Techno-economic feasibility study of residential hydrogen fuel cells compared to solar PV systems in South Africa

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ABSTRACT

This study critically examines the techno-economic feasibility of residential hydrogen fuel cell systems in South Africa, comparing their viability against solar Photovoltaic (PV) systems. Drawing on the strategic insights of Japan's Panasonic Ene-Farm program, this research employs a quantitative modelling approach, integrating a Fermi estimate framework with mass-energy balance calculations and scenario-based sensitivity analysis. The objective is to elucidate the Total Cost of Ownership (TCO) of hydrogen fuel cells within the South African residential energy landscape, accounting for technological, economic, and policy-driven variables.

The findings reveal that while the Ene-Farm system demonstrates high thermodynamic efficiency through combined electricity generation and heat recovery, its economic sustainability is constrained by a high TCO and dependence on methane as a feedstock. In contrast, solar PV systems, characterized by lower capital costs, zero fuel dependency, and extended operational lifespans, emerge as a more economically viable and scalable alternative. Even under optimistic subsidy scenarios modelled on Japan's policy interventions, hydrogen fuel cells remain significantly less competitive than solar PV, which consistently exhibits a lower cost per unit of energy generated.

This study contributes to the broader discourse on residential energy transitions by providing a comparative analysis of two alternative energy pathways. The results highlight key techno-economic considerations for future energy planning in South Africa, where policy frameworks, financial mechanisms, and infrastructure readiness will influence the viability of different technologies. While solar PV presents a compelling case for cost-effectiveness and scalability, hydrogen fuel cells may find application in niche scenarios where their combined heat and power capability provides additional value. These insights offer a data-driven perspective for stakeholders evaluating long-term energy strategies in alignment with South Africa's broader sustainability objectives.

KEY WORDS – Hydrogen fuel cells, Total Cost of Ownership, Ene-Farm, South Africa, Solar PV, Techno-economic feasibility, Energy transition, Fermi estimate, Scenario analysis.

DECLARATION

I, Linina Bedhesi, declare that this research report is my own work except as indicated in the references and acknowledgements. It is submitted in partial fulfilment of the requirements for the degree of Master of Management in Energy Leadership at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in this or any other university.

Name: Linina Bedhesi Signature:

Signed at ……Pretoria…………..

On the ……28………………………. day of ……February……………… 2025….

DEDICATION

I dedicate this work to my beloved husband, Nashvir, and our two wonderful sons, Aarav and Kiaan. Your love and support illuminate my life, and I am forever grateful for the light you bring into my journey.

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With profound reverence and devotion, I offer my deepest gratitude to **Mahadev**, the Supreme Destroyer of obstacles and the Eternal Source of wisdom and strength. Through His divine grace, I have found the resilience, strength, and perseverance needed to navigate this journey. Aum Namah Shivaya! Har Har Mahadev!

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To my beautiful boys: Aarav, thank you for understanding when Mum had to focus on her studies, and baby Kiaan, who grew inside me while I attended lectures—this journey has been as much yours as it has been mine.

To my beloved parents in heaven, I carry your love, lessons, and strength in my heart every day. Though you are no longer here, your guidance and unwavering belief in me continue to inspire and uplift me. I dedicate this achievement to you, knowing that you are watching over me with pride.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS AND ABBREVIATIONS

- BRICS: Brazil, Russia, India, China and South Africa
- CHP: Combined Heat and Power
- CO_2: Carbon Dioxide
- DC: Direct Current
- DSI: Department of Science and Innovation
- DST: Department of Science and Technology
- Ene-Farm: Energy Farm (Japanese Residential Hydrogen Fuel Cell Program)
- EU: European Union
- GHG: Greenhouse Gas
- HFCT: Hydrogen Fuel Cell Technology
- HySA: Hydrogen South Africa
- IEA: International Energy Agency
- LHV: Lower Heating Value
- LPG: Liquefied Petroleum Gas
- METI: Ministry of Economy, Trade and Industry (Japan)
- $MtCO_2e$: Million Metric Tons of CO_2 equivalent
- NPV: Net Present Value

- PEMFC: Proton Exchange Membrane Fuel Cell
- PV: Photovoltaic
- ROI: Return On Investment
- SMR: Steam Methane Reforming
- SOFC: Solid Oxide Fuel Cell
- TCO: Total Cost of Ownership
- UNFCCC: United Nations Framework Convention on Climate Change
- US$: United States Dollar

CHAPTER 1. INTRODUCTION

1.1 Purpose of the Study

This study investigates the feasibility of hydrogen-based fuel cell energy storage systems in South Africa, with a focus on the technological and economic factors influencing their viability. As energy challenges persist, alternative storage solutions are being explored globally, with Japan's Ene-Farm program (Beciri, 2012) serving as a notable case study. This research evaluates whether similar approaches could be adapted within South Africa's unique energy landscape, considering key infrastructural, financial, and policy-related constraints.

To achieve this, the study employs a quantitative methodology, centred on calculating the Total Cost of Ownership (TCO) of the Panasonic Ene-Farm system within the South African context. The TCO facilitates a robust framework for assessing the long-term financial implications and viability of hydrogen fuel cell technology, compared to alternative off-grid energy systems, such as solar PV. This aligns with the broader goal of enabling informed decision-making for policymakers, businesses, and consumers in transitioning to sustainable energy solutions, while still addressing energy security concerns.

The study uses a Fermi estimate – a back-of-the-envelope calculation technique that combines readily available data with logical reasoning – to conduct a techno-economic analysis. This approach ensures that both technical performance and economic viability are rigorously evaluated. These methods are applied in Chapter 4 to validate key assumptions and present quantitative outcomes, comparing the performance of Ene-Farm systems to solar PV systems under South African conditions.

Additionally, this research examines Japan's Basic Hydrogen Strategy (Bocobza & Tanabe, 2023) and the success factors of the Ene-Farm cogeneration system, identifying how these factors can potentially inform South Africa's transition to sustainable residential energy. The comparative analysis quantifying the potential benefits and limitations of hydrogen-based solutions is presented in Chapter 4.

1.2 Context of the Study

With climate change accelerating due to rising greenhouse gas emissions, countries worldwide are ramping up efforts to curb their environmental impact. Under the Paris Agreement (UNFCCC, 2018), a global pact established in 2015 and ratified by 195 nations, governments have committed to keeping global temperature rise well below 2°C. Unlike the 1997 Kyoto Protocol, which placed more responsibility on developed nations, the Paris Agreement calls for a shared commitment to achieving net-zero emissions. As part of this global effort, South Africa has pledged to cut its greenhouse gas emissions to **"398-510 million metric tons of CO_2 equivalent ($MtCO_2e$)"** by 2025 and **"350-420 $MtCO_2e$"** by 2030 (UNFCCC, 2022), with an ultimate goal of reaching net-zero emissions by 2050 (Transparency, 2021).

The BRICS nations face a complex challenge: balancing economic growth with environmental sustainability while navigating carbon-heavy industries, limited clean energy access, and financial constraints. Shifting to a low-carbon economy requires massive investments in green technology, infrastructure, and workforce adaptation. However, the transition is not just technical – it carries social and economic implications, particularly for communities reliant on traditional industries.

In South Africa, these challenges are even more pressing. Energy insecurity and accessibility issues, worsened by persistent load-shedding ("Load Shedding," 2022), make renewable energy adoption particularly difficult. A stable and reliable power supply is critical for economic growth, yet the country remains heavily dependent on coal. While South Africa must address its immediate energy crisis, it also needs to invest in long-term sustainable solutions that align with its climate commitments. This means finding innovative energy strategies that balance short-term reliability with long-term sustainability.

One country that has made significant progress in hydrogen energy is Japan. Through strategic partnerships with companies like Tokyo Gas, Osaka Gas, Panasonic, and Toshiba, Japan has successfully integrated hydrogen into its national energy strategy (Makino, 2020). The Ene-Farm system, one of Japan's key innovations, has demonstrated high efficiency in residential fuel cell applications (Nishizaki, 2012). However, it is important to recognize that Ene-Farm currently relies on natural gas – a fossil fuel that produces CO_2 during reforming. While cleaner than coal, which emits around 0.34 kg CO_2 per kWh, natural gas still contributes to greenhouse gas emissions, making decarbonization dependent on a shift to green hydrogen. The long-term vision is to transition from natural gas to green hydrogen, allowing fuel cells to run on clean energy with no CO_2 emissions. While this is technically feasible, achieving it depends on hydrogen production advancements and cost reductions.

Ene-Farm Fuel Cell Systems

There are two main types of Ene-Farm fuel cell units: the Proton Exchange Membrane Fuel Cell (PEMFC) type and the Solid Oxide Fuel Cell (SOFC) type. This study will focus on the PEMFC type, which is based on several key factors that make it particularly suitable for residential settings (Ellamla, 2015):

1. **Operating Temperature:** PEMFC systems operate at a lower temperature (approximately 80°C), which enhances safety and practicality for home use,

compared to the higher operating temperatures of SOFC systems which run at 600 – 1 000°C and are better suited to industrial use.

2. **Start-Up Time:** PEMFC systems have a faster start-up time, making them more responsive to the fluctuating power demands typical in residential applications.

3. **Compact Design:** The compact nature of PEMFC systems facilitates easier installation and integration into an existing residential infrastructure.

4. **Efficiency:** PEMFC systems achieve an electrical efficiency of around 37 – 39%, with an overall efficiency (including heat recovery) of up to 90%, providing both electricity and heat for household use efficiently.

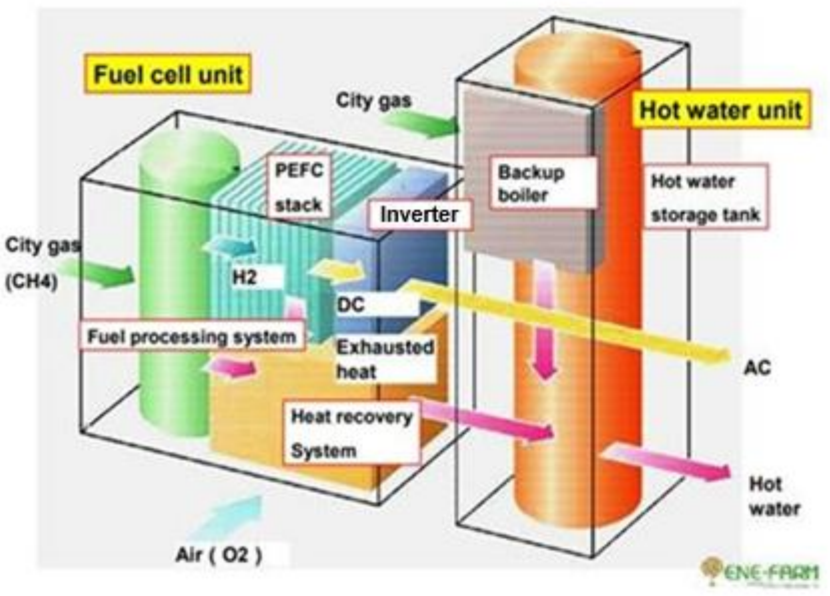

Figure 1: A Typical Proton Exchange Ene-Farm Fuel Cell (Simader & Vidovic, 2022)

Japan's dedication to hydrogen technology is a central component of its strategy to mitigate greenhouse gas emissions and move towards a sustainable energy future. Similarly, South Africa is initiating efforts to capitalise on the potential of hydrogen energy, as detailed in the South African Hydrogen Society Roadmap (DSI, 2021). This initiative reflects a strategic policy alignment with global trends towards clean and sustainable energy sources. The relevance of Japan's advancements in hydrogen technology to the South African context is found in the adaptability and applicability of these innovations in addressing local energy challenges. By examining Japan's policy development approach, infrastructure investment, and technological innovation in hydrogen energy, South Africa can identify best practices and potential pitfalls in establishing its own hydrogen economy.

This study further aims to serve as a learning model for South Africa by identifying and analysing gaps in existing research. In terms of addressing climate change, it is crucial to understand the implications of these technologies. While a solar PV system generates no CO_2 during operation, the issue with hydrogen fuel cells depends on the production method. If the hydrogen is produced from natural gas (grey hydrogen), it is not carbon-neutral, due to CO_2 emissions during the reforming process. However, the presumption for this work, as mentioned previously, and based on the "South African Hydrogen Society Roadmap" (DSI, 2021), is that green hydrogen might become more available in the future, which could make hydrogen fuel cells a viable and sustainable energy solution.

Hydrogen fuel cell systems, even when currently using natural gas as a primary energy source, can provide advantages over solar PV systems in specific scenarios within the South African context. Several factors justify this investigation:

1. **Energy Density and Storage (Falama *et al*, 2023):** Hydrogen fuel cells offer higher energy density as well as more reliable storage capabilities, when

compared to batteries used with solar PV systems. This can be particularly advantageous in situations where energy storage and consistency of supply are critical.

2. **High-Density Living Environments:** In urban areas with high-density housing, such as apartment blocks, there may be insufficient roof space to install enough solar PV panels to meet the energy demands of all residents. Hydrogen fuel cells can be a more compact and scalable solution for providing both electricity and heating in such environments.

3. **Backup Power:** Hydrogen fuel cells can provide continuous power generation, even during periods of low sunlight or power outages (U.S. Department of Energy, 2024). It thus offers a more reliable backup power solution compared to solar PV systems, which depend on battery storage that might not be sufficient for extended outages.

4. **Heat Generation:** Hydrogen fuel cells produce both electricity and heat (Simader & Vidovic, 2022), which can be utilized for residential heating needs. This Combined Heat and Power (CHP) capability increases overall system efficiency and can reduce the need for separate heating systems, which is especially beneficial in colder seasons.

5. **Infrastructure and Transition:** Implementing hydrogen fuel cells, using natural gas as a transitional step, allows for the gradual development and deployment of hydrogen infrastructure. As green hydrogen production becomes more feasible and widespread, these systems can transition to using green hydrogen, thereby achieving greater sustainability in the long-term.

This study further aims to serve as a learning model for South Africa by identifying and analysing gaps in existing research, such as the economics centred around stationary hydrogen fuel cell adoption, and exploring how Japan's journey towards a hydrogen society can inform South African strategies for a sustainable energy transition. This context sets the stage for a comprehensive exploration of the potential for hydrogen fuel cell technology in South Africa, highlighting the need for a nuanced approach that considers both the socio-economic and environmental challenges unique to transitioning economies.

1.3 Research Problem

South Africa faces a dual challenge of mitigating greenhouse gas emissions and addressing persistent energy insecurity. While the country has committed to achieving net-zero carbon emissions by 2050, it remains heavily reliant on coal for energy generation, contributing significantly to global greenhouse gas emissions. Frequent load-shedding, inadequate infrastructure, and limited access to clean energy solutions exacerbate the need for reliable and sustainable energy alternatives.

Hydrogen-based fuel cell systems, such as Japan's Ene-Farm program, have demonstrated the potential to address such challenges by offering decentralized and efficient energy solutions. However, the economic feasibility, technical performance, and infrastructure requirements for deploying such systems in South Africa remain largely unexplored. Unlike Japan, South Africa lacks a well-developed natural gas and hydrogen infrastructure, and its socio-economic conditions differ significantly, raising questions about the practicality and scalability of hydrogen fuel cells in the residential sector.

This research addresses these uncertainties by assessing the techno-economic feasibility of hydrogen fuel cell systems within the South African residential context. By leveraging insights from Japan's Ene-Farm program and conducting a comparative analysis with solar PV systems, the study evaluates whether hydrogen fuel cells can serve as a viable alternative to meet South Africa's energy demands while aligning with its sustainability goals.

1.4 Research Objectives

The objectives of this study are delineated as follows:

- To develop a dynamic Fermi estimate model for evaluating the economic feasibility of hydrogen fuel cell technologies in the South African residential context, particularly in urban apartment environments.

- To analyse the technological advancements and key success factors of Japan's Ene-Farm hydrogen fuel cell program, identifying elements that contributed to its adoption and market penetration.

- To compare the Total Cost of Ownership (TCO) of Ene-Farm hydrogen fuel cell systems with solar PV systems in South Africa, considering varying usage scenarios.

- To conduct a sensitivity analysis of key variables, such as fuel costs, efficiency rates, and economic incentives, to determine their impact on the economic viability of hydrogen fuel cell systems.

1.5 Significance of the Study

This research addresses critical knowledge gaps in hydrogen fuel cell technology adoption within South Africa. By comparing Japan's advancements with South Africa's energy landscape, the study identifies best practices and potential challenges for integrating hydrogen energy systems. This approach yields novel insights into the adaptation of hydrogen technologies, thereby offering a solid foundation for policy modifications and strategic investment planning. Such efforts are aimed at promoting an environment conducive to the development of the hydrogen economy (IEA, 2023a).

This work also seeks to analyse the socio-economic benefits of leveraging hydrogen fuel cell technology. As it stands, hydrogen holds the potential of providing energy with less (turquoise hydrogen/grey hydrogen) or no carbon emission (green hydrogen) (Kovač *et al*., 2021) as compared to coal, and is seen as a promising solution to environmental stewardship. Apart from this, the transition to hydrogen energy is particularly significant for rural and underserved areas, offering a path to reliable, off-grid energy access (Mandelli *et al*., 2016). By enabling rural electrification, hydrogen technology can potentially support educational opportunities, healthcare improvements, and agricultural advancements, thereby reducing inequalities and promoting social cohesion. While this study focuses on an urban residential case (i.e., a Johannesburg apartment), the insights into system scalability, energy reliability, and fuel infrastructure provide a foundation for assessing potential rural applications in future research.

Furthermore, this research introduces methodological innovations, particularly through the development of a dynamic Fermi estimate model. This innovative approach facilitates a detailed and nuanced examination of the economic dimensions of hydrogen fuel cell technologies in South Africa. The study enhances the comprehensive understanding of the financial dynamics associated with hydrogen fuel cell technology, addressing a notable gap in the existing knowledge within the South African context.

One critical area that this research explores, is the potential advantages of hydrogen fuel cells over solar PV in high-density living environments. According to a 2021 paper in Renewable and Sustainable Energy Reviews (Yue, 2021), hydrogen has significant potential for scaling up renewable energy, but its integration into power systems remains under-researched. Hydrogen fuel cells offer higher energy density and more reliable storage than solar PV batteries (Falama *et al*., 2023), making them ideal for urban areas with limited roof space. They provide a compact solution for electricity and heating and offer continuous power generation during low sunlight.

The long-term implications of this study extend beyond immediate policy and economic considerations, projecting a vision for a sustainable and resilient national energy system that aligns with South Africa's commitments under the Paris Agreement and its broader ambitions for a net-zero future. This work is also significant in addressing some of the strategic goals highlighted in South Africa's National Hydrogen and Fuel Cell Technologies Research, Development and Innovation Strategy (DST, 2007).

