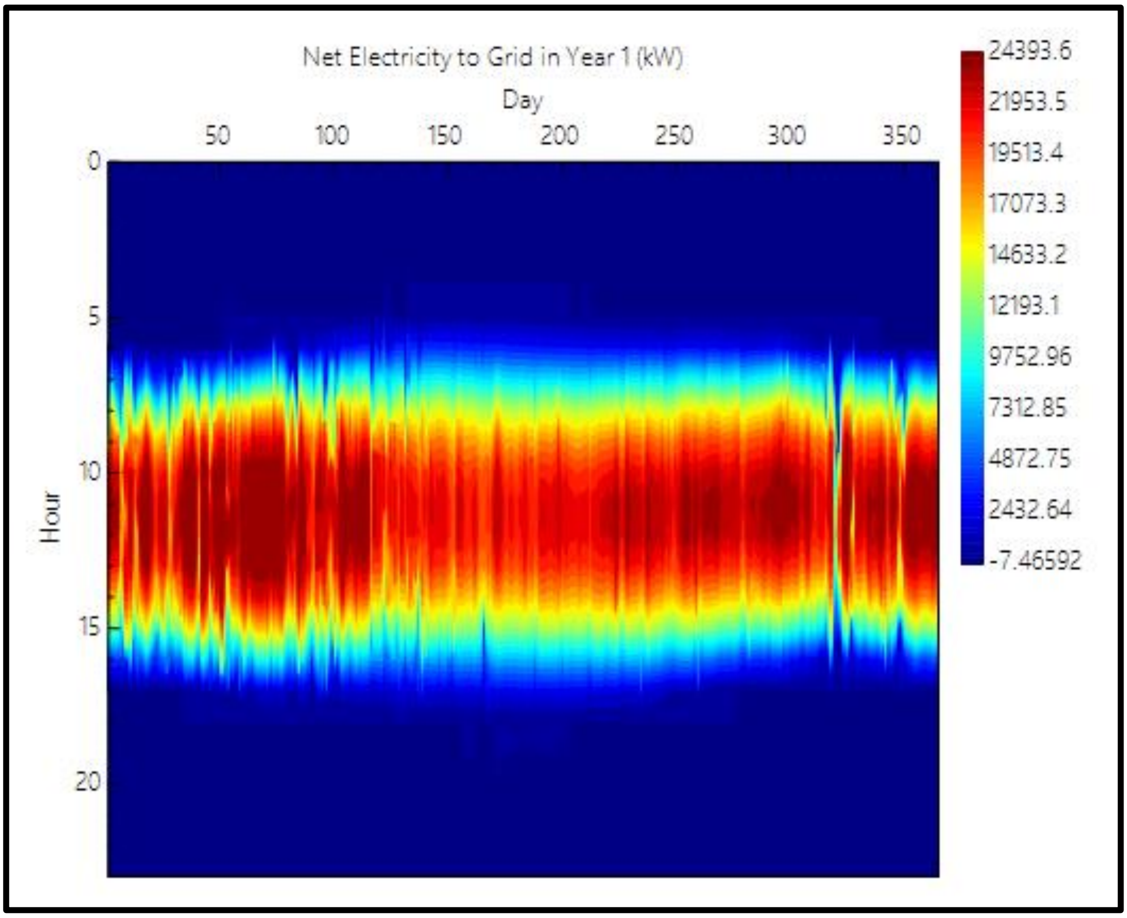

Figure 4.9: The net electricity to grid.

Chapter Five: Conclusion and Recommendations

5.1. Conclusion

The thesis research focuses on hydrogen storage to be included in a sustainable, friendly environment grid system. The grid's fixed photovoltaic (PV) plant capacity is assumed to be 30 MW per year. The hydrogen production and the legislative framework need to define commercial deployment models explicitly. More technology advancements are expected to minimize extraction, storage, and transportation costs and more investment in the infrastructure supporting Neom city. Hydrogen storage could provide a fully clean store with high energy density. The assumption involves the hydrogen storage tank to store the remaining solar energy from the plant to limit CO_2 emission based on the "2030" vision. Identifying the heat and mass transfer to and from the metal hydride reactor bed is critical in the storage process. So, the mathematical model has been developed to simulate a metal hydride hydrogen storage. Moreover, a techno-economic study of adding hydrogen storage in a photovoltaic (PV) plant has been presented. The techno-economic study including payback period (PP), intern rate of return (IRR), and other financial parameters has been presented using the system advisor model (SAM). The following conclusions are drawn from metal hydride hydrogen storage and the techno-economic study:

- The metal hydride hydrogen storage has been modelled and simulated successfully.
- The changes in hydride density over time increased the metal density.
- The hydrogen storage capacity reduces with time as it reacts with the metal, and it affected by the cooling efficiency.
- The techno-economic study of PV plant has been calculated successfully by using the System Advisor Model (SAM).
- The estimates of the PV plant with hydrogen storage intern rate of return at 10% and the year of completion at the end of year 8, which is considered relatively good.
- The net present value of the PV plant with hydrogen storage is considered \$6,887,662, which means more time value of money from the supplied value.

- Despite the techno-economic assessment in this thesis being limited to a PV plant with a total capacity of 30 MW on-grid, it is straightforward to extend the capacity of the store and the analysis to other plants for further exploration.

5.2.Recommendations

This study revealed the importance of green hydrogen storage when integrated with the PV plant as in the case of Neom city based on Saudi Arabia's vision 2030. The following recommendations are hereby may be considered:

1. Implementation and expand the mathematical modeling and simulation to investigate mass and heat transfer inside the hydrogen storage including hydrating and dehydriding processes to achieve completion and prevent hydride bed meltdown.
2. Improved heat transmission inside the tank during the fueling process can reduce the need for further compression effort.
3. Since the financial results show that PV plants with hydrogen storage have higher outcomes than without hydrogen, the builders of renewable energy projects should involve hydrogen storage.

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Appendices

Appendix A.

IEOM Society International

The 3rd African International Conference on

Industrial Engineering and Operations Management

Nsukka, Nigeria, April 5-7, 2022, Host: University of Nigeria, Nsukka

Certificate of Presentation

Mashael A. Rajeh and Mohamed F. El-Amin

College of Engineering Effat University, Jeddah, Saudi Arabia.

Delivered an Oral Presentation entitled "ID 144 Techno-Economic Study of Adding Hydrogen Storage to PV Plant in Neom City." at the 3rd African International Industrial Engineering and Operations Management Conference Virtually via Zoom.

Engr. Dr. Paul A. Ozor
Conference Chair, 2022 Nigeria
Head, Department of Mechanical Engineering, University of Nigeria Nsukka

Ahad Ali, Ph.D.
Conference Chair, 2022 Nigeria
Executive Director – IEOM Society
Associate Professor and Director of Industrial Engineering Program
Lawrence Technological University, Southfield, Michigan, USA

Professor Donald M. Reimer
Conference Program Chair, 2022 Nigeria
Director of Membership and Chapter Development – IEOM Society International
Adjunct Faculty – Lawrence Tech University
Southfield, Michigan, USA

Sponsors and Partners

Appendix B.

System Advisor Model Report

Detailed Photovoltaic	30.0 DC MW Nameplate	24.65, 46.7
Single Owner	$1.03/W Installed Cost	UTC +3

Performance Model

Modules	
Jinko Solar Co._ Ltd JKMS395M-72L-V-MX3	
Cell material	Mono-c-Si
Module area	1.92 m²
Module capacity	395.37 DC Watts
Quantity	75,872
Total capacity	30 DC MW
Total area	145,674 m²

Inverters	
SMA America: SC750CP-US (with ABB EcoDry Ultra trans	
Unit capacity	770 AC kW
Input voltage	545 - 820 VDC DC V
Quantity	32
Total capacity	24.64 AC MW
DC to AC Capacity Ratio	1.22
AC losses (%)	1.00

Array	
Strings	4,742
Modules per string	16
String Voc (DC V)	792.00
Tilt (deg from horizontal)	25.00
Azimuth (deg E of N)	180
Tracking	no
Backtracking	-
Self shading	no
Rotation limit (deg)	-
Shading	no
Snow	no
Soiling	yes
DC losses (%)	2.49

Performance Adjustments	
Availability/Curtailment	none
Degradation	none
Hourly or custom losses	none

Annual Results (in Year 1)	
GHI kWh/m²/day	5.88
POA kWh/m²/day	147.00
Net to inverter	56,992,000 DC kWh
Net to grid	54,810,000 AC kWh
Capacity factor	20.9
Performance ratio	0.79