1.6 Delimitations of the Study

Hydrogen Fuel Cell Technology feasibility studies are multi-faceted in their own respect. The focus of this work is limited to a comparative study of techno-economic costs. The boundaries of this research are discussed below.

i. **Geographical Scope:** This study is delimited to South Africa. While global advancements and strategies, particularly Japan's hydrogen strategy, are considered for comparative analysis, the primary focus is on the application and implications within the South African context. Other countries' hydrogen strategies and implementations are outside the scope of this study.

ii. **Technology Focus:** The scope of this research is limited to hydrogen-based fuel cell energy storage systems, focusing specifically on Proton Exchange Membrane Fuel Cell (PEMFC) technology. A key limitation of this study is the current reliance on natural gas as a fuel source for PEMFC systems. While natural gas provides a transitional step, it is not carbon-neutral, and the ultimate goal is to transition to green hydrogen to fully realize the environmental benefits. This study targets the potential applicability of PEMFC technology in the South African residential sector, especially in high-density urban areas with limited roof space for solar panels and where reliable backup power during outages is critical.

iii. **Sector of Application:** The study is delimited to the residential energy sector in South Africa. The potential applications of hydrogen fuel cells in commercial, industrial, or transportation sectors are not within the scope of this research. The focus is specifically on the integration and economic feasibility of hydrogen fuel cells in residential settings.

iv. **Economic Analysis Methodology:** The economic feasibility assessment will primarily utilize a quantitative Fermi estimate model. While other economic assessment methodologies, such as cost-benefit analysis, life-cycle cost analysis, or payback period analysis, might be mentioned for context, they will not be applied in-depth in this study. The choice of the Fermi estimate is a delimitation to provide a focused and specific analysis of cost variables affecting hydrogen fuel cells in South Africa.

v. **Temporal Scope:** This study is delimited to analysing current data and strategies, particularly those outlined in the Hydrogen Society Roadmap of South Africa (DSI, 2021) and Japan's Basic Hydrogen Strategy (Ministerial Council on Renewable Energy, Hydrogen and Related Issues, 2017). Future projections and scenarios will be based on current data; however, long-term predictions beyond a 10-year horizon are outside the scope of this study.

vi. **Policy Analysis:** While policy implications are considered, especially in the context of Japan's policy framework and its relevance to South Africa, a comprehensive analysis of all relevant policies, regulations, and legislation affecting hydrogen fuel cell technology adoption in South Africa is not included. The study will focus on major policies as they relate to the economic feasibility and implementation strategy of hydrogen fuel cells.

vii. **Stakeholder Focus:** This research will primarily consider the perspective of policymakers, technology providers (for example, companies like Panasonic for Ene-Farm and Osaka gas), and residential energy users. While other stakeholders such as governments, environmental agencies, and commercial businesses are crucial to the broader hydrogen economy, their perspectives will be referenced only as they impact the main focus areas of the study. Detailed stakeholder analyses involving these other groups are delimited out.

This research establishes a targeted exploration of the economic feasibility of hydrogen fuel cell technology within the South African residential sector, leveraging a comparative analysis with Japan's pioneering strategies. By setting deliberate boundaries around the factors mentioned above, this study aims to carve out a niche that address specific gaps in the current body of knowledge.

1.7 Definition of Terms

Total Cost of Ownership (TCO): A thorough assessment of all costs related to purchasing, operating, and maintaining a product or system throughout its entire lifecycle. In this research, TCO encompasses the initial purchase price, installation fees, operational costs, maintenance expenses, and any other associated costs.

Fermi Estimate: A technique for estimating the size of a quantity, based on educated guesses and simple calculations, often used when precise data is unavailable. This research employs Fermi estimates to approximate the costs associated with adopting hydrogen fuel cell energy systems in South Africa.

Techno-Economic Analysis: An evaluation method that considers both the technical performance and economic viability of a technology or system. This analysis helps in understanding whether a technology is feasible and cost-effective.

Hydrogen Fuel Cell: A device that generates electricity by converting chemical energy from hydrogen through a reaction with oxygen, resulting in water and heat as the only by-products. Hydrogen fuel cells are employed in numerous applications, such as residential energy storage and power generation.

Ene-Farm Program: A Japanese initiative promoting the use of residential hydrogen fuel cells, specifically the Ene-Farm system, which is designed for cogeneration of heat and electricity in homes. The program aims to enhance energy efficiency and sustainability.

Photovoltaic (PV) System: A solar power system that converts sunlight directly into electricity, using photovoltaic cells. These systems are often coupled with batteries for energy storage and inverters to convert the electricity from DC to AC for household use.

Lithium-Ion Battery: A type of rechargeable battery, commonly used for energy storage in solar PV systems.

Sensitivity Analysis: A method used to predict the outcome of a decision, given a certain range of variables. In this study, it identifies how different input parameters affect the economic viability of hydrogen fuel cell technologies.

Energy Security: The continuous access to energy resources at an affordable cost. In this context, it pertains to South Africa's capability to maintain a stable and dependable energy supply using alternative technologies.

Sustainability: The capacity to fulfil current energy requirements without jeopardizing the ability of future generations to meet their own needs. Sustainable energy solutions are environmentally friendly, economically viable, and socially acceptable.

1.8 Assumptions

The foundational premises of this investigation rest on several pivotal assumptions. These assumptions are integral to constructing the framework of this study, offering clarity on the groundwork that shapes the analysis and underpins the conclusions. To effectively assess the economic viability of deploying hydrogen-based fuel cell energy storage systems in South Africa—using Japan's strategic approach as a comparative reference—the following assumptions are made.

This study:

i. Assumes that the data from Japan's Ene-Farm program and South Africa's energy sector, for example cost data, is accurate and reliable, which is crucial for valid TCO calculations.

ii. Assumes that the technological performance of the Ene-Farm hydrogen fuel cell system observed in Japan can be replicated in South Africa. This assumes similar efficiency and effectiveness under South African conditions, without modifications to the system.

iii. Assumes that economic conditions, including energy prices and market dynamics, will remain relatively stable.

iv. Assumes that the current policy and regulatory frameworks will support the adoption of hydrogen fuel cell technologies. This follows the global trend towards sustainable energy solutions and is essential for feasibility.

v. Assumes that hydrogen fuel cells and solar PV systems can be fairly compared in terms of generation and storage capabilities. Ensuring a balanced evaluation of these technologies is critical for a meaningful analysis.

vi. Assumes that the residential sector in South Africa will be willing to adopt the Ene-Farm hydrogen fuel cell system if it proves economically viable and technically feasible.

vii. Assumes that the cost variables identified for the Fermi estimate are the most significant ones affecting the economic feasibility of hydrogen fuel cells in South Africa and that the estimation technique provides a reasonable approximation of real-world costs.

viii. Assumes that the Ene-Farm technological design in Japan as it is, is fit for purpose in South Africa.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter critically examines the potential adoption of small-scale stationary hydrogen fuel cells for residential use in South Africa. It focuses on a comparative assessment and economic viability, utilizing global studies and cases that have demonstrated the potential for such technology to achieve market diffusion. The structure of the review is organized around key sub-objectives or research questions that collectively explore both the technical innovations and economic implications of implementing such technologies, compared to existing solutions such as solar PV systems.

The review systematically investigates theoretical frameworks, major studies, and pivotal debates in this field, identifying gaps and areas needing further research. Each section will align with specific research objectives, gradually building towards a set of hypotheses that are directly informed by the findings discussed throughout this chapter. A consistency table matrix will be introduced at the end of the chapter to explicitly connect these hypotheses with the review's overarching research questions.

2.2 Background and Global Context

2.2.1 *The role of hydrogen in the energy transition*

Hassan *et al*. (2024) highlighted that the global energy landscape is undergoing a transformative shift, with hydrogen emerging as a key player in sustainable energy solutions. While this transition is still in progress, substantial investments and research efforts are exploring hydrogen's role alongside direct renewable energy use. Rather than competing with other renewable technologies, hydrogen is increasingly viewed as a complementary solution, particularly in energy storage, transportation, and heavy industry, where direct renewables may be less efficient or practical (Hassan *et al*., 2024). One of its critical advantages is mitigating the intermittency of renewable energy sources, ensuring a more stable and reliable power supply. Hydrogen technologies have evolved significantly, from early theoretical concepts in the 19th century (Verne, 2004) to modern applications across the energy sector (Lebrouhi *et al.*, 2022), driven by advancements in production, purification, and utilization.

2.2.2 *Global hydrogen strategies and policy developments*

Internationally, the interest in hydrogen as a sustainable energy carrier has gained substantial momentum, which has been catalysed by collaborative efforts and strategic initiatives. As an example, the Hydrogen Council (About the Council, 2017) is a global initiative led by CEOs from over 100 leading energy, transport, industry, and investment companies, committed to using hydrogen to facilitate the energy transition and help meet the world's climate goals.

Similarly, the International Energy Agency (IEA, 2023b) has been instrumental in propelling hydrogen energy to the forefront of the global energy agenda. The IEA provides critical analysis, policy recommendations, and a platform for international cooperation through its hydrogen projects. In 2019, the IEA, released a report in conjunction with the G20 titled "Future of Hydrogen" (IEA, 2019), which lays down a comprehensive roadmap for expanding hydrogen's role in energy systems. This report highlights opportunities, challenges, and strategies for global stakeholders. These are just two examples amongst an array of international organizations that exist with vested interest in hydrogen for energy transition. At the heart of this study is an examination of Japan's Basic Hydrogen Strategy, which provides a detailed framework for harnessing hydrogen to enhance energy security and mitigate carbon emissions. This strategy highlights the critical role of cutting-edge technologies and regulatory support in facilitating the transition to energy systems that are both sustainable and economically viable.

2.2.3 *Green hydrogen and its role in decarbonization*

The deployment of green hydrogen technologies, particularly those based on electrolysis using renewable energy, is regarded as essential for achieving decarbonization targets. Advances in hydrogen production, storage, and utilization have the potential to significantly reduce greenhouse gas emissions, contributing to the objectives set under the Paris Agreement.

Despite these potential benefits, green hydrogen adoption is constrained by cost and infrastructure challenges (Ma *et al*., 2024). The production of hydrogen via electrolysis remains energy-intensive and cost-prohibitive compared to fossil fuel-based alternatives. Additionally, the storage and transport of hydrogen require specialized infrastructure, due to its low volumetric energy density and flammability risks. As a result, blue hydrogen, which incorporates Carbon Capture and Storage (CCS) to reduce emissions, and grey hydrogen, produced from natural gas without CCS, continue to dominate global hydrogen production. The transition to green hydrogen is expected to require technological advancements and policy-driven cost reductions to achieve widespread adoption (Ma *et al.*, 2024).

2.2.4 *Hydrogen development in Africa and South Africa's strategic positioning*

In the African context, the development of hydrogen energy is at a nascent stage but holds transformative potential, particularly given the continent's rich renewable energy resources. Africa's potential in the global green hydrogen market (White &

Case, 2023) could catalyse the development of crucial infrastructure and create extensive economic opportunities through foreign investments and job creation. This transition presents a unique opportunity to bridge the substantial energy gap on the continent, where approximately 600 million individuals currently lack access to electricity (Grobbelaar & Ngubevana, 2022). Furthermore, the potential to export African green hydrogen robustly could trigger a wave of foreign investment, driving the development of critical infrastructure across Africa and generating employment opportunities throughout the value chain in a just energy transition (Grobbelaar & Ngubevana, 2022).This prospect of transitioning to green hydrogen aligns with Africa's broader objectives which are highlighted in Agenda 2063 (2015).

South Africa's strategic positioning is underlined by its considerable renewable energy potential (Jain & Jain, 2017). The South African government has recognized this potential, as evidenced by initiatives such as the Hydrogen South Africa (HySA) program and the Hydrogen Society Roadmap (DSI, 2021) which was designed to guide the country's efforts in harnessing hydrogen as a pivotal element for its energy future, economic development and environmental sustainability. The HySA program was launched with the aim of positioning South Africa as a leader in the global hydrogen economy, particularly leveraging its rich platinum group metals for advancements in hydrogen and fuel cell technologies. HySA's objective is to stimulate local innovation, generate intellectual property, and build a skilled human capital resource in the field of hydrogen fuel cell technology. This interest aligns with the country's energy needs, aiming to develop and commercialize hydrogen technology for both domestic use and international markets, which will in turn drive economic growth, and diversify South Africa's energy sources.

2.2.5 *Challenges associated with hydrogen adoption*

While hydrogen is advocated by many as a key player in the future energy mix, it is essential to acknowledge the challenges associated with its adoption as well. Based on "Large Scale of Green Hydrogen Storage: Opportunities and Challenges" (Ma *et al*., 2024) some of the problems are highlighted below:

- **Economic Viability**: The cost of green hydrogen production remains high, compared to fossil fuel-based alternatives, necessitating policy interventions and technological improvements to drive cost reductions.

- **Infrastructure Development**: The lack of hydrogen transport, storage, and refuelling infrastructure presents a significant barrier to widespread deployment.

- **Market Adoption**: Hydrogen technologies require consumer acceptance, which may be limited by high upfront costs and a lack of public awareness.

- **Environmental Impact**: While green hydrogen offers zero-emission energy, grey hydrogen production still relies on fossil fuels, reducing its overall sustainability benefits.

To address these barriers, a transitional approach utilizing grey and blue hydrogen, has been proposed has been proposed in global literature as an interim solution, facilitating infrastructure development while scaling up green hydrogen production (Kovač *et al*., 2021).

2.3 Comparative Analysis of Hydrogen Fuel Cell Adoption

Japan, Korea, and China are at the forefront of advancements in hydrogen fuel cell technology, each with distinct strategies aimed at integrating hydrogen into their energy ecosystems. Japan leads with their futuristic woven city prototype, which is a venture into next-generation urban planning. This initiative, led by Toyota, transforms the concept of a smart city into reality by integrating hydrogen fuel cells as a key energy source, thus powering the entire city's infrastructure (Toyota Woven City, 2023). This project represents a dynamic experiment in sustainable living and technological integration, which positions it as a model for future cities globally.

Japan's leadership in the hydrogen domain is exemplified through several projects and policies that aim to incorporate hydrogen as a cornerstone of its energy strategy. The Basic Hydrogen Strategy (Ministerial Council on Renewable Energy, 2017), (Bocobza & Tanabe, 2023), outlines a comprehensive framework for hydrogen integration, focusing on enhancing energy security and reducing carbon emissions. This strategy is instrumental in their efforts to develop a hydrogen society by 2050.

A key aspect of Japan's hydrogen strategy is the deployment of hydrogen in various sectors including transportation, residential energy systems, and industrial processes. The introduction of the Toyota Mirai, the world's first commercially viable fuel cell vehicle, and the development of residential hydrogen systems like Panasonic's Ene-Farm, are indicative of Japan's approach to embedding hydrogen technologies in everyday use. Furthermore, the steel industry, represented by initiatives like those of Nippon Steel, showcases hydrogen's role in reducing industrial carbon emissions significantly.

In addition to these domestic applications, Japan's hydrogen initiatives also include large-scale projects such as the Fukushima Hydrogen Energy Research Field. This facility is one of the world's largest hydrogen production plants, utilizing renewable energy sources to produce hydrogen. This project not only demonstrates the feasibility of large-scale hydrogen production but also highlights the potential of hydrogen to serve as a storage medium for renewable energy, which may address intermittency issues.

The strategic use of hydrogen in Japan is also reflected in its urban planning and public transportation systems. The integration of hydrogen fuel cells in buses and the establishment of hydrogen refuelling stations are part of a broader effort to create a sustainable urban mobility landscape. This approach was prominently featured during the Tokyo 2020 Olympic and Paralympic Games, where hydrogen technology was featured as a legacy of the event, aiming to transition Tokyo towards a carbon-neutral future.

This review elucidates Japan's multifaceted approach to hydrogen technology, which combines policy, innovation, and international collaboration. Building on the established foundation of hydrogen technology integration in Japan, this study will focus on the residential application of hydrogen fuel cell technology by conducting a study on the Ene-Farm system, namely the success factors that contributed towards its market penetration, as well as a cost comparison for such technology in the South African landscape. Ene-Farm represents Japan's pioneering venture into residential hydrogen fuel cells, providing a sustainable energy solution by converting hydrogen into electricity and heat for home use. This initiative is particularly significant as it embodies a practical implementation of hydrogen technology that directly impacts daily living. This is particularly pertinent in addressing the issues of access to energy, energy security and reducing greenhouse gas emissions in South Africa. Figure 2 shows the cost reduction of the Ene-Farm unit with subsidies over a 10-year period in Japan (one of the main success factors).

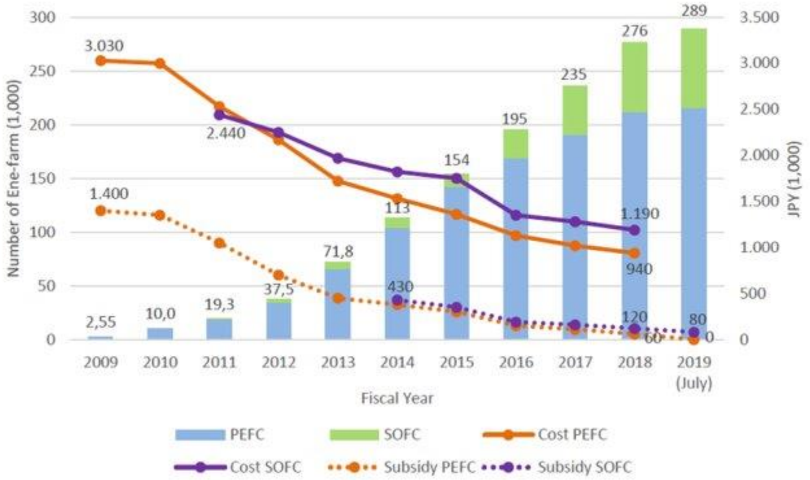

Figure 2: Number of Ene-Farm Units Sold Over a 10-Year Period in Japan, Including Cost Evolution with Subsidies (Simader & Vidovic, 2022)

The transition to a hydrogen-based society, while ideal in its pursuit of carbon neutrality, presents certain pragmatic challenges, such as infrastructure development, upfront costs, and storage and transportation, which necessitate the adoption of interim solutions. One such solution is the utilization of grey hydrogen, which, despite being produced from fossil fuels, serves as a critical transitional pathway towards the establishment of greener hydrogen production methods. In the journal article "Hydrogen in Energy Transition: A Review" (Kovač *et al*., 2021), the author highlights the role of grey hydrogen as a transitional solution that enhances the scalability and economic feasibility of hydrogen technologies. This interim approach supports the gradual development and optimization of more sustainable production methods that utilize renewable energy sources. Additional technologies that mitigate greenhouse gas emissions include blue hydrogen, which employs carbon capture techniques to prevent greenhouse gas emissions, and turquoise hydrogen, where the carbon by-product of pyrolysis is solidified. This study will investigate the ramifications of a transitional approach (grey hydrogen) within the residential hydrogen usage framework, evaluating both the immediate potential and long-term viability.

A preceding study pertinent to this research, titled "Success Factors for Demonstration Projects of Small-Scale Stationary Fuel Cells in Residential Buildings" (Simader & Vidovic, 2022), investigated the key elements, contributing to the successful deployment of fuel cell technology within residential sectors across Europe. This research draws extensively on the effective strategies that facilitated the integration of hydrogen fuel cells into residential settings in Japan, particularly through the Ene-Farm program. The critical success factors identified include strategic governmental initiatives, robust industrial partnerships, and the cultivation of a high-volume market that significantly reduced costs and promoted broad adoption. These elements have proven central to Japan's progress in obtaining substantial market penetration of hydrogen fuel cell technology within its residential sector.

In contrast, the study (Simader & Vidovic, 2022) also accentuates the different circumstances affecting technology adoption within the European context, notably in Austria. Unlike Japan, whose approach is deeply embedded in a comprehensive national framework aimed at cultivating a hydrogen society, European projects such as PACE (Hart *et al*., 2020) have not yet catalysed a comparable transformation in the market dynamics of fuel cell technology. The findings highlight the necessity for strategies that are specifically tailored to the distinct environmental, economic, and social contexts of European countries, to replicate Japan's success.

This comparative analysis highlights not only the key success factors but also the necessity of adaptive strategies that align with local conditions to facilitate the effective deployment of hydrogen fuel cell technologies. The findings from this research inform the present study's approach, particularly in assessing the feasibility of adapting Japan's Ene-Farm model to the South African context. A critical aspect of this adaptation involves exploring grey hydrogen as a transitional solution within a phased strategy for integrating green hydrogen in the long-term.

Japan's hydrogen strategy demonstrates the pragmatic use of grey hydrogen, produced from natural gas or LPG, as an intermediate step toward fully decarbonized hydrogen production. This approach acknowledges the technological and economic challenges associated with an immediate transition to green hydrogen while ensuring market readiness and infrastructure development. While not the ultimate objective, grey hydrogen has played a crucial role in enabling early adoption, lowering initial costs, and encouraging market acceptance of hydrogen-based energy solutions.

2.4 Comparative Analysis of Fuel Cell Technologies

A comparative analysis (MacLean-Blevin, 2024) of fuel cell technologies provides valuable insights into the key factors influencing their adoption across different markets. This section examines the specific elements that have contributed to the success of Japan's Ene-Farm program and contrasts them with the hydrogen fuel cell initiatives implemented in Europe. The analysis highlights differences in policy support, financial incentives, market conditions, and technological advancements, offering potential lessons for South Africa.

Japan's Ene-Farm Program

Japan's Ene-Farm program represents a significant advancement in residential hydrogen fuel cell technology. It has demonstrated considerable success in integrating these systems into everyday residential use. The key success factors of the Ene-Farm program include strong policy support, financial incentives, and strategic partnerships among government, industry, and research institutions. These factors have enabled widespread adoption and market penetration. This model could serve as a potential learning exercise for South Africa when making decisions about incorporating hydrogen fuel cell technology into the energy mix. The Ene-Farm's cogeneration capability, which efficiently utilizes both the electricity and heat generated, presents potential advantages over conventional systems like solar PV systems with lithium ion batteries, which are primarily designed for electricity storage, however on the other hand, it poses significant upfront costs which can be a barrier to widespread adoption, especially in South Africa (Staffell & Green, 2013). Table 1 discusses the success factors that led to Japan's market penetration of the Ene-Farm program based on the following literature: "Success Factors for Demonstration Projects of Small-Scale Stationary Fuel Cells in Residential Buildings" (Simader & Vidovic, 2022), "Residential Fuel Cell Ene-Farm" (Tokyo Gas Co. Ltd.), and "New and Improved Home Fuel Cell "'Ene-Farm'" (Panasonic Group, 2011).

Table 1: Japan's success factors for the Ene-Farm hydrogen fuel cell program

Success Factor	Description
Clear Strategic Goals	The Japanese government set clear targets for hydrogen and fuel cells within its national energy strategy, aiming to install 5.3 million Ene-Farm units by 2030.
Government and Industry Commitment	Long-term commitment from both the government and industry facilitated large-scale deployment and sustained development of the technology.
Product Quality and Distribution	High product quality, simple distribution channels, and one-stop-shop installation and maintenance services ensured easy adoption and customer satisfaction.
Market Adaptation	Products were tailored to meet the specific demands of Japanese households, focusing on hot water and electricity needs.
Economies of Scale	Large market volume enabled standardization, product iterations, cost reductions, and economies of mass production, making the technology more affordable over time.
Resilience and Reliability	The ability of Ene-Farm systems to provide electricity and hot water during power outages increased their appeal in disaster-prone Japan.
Environmental and Economic Benefits	Ene-Farm systems significantly reduced CO_2 emissions and energy costs for households, contributing to national energy and climate policy goals.
Technological Innovation	Continuous improvements in power generation efficiency, durability, and integration into building automation systems kept the technology competitive and effective.

2.4.1 *European comparison*

In Europe, the adoption of hydrogen fuel cell technologies, such as those promoted by the PACE project, provides a different perspective on regulatory and market conditions. Europe's decentralized approach requires tailored strategies for each country, which can slow adoption but also allow for localized solutions. The comparative analysis of Japan and Europe (Simader & Vidovic, 2022) offers insights into different regulatory environments and market dynamics. Having such literature readily available can inform and potentially guide the development of tailored strategies for adopting hydrogen fuel cells in South Africa's unique socio-economic and environmental context. The lessons from Europe's challenges and successes are valuable for understanding how to effectively implement hydrogen technologies in diverse contexts.

Table 2: Key comparisons between Japan and Europe's success factors for implementing HFCT

Key Comparisons	Japan	Europe	Implications for South Africa
Policy Support	Strong, centralized policy support with clear national targets.	Varied levels of policy support depending on the country, leading to a more decentralized approach.	Strong, centralized policy support in South Africa could facilitate smoother adoption and integration of hydrogen fuel cells.
Financial Incentives	Significant financial incentives and subsidies.	Financial incentives vary by country, with some offering substantial support and others less so.	Implementing substantial financial incentives could lower the initial adoption barrier for South African households.

Key Comparisons	Japan	Europe	Implications for South Africa
Market Adaptation	Products tailored to local needs (hot water and electricity)	Products adapted to varied local needs across different countries.	Tailoring products to meet the specific energy needs of South African households could enhance adoption rates.
Technological Advancements	Continuous innovation and improvements in technology	Diverse technological advancements depending on local R&D efforts.	Investing in local R&D and technological innovation is crucial for the successful implementation of hydrogen fuel cells.

2.4.2 *Hypothesis 1*

The factors that contributed to the adoption of hydrogen fuel cell technology in Japan differ significantly for South Africa.

2.4.3 *Hypothesis 2*

The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.

2.5 Economic Viability of Hydrogen Fuel Cells in the South African Residential Sector

Evaluating the economic feasibility of hydrogen fuel cell technology within the South African residential sector requires a comprehensive assessment of cost structures, operational efficiency, and potential financial support mechanisms. This section introduces a methodological framework for analysing these economic factors, with a specific focus on the Total Cost of Ownership using the Fermi estimate model. By comparing the financial implications of hydrogen fuel cell systems with established alternatives, such as solar PV systems with lithium-ion battery storage, this analysis aims to determine the extent to which hydrogen-based solutions can provide a cost-competitive and sustainable energy option for residential applications in South Africa. Understanding these economic considerations is essential for informing policy development, investment strategies, and consumer decision-making in the country's energy transition.

2.5.1 *Cost analysis*

A critical factor in determining the viability of hydrogen fuel cells is a detailed examination of the cost components associated with their deployment. These include capital expenditures (CAPEX), covering initial installation costs, as well as operational expenditures (OPEX), which account for fuel costs, maintenance, and system efficiency over its lifespan. The Fermi estimate model is employed to approximate the TCO of hydrogen fuel cell systems, enabling a structured evaluation of cost variables and their potential impact on adoption rates.

One of the primary barriers to the widespread adoption of hydrogen fuel cells is the high upfront investment required for installation. However, as observed in Japan, government subsidies and financial incentives can significantly offset these costs, facilitating early adoption. Japan's Ene-Farm program provides an illustrative example, where state-supported subsidies and industry collaborations have contributed to gradual price reductions through economies of scale.

Operational costs are heavily influenced by the cost of hydrogen production and supply chain logistics. In Japan, the Osaka Gas model has demonstrated how utility-backed incentives can reduce household expenditure on fuel by promoting the use of grey hydrogen as a transitional energy source (Rose, 2015). Implementing comparable financial mechanisms in South Africa could reduce the initial costs associated with hydrogen fuel cell adoption, thereby improving affordability.

Maintenance and efficiency considerations are also essential in determining long-term economic feasibility. Hydrogen fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), as used in Ene-Farm units, have demonstrated high reliability and extended operational lifespans when compared to traditional combustion-based energy systems. Their potential to provide both electricity and heat in Combined Heat and Power (CHP) applications could further enhance economic competitiveness, particularly in high-density urban environments where solar PV installations may be constrained by space limitations. However, further cost-benefit analyses and long-term performance assessments specific to South Africa's market conditions are required to validate these assumptions.

2.5.2 *Hypothesis 3*

The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly, based on different technological and economic assumptions.

2.5.3 *Hypothesis 4*

Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are mitigated through subsidies.

2.6 Conclusion of Literature Review

Despite growing global interest in hydrogen fuel cell technologies, there is limited research on their techno-economic feasibility in the South African residential sector. Most existing studies focus on large-scale industrial applications or transport sectors, leaving a gap in understanding how stationary fuel cells can integrate into residential energy systems. Additionally, while Japan's Ene-Farm program serves as a proof-of-concept benchmark, there is no established framework for adapting its model to a developing economy with a different energy mix, regulatory environment, and socio-economic conditions. Previous research lacks a comprehensive comparative analysis of hydrogen fuel cells and their primary alternative to grid power – solar PV systems in South Africa – particularly through the use of Fermi estimates and scenario-based cost modelling. This study directly addresses these gaps by adapting Ene-Farm lessons to the South African context, constructing a Fermi estimate-based TCO model, and conducting a robust sensitivity analysis. The insights from this research provide a much-needed evidence base for policymakers and investors, contributing to the broader discourse on sustainable energy transitions in emerging markets.

2.6.1 *Summary of key findings*

1. **Global Adoption and Technological Advancements:** Hydrogen fuel cells are gaining traction worldwide, with Japan leading efforts through the Ene-Farm program, driven by strategic policies and industry collaboration.

2. **Comparative Analysis:** Japan's centralized policy approach contrasts with Europe's decentralized model, offering insights into regulatory and market dynamics that could inform South Africa's strategy.

3. **Economic Viability:** Government subsidies and financial incentives play a crucial role in reducing initial adoption costs, while transitional technologies like grey hydrogen can facilitate market entry.

4. **Potential for South Africa:** South Africa has the potential to adopt hydrogen technology, leveraging its renewable energy resources and strategic initiatives like the HySA program. The review identified key factors for success, including government support, industry collaboration, and tailored economic strategies.

2.6.2 *Hypotheses*

The hypotheses that were developed from the literature review are summarized below. Note that the results and analysis chapter will follow the sequence of the hypotheses as listed below.

Hypothesis 1: The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly based on different technological and economic assumptions.

Hypothesis 2: Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are mitigated through subsidies.

Hypothesis 3: The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.

Hypothesis 4: The factors that contributed to the adoption of hydrogen fuel cell technology in Japan differ significantly for South Africa.

Table 3: Consistency table: research questions and propositions

RQ #	Research Questions	Hyp #	Hypotheses
1	What are the economic implications of implementing hydrogen fuel cells in the South African residential sector, and what is the Total Cost of Ownership under various scenarios?	1	The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly, based on different technological and economic assumptions.
2	How can the adoption of hydrogen fuel cell technology be optimized for residential energy use in South Africa, considering the factors that influence adoption in Japan's Ene-Farm program?	2	Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are mitigated through subsidies.
3	Can Japan's Ene-Farm policy framework be adapted for South Africa?	3	The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.
4	What key barriers affect residential hydrogen fuel adoption in South Africa when comparing to Japan?	4	The factors that contributed to the adoption of hydrogen fuel cell technology in Japan differ significantly for South Africa.

CHAPTER 3. RESEARCH METHODOLOGY

Chapter 3 outlines the research methodology designed to address the hypotheses and research questions emerging from the literature review. The primary focus is on detailing the quantitative approach that will be employed to generate robust and reliable findings, particularly through the use of a Fermi estimate model to quantify the Total Cost of Ownership (TCO) in South Africa. Additionally, this chapter will describe Japan's policies and interventions that facilitated the successful adoption of hydrogen fuel cell technology, providing a context for understanding potential strategies and pitfalls applicable to the South African setting.

3.1 Research Approach

This study adopts a quantitative research approach to assess the techno-economic feasibility of hydrogen fuel cell technology in South Africa. The research focuses on estimating the Total Cost of Ownership (TCO) and evaluating its viability under different economic and policy scenarios. The study applies a Fermi estimate model to approximate costs where precise data is limited. It involves breaking down a problem into smaller, more manageable components and using educated guesses to estimate each component (Nityananda, 2014). Furthermore, it integrates scenario analysis to assess the impact of external factors such as subsidies, fuel costs, and market conditions.

The theory behind Fermi estimates includes key aspects such as approximation and simplification, robustness to uncertainty, and iterative refinement. Fermi estimates simplify complex problems by making reasoned approximations based on known data and logical reasoning. This method is particularly useful for addressing business problems (Anderson, 2010) because they allow for rapid, approximate calculations that can guide decision-making in situations where detailed data is unavailable.

A key feature of this approach is the scaling analysis, which compares the economic feasibility of hydrogen fuel cells to solar PV systems by adjusting system sizes to meet identical energy demands. The rule of two-thirds (Randall, 2020) is applied to scale the Ene-Farm PEMFC system, ensuring a fair cost comparison with the solar PV system, which is scaled using a component-specific cost model. The economic viability of both systems is further assessed through cost-per-kW metrics, which provide insight into affordability and scalability. To ensure a robust analysis, sensitivity testing is conducted to evaluate how variations in fuel prices, efficiency rates, and economic incentives affect overall costs.

The methodology also includes a comparative policy evaluation of Japan's Ene-Farm program and South Africa's hydrogen strategy, identifying potential barriers and opportunities for local implementation. By integrating these analytical techniques, the study provides a comprehensive framework for assessing whether hydrogen fuel cells can serve as a viable residential energy solution in South Africa, considering technical, economic, and infrastructural constraints.

3.2 Research Design

This study employs a quantitative methodology centred around a techno-economic feasibility assessment of hydrogen fuel cell systems in South Africa, using Japan's Ene-Farm program as a benchmark. The research integrates a Fermi estimate model to approximate the Total Cost of Ownership (TCO) for hydrogen fuel cells and solar PV systems under South African conditions. Additionally, scenario and sensitivity analyses are conducted to evaluate the impact of policy interventions, and technological advancements on system viability.

The research design is structured into three key analytical components:

1. **Technological Performance Analysis**

    - Evaluates the energy efficiency, fuel consumption, and heat recovery potential of the Ene-Farm system.

    - Assesses solar PV system performance under real-world operational constraints in South Africa.

    - Employs mass-energy balance equations to estimate fuel requirements, heat recovery, and energy yields.

2. **Economic Feasibility Assessment**

    - Computes the TCO for both systems over their respective lifespans using cost data from online sources, policy documents, and industry reports.

    - Includes fuel cost projections, operational expenditures, and subsidy considerations.

    - Conducts cost scaling analysis to model system affordability at various capacities (1 kW – 5 kW).

3. **Scenario and Sensitivity Analysis**

    - Examines different economic and policy scenarios, including baseline, optimistic, and pessimistic cases.

- Assesses how variations in fuel prices, efficiency rates, and subsidies affect the TCO of hydrogen fuel cells.

- Compares the economic and technical feasibility of solar PV as an alternative energy source.

This structured approach facilitates a rigorous evaluation of the feasibility of hydrogen fuel cell adoption in South Africa, incorporating both technical performance and economic viability. The findings contribute to a data-driven assessment that can support policy formulation, investment strategies, and energy planning decisions.

3.3 Data Collection Methods

To ensure a comprehensive assessment of the topic, this study utilizes multiple secondary data sources. These sources capture both technical and economic factors influencing the adoption of hydrogen fuel cells in the residential sector.

Table 4: Table to describe data collection methods

Data Collection Method	Description	Justification
Policy Documents	Review of policy documents from the Japanese government and South African authorities.	Provides insights into the regulatory and strategic environment, supporting hydrogen fuel cell technology, highlighting government incentives, subsidies, and policies.
Technical Documents	Manufacturer specifications, academic research, and industry white papers on hydrogen fuel cells and solar PV.	Essential for calculating energy demand, fuel consumption, and system efficiency.

Data Collection Method	Description	Justification
Market and Industry Reports	Publicly available pricing data on hydrogen fuel cells, methane costs, and solar PV components from industry reports and governmental sources.	Supports Total Cost of Ownership (TCO) calculations using verified secondary data.
Financial Reports	Banking and financial institution reports on loan structures, interest rates, and financing options for renewable energy systems.	Used to incorporate realistic financing assumptions in economic models.
Fuel Pricing Data	Methane pricing trends, gas supplier tariff structures, and publicly available energy pricing reports.	Supports Fermi estimate model.
Cost Scaling References	Industry benchmarks on scaling trends for energy systems (e.g. NREL cost reports for solar PV (Ramasamy, 2020)	Ensures accurate cost projections as system capacities scale.
Research Papers and Academic Publications	Peer-reviewed journals and conference proceedings.	Offers in-depth academic analysis and research findings on the Ene-Farm program.
Media Reports and Industry Publications	Energy industry news and general news outlets.	Up-to-date coverage and public perception analysis.

3.4 Population and Sample

The following section outlines the population and sample for the study, defining the specific criteria for inclusion and exclusion of sources. This research focuses on the adoption of hydrogen fuel cell technology for residential use in South Africa, leveraging a variety of data sources. Each source is considered a population in its own right, and the criteria for selection are carefully justified to ensure the data collected is relevant, comprehensive, and conducive to answering the research questions. By clearly defining the population and sample, this study will provide a robust foundation for analysing the potential for hydrogen fuel cells in the South African residential energy sector.

3.4.1 *Population*

The population for this research comprises various sources of data that is relevant to the topic. Specifically, the population includes:

- **Policy Documents:** Publications from the Japanese government and South African authorities that provide insights into the regulatory and strategic environment supporting hydrogen fuel cell technology.

  Inclusion Criteria: Documents must be official publications related to energy policies, strategic plans, or regulatory frameworks.

  Exclusion Criteria: Documents published before 2010 are generally excluded unless they offer foundational context that remains relevant to national energy planning, particularly in the early development of hydrogen and renewable energy strategies.

- **Technical Documents:** Technical specifications, performance data, and research papers on the Ene-Farm program and fuel cell units from manufacturers and research institutions.

  Inclusion Criteria: Publications that detail the technical aspects of the Ene-Farm units, including efficiency, energy output, and integration into residential settings.

Exclusion Criteria: Documents lacking technical depth or not peer-reviewed.

- **Media Reports:** News articles, industry magazines, and online publications that cover the Ene-Farm program and the broader hydrogen fuel cell industry.

  Inclusion Criteria: Recent (within the last 10 years where possible) and relevant reports that discuss the adoption, public perception, and developments in the hydrogen fuel cell market.

  Exclusion Criteria: Opinion pieces without factual backing or sources older than five years.

- **Market and Industry Reports:** Ensures cost data remains objective and is sourced from reputable entities.

  Inclusion Criteria: Reports published by energy consultancies, banks, government entities, and industry bodies; pricing data from public sources such as financial statements, industry databases, and academic cost studies.

  Exclusion Criteria: Outdated cost estimates (published before 2010).

The chosen population ensures that the data collected is relevant, current, and specific to the research objectives. This selection will provide comprehensive insights into the technical, economic, and regulatory aspects of hydrogen fuel cell adoption in South Africa.

3.4.2 *Sample and sampling method*

The study utilises purposive sampling by selecting data sources that provide the most relevant and comprehensive information on the adoption of hydrogen fuel cells and solar PV systems for residential use in South Africa. The sample consists of key policy documents, technical reports, financial analyses, and market studies that contribute to the techno-economic evaluation of the two energy technologies.

The sample is drawn from the following categories:

1. **Policy Documents**

- **Sample Size:** 5 – 10 key policy documents from Japanese and South African governments.

- **Sampling Method:** Purposive sampling of energy policies, regulatory frameworks, and government strategies that outline hydrogen fuel cell and solar PV adoption.

- **Justification:** Provides insights into subsidies, incentives, and energy transition policies relevant to the study.

2. **Technical Reports and Research Papers**

- **Sample Size:** 15 – 20 technical documents and peer-reviewed research papers.

- **Sampling Method:** Purposive sampling of sources that detail Ene-Farm as well as general PEMFC's performance metrics, fuel cell efficiency, solar PV system characteristics, and energy conversion processes.

- **Justification:** These documents offer the technical foundation for the mass-energy balance calculations and system performance analysis.

3. **Market and Industry Reports**

- **Sample Size:** 5 – 10 publicly available financial reports, energy market studies, and cost analyses.

- **Sampling Method:** Purposive sampling of pricing data, cost scaling models, and financing trends for hydrogen fuel cells and solar PV in South Africa.
- **Justification:** Supports the Fermi estimate model by providing realistic cost inputs for investment analysis and Total Cost of Ownership (TCO) calculations.