Financial Model

Project Costs	
Total installed cost	$30,826,793
Salvage value	$0

Analysis Parameters	
Project life	25 years
Inflation rate	2.5%
Real discount rate	6.4%

Financial Targets and Constraints	
Solution mode	Calculate IRR
PPA price (bid price)	4 cents/kWh
PPA escalation rate	1 %/year

Tax and Insurance Rates	
Federal income tax	21 %/year
State income tax	7 %/year
Sales tax (% of indirect cost basis)	5%
Insurance (% of installed cost)	0 %/year
Property tax (% of assessed val.)	0 %/year

Incentives	
Federal ITC	26%
Depreciation	Depreciation allocations defined with no bounus depreciation

Results	
Nominal LCOE	5.1 cents/kWh
PPA price (year one)	4 cents/kWh
Project IRR	0.6% in Year 20
Project NPV	$-4,030,800

Figure. Report for PV plant without hydrogen storage.

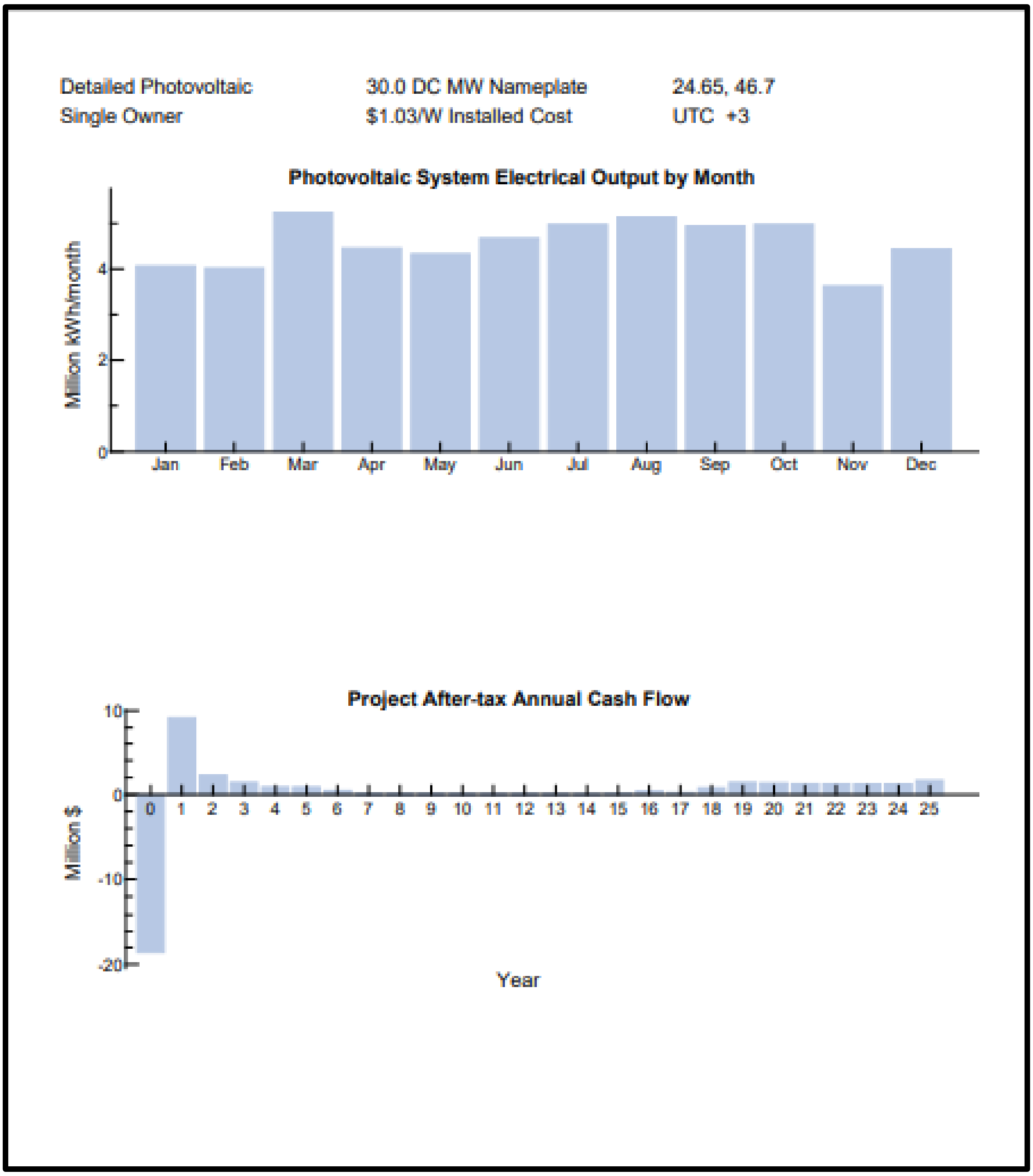

Figure. For PV plant without hydrogen storage.

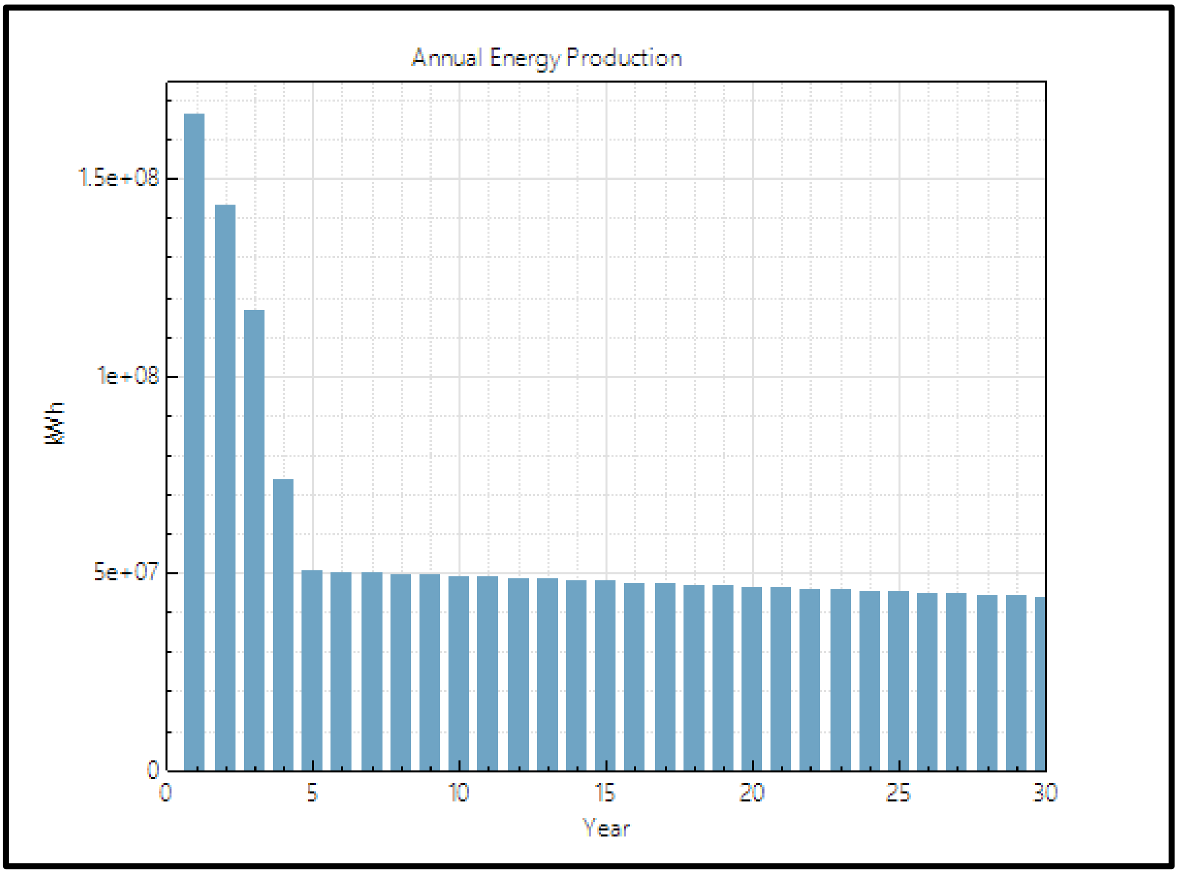

Figure. For annual energy production without hydrogen storage.