4. Media Reports and Industry Publications

- **Sample Size:** 10 – 15 industry reports, news articles, and sector-specific publications.
- **Sampling Method:** Purposive sampling of recent reports (within the last 10 years) that discuss market adoption trends, public perception, and real-world implementation challenges.
- **Justification:** Ensures the study accounts for practical adoption barriers and emerging trends influencing hydrogen fuel cell feasibility.

This sampling strategy ensures that all sources contribute directly to the research objectives, providing a comprehensive, data-driven evaluation of hydrogen fuel cell adoption in South Africa relative to solar PV systems.

3.5 The Research Instrument

This section outlines the research instruments used to collect, analyse, and interpret data for assessing the techno-economic feasibility of hydrogen fuel cells in the South African residential sector. The study relies on quantitative modelling techniques, including a mass-energy balance, a Fermi estimate model for Total Cost of Ownership (TCO), and a scenario analysis framework.

3.5.1 *Data collection tools*

1. **Document Analysis Guide:** A structured document analysis guide will be used to systematically collect data from various sources. This guide will help ensure that all relevant information is gathered consistently and comprehensively. The following categories as detailed in Table 5 will be examined.

Table 5: Description of categories to be examined

Category	Items to be Examined
Technological Adoption	• Description of Ene-Farm technology and solar PV systems. • Key technical milestones and innovations.
Economic Factors	• Initial investment costs (Ene-Farm and solar PV). • Fuel costs for methane. • Economic incentives (subsidies, tax rebates). • TCO calculation parameters.
Policy Factors	• Japan's policy strategies supporting Ene-Farm. • South African hydrogen energy policies. • Existing renewable energy incentives in SA.
Social Factors	• Public perception and market readiness. • Social impact of hydrogen fuel cells and solar PV.

2. **Fermi Estimate Model Template:** A custom spreadsheet model will be developed in Microsoft Excel, implementing the Fermi estimate method to approximate the Total Cost of Ownership for Ene-Farm and solar PV systems in South Africa. The model accounts for:

- Initial capital investment.
- Fuel consumption and associated costs.
- Operational efficiency and system lifespan.
- Maintenance costs (if applicable).
- Capital replacement costs.
- Economic incentives and policy interventions.

3. **Scenario Analysis Framework:** A framework for conducting scenario analysis will be used to incorporate different policy interventions and market conditions. This framework will include:
    - Baseline scenario (current conditions).
    - Optimistic scenario (favourable technical and economic incentives, low fuel costs).
    - Pessimistic scenario (unfavourable economic conditions, unfavourable technical conditions).

3.5.2 *Technological model*

This study employs a mass-energy balance model to determine the technical performance of Ene-Farm and solar PV systems under South African conditions. The calculations focus on energy generation, efficiency, and fuel consumption.

1. **Mass-Energy Balance Calculations:** These calculations will determine the hydrogen fuel requirements, efficiency rates, and operational lifespan of the fuel cell systems. The steps include:

- **Natural Gas Supply and Reforming:** Estimating hydrogen production from natural gas through Steam Methane Reforming (SMR) and water-gas shift reactions.

- **PEM Fuel Cell Stack:** Calculating electrical energy output and waste heat generation from the hydrogen-oxygen reaction in the fuel cell stack.

- **Heat Recovery Unit:** Evaluating the utilization of waste heat for domestic heating, for example: boiling water for bathing and cooking.

2. **Energy Balance:** The energy balance will be calculated to understand the system's efficiency and performance.

   The mass- and energy balance model provides a detailed representation of the processes within the Ene-Farm PEMFC system. The following block flow diagram, Figure 3, illustrates the mass- and energy flows within the Ene-Farm PEM fuel cell unit.

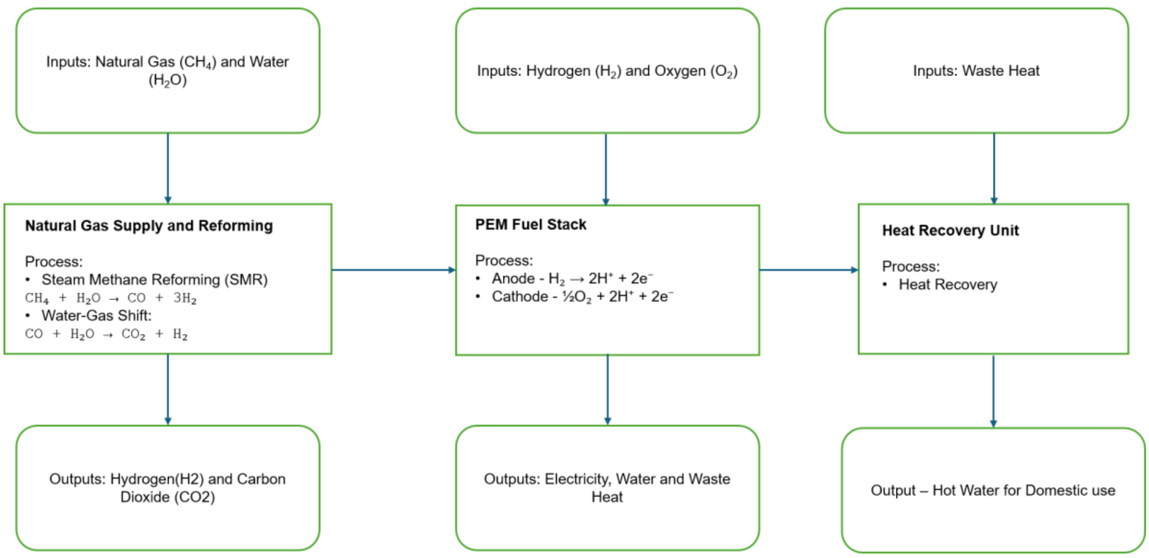

Figure 3: Block Flow Diagram to Represent the Mass- and Energy Flows of an Ene-Farm PEMFC System

The technological model for the Ene-Farm PEMFC system includes three main blocks: Natural Gas Supply and Reforming, PEM Fuel Cell Stack, and Heat Recovery Unit. In the first block, natural gas (CH_4) and water (H_2O) undergo Steam Methane Reforming (SMR) and water-gas shift reactions to produce hydrogen (H_2) and carbon dioxide (CO_2). In the PEM Fuel Cell Stack, hydrogen (H_2) and oxygen (O_2) undergo anode and cathode reactions to produce electricity, water (H_2O), and waste heat. The Heat Recovery Unit utilizes the waste heat to produce hot water for domestic use. Key calculations will include estimating hydrogen fuel requirements, determining fuel cell efficiency, and estimating the operational lifespan of the fuel cell systems. For this model, the following is assumed: an adiabatic system, complete fuel conversion, and constant operating conditions.

The energy balance for the Ene-Farm PEMFC system involves calculating the energy input and output to understand the system's efficiency and performance. This section outlines the steps and key equations used in the energy balance analysis.

Energy Input: Derived from the Lower Heating Value (LHV) of methane (natural gas).

- Methane LHV = 13.89 kWh/kg (50 MJ/kg) (typical accepted value (The Engineering Toolbox, 2003)).
- Molar Mass of CH_4 = 16 g/mol (0.016 kg/mol).
- Energy Content per Mole of CH_4 = Methane LHV × Molar Mass of CH_4 = 800 kJ/mol.

Energy Output: Consists of the electrical energy and heat energy generated by the fuel cell.

3. **Electrical Energy**

- Efficiency ($\eta_{electric}$) = 37% – 39% (Nishizaki, 2012).
- Electrical Energy Output = $\eta_{electric}$ × 800 kJ / mol, assuming 37% efficiency (conservatism), the electrical energy output = 296 kJ / mol.

4. **Heat Energy**

- Total System Efficiency (η_{total}) = 90%.
- Heat Energy Output = (η_{total} - $\eta_{electric}$) × 800 kJ/ol, assuming total efficiency of 90% and an electrical efficiency of 37%, the total heat output = 424 kJ / mol.

Note: The methodology presented in this section describes the mass-energy balance approach using fundamental principles and standard units, such as kJ/mol for energy calculations. However, in the results and analysis (Chapter 4), certain unit conversions have been applied to align with real-world economic and industry practices. For example, methane energy values are reported in kWh/kg rather than kJ/mol to facilitate cost-based comparisons. This adjustment ensures that the technical calculations remain robust while the final analysis remains relevant to practical implementation. Despite these variations, the underlying principles and equations remain consistent across both chapters.

The total energy balance is given by:

Total Energy Input = Electrical Energy Output + Heat Energy Output

3.5.3 *Economic model*

The economic model utilises the Fermi estimate to quantify the Total Cost of Ownership (TCO) in units of US$ for the Ene-Farm PEMFC system, integrating input parameters derived from the technological model and relevant economic data. TCO serves as a key metric in techno-economic feasibility studies, as it accounts for all costs associated with system acquisition, installation, operation, fuel consumption, and maintenance over its lifespan. This model allows for scenario testing to evaluate cost sensitivities under different policy interventions, market fluctuations, and energy pricing conditions, ensuring robust cost optimization and comparative analysis.

To maintain consistency, all cost estimations assume a fixed exchange rate at the time of analysis, with no adjustments for future currency fluctuations. The study adopts a static conversion approach, treating the Japanese Yen (JPY), South African Rand (ZAR), and United States Dollar (US$) at their respective rates during the calculation period. This approach ensures that cost comparisons remain standardized throughout the analysis while focusing on the fundamental economic feasibility of hydrogen fuel cell technology in the South African context.

Table 6: Input and output parameters for the Fermi estimate model

Input Parameter (US$)	Explanation
Initial Investment Costs	Capital costs for the hydrogen fuel cell systems, installation, and commissioning costs.
Operational Costs	Maintenance and repair costs, costs of raw materials and supplies.
Fuel Costs	Cost per unit of hydrogen fuel, quantity of fuel required (from mass-energy balance).
Economic Incentives	Government grants, subsidies, tax incentives, and rebates – possible perturbation factors to investigate sensitivity.

Input Parameter (US$)	**Explanation**
Output Parameter	**Explanation**
Total Cost of Ownership	Comprehensive estimate of the TCO, including all associated costs over the lifespan of the system.
Annualized Costs	Breakdown of costs over the lifespan of the hydrogen fuel cell systems, annual operating costs.
Sensitivity Analysis	Impact of variations in fuel prices, operational costs, and economic incentives on the TCO.

Methodology for Formulating the Mathematical Model:

- Gather data from relevant literature to establish baseline values for input parameters.
- Use mass-energy balance results to input accurate fuel requirements and efficiency rates into the model.
- Create a dynamic spreadsheet model that allows for the input of various parameters and automatic recalculation of outputs.
- Ensure transparency and flexibility of the model to test different scenarios and assumptions.
- Analyse the results to determine the feasibility and economic viability of hydrogen fuel cell adoption in South Africa.
- Compare the TCO with the alternative solar PV system to provide context and insights.

By integrating the Fermi estimate with the insights from the document analysis, this study aims to provide a comprehensive and holistic assessment of the adoption of hydrogen-based fuel cell energy storage systems in South Africa. The dynamic nature of the model allows for continuous updates and refinements as new data becomes available, ensuring the robustness and relevance of the findings.

3.6 Procedure for Data Collection

Since this research is based on document analysis, the data collection process follows a systematic approach to ensure that comprehensive and relevant data is gathered. Relevant documents are identified through searches using academic databases (e.g. Google Scholar, JSTOR and ResearchGate) and governmental websites. These sources include policy papers, government reports, industry analyses, and academic articles relevant to the topic.

A **keyword-based search strategy** refines the selection, focusing on terms such as *"hydrogen fuel cell technology", "Ene-Farm program", "South Africa energy policy",* and *"hydrogen energy adoption".* The selection criteria prioritize:

- **Recent Publications**: Documents published within the last 10 years to ensure that the research reflects current technological and policy contexts.
- **Relevance**: Documents that provide detailed insights into technological adoption, economic factors, policy frameworks, and social impacts.

To improve efficiency in document screening and refinement, Artificial Intelligence (AI) tools are utilized to perform quick scans and relevance assessments of large volumes of documents. AI-assisted tools facilitate:

- Rapid keyword-based filtering to exclude irrelevant documents.
- Summarization of key sections to assess content relevance before full review.

- Pattern recognition to identify recurring themes across multiple sources.

A structured document analysis guide is applied to extract and categorize key information from selected sources. The Fermi estimate model requires quantitative input parameters, which are sourced from policy documents, industry reports, and publicly available technical data.

Document analysis is chosen for its systematic and non-intrusive nature, ensuring cost-effectiveness and replicability. This approach allows for a comprehensive review of existing knowledge.

3.7 Data Analysis and Interpretation

3.7.1 *Document data analysis*

The data collected through document analysis will be analysed, using thematic analysis, which is a widely accepted method for identifying, analysing, and reporting patterns (themes) within data. The thematic analysis will follow the steps outlined in Braun and Clarke (Braun and Clarke, 2006), which includes familiarization with the data, generating initial codes, searching for themes, reviewing themes, defining and naming themes, and producing the report. This method allows for a systematic approach to data analysis, ensuring that insights derived from the document analysis are rigorously examined and interpreted.

The choice of thematic analysis is justified by its flexibility and its ability to provide detailed, nuanced insights into complex data. It allows for both inductive and deductive approaches, enabling the researcher to explore emergent themes as well as predefined categories based on the research questions.

3.7.2 *Quantitative data analysis*

For the quantitative data derived from the Fermi estimate model, the analysis will focus on calculating the total cost of ownership using descriptive statistics and sensitivity analysis. Descriptive statistics will be used to summarize the key input parameters (such as initial investment costs, operational costs, and fuel costs) and to provide an overall picture of the TCO.

Tools and Methods

1. **Sensitivity Analysis**

Sensitivity analysis will be conducted to assess the impact of variations in key input parameters on the TCO. This involves systematically varying a parameter within a realistic range and observing the resulting changes in the TCO. This type of sensitivity analysis is known as "one-way or univariate sensitivity analysis" (McCabe *et al*., 2020). This helps to isolate the effect of a parameter on the TCO.

2. Scenario Analysis

Scenario analysis involves evaluating the TCO under different combinations of input parameters to reflect potential future states. This method helps to understand the range of possible outcomes under various conditions. To perform scenario analysis, different scenarios will be defined, based on combinations of key input parameters. For example, an Optimistic Scenario might involve low fuel costs, high efficiency rates, and high economic incentives. Conversely, a Pessimistic Scenario could include high fuel costs, low efficiency rates, and low economic incentives. A Baseline Scenario will represent average values for all parameters.

For each defined scenario, the TCO will be calculated. The results will then be compared, to understand how different combinations of parameters affect the TCO. This approach allows for the identification of the most critical factors and their potential impact on the overall costs. The justification for using scenario analysis lies in its ability to provide a more comprehensive view of the potential variability in TCO. This helps in preparing for different future conditions and aids in strategic decision-making, ensuring that the analysis considers a range of possible outcomes.

3.8 Limitations of the Study

- The reliance on document analysis means that the study is limited by the availability and quality of existing documents. This can result in gaps or biases in the data collected, especially if key documents are unavailable or lack comprehensive information.

- The Fermi estimate method relies on educated guesses and approximations, which can introduce uncertainties in the calculated TCO. The accuracy of these estimates depends on the quality and precision of the input data.

- Sensitivity and scenario analyses depend on the assumptions made about the range and variability of input parameters. Incorrect assumptions or overlooked variables can lead to misleading conclusions about the robustness and feasibility of hydrogen fuel cell adoption.

- Document analysis is inherently static, relying on existing information that may not reflect the latest developments or emerging trends in the field of hydrogen fuel cell technology and policy.

- Rapid advancements in hydrogen fuel cell technology or significant changes in economic conditions and policies can quickly render the study's findings outdated. The dynamic nature of the field means that conclusions drawn today may not hold true in the near future.

- The documents analysed may come from sources with specific agendas or biases, such as government reports or industry publications. This can affect the objectivity and balance of the information collected and analysed.

3.9 Validity and Reliability

Ensuring the validity and reliability of research findings are crucial for establishing the rigor and credibility of this study. The study employs quantitative methods, thus focusing on ensuring external validity, internal validity, reliability, and objectivity. Below are the specific measures taken to maximize the validity and reliability of the findings.

3.9.1 *External validity (generalizability) OR transferability*

Transferability refers to the extent to which the findings of this study can be applied to other contexts or settings. Given that this research focuses on the adoption of hydrogen-based fuel cell energy storage systems in South Africa and Japan's

Ene-Farm program, the specific findings may not be directly generalizable to all other countries or regions. However, by providing detailed contextual information and a thorough analysis of the factors influencing adoption, this study aims to enhance transferability. Other researchers or practitioners can use the insights and methodologies from this study to explore similar contexts, adjusting for local conditions and variables. This approach aligns with the concept of transferability as outlined by Lincoln (1986), where the responsibility of demonstrating applicability lies with those seeking to transfer the findings to a different context.

3.9.2 *Internal validity OR credibility*

Internal validity concerns the extent to which the study accurately measures what it intends to measure. This study employs several techniques to ensure high internal validity:

- **Detailed Technological Model:** The mass-energy balance calculations and the Fermi estimate model are based on accurate technical data, ensuring that the calculations of TCO are valid.

- **Scenario Analysis:** The use of realistic and well-defined scenarios helps to ensure that the findings are relevant to actual policy and market conditions.

- **Triangulation:** Cross-verifying information from multiple sources (e.g. technical documents, policy papers, financial reports) helps to ensure the accuracy and validity of the data used in the analyses.

These steps align with the strategies for enhancing credibility in qualitative research as suggested by (Tracy, 2010).

3.9.3 *Reliability OR dependability*

Reliability refers to the consistency of the research findings over time. To enhance reliability, the study implements the following measures:

- **Structured Data Collection:** Using a standardized document analysis guide, ensures consistency in how data is collected and recorded.
- **Transparent Methodology:** Detailed documentation of the research process, including the steps taken in mass-energy balance calculations, Fermi estimate modelling, and scenario analysis, allows for reproducibility.
- **Statistical Tools:** Utilizing tools like Excel Solver for sensitivity analysis, ensures that the calculations and analyses are performed consistently and accurately.

Furthermore, maintaining an audit trail (Lincoln, 1986), will allow for the documentation of all decisions and changes made during the research process, enabling future researchers to replicate the study. Regular peer debriefing sessions will also be conducted to review and critique the research process and findings, ensuring consistency and reliability.

3.9.4 *Objectivity OR confirmability*

The following measures are taken to ensure objectivity:

- **Audit Trail:** Maintaining a detailed record of all decisions, data sources, and analytical steps helps ensure transparency and allows for external verification of the findings.

- **Peer-Review:** Seeking feedback from experts in the field during the research process helps to minimize researcher bias and ensures that the findings are based on objective analysis.

- **Use of Established Methods:** Employing well-established quantitative methods, such as the Fermi estimate model and scenario analysis, helps to maintain objectivity and reliability in the research findings.

3.10 Ethical Considerations

Confidentiality was ensured by anonymizing all sensitive information, with data securely stored and accessible only to the research team involved in this study. Ethical approval was granted by Wits University, confirming that the research complies with institutional ethical guidelines and upholds the highest standards of integrity and confidentiality.

3.11 Consistency Table

Table 7: Consistency table: research questions, propositions, data collection and data analysis

RQ #	Research Questions	Hyp #	Hypotheses	Data Collection Detail	Data Analysis Method
1.	What are the economic implications of implementing hydrogen fuel cells in the South African residential sector, and what is the Total Cost of Ownership under various scenarios?	1.	The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly, based on different technological and economic assumptions.	Document analysis (technical specifications, pricing data, economic reports), Fermi estimate model.	Scenario analysis, sensitivity analysis.
2.	How can the adoption of hydrogen fuel cell technology be optimized for residential energy use in South Africa, considering the factors that influence adoption in Japan's Ene-Farm program?	2.	Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are mitigated through subsidies.	Document analysis (technical specifications, pricing data, economic reports), Fermi estimate model.	Scenario analysis, sensitivity analysis.

RQ #	Research Questions	Hyp #	Hypotheses	Data Collection Detail	Data Analysis Method
3.	Can Japan's Ene-Farm policy framework be adapted for South Africa?	3.	The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.	Document analysis (policy papers, government reports, industry analyses, academic articles).	Thematic analysis, Comparative policy evaluation.
4.	What key barriers affect residential hydrogen fuel adoption in South Africa when comparing to Japan?	4.	The factors that contributed to the adoption of hydrogen fuel cell technology in Japan differ significantly for South Africa.	Document analysis (policy papers, government reports, industry analyses, academic articles).	Thematic analysis (policy comparison, market analysis, and identification of key barriers).

CHAPTER 4. PRESENTATION OF RESULTS AND DISCUSSION

4.1 Introduction

Chapter 4 evaluates the energy performance, cost implications, and scalability of the Ene-Farm system and solar PV systems for residential use in South Africa. Building on the research hypotheses outlined earlier, the analysis focuses on the Total Cost of Ownership (TCO) for each system under varying technological and economic scenarios. By integrating quantitative results from the Fermi estimate models with contextual discussions, the findings provide a comparative understanding of the two systems' feasibility. The discussion addresses the following: energy performance, scaling the technologies, and policy measures.

4.2 Results Pertaining to Hypothesis 1

Hypothesis 1: The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly, based on different technological and economic assumptions.

4.2.1 *Energy consumption estimate model for an urban apartment*

To estimate the basic energy consumption requirements, a typical urban apartment with four occupants (two adults and two children) in Johannesburg, South Africa, is considered. This model has been chosen, because apartment living may not have favourable conditions for solar PV installations. The hypothetical household reflects common energy usage patterns for lighting, appliances, water heating, and entertainment. Table 8 gives a summary of the key areas of consumption that were chosen for this study.

Table 8: Baseline scenario to determine electricity consumption in a Johannesburg apartment

Electrical Components	Power (W) per Component	Number of Components	Hours in Use	Daily Energy Demand (kWh)	Monthly Energy Demand (kWh)
LED Bulb	10	8	5	0.4	12
Fridge	150	1	9	1.35	40.5
Stove	2 000	1	1	2	60
Microwave	800	1	0.5	0.4	12
Kettle	1 500	1	0.5	0.75	22.5
Tumble Dryer	800	1	2	1.6	48
Washing Machine	500	1	2	1	30
Oven/Heaters	3 000	1	2	6	180
TV/Laptop, etc.	200	3	5.5	3.3	99
Other Miscellaneous e.g. Hair Dryer, etc.	1 000	1	1.75	1.75	52.5
				18.55	**556.5**

Table 8 is based on the following assumptions:

- Adults consume more energy when working from home.
- Children contribute to lighting, shared appliances and entertainment.
- A conservative approach is applied whereby maximum appliance use duration is modelled for a comprehensive view.
- Modern, energy efficient appliances are assumed.

The daily energy demand of 18.55 kWh / day aligns closely with reported averages of 20 kWh/day in South African households (Editor, 2024). Moving forward, the baseline scenario for this study is 18.55 kWh/day which is used for the techno-economic models of both systems.

4.2.2 *Technical performance assessment of the Ene-Farm and solar PV energy systems*

This section presents the results of the calculations (Appendix A) concerning energy consumption, fuel requirements, and operational contributions of the Ene-Farm and solar PV systems. These results serve as the foundation for evaluating the feasibility and cost-effectiveness of both systems in addressing residential energy demands.

The technical analysis is based on specific assumptions detailed below.

i. Ene-Farm PEMFC System Assumptions:

- **Electrical Efficiency:** 37% (Nishizaki, 2012).
- **Fuel Source:** Methane (natural gas), converted to hydrogen via Steam Methane Reforming (SMR) (Nishizaki, 2012).
- **Heat Recovery Efficiency:** 50% conservative (Hydrogeit, 2015).

- **Steam Methane Reforming (SMR) Efficiency:** 70% (McHugh, 2005).
- **The Hot Water Boiler Specifications is taken from the Ene-Farm Literature:** 200 litre capacity heated to 65°C (J. L. G. Association, 2022).
- **Lower Heating Value (LHV) of Methane:** 13.89 kWh/kg (50 MJ/kg) (Toolbox, 2003) .

ii. Solar PV System Assumptions:

- **System Capacity:** 5 kW inverter, 5 kWh battery.

  Note: The system consists of a 5 kW inverter and a 5 kWh battery, designed to provide power during peak hours when sunlight is less (4 PM – 8 PM). The total daily household energy demand is 18.55 kWh, but the system specifically supports energy needs during peak demand periods when grid electricity usage is highest. This does not imply that the entire 18.55 kWh is consumed solely during peak hours – rather, the battery is sized to contribute to load shifting and supplement energy supply when solar PV generation is unavailable.

- **Excess Energy Use:** Excess solar energy is directed to water heating.
- The solar PV system can operate at maximum capacity under favourable conditions.
- **Daylight Hours:** The system assumes 5 kW output for five daylight hours (10 AM – 3 PM) in Johannesburg.
- **Geyser:** Same specifications as Ene-Farm with a geyser efficiency of 90%.

4.2.2.1 *Fuel and heating calculations*

This section presents the methane fuel requirements necessary to meet a household's daily energy demand of 18.55 kWh/day. The calculational model accounts for energy savings, enabled by heat recovery from the Steam Methane Reforming (SMR) process (Fuh, 2024). Furthermore, the analysis incorporates the contribution of surplus solar energy to water heating. This section evaluates methane efficiency and highlights how heat recovery reduces energy consumption.

1. Technical Results for the Ene-Farm and Solar PV Energy Systems

A mathematical model was developed to assess how each system meets residential electricity and water heating demands. All technical calculations are detailed in Appendix A. The analysis considers a household baseline scenario with a daily energy demand of 18.55 kWh and a geyser capacity of 200 litres, requiring water to be heated from 15°C to 65°C. The calculations account for the efficiency of the geyser, the energy recovery capabilities of the Ene-Farm system, and the surplus energy available from the solar PV system under optimal sunlight conditions.

For the Ene-Farm system, the model incorporated the energy input required to meet the household's electricity demand, the amount of methane consumed, and the heat recovered from the system for water heating. For the solar PV system, the model assessed the total energy generated, household energy use, battery storage, and the resulting excess energy available for water heating.

The key technical parameters derived from these calculations are summarized in Table 9.

Table 9: Heating and fuel requirements for the Ene-Farm and solar PV energy systems (Appendix A)

Parameter	Value (Baseline Scenario)	Description
Geyser Heating (kWh/ Day)	11.6	Useful energy (excluding losses) required to heat 200 litres of water.
Methane Energy Input (kWh/Day)	50.14	Methane energy input for Ene-Farm.
Methane Required (kg/ Day)	3.61	Daily methane consumption.
Heat Recovery (kWh/ Day)	25.07	Waste heat recovered from Ene-Farm.
Solar Excess Energy (kWh)	1.45	Surplus solar energy for water heating.

The results demonstrate the following observations:

- **Geyser Heating Energy:** Heating 200 litres of water to 65 °C requires 11.6 kWh/ day of useful energy. When accounting for a geyser efficiency of 90%, the total energy input required is 12.89 kWh/day, so that 90% of the total is sufficient.
- **Ene-Farm System:** The system's 25.07 kWh/day of recovered heat meets water heating demands without extra energy input.
- **Solar PV System:** After meeting the household energy requirements and battery storage demands, the solar PV system provides 1.45 kWh/day of

surplus energy. This is significantly below the 12.89 kWh/day required for water heating, resulting in a shortfall of 11.44 kWh/day.

- **Energy Source Dependency:** The Ene-Farm system relies on methane as a fuel source, consuming 3.61 kg/day to generate electricity and recover heat. In contrast, the solar PV system operates entirely on renewable solar energy, eliminating fuel dependency but requiring supplementary measures to address the energy deficit for water heating.

4.2.2.2 *Grid-tied solar PV system considerations*

In the previous analysis, the solar PV system was assumed to be off-grid, meaning it was designed to meet the full energy demand of the household without external power sources. However, real-world conditions require consideration of seasonal and weather-related variations in solar availability. A grid-tied system allows for electricity import when solar generation is insufficient, particularly on cloudy or rainy days.

Assumptions:

- The system remains connected to the municipal electricity grid for backup power.
- Cloudy days significantly reduce solar PV output – typically producing only 10 – 25 % of peak capacity, depending on cloud cover density (Morgan, 2024). This is the unfavourable case.
- Johannesburg experiences approximately 2 349 cloudy hours per annum (Appendix A).
- On these days, the household will import electricity from the grid to meet energy shortfalls.

- The electricity tariff for block 1 consumption i.e. 0 – 600 kWh/month is around R3.29 per kW (Town, 2024).
- For simplicity, it is assumed that the electricity tariff rates remain steady over the system's lifespan.

While Johannesburg records approximately 2 349 cloudy hours per annum, these are not continuous full days of cloud cover. Rather, this represents shorter periods of cloudiness scattered across the year. For this study, these hours are aggregated into blocks of reduced generation during peak sun hours (approximately 5 hours/day), resulting in an estimated 470 'cloudy blocks' where solar PV efficiency is substantially impaired. This approach enables a fair assessment of generation deficits without assuming full-day blackout scenarios and aligns with Fermi estimation methodology used for pre-feasibility modelling.

4.2.3 *Comparative techno-economic analysis of Ene-Farm and solar PV energy systems*

This section compares the techno-economic performance of the Ene-Farm hydrogen fuel cell system, and the solar PV system based on two key criteria:

- **Energy Performance:** Efficiency in meeting daily energy demands and utilization of surplus energy for secondary purposes (e.g. water heating).
- **Cost Analysis:** Evaluation of initial investments, operational costs, and overall fuel dependency.

4.2.3.1 *Energy performance with grid-tied solar PV and Ene-Farm systems*

To comprehensively compare the Ene-Farm system, off-grid solar PV, and grid-tied solar PV, this section evaluates their ability to meet household energy demands under different scenarios. The analysis considers:

- **Daily Household Energy Demand:** 18.55 kWh.
- **Water Heating Demand:** 11.6 kWh day.
- Energy availability under clear vs. cloudy conditions for solar PV systems.
- Fuel and heat recovery contributions for Ene-Farm.

Table 10 presents the comparative performance of all three systems showing that while the Ene-Farm PEMFC offers high overall energy efficiency and integrated heat recovery, its dependency on methane and high capital cost reduce its economic attractiveness. In contrast, off-grid solar PV systems provide greater cost-effectiveness and independence from fuel sources, while grid-tied solar PV systems offer reliability during clear days but face significant performance drops and grid dependency on cloudy days.

Table 10: Energy performance comparison – Ene-Farm vs. solar PV (off-grid & grid-tied)

Metric	Ene-Farm PEMFC	Off-Grid Solar PV (5 kW)	Grid-Tied Solar PV (5 kW – Clear Days)	Grid-Tied Solar PV (5 kW – Cloudy Days)
System Capacity	1 kW (scalable)	5 kW	5 kW	5 kW

Metric	Ene-Farm PEMFC	Off-Grid Solar PV (5 kW)	Grid-Tied Solar PV (5 kW – Clear Days)	Grid-Tied Solar PV (5 kW – Cloudy Days)
Daily Energy Output (kWh)	18.55 (baseline)	25	25	2.5 – 6.25 (10 – 25% output)
Efficiency (%)	37% electrical, 50% heat recovery	~20% panel efficiency (abundant sunlight availability)	~20% panel efficiency	~20% panel efficiency
Excess Energy for Heating (kWh/ Day)	25.07 (heat recovery)	1.45 (excess solar energy)	1.45 (excess solar energy)	0 (no surplus energy)
Grid Import Required (kWh/Day)	N/A (fully independent)	N/A (fully independent)	0 kWh (self-sufficient)	12.3 – 16.05 kWh
Fuel Dependency	High (methane)	None (renewable)	None (renewable)	Partial (grid reliance on cloudy days)
Water Heating Feasibility	Fully covered via heat recovery	Needs additional solar geysers or resistive heating	Needs additional solar geysers or resistive heating	Needs additional heating system - grid import dependency

Technical Performance Discussion

The analysis evaluates the energy performance of both the Ene-Farm and solar PV systems in meeting residential electricity and water heating demands. The calculations incorporate efficiency metrics and energy recovery potential.

- **Ene-Farm System**

  With a system capacity of 1 kW, the Ene-Farm generates 18.55 kWh/day, sufficient to meet baseline household electricity needs. Its standout feature is its ability to recover 25.07 kWh/day of heat, which exceeds water heating requirements. The efficiency is enabled by a combination of 37% electrical efficiency and 50% heat recovery, making it highly effective for homes requiring both electricity and consistent water heating.

- **Solar PV System**

  The 5 kW solar PV system produces 25 kWh/day under optimal sunlight conditions, demonstrating its ability to generate energy beyond the household's electricity needs (18.55 kWh/day). While it efficiently allocates 5 kWh for battery charging, the 1.45 kWh/day of excess energy for water heating is insufficient to meet the 12.89 kW/day required for a 200 litre geyser. This shortfall highlights the need for supplementary components, such as additional panels or solar geysers, to address water heating demands effectively.

  In the case of a grid-tied solar PV system, performance remains optimal on clear days, eliminating the need for grid electricity. However, on cloudy days, solar PV generation drops to between 2.5 – 6.25 kWh/day, requiring electricity imports from the grid to cover the remaining demand. This dependency introduces additional operational costs, and therefore, grid-tied solar PV systems provide flexibility, but at the cost of intermittency-related expenses.

4.2.3.2 *Cost analysis – Ene-Farm PEMFC system versus solar PV system*

This section provides a detailed comparison of the Total Cost of Ownership (TCO) for the Ene-Farm hydrogen fuel cell system and the solar PV system. The analysis evaluates the financial feasibility of these systems in the South African residential context, using the baseline assumptions outlined in 4.2.1. In addition, the cost implications of having a grid-tied solar PV system are also assessed.

Background and Methodology

The cost model development, detailed in Appendix B, was conducted to assess the long-term economic viability of the two energy systems, incorporating variations in energy demand, fuel dependency, and system lifespan. For the Ene-Farm system, the analysis includes the initial purchase price, methane fuel costs, and operating lifespan. For the solar PV system, the analysis accounts for the upfront system cost, replacement costs for inverters and batteries, and a longer operational lifespan, along with potential grid electricity expenses in the grid-tied scenario.

Key Assumptions

The following assumptions were used as the basis for the cost models:

- **Exchange Rate:** US$1 = R18.00.
- **Daily Energy Demand:** 18.55 kWh/day, excluding water heating.
- **System Lifespan:**
  - Ene-Farm: 10 years – operational lifespan (Simader & Vidovic, 2022).
  - Solar PV: 25 years, with inverter and battery replacement at year 10 and year 20 (Babin, 2023).

Note: For consistency and comparability, both the solar PV system and the Ene-Farm hydrogen fuel cell system are evaluated over a standardized 25-year operational lifespan.

- **Natural Gas Price:** Methane fuel costs range between R220.00 and R320.00/ GJ. A midpoint value of R270.00/GJ (US$15/GJ) was used for this analysis (Energas, 2019).

- **Methane Lower Heating Value (LHV):** 50 MJ/kg (13.89 kWh/kg) (W. N. Association, 2020).

- **Initial Investment:**

  - **Ene-Farm:** US$5 200 for a 1 kW PEMFC system (~800 000 Yen) (Simader & Vidovic, 2022).

  - **Solar PV:** R160 000.00 (US$11 111.11 for a 5 kW system) (Appendix B).

- **Maintenance Costs:** Solar PV maintenance costs are considered minimal and therefore negligible. The Ene-Farm system includes free maintenance and repairs under its 10-year warranty (Simader & Vidovic, 2022).

Detailed calculations for both systems are provided in Appendix B.

4.2.3.2.1 *Total cost of ownership for the 1 kW Ene-Farm PEMFC fuel cell system*

The TCO for the 1 kW Ene-Farm system was calculated, based on its methane consumption and operating lifespan. Table 11 summarizes the input and output parameters used in the analysis, together with the results.

Table 11: TCO input and output parameters for the Ene-Farm system

Parameter	Value Taken from Reference Documents	Unit	Source/ Calculation
Input Parameters			
Initial Investment (Purchase Price of System)	5 200	US$	Reference documents (Simader & Vidovic, 2022)
Daily Methane Consumption	3.61	kg/day	Calculated
Annual Methane Consumption	1 317.65	kg/year	Daily methane consumption × 365
Methane Fuel Cost	15	US$/GJ	Reference documents (Energas, 2019)
Lifespan	10	Years	Reference documents (Simader & Vidovic, 2022)
Output Parameters			
Methane Energy Input (Daily)	50.14	kWh/day	Daily energy demand ÷ Electrical efficiency
Methane LHV	13.89	kWh/kg	Reference documents (W. N. Association, 2020)

Parameter	Value Taken from Reference Documents	Unit	Source/ Calculation
Cost per kWh (Methane)	0.054	US$/kWh	Methane cost ÷ Conversion factor (277.78 kWh/GJ)
Annual Methane Energy Consumption	18 302.16	kWh/year	Annual methane consumption × Methane LHV
Annual Methane Cost	988.32	US$/year	Annual methane energy consumption × Cost per kWh
Total Cost of Ownership over 10 years (TCO_{10yr})	**15 083.20**	**US$**	**Initial investment + (Annual methane cost × Lifespan)**
Total Cost of Ownership over 25 years (TCO_{25yr})	**45 249.60**	**US$**	**($TCO_{10yr} \times 3$)**

Observations from Table 11

For the baseline case, the Total Cost of Ownership of the 1 kW Ene-Farm system is estimated to be US$15 083.20 over a 10-year lifespan. This includes the initial purchase price of US$5 200 and the cumulative methane fuel costs of US$988.32/ year.

When normalised to a 25-year horizon to align with the assumed lifespan of the solar PV system, the Ene-Farm's Total Cost of Ownership increases proportionally to US$45 249.60. This reflects the need for two full system replacements (at years 10 and 20), as well as ongoing fuel costs. The calculation assumes identical cost per unit across all time intervals and does not incorporate discounting or inflation. This simplification is applied to maintain a consistent and comparable basis with the solar PV system, which is also evaluated over a 25-year period. The significantly higher cumulative expenditure underscores the long-term economic disadvantage of the hydrogen system under current market conditions.

Note: In later sections, the TCO of the Ene-Farm system is scaled to a 5 kW capacity to enable a direct comparison with the 5 kW solar PV system.

4.2.3.2.2 *Total cost of ownership for the 5 kW solar PV system*

The TCO for the 5 kW solar PV system was calculated over a 25-year lifespan, accounting for the initial purchase cost and two replacements of the inverter and battery at year 10 and year 20. Table 12 summarizes the parameters and results detailed in Appendix B.

Table 12: Input parameter data for the solar PV system

Parameters	Value from Online Resources	Unit	Source/Calculation
Input Parameters			
Initial Investment (Purchase Price of System)	160 000.00	ZAR	Calculation (Appendix B, section iii)
Replacement Cost (Inverter and Battery)	80 000.00	ZAR	Reference documents/online resources (DIRECT, 2025)

Parameters	Value from Online Resources	Unit	Source/Calculation
Lifespan	25	Years	Reference documents/online resources (Huwawei, 2023)
Replacement Timeline	10, 20	Years	Reference documents/online resources (Babin, 2023)
Exchange Rate	18.00	ZAR/US$	Assumed for currency conversion
Output Parameters			
Total Cost of Ownership (TCO)	240 000.00	ZAR	Initial investment + Replacement cost
TCO (US$)	**13 333.33**	**US$**	**TCO (ZAR) ÷ Exchange rate**
Number of Replacements (In 25 Years)	2	Count	Replacement timeline (10 years) within lifespan

Observations from Table 12:

Table 12 shows that in South Africa, for the baseline scenario, the total cost of ownership of the 5 kW solar PV system is estimated to be **US$13 333.33** over a 25-year lifespan. This cost includes both the initial investment and the replacement cost after 10 and 20 years.

4.2.3.2.2.1 *Grid-tied 5 kW solar PV system*

In addition to the off-grid model, a grid-tied 5 kW solar PV system was evaluated over a 25-year lifespan, incorporating the initial purchase cost, two replacement costs for the battery and inverter, and the cost of purchasing grid electricity during cloudy days. The input parameters are the same as in Table 12. Detailed calculations can be found in Appendix B, section iv. The output parameters are summarized in Table 13.

Table 13: Total cost of ownership: grid-tied solar PV system

Parameter	Value	Unit	Calculation
Lower Bound TCO (10% Efficiency Cloudy Days)	860 830.05	ZAR	160 000.00 + 80 000.00 + 620 830.05 (Appendix B)
Lower Bound TCO (US$)	**47 823.89**	**US$**	**TCO (ZAR) ÷ Exchange rate**
Upper Bound TCO (25% Efficiency Cloudy Days)	715 776.30	ZAR	160 000.00 + 80 000.00 + 475 776.30 (Appendix B)
Upper Bound TCO (US$)	**39 765.35**	**US$**	**TCO (ZAR) ÷ Exchange rate**

- Under worst-case cloudy conditions (10% output efficiency), the grid-tied TCO is US$ 47 823.89.
- Under best-case cloudy conditions (25% output efficiency), the grid-tied TCO is US$ 39 765.35.

4.2.3.2.3 *Comparison of key metrics*

The technical and economic performance of both systems is summarized in **Table 13** for direct comparison.

Table 14: Comparison of key metrics between Ene-Farm PEMFC and solar PV systems

	Metric	Ene-Farm PEMFC	Solar PV System – Off-Grid	Grid-Tied Solar PV System
1	**System Capacity**	1 kW (scaled-up to 5 kW in the next section)	5 kW	5 kW
2	**Daily Energy Output (kWh)**	18.55	25	25 (clear)/ 2.5 – 6.25 (cloudy)
3	**Efficiency (%)**	37% electrical, 50% heat recovery	20% panel efficiency	20% panel efficiency
4	**Excess Energy for Heating (kWh/Day)**	25.07	1.45	Up to 1.45 on clear days (0 on cloudy days)
5	**Initial Investment (US$)**	5 200	11 111.11 (scaled-up to meet geyser heating requirements in the next section)	11 111.11 (battery + inverter size may be reduced, but grid reliance adds cost)
6	**Total Cost of Ownership (US$)**	45 249.60	13 333.33	39 765.35 – 47 823.89 (depending on cloudy day efficiency)
7	**Lifespan (Years)**	25	25	25

	Metric	Ene-Farm PEMFC	Solar PV System – Off-Grid	Grid-Tied Solar PV System
8	**Operational Fuel Dependency**	High (requires methane)	None (renewable energy)	Partial (grid reliance on cloudy days)
9	**Water Heating Efficiency**	Covered via heat recovery	Not sufficient without additional panels, etc.	Not sufficient without additional panels, etc. (grid fall back for hot water if needed)

Observations and Discussion from Table 13

- The TCO of the Ene-Farm system is US$45 249.60 over 25 years, assuming three complete system lifecycles. In contrast, the off-grid solar PV system incurs a TCO of US$13 333.33, while the grid-tied PV system ranges between US$ (39 765.35 – 47 823.89), depending on the proportion of cloudy day reliance.

- The solar PV systems are significantly more cost-effective over the 25-year horizon, primarily due to their zero fuel costs and limited replacement requirements (mainly batteries and inverters around years 10 and 20).

- The Ene-Farm system meets the household's exact daily electrical demand of 18.55 kWh and also provides a substantial 25.07 kWh/day of thermal energy through heat recovery—sufficient for household water heating needs.

- The solar PV system generates 25 kWh/day, but the excess energy of 1.45 kWh/day is insufficient to meet water heating demands without additional components like solar geysers or more panels.
- The solar PV system generates 25 kWh/day, with only 1.45 kWh/day of usable excess energy, which is generally insufficient for water heating without the addition of solar thermal systems or upsized PV capacity.
- The Ene-Farm system relies on methane, leading to ongoing fuel costs and dependency on fuel supply chains.
- The solar PV system is independent of external fuel sources, leveraging renewable energy, making it more environmentally friendly and economically stable over time.
- The 25-year comparison assumes no discounting and identical unit costs across time, providing a consistent baseline for techno-economic evaluation.

4.2.3.3 *Cost scaling and comparative analysis*

Building on the findings from the baseline Total Cost of Ownership (TCO) analysis, this section evaluates the scalability of the Ene-Farm and solar PV systems. The focus is on understanding the cost implications of scaling each system to meet higher energy demands and comparing their economic and technical feasibility. The analysis also explores the solar PV system's ability to address water heating requirements.

i) Scaling Ene-Farm to 5 kW

The Ene-Farm PEMFC fuel cell unit analysed in the baseline scenario is a 1 kW residential system. To enable a fair techno-economic comparison with the 5 kW solar PV system, the Total Cost of Ownership (TCO) was scaled using the two-thirds power law (Randall W. Whitesides, 2020), which reflects non-linear cost behaviour as system capacity increases. This approach assumes modular scalability of the Ene-Farm system, consistent with its distributed residential deployment model.

Based on this scaling method, the TCO of a 5 kW Ene-Farm system over a 10-year period is estimated as: US$44 103.54 (Appendix B).

To align with the 25-year analysis window used for the solar PV system, this scaled TCO is extended by accounting for full system replacements at year 10 and again at year 20.

The total 25-year cost is therefore: US$132 310.62 (Appendix B).

ii) Scaling Solar PV to Meet Water Heating Needs

To meet both electricity and water heating requirements, the solar PV system must be scaled to accommodate the total household energy demand, estimated as:

- **Baseline Electricity Demand:** 18.55 kWh/day.
- **Water Heating Demand:** 11.6 kWh/day.
- **Battery Charging Demand:** 5 kWh/day.
- **Total Demand:** 35.15 kWh/day.

For an optimal sunlight period of five hours per day, the required capacity of the solar PV system was calculated as 7.03 kW (Appendix B). A component-specific scaling approach was applied. Base component costs were derived from the 25-year TCO of the 5 kW system, which included all expected lifecycle replacements.

The scaling applied reflects full lifecycle-adjusted costs. The results of the scaling analysis are summarized in Table 15.

Table 15: Scaled cost of solar PV components for a 7.03 kW system

Component	% Cost of Total (%)	Calculated Cost (US$)	Exponent (n)	Scaled Cost (US$)
Solar panels	40	5 333.33	0.9	7 247.45
Inverter	20	2 666.66	0.7	3 385.00
Battery	20	2 666.66	0.6	3 271.60
Soft costs	20	2 666.66	0.9	3 623.73
TCO				**17 527.77**

Note: Soft costs refer to non-hardware expenses associated with the installation and deployment of energy systems. These typically include permitting fees, labour, system design, customer acquisition, inspections, and certification.

Observations from Table 15

- Scaling the solar PV system to 7.03 kW increases its initial TCO to US$17 527.77, based on component-specific scaling using industry-accepted exponents.
- This TCO figure is inclusive of full 25-year lifecycle costs, including replacement cycles for inverters and batteries. This is because the base cost percentages used for scaling were derived from a 25-year TCO model that already accounted for two full replacements of these components.

- Among all components, solar panels contribute the largest share to the TCO (US$7 247.45), scaling almost linearly with system capacity due to their modular design (exponent = 0.9).

- Inverters and batteries benefit from favourable economies of scale (scaling exponents = 0.7 and 0.6 respectively), leading to less dramatic cost increases despite capacity expansion.

- The absence of operational fuel costs ensures that the solar PV system's TCO remains competitive, even at higher capacities.

- Compared to the 5 kW Ene-Farm system (TCO = US$132 310.62 over 25 years), the 7.03 kW solar PV system offers a significantly lower TCO, while simultaneously supporting electricity and thermal energy needs.

iii) Cost Scaling for Grid-Tied solar PV to Heat Geyser Water on Cloudy Days

To supply both household electricity (18.55 kWh/day) and water heating (≈12.89 kWh/day), the system must provide approximately 31.44 kWh/day. A grid-tied configuration still relies on Eskom electricity during cloudy days, where solar generation can fall between 10 – 25% of peak output. Below is an illustrative component-wise scaling for a 7 kW system, plus an estimate of annual grid imports under worst-case conditions.

Table 15 shows the TCO of the scaled 7 kW base system ~US$17 527.77.

For the worst-case scenario on a cloudy day i.e. 10% output, Table 16 summarizes the key parameters and TCO for the 7 kW grid-tied solar PV system.

Table 16: Key parameters and TCO for the 7 kW grid-tied solar PV system (worst-case 10% output)

Parameter	Value	Explanation
System Capacity	7 kW	Sized to meet 31.44 kWh/day
Capital Cost	US$17 527.77	Previously calculated
Worst-Case Cloudy Day Output	3.5 kWh/day	10% of 7 kW for 5 hours
Daily Shortfall	27.94 kWh/day	Appendix B
Annual Shortfall	~1 537 kWh/year	Assuming 55 cloudy days (worst-case blocks)*
Tariff	US$0.18/kWh	R3.292 / kWh at US$1 = R18.00 (Town, 2024)
Annual Grid Cost	~US$277.00	1 537 kWh × US$0.18/kWh
25-Year Grid Cost	~US$6 925.00	277 × 25
Total Cost of Ownership (TCO)	US$24 452.77	17 527.77 + 6 925.00 (Appendix B)

***** The assumption of 55 cloudy days per year is derived from Johannesburg's 2 349 annual cloudy hours, equating to approximately 470 five-hour cloudy blocks, which, when aggregated, represent full-day equivalents based on typical solar peak hour distribution.

Observations from Table 16

- **Cloudy Day Dependence:** At 10% solar efficiency, the system only produces 3.5 kWh/day, requiring 27.94 kWh/day from the grid on those worst-case blocks.

- **Lifetime Grid Purchases:** Over 25 years, grid reliance adds ~US$6 925.00 to the TCO, culminating in a final TCO of US$24 452.77.
- **Trade-Off:** This approach mitigates the need for oversized batteries but increases long-term operational costs due to cloudy day grid imports.

iv) Cost Comparison across Capacities

Figure 4 illustrates the cost scaling behaviour of the Ene-Farm and solar PV systems, highlighting differences in TCO trends as capacity increases.

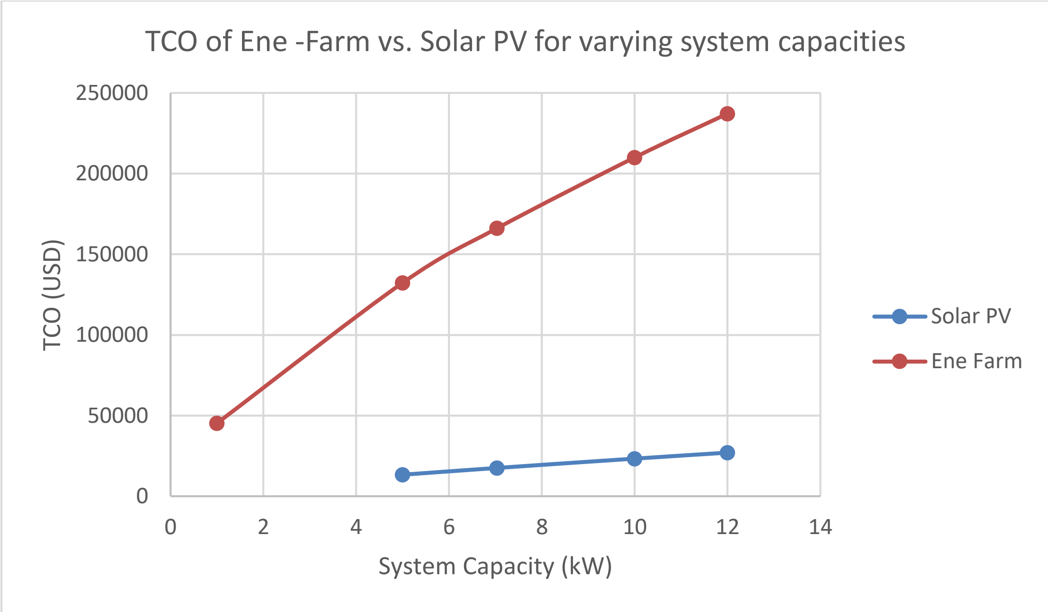

Figure 4: Plot Illustrating the Increase in Total Cost of Ownership with Capacity Scaling for Ene-Farm and Solar PV Energy Systems

General Discussion

Figure 4 highlights the scaling behaviour of the Total Cost of Ownership (TCO) for the Ene-Farm and solar PV systems.

The TCO for the Ene-Farm system initially rises steeply, primarily due to its reliance on methane as a fuel source, which contributes significantly to operational costs. This high dependency on external fuel not only increases costs but also makes the system more vulnerable to price fluctuations in natural gas markets. The gradient of the TCO curve begins to flatten at larger capacities, reflecting economies of scale achieved through modularity. However, the overall

TCO for the Ene-Farm system remains substantially higher than that of the solar PV system, largely due to its shorter manufacturer lifespan (10 years) which necessitates two complete system replacements over a 25-year evaluation window. Although modular scalability introduces some economies of scale—modelled using the two-thirds power law—the system's TCO remains high, reaching US$132 310.62 for a 5 kW configuration over 25 years. A significant portion (approximately 65.5%) of this cost is attributable to ongoing methane fuel expenses, making the system vulnerable to fluctuations in natural gas prices and availability.

In contrast, the solar PV system exhibits a more gradual and linear increase in TCO as capacity scales. This trend is primarily attributable to the absence of operational fuel costs and the cost-effectiveness of scaling key components, such as inverters and batteries, which benefit from economies of scale. For instance, scaling to a 7.03 kW system, necessary to cover both electricity (18.55 kWh/day) and water heating needs (12.89 kWh/day), increases the TCO to only US$17 527.77 over 25 years — significantly less than the US$132 310.62 required to scale the Ene-Farm to 5 kW for the same period (Appendix B).

From a technical perspective, the Ene-Farm system offers an advantage in its ability to integrate electricity generation and heat recovery. This allows it to meet both daily electricity and water heating requirements without the need for additional components or infrastructure. However, this technical advantage is offset by its reliance on methane, which introduces ongoing operational costs and emissions, making it less suitable for long-term, sustainable residential applications.

On the other hand, the solar PV system, while requiring supplementary measures such as additional panels to fully meet water heating demands, benefits from its reliance on renewable solar energy. This independence from external fuel sources not only reduces long-term costs but also aligns with South Africa's abundant sunlight availability (Abdelrazik, 2022), making it a more sustainable and environmentally friendly option.

In grid-tied configurations, solar PV systems introduce a trade-off: they avoid oversized batteries by importing electricity on cloudy days, but incur long-term grid costs. Under worst-case scenarios (10% solar output efficiency), the system relies on 27.94 kWh/day from the grid for a cumulative 55 cloudy days annually, adding US$6 925 to the 25-year TCO — bringing the total to US$24 452.77 (Town, 2024; Appendix B). Even in this conservative case, solar PV remains more cost-effective than its hydrogen-based counterpart.

Discussion on Economic and Policy Implications

The economic analysis highlights the importance of fuel independence in reducing the long-term cost of ownership for residential energy systems. For South Africa, where sunlight is a readily available resource, investments in solar PV systems offer a more viable and sustainable solution, compared to the infrastructure-heavy and fuel-dependent Ene-Farm system. Furthermore, scaling solar PV systems to larger capacities demonstrates significant cost advantages, reinforcing their suitability for meeting both urban and rural energy demands. In the case of the grid-tied solar PV system, high electricity prices penalize smaller systems with heavy grid reliance. Innovative tariffs or net-metering can help households sized at 5 kW or below manage operational costs.

The modularity and integrated heat recovery features of the Ene-Farm system suggest potential niche applications, particularly in areas where natural gas infrastructure is already established, or where the dual generation of electricity and heat can provide significant efficiency gains. Future research could explore hybrid systems that combine solar PV with heat recovery technologies to leverage the strengths of both systems.

4.3 Results and Discussion Pertaining to Hypotheses 2 and 3

Hypothesis 2: Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are mitigated through subsidies.

Hypothesis 3: The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.

The successful adoption of hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program (Simader & Vidovic, 2022), provides valuable lessons on addressing the economic and infrastructural challenges associated with these systems. However, the feasibility of replicating such strategies in South Africa requires a thorough examination of local energy policies, subsidy frameworks that are currently available, and market conditions.

This section explores Japan's approach to mitigating costs and evaluates its applicability to South Africa. It contrasts the two countries' policy landscapes, energy priorities, and economic contexts, shedding light on potential barriers and opportunities for hydrogen fuel cell adoption in the South African residential sector.

4.3.1 *Japan's approach to mitigating costs*

Japan's Ene-Farm program overcame high upfront and operational costs through a strategic combination of government subsidies, industry partnerships, and policy frameworks. These factors, outlined in (Simader & Vidovic, 2022), provide critical insights into enabling wide-scale deployment of hydrogen fuel cells in residential settings. Below is a list of the factors that contributed towards Japan's integration of Ene-Farm systems in the residential sector taken from (Simader & Vidovic, 2022).

1. **Direct Purchase Subsidies:** Japan initially subsidized 50% of the system purchase cost which was critical factor in driving early adoption. This level of support lowered the Total Cost of Ownership (TCO) for households, addressing one of the largest barriers to entry.

2. **Operational Incentives:** Incentives also extended to operational costs, particularly for methane through discounted residential gas tariffs and bundled service plans offered by utilities, which reduced the long-term fuel expenses for Ene-Farm users. This ensured that the systems remained affordable even after installation.

3. **Industry Partnerships:**

   - Gas utilities like Tokyo Gas partnered with manufacturers such as Panasonic and Toshiba to streamline system distribution, installation, and servicing.

   - Collaborative efforts led to economies of scale, with manufacturers reducing production costs while utilities ensured reliable supply chains and maintenance services.

4. **Policy Integration:** Hydrogen technology was integrated into Japan's national energy strategy since 2017. Hydrogen energy infrastructure was supported by long-term subsidies and policies that target clean energy solutions as part of their pledge to achieve net-zero emissions by 2050 (*Basic Hydrogen Strategy (EN).pdf*, 2017).

4.3.2 *South African energy policies and subsidies*

South Africa's energy landscape differs significantly from Japan's, presenting unique challenges as well as potential opportunities for adopting hydrogen fuel cell technology. Current policy documents, such as the *Hydrogen Society*

Roadmap (DSI, 2021) and the *Proposed Green Hydrogen Commercialisation Strategy* ((DTIC, 2022), highlight hydrogen's role in decarbonization but lack the comprehensive support mechanisms evident in Japan. Key existing subsidies (Geddes, 2024) include:

1. **Fossil Fuel Subsidies:** South Africa allocates 35.0 billion rand annually to VAT exemptions and fuel levy refunds, primarily benefiting petroleum and natural gas industries.

2. **Electricity Subsidies:** The Free Basic Electricity (FBE) program, with a budget of 10.6 billion rand, provides 50 kWh/month to disadvantaged households.

3. **Hydrogen Incentives:** While the *Hydrogen Society Roadmap* highlights hydrogen's role in decarbonization, it lacks direct subsidies for residential fuel cell adoption – a potential area for further exploration.

4. Additionally, the 2023 *Solar Energy Tax Credit* allowed individuals to claim a rebate of 25% on new PV panel installations, capped at R15 000.00. Note that this tax incentive was included in the analysis as it represents a recent policy effort to promote residential solar adoption, illustrating the government’s willingness to support renewable energy, even if temporarily. Its inclusion provides contextual relevance to policy-driven affordability for solar PV systems during the study period.

Table 17: Comparison of Japan's and South Africa's energy policies

Aspect	Japan's Approach	South Africa's Energy Policies
Direct Purchase Subsidies	Subsidized 50% of purchase costs to lower TCO.	No direct subsidies for hydrogen fuel cells.

Aspect	Japan's Approach	South Africa's Energy Policies
Operational Incentives	Subsidies for methane costs ensured affordability for operational expenses post-installation.	No existing operational subsidies for hydrogen systems.
Industry Partnerships	Collaboration' with manufacturers and utilities streamlined costs.	Potential partnerships (e.g. Sasol) require substantial investment.
Policy Integration	Hydrogen fuel cells integrated into Japan's national energy strategy, supported by long-term subsidies and clean energy policies.	South Africa's Hydrogen Society Roadmap emphasizes decarbonization but lacks detailed policies or funding for residential hydrogen adoption.
Fossil Fuel Subsidies	Minimal, with priority on clean energy.	Existing fossil fuel subsidies could be redirected to support cleaner sources of electricity.
Electricity Subsidies	Not applicable to hydrogen adoption.	Programs like Free Basic Electricity (FBE) could potentially be modified to support hydrogen fuel cells for households.
Tax Incentives	Tax incentives promoted CO_2 reduction and increased system installations by 2023 (Japan LP Gas Association, 2022).	The 2023 solar energy tax credit provided a 25% rebate, showing potential for hydrogen-related incentives.

Discussion on Hypotheses

The comparative analysis of Japan's and South Africa's energy policy landscapes highlights fundamental differences that have significant implications for the feasibility of residential hydrogen fuel cell systems in South Africa. These differences highlight the challenges of directly replicating Japan's Ene-Farm model in a South African context.

Economic Feasibility of Subsidies in South Africa

In Japan, the success of the Ene-Farm program was driven by substantial subsidies, covering up to 50% of the system's purchase cost and extending to operational incentives for methane. This subsidy structure reduced the Total Cost of Ownership (TCO) to levels accessible for middle-class households and encouraged early adoption. However, implementing such an extensive subsidy program in South Africa would face significant fiscal constraints:

1. **Public Budget Allocation**

   South Africa already allocates 35 billion rand annually to fossil fuel subsidies and 10.6 billion rand to electricity subsidies under the Free Basic Electricity (FBE) program. Redirecting these funds to support hydrogen fuel cell adoption would necessitate a shift in policy priorities and significant political will, particularly in a context where electricity access and affordability are critical issues for large segments of the population (Ye & Koch, 2023).

2. **Magnitude of Subsidy**

   For hydrogen fuel cells to be competitive in South Africa, subsidies would need to offset high upfront costs (e.g. US$5 200.00 for a 1 kW Ene-Farm system) and ongoing methane costs. Given the country's lower GDP per capita and high unemployment rate (Momentum, 2023), the subsidy burden would be disproportionately higher relative to Japan. This raises questions about the sustainability and equity of such an approach.

3. **Opportunity Cost**

   Subsidizing hydrogen fuel cells on a large scale would divert resources from more cost-effective and scalable renewable energy solutions like solar PV, which already benefits from supportive policies such as the 2023 Solar Energy Tax Credit. Solar PV's lower TCO and alignment with South Africa's abundant sunlight make it a more economically feasible option for widespread residential deployment.

Reticulation Costs and Infrastructure Challenges

The feasibility of hydrogen fuel cell adoption in South Africa is also heavily constrained by the lack of hydrogen reticulation infrastructure. In Japan, the deployment of Ene-Farm systems was supported by a well-established natural gas network, which minimized additional infrastructure costs. In contrast:

1. **Lack of Existing Infrastructure**

   South Africa's limited natural gas distribution network would require significant investment in pipelines, storage facilities, and hydrogen distribution channels to support widespread adoption of residential fuel cells. These infrastructural costs would substantially increase the overall implementation expense, rendering the technology less competitive compared to alternatives like solar PV.

2. **Transitioning to Green Hydrogen**

   If the long-term goal is to transition Ene-Farm systems to green hydrogen as part of South Africa's decarbonization strategy, the cost and energy efficiency implications become increasingly prohibitive. Producing green hydrogen via electrolysis — powered by renewable energy — is currently far more expensive than methane reforming (Franzmann, 2023), and the round-trip efficiency is notably poor compared to direct electricity use from solar PV. However, in dense urban environments such as apartment complexes where rooftop space is limited, solar PV may not be a viable standalone option. In such cases, hydrogen fuel cell systems — especially when paired with heat recovery — could offer a compact and reliable alternative, justifying their use despite higher operational costs. These niche applications may present targeted opportunities for hydrogen integration, even as broader residential use remains constrained by efficiency and economic barriers.

3. **Energy Efficiency Considerations**

   Transitioning to green hydrogen introduces additional inefficiencies, as the process of producing, storing, and distributing hydrogen incurs energy losses at multiple stages. Solar PV, by comparison, directly converts sunlight into electricity without intermediate conversion losses, making it a more efficient solution for meeting residential energy demands.

Technical and Market Considerations

While hydrogen fuel cells offer technical advantages, such as combined heat and power generation, their applicability in South Africa is limited by differences in energy priorities and market dynamics:

1. **Market Readiness**

   The adoption of Ene-Farm in Japan was facilitated by a high degree of urbanization (discussed in next section), dense housing arrangements, and a strong focus on decarbonization. In South Africa, where urbanization levels are lower and housing is less densely concentrated, modular and scalable energy solutions like solar PV are more suitable for addressing diverse residential energy needs.

2. **Focus on Energy Security**

   South Africa's energy policy priorities are shaped by persistent issues of load-shedding and grid instability. Solar PV systems, with battery storage, provide an immediate solution to these challenges, whereas hydrogen fuel cells would require significant lead times for infrastructure development and market penetration.

4.4 Results and Discussion Pertaining to Hypothesis 4

Hypothesis 4: The factors that contributed to the adoption of hydrogen fuel cell technology in Japan differ significantly for South Africa.

The adoption of hydrogen fuel cell technology, as demonstrated in Japan's Ene-Farm program, was influenced by a unique combination of geographical, climatic, technological, economic, and social factors. These factors differ substantially from those in South Africa, presenting distinct challenges for implementing similar systems. The data comparison table can be found in Appendix B together with references where applicable.

1. **Geography and Population Density**: Japan's high urbanization rate of 92% (Statista, 2023a) and dense urban environments facilitated the adoption of compact hydrogen systems like Ene-Farm, which efficiently provided electricity and heating for smaller households (Simader & Vidovic, 2022). In comparison, South Africa's urbanization rate is significantly lower, with 68.82% of the population living in urban areas (Statista, 2023b). This highlights the vast differences in urban density, and suggests that South Africa's urban landscape, characterized by more spread-out living

arrangements and less densely populated areas, necessitates modular and scalable hydrogen systems to address the diverse energy needs of its urban and rural populations effectively.

2. **Climate:** Japan's climate features cold winters, with significant snowfall in many regions, leading to increased energy demand for heating. Hydrogen systems like Ene-Farm are particularly advantageous in such conditions, as they provide both electricity and heat, efficiently addressing winter heating needs. Conversely, South Africa experiences mild winters with no significant snowfall and an average daytime temperature of 26°C (World Bank Group, 2021), reducing the need for extensive heating. The primary energy demand in South Africa is for water heating and electricity, making hydrogen systems less critical for winter heating but still valuable for household energy needs in areas with unreliable electricity.

3. **Technological:** Japan's adoption of the Ene-Farm PEMFC fuel cell system reflects its focus on energy efficiency and reducing carbon emissions through advanced technologies. The system's ability to generate both electricity and heat, makes it particularly suited to urban residential settings where space for energy generation systems is limited, and efficient energy use is a priority. Additionally, the dual-generation feature aligns with Japan's broader environmental goals and its commitment to reducing household carbon footprints. In contrast, South Africa's reliance on solar PV systems stems from the urgent need to address frequent power outages caused by load-shedding, which has severely impacted energy reliability. The adoption of solar PV technology is driven less by environmental considerations and more by the necessity to ensure consistent energy access. While solar PV systems are effective in harnessing South Africa's abundant sunlight, their ability to address heating needs is limited compared to the Ene-Farm system.

4. **Socio-Economic:** Japan's robust economic position, with a GDP per capita of US$33.77 million, an average annual income of US$39 350.00, and a low unemployment rate of 2.6% (World Data, 2025), allows the government and consumers to invest in advanced technologies like hydrogen fuel cells. In contrast, South Africa's GDP per capita is significantly lower at US$6.02 million, with an average annual income of US$6 480.00 and a high unemployment rate of 28% (Worldometer, 2025). These economic disparities indicate that South Africa will require substantial government subsidies and financial mechanisms to make hydrogen fuel cell systems affordable for households, especially if this technology will be deployed in rural areas. Currently, South Africa's power utility, Eskom, employs around 39 000 people (Smith, 2023) and the coal mining sector employs more than 100 000 people (Steenkamp, 2024). If South Africa had to take a similar approach to reduce their carbon emissions as Japan did, this would mean that around 0.5% of the country's total employment would be lost (Steenkamp, 2024).

5. **Energy Balance (World Data, 2025):** Japan's energy production capacity of 3 065 474 GWh reflects its advanced industrial economy, which is a major driver of its energy consumption. The country's large manufacturing and export-oriented industries, such as automotive and electronics, require vast amounts of energy, contributing to its significant carbon footprint of 1.01 billion tons CO_2 emissions annually. Hydrogen fuel cells are part of Japan's strategy to decarbonize its industrial energy demand while providing residential energy solutions. South Africa, with a much lower energy production capacity of 555 480 GWh, has a relatively smaller industrial base. However, industries like mining and manufacturing still dominate the country's energy consumption. The high energy demand from industries, coupled with frequent load-shedding, creates significant strain on South Africa's electricity grid. Hydrogen fuel cell systems offer a dual benefit: they can reduce reliance on the grid by providing off-grid power solutions and enhance energy reliability

for both households and industries. Additionally, their integration with renewable energy can support decarbonization efforts and reduce CO_2 emissions.

4.5 Discussion and Summary of Results

This section consolidates the findings presented in Chapter 4, integrating technical performance, cost analysis, and scalability to evaluate the feasibility of Ene-Farm and solar PV systems for residential energy needs in South Africa.

4.5.1 *Hypothesis 1*

Technical Performance

The Ene-Farm system demonstrated higher efficiency through its combined electricity generation and heat recovery capabilities. It was able to meet the baseline energy demand (18.55 kWh/day) while generating an additional 25.07 kWh/day for water heating.

In comparison, the solar PV system, with an output of 25 kWh/day, only produced 1.45 kWh/day of excess energy under optimal conditions. This was insufficient to meet water heating requirements without additional components, such as solar geysers or supplementary panels.

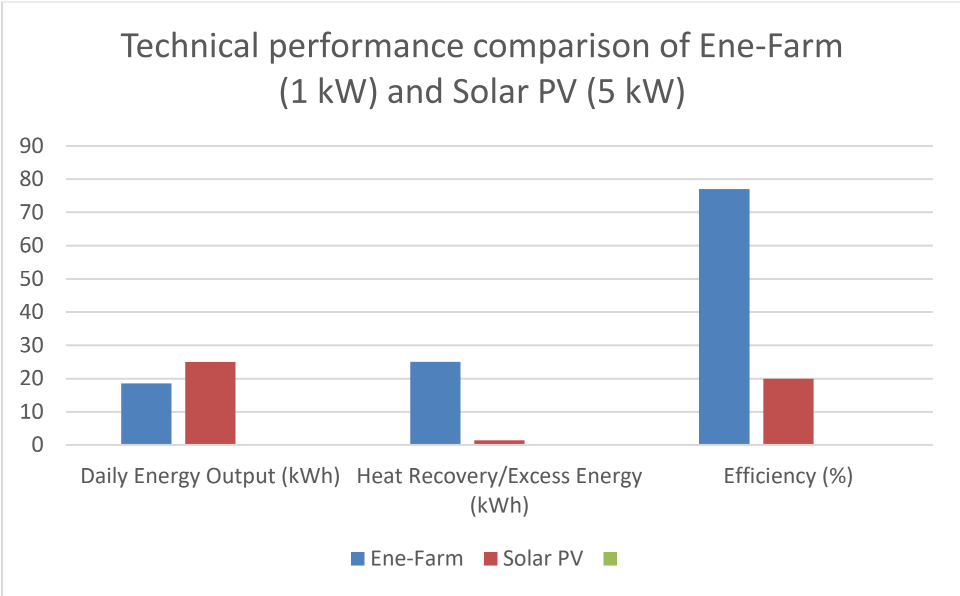

Figure 5: Technical Performance Comparisons

Figure 5 demonstrates that while the Ene-Farm system excels in heat recovery and water heating, it is limited to 1 kW capacity in its baseline configuration. This necessitates continuous operation to meet daily energy demands, a significant limitation compared to the solar PV system's ability to produce energy more rapidly (e.g. 5 kW output in just one hour under optimal sunlight).

Cost Analysis and Subsidy Considerations

The Total Cost of Ownership analysis revealed a clear economic advantage for the solar PV system. Over a 25-year lifespan, the solar PV system's TCO was calculated to be US$13 333.33 for a 5 kW system, compared to US$45 249.60 for a 1 kW Ene-Farm system over the same period.

To explore the impact of subsidies, a 50% direct purchase subsidy—similar to Japan's hydrogen fuel cell program—was applied to the scaled 5 kW Ene-Farm system. This reduced its TCO from US$132 310.63 to US$66 155.32:

- Cost per kW for solar PV: US$ 13 231.06

- Cost per kW for the subsidized Ene-Farm system: US$4 409.38.

Despite the subsidy, the Ene-Farm's per-kW cost remains almost 5× higher than that of solar PV, highlighting the continued cost gap between fuel cell and solar PV technologies for residential-scale applications in South Africa.

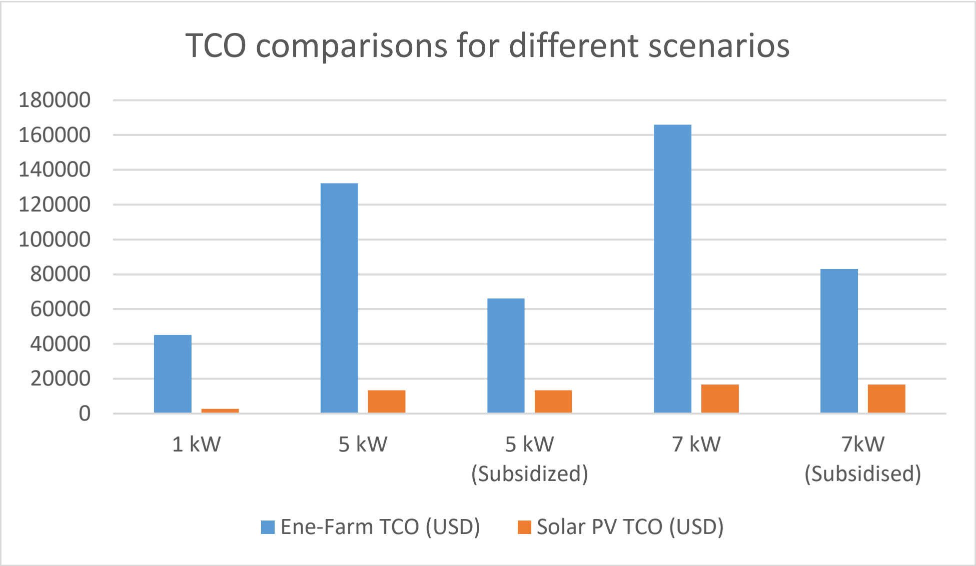

Figure 6: TCO Comparisons under Different Scenarios

Figure 6 shows that the Ene-Farm system's TCO increases to US$132 310.63 when scaled to 5 kW, making it significantly less competitive than solar PV. Even with subsidies, the cost per kW for the Ene-Farm system is not comparable to that of solar PV, making it a less attractive solution for residential energy needs in South Africa. From a business standpoint, the cost per kW is calculated to observe differences in economic feasibility between the two systems.

- The **cost per kW** for the solar PV system based on the TCO of a 5 kW system is US$2 666.67.

- The **cost per kW** for the Ene-Farm system (1 kW) is US$45 249.60, which is approximately 17× higher than that of solar PV, making it economically less viable without external funding mechanisms.
- With a 50% subsidy, the 5 kW Ene-Farm system reduces to US$66 155.32, resulting in US$13 231.06/kW, still nearly 5× higher than solar PV

For business decision-making, these findings highlight the importance of:

a) **Scaling Sensitivity:** Solar PV's lower cost per kW at higher capacities makes it more attractive for households and businesses requiring larger energy solutions.

b) **Subsidy Impact:** While subsidies improve the economic viability of the Ene-Farm system, they do not reduce its cost per kW to levels comparable with solar PV. This suggests that substantial financial support would be required for hydrogen fuel cells to become competitive. However, it is important to recognize that heavy subsidization can create a false sense of viability, potentially masking the technology's true market competitiveness.

c) **Strategic Positioning:** Businesses seeking cost-effective, scalable solutions would likely favour solar PV systems unless Ene-Farm systems are tailored to niche markets where heat recovery offers significant added value.

Discussion on Grid-Tied Solar PV Systems

The analysis of grid-tied solar PV systems highlights both opportunities and challenges compared to off-grid solar PV and Ene-Farm systems. While grid-tied systems reduce reliance on oversized batteries and lower upfront costs, their long-term Total Cost of Ownership (TCO) increases due to dependency on grid electricity during cloudy days.

For instance, the grid-tied 5 kW solar PV system incurs a TCO between US$39 765.35 and US$47 823.89 over 25 years, depending on cloudy day efficiency assumptions. In contrast, the off-grid solar PV system maintains a significantly lower TCO of US$13 333.33 due to its independence from the grid. When scaled to 7 kW, the off-grid solar PV system remains the more cost-effective option, as it eliminates grid electricity costs altogether. The 7 kW grid-tied system, with a TCO of US$17 527.77, remains more expensive than its off-grid counterpart due to continued reliance on purchased electricity during low-solar-output periods.

However, grid-tied systems may still be preferable in cases where:

- Grid stability provides a reliable backup when solar generation is insufficient.
- Users prefer to avoid battery maintenance and lifecycle management, since grid-tied systems rely on grid electricity rather than full energy storage.

While grid-tied solar PV systems offer flexibility and scalability, their TCO remains higher than off-grid solar PV solutions and significantly lower than the Ene-Farm system. For households with access to stable grid electricity, grid-tied systems provide an intermediate solution, though their long-term competitiveness depends heavily on policy interventions and energy pricing dynamics.

4.5.2 *Hypothesis 2*

Hypothesis 2 posited that hydrogen fuel cell technology could be viable for South African households if costs are mitigated through subsidies. While subsidies modelled on Japan's Ene-Farm program significantly reduce the Total Cost of Ownership (TCO) for hydrogen fuel cells, the system remains economically less competitive compared to solar PV systems. This highlights a need for substantial financial and policy support to make hydrogen fuel cells feasible for residential adoption, however in the context of the South African residential sector, this would not be feasible.

4.5.3 *Hypothesis 3*

Hypothesis 3 suggested that Japan's successful integration of hydrogen fuel cell technologies could be replicated in South Africa. While Japan's policy-driven adoption was enabled by direct purchase subsidies, operational incentives, and strong industry partnerships, South Africa's distinct socio-economic conditions and lack of hydrogen infrastructure, present significant challenges. The potential to replicate Japan's approach depends on addressing the structural barriers present in South Africa.

4.5.4 *Hypothesis 4*

Hypothesis 4 examined whether the factors driving hydrogen fuel cell adoption in Japan differ significantly for South Africa. Key differences include South Africa's lower urban density, milder climate, and the growing reliance on solar PV systems as an alternative to intermittent grid supply. These factors highlight the need for South Africa to focus on leveraging its abundant solar energy potential while addressing energy reliability and affordability for underserved regions, rather than replicating Japan's hydrogen fuel cell adoption strategy directly.

4.6 Comparison of Literature review and own Findings

Table 18: Comparison of literature review and findings

RQ #	Research Questions	Hyp #	Hypotheses	Data Collection Detail	Data Analysis Method	Findings from Own Study
1.	What are the economic implications of implementing hydrogen fuel cells in the South African residential sector, and what is the Total Cost of Ownership under various scenarios?	1.	The Total Cost of Ownership for hydrogen fuel cell systems in South Africa varies significantly, based on different technological and economic assumptions.	Document analysis (technical specifications, pricing data, economic reports), Fermi estimate model.	Scenario analysis, sensitivity analysis.	TCO for hydrogen fuel cells (Ene-Farm) in South Africa is significantly higher, compared to solar PV systems, primarily due to fuel dependency and shorter system lifespans. Scaling the Ene-Farm system to 5 kW further increases TCO, making it less competitive. Solar PV remains more cost-effective due to zero fuel costs and economies of scale. While subsidies modelled on Japan's program reduce TCO, they do not fully bridge the cost gap.
2.	How can the adoption of hydrogen fuel cell technology be optimized for residential energy use in South	2.	Implementing hydrogen fuel cell technology in South African residential sectors is potentially viable if costs are	Document analysis (technical specifications, pricing data, economic reports),	Scenario analysis, sensitivity analysis.	Japan's 50% purchase subsidies and operational incentives were critical. South Africa lacks similar mechanisms, with existing

RQ #	Research Questions	Hyp #	Hypotheses	Data Collection Detail	Data Analysis Method	Findings from Own Study
	Africa, considering the factors that influence adoption in Japan's Ene-Farm program?		mitigated through subsidies.	Fermi estimate model.		subsidies focused on fossil fuels and solar PV. Infrastructure investment and policy adaptation are required to replicate Japan's strategies.
3.	Can Japan's Ene-Farm policy framework be adapted for South Africa?	3.	The integration of residential hydrogen fuel cell technologies, as demonstrated by Japan's Ene-Farm program, can be replicated in South Africa with similar policy frameworks and industry partnerships.	Document analysis (policy papers, government reports, industry analyses, academic articles).	Thematic analysis, comparative policy evaluation.	Japan's dense urban areas and cold climate align with compact hydrogen systems. South Africa's lower urban density, mild climate, and reliance on solar PV highlight a mismatch for direct replication. South Africa's energy solutions must focus on scalability and affordability, leveraging abundant solar resources.
4.	What key barriers affect residential hydrogen fuel adoption in South Africa when comparing to Japan?	4.	The factors that contributed to the adoption of hydrogen fuel cell technology in	Document analysis (policy papers, government reports, industry	Thematic analysis (policy comparison, market analysis,	Japan's integration relied on subsidies, established infrastructure, and strong partnerships. South Africa lacks a hydrogen distribution network, and the dominance of solar PV

RQ #	Research Questions	Hyp #	Hypotheses	Data Collection Detail	Data Analysis Method	Findings from Own Study
			Japan differ significantly for South Africa.	analyses, academic articles).	and identification of key barriers).	as a solution to load-shedding limits the feasibility of hydrogen fuel cells in residential applications. Hydrogen may be more suitable for niche applications rather than large-scale residential adoption in South Africa.

CHAPTER 5. CONCLUSION

This study provides a detailed evaluation of the Ene-Farm hydrogen fuel cell system and solar PV systems for residential energy applications in South Africa, focusing on their technical performance, cost implications, and scalability. The analysis highlights that while the Ene-Farm system demonstrates high technical efficiency through its combined electricity generation and heat recovery capabilities, its economic feasibility is constrained by a high Total Cost of Ownership and reliance on methane fuel. In contrast, the solar PV system, characterized by lower upfront and operational costs, longer lifespan, and reliance on an abundant renewable energy source, presents a more viable solution for residential energy needs in South Africa.

Furthermore, the analysis of grid-tied configurations reveals that while these systems reduce battery dependency and provide backup reliability, their TCO increases due to grid electricity costs during cloudy periods. Even when scaled to 7 kW to meet both electricity and water heating demands, off-grid solar PV remains more affordable over 25 years than the Ene-Farm system—even with subsidies applied.

Although subsidies improve the affordability of hydrogen fuel cells, they do not bring the cost per kilowatt in line with that of solar PV. This highlights the need for careful policy consideration when allocating financial support, especially when more economical renewable alternatives exist. While subsidizing any technology can alter its competitiveness, such strategies should be aligned with broader energy goals, long-term affordability, and infrastructure readiness.

The findings also emphasize the contextual gap between Japan's "successful" Ene-Farm rollout and the current South African energy landscape. The lack of hydrogen infrastructure, limited natural gas availability, and economic constraints make large-scale deployment of hydrogen fuel cells less feasible in the short to medium term. In contrast, solar PV systems align strongly with the country's renewable energy potential, cost sensitivity, and decentralized energy needs.

There remains considerable opportunity for further research that were beyond the scope of this research. These include conducting a full life-cycle assessment to quantify the environmental impacts of hydrogen fuel cells, particularly comparing grey versus green hydrogen pathways. Such assessments would provide a more holistic understanding of long-term sustainability. Additionally, segmentation analysis to identify which household types, income brackets, or geographic regions are best suited for hydrogen technologies could help guide more targeted adoption strategies. Further investigation into hybrid systems, integrating solar PV with hydrogen fuel cells, thermal storage, or other renewable sources, may also yield valuable insights into achieving higher reliability, efficiency, and resilience in residential energy applications.

Ultimately, solar PV systems offer a more scalable, cost-effective, and contextually appropriate solution for residential energy in South Africa. While hydrogen fuel cells may hold promise in specific applications or future market conditions, overcoming current economic and infrastructural barriers will be essential for their broader adoption. Prioritizing investments in solar PV, supported by local manufacturing, policy stability, and smart grid development, can significantly advance the country's transition toward a more sustainable and resilient energy future.

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APPENDIX A

Technological Calculations

1. Fundamental Equations Used for the Technical Analysis

The equations below are used to calculate energy and fuel requirements.

	$$Daily\ Energy\ Use\ (kWh) = \frac{Power(W) \times Hours\ of\ use}{1\ 000}$$	
	$$Energy\ required\ for\ heating(Q) = m \times c \times \Delta T$$ Where: $m \approx$ mass of water (200 kg) $c =$ 4.18 kJ/kg°C (specific heat of water) $\Delta T =$ (65°C - 15°C) = 50°C	
	$$Methane\ Energy\ (kWh) = \frac{Daily\ energy\ demand\ (kWh)}{PEMFC\ efficiency}$$	
	$$Methane\ Required\ \left(\frac{kg}{day}\right) = \frac{Methane\ energy\ (kWh)}{LHV\ of\ methane\ (\frac{kWh}{kg})}$$	
	$$Recovered\ Heat\ \left(\frac{kW}{h}\right) = Total\ methane\ energy\ input\ (kWh) \times Heat\ recovery\ efficiency$$	
	$$Excess\ Solar\ Energy\ (kWh) = Daily\ solar\ generation\ (kWh) - Household\ demand - battery\ storage\ (kWh)$$	

2. Fuel and Heating Calculations

i) Water Heating Calculations

Volume of Water to be Heated:

This is the geyser/boiler capacity: 200 litres which is approximately 200 kg since the density of water is approximately 1 kg/litre under standard temperature and pressure.

Temperature Rise:

In most households, the water temperature required for activities like bathing, cleaning, and other uses is set at 65°C (Ene-Farm boiler temperature/geyser temperature) (Energy, 2022). The incoming cold-water temperature (from municipal supply or groundwater) is typically 15°C in many locations, including South Africa. This temperature can vary slightly, depending on the season and region, but is a reasonable average for calculations (HSE, 2014).

Therefore:

- Cold water temperature = $15°\mathrm{C}$.
- Hot water temperature = $65°\mathrm{C}$.
- $\Delta \mathrm{T} = 65°\mathrm{C} - 15°\mathrm{C} = 50°\mathrm{C}$.

Energy Required in Joules:

$$(Q) = m \times c \times \Delta T$$

$$Q(heat\ required\ for\ water) = 200\ kg \times \frac{4.18\ \mathrm{kJ}}{\mathrm{kg°C}} \times 50°\mathrm{C} = 41\ 800\ \mathrm{kJ}$$

Energy Required in kWh/Day:

To convert from Joules to kWh,

$$1\ kWh = 3\ 600\ kJ.$$

$$\text{Energy required (kWh/day)} = \frac{41\ 800\ kJ}{3\ 600\ kJ/kWh} \approx \frac{11.6\ kWh}{day}.$$

This means that 11.6 kWh of energy is required to heat up 200 litres of water to a temperature of 65°C in a day.

---

ii) Methane Fuel Consumption for Electricity and Heating

The Ene-Farm system uses a high-efficiency PEM fuel cell that generates electricity and captures waste heat. The waste heat is utilized for water heating. Therefore, the daily fuel (methane) requirement is determined by the electricity demand of the system, as the water heating demand is met by the waste heat.

For an electricity demand of 18.55 kWh, the methane energy input is calculated as:

$$Methane\ Energy\ input\left(\frac{kWh}{day}\right) = \frac{Daily\ energy\ demand\ \left(\frac{kWh}{day}\right)}{PEMFC\ efficiency}$$

$$Methane\ energy\ input\left(\frac{kWh}{day}\right) = \frac{18.55\frac{kWh}{day}}{0.37} = 50.14\frac{kWh}{day}.$$

Where the PEMFC efficiency is 37%.

- To calculate how much methane is required daily to produce **50.14 kWh/day**, the Lower Heating Value (LHV) of methane is used:

$$Methane\ Required\ \left(\frac{kg}{day}\right) = \frac{Methane\ energy\ (kWh)}{LHV\ of\ methane\ \left(\frac{kWh}{kg}\right)}$$

$$Methane\ required\ \left(\frac{kg}{day}\right) = \frac{50.14\,\frac{kWh}{day}}{13.89\ kWh/kg} \sim 3.61\,\frac{kg}{day}.$$

Where the LHV of methane is 13.89 kWh/kg.

(**Note:** To calculate the amount of methane required to produce 50.14 kWh/day, the LHV of methane is used to determine the fuel energy available for conversion into usable energy. Assuming system efficiency and energy conversion losses, the LHV provides a realistic estimate of the fuel input needed for the given energy output.)

In summary, the daily methane requirement for the Ene-Farm system is determined by the system's electricity demand and the efficiency of the PEM fuel cell. As a result, the energy needed to heat the water does not directly contribute to the amount of methane required, provided that the waste heat is sufficient for this purpose.

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iii) Annual Methane Consumption

The annual methane consumption is calculated by multiplying the daily methane consumption by the number of days in a year:

- $Annual\ methane\ consumption\ \left(\frac{kg}{year}\right) = 3.61\left(\frac{kg}{day}\right) \times 365\ days = 1\ 317.65\,\frac{kg}{year}$.

- $Annual\ methane\ energy\ consumption\ \left(\frac{kWh}{year}\right) =$

  $Annual\ methane\ consumption\left(\frac{kg}{year}\right) \times LHV\ of\ methane\ \left(\frac{kWh}{kg}\right) = 1\ 317.65 \times 13.89 \sim 18\ 302.16\,\frac{kWh}{year}$.

---

iv) Water Heating Calculations for the Ene-Farm and Solar PV Systems

The baseline case of 18.55 kWh/day is considered for the calculations to follow.

The recovered heat from the Ene-Farm system is calculated using the total methane energy input and the heat recovery efficiency:

$$Recovered\ Heat\ \left(\frac{kW}{h}\right) = \ Total\ methane\ energy\ input\ (kWh) \times Heat\ recovery\ efficiency$$

$$Recovered\ heat\ \left(\frac{kWh}{day}\right) = 50.14\ \times 0.5 = 25.07\,\frac{kWh}{day}.$$

Where the heat recovery efficiency of the Ene-Farm system is around 50%.

This value represents the portion of input energy captured as usable waste heat for water heating.

---

v) Excess Energy with Solar PV

For the solar PV system, the daily solar energy generation is:

$Solar\ energy\ generation\ \left(\frac{kWh}{day}\right) = 5\ kW \times 5\ hours\ of\ sunlight = \frac{25\ kWh}{day}$.

The excess energy is:

$$Excess\ energy\ \left(\frac{kWh}{day}\right)$$
$$= 25\ (daily\ solar\ energy\ generation)$$
$$- 18.55\ (baseline\ requirement) - 5\ (battery\ storage) \sim 1.45\frac{kWh}{day}.$$

---

vi) Number of Cloudy Days Estimate

- Johannesburg has around 3 126 hours of sunshine annually (Climate, 2024).
- Total hours in a year: $365\ days\ \times 24\ hours = 8\ 760\ hours$.
- The number of dark hours can be estimated as:

$$8\ 760 - (3\ 126 + 2\ 349) = 3\ 285\ hours.$$

This is ~9 hours of darkness per day on average:

$$\frac{3\ 285}{365} \approx 9\frac{hours}{night}.$$

Hence, the **total** $3\ 126\ (\text{sunny}) + 2\ 349\ (\text{cloudy}) + 3\ 285\ (\text{dark}) = 8\ 760\ \text{hours}$.

- Assuming **5 peak sunlight hours/day** as the ideal generation window.
- **2 349 cloudy hours** is how many hours solar output is **heavily reduced**.
- **Divide** 2 349 by 5 to find how many **peak-sun blocks** are cloudy:

$$\frac{2\ 349\ cloudy\ hours}{5\ peak\ sun\ hours} \approx 469.8 \approx 470\ blocks.$$

Note: These are not literal calendar days. They are 470 blocks of 5 hours each, during which you lose peak solar potential. Some calendar days might have partial clouding over multiple times or partial hours, so this is a Fermi estimate.

vii) Energy Output on a Cloudy Day

Assumptions:

- **System Size:** 5 kW.
- **Solar Panel Efficiency:** 20% (best-case under full sun).
- **Cloudy Day Efficiency Range:** 10% – 25% of peak capacity.

Hence:

Clear day output (ideal) = $5 \text{ kW} \times 5 \text{ hours} = 25 \text{ kWh/day}$.

The energy output on a cloudy day is given below.

a) Lower bound (10% output efficiency):

$$5\ kW\ \times (5\ \times 0.10)\ hours = 2.5\ kWh/day$$

b) Upper bound (25% of output efficiency):

$$5\ kW\ \times (5\ \times 0.25)\ hours = 6.25\ kWh/day$$

Therefore, the energy shortfall for the lower bound = $(18.55 - 2.5)$ kWh/day = 16.05 kWh/day, and the energy shortfall for the upper bound = $(18.55 - 6.25)$ kWh/day = 12.3 kWh/day.

---

viii) Grid Electricity Import Requirement per Year

Since we have **470 cloudy blocks** (each block being a 5-hour chunk where output is reduced), we multiply each block by the **daily shortfall** to get annual totals:

1. **Lower Bound (10% output):**

$$470\ blocks\ \times 16.05\,\frac{kWh}{block} = 7\ 543.5\,\frac{kWh}{year}.$$

2. **Upper Bound (25% output):**

$$470\ blocks\ \times 12.3\,\frac{kWh}{block} = 5\ 781.0\,\frac{kWh}{year}.$$

Hence, under worst-case (10% efficiency on all cloudy blocks), you would need to **import** $\sim 7\ 543.5\ \mathrm{kWh/year}$ from the grid; under best-case (25% efficiency), $\sim 5\ 781\ \mathrm{kWh/year}$.

APPENDIX B

Economic Calculations

i) Methane Cost Calculations

The cost of methane per kWh is calculated as (Energas, 2019):

$$Cost\ per\ kWh(USD) = \frac{Methane\ cost\ \left(\frac{US\$}{GJ}\right)}{Conversion\ factor\ \left(\frac{kWh}{GJ}\right)} = \frac{15}{277.78} = \frac{0.054US\$}{kWh}.$$

Annual Methane Cost (US$/year):

$$Annual\ methane\ cost$$
$$= Annual\ methane\ energy\ consumption\ \left(\frac{kWh}{year}\right) \times Cost\ per\ kWh$$
$$= 18\ 302.16 \times 0.054 \sim 988.32\frac{US\$}{year}.$$

---

ii) Total Cost of Ownership (TCO) for 1 kW Ene-Farm over 25 years

The TCO for the Ene-Farm system based on a 10-year operational lifespan is calculated as:

$$TCO_{10yr}\ (US\$) = Initial\ Investment + (Annual\ Methane\ Cost \times Lifespan)$$
$$= 5\ 200 + (988.32 \times 10) = US\$15\ 083.20$$

As the Ene-Farm system requires full replacement every 10 years, the 25-year TCO must account for three complete units (at years 0, 10, and 20). Thus, the total cost over 25 years is estimated as:

$$TCO_{25yr} = TCO_{10yr} \times 3 = US\$45\ 249.60$$

Note: This assumes identical cost per unit across all time intervals and does not apply discounting. It is used to maintain a consistent basis for comparison with solar PV systems evaluated over 25 years.

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iii) Total Cost of Ownership (TCO) for 5 kW Solar PV over 25 years

Upfront Cost Calculation: The purchase price of a 5 kW solar PV system is available online (Huwawei, 2023). To estimate an initial cost of the system, a validation calculation was done to determine whether the financed option and cash price option are in agreement.

To calculate the principal cost of a 5 kW solar PV system with financing, the following assumptions and parameters are used:

- Based on the Huawei Solar PV pricing (Huwawei, 2023), the 5 kW system purchase price is between R70 000 and R140 000 plus an additional R20 000.00 for installation.

- For a loan option with financing, a 5 kW solar PV system in South Africa, the monthly repayment is around R3 016.89 (Labuschagne, 2023) with a loan term of typically 5 years (60 months) (Bank, 2025).

- The interest rate for solar PV financing is around prime interest rate plus 2.5%, with the prime interest rate being 11.25% at the time of analysis. The total interest rate will be 13.75% annually (0.1375) or 1.1458% monthly (0.011458 (Bank, 2025)).

In general, The Equal Monthly Instalment (EMI) is calculated using the following formula:

$$EMI = \frac{P.r.(1+r)^n}{(1+r)^n - 1}$$

Where:

- $\mathrm{P} = \text{Principal loan amount (to be calculated)}$
- $\mathrm{r} = \text{Monthly interest rate } (13.75\% \div 12 = 0.011458).$
- $\mathrm{n} = \text{Loan term in months } (60 \text{ months}).$

The goal is to validate the initial cost of a 5 kW solar PV system and hence solve for the principal amount (no interest) in the equation. The EMI = R3 016.89 (Labuschagne, 2023).

Rearranging the equation and solving for P:

$$P = \frac{EMI \times [(1+r)^n - 1]}{r.(1+r)^n}$$

The table below gives the input and output parameters for calculating P.

Parameter	**Value**	**Unit**	**Explanation**
Input Parameters			
EMI	3 016.89	ZAR/month	Monthly instalment for the loan.
Annual Interest Rate	13.75%	Percentage	Prime interest rate plus 2.5%.
Monthly Interest Rate (r)	0.011458	Decimal	Annual rate divided by 12 months.
Loan Term (n)	60	Months	5 years.
$(1+r)^n$	1.980979	-	Growth factor over 60 months.
$(1+r)^n - 1$	0.980979	-	

Output parameters			
Numerator: $EMI \times [(1+r)^n - 1]$	2 959.50	ZAR	Product of EMI and the growth factor difference.
Denominator: $(1+r)^n - 1$	0.0226987	-	Product of interest rate and growth factor.
Principal loan amount	130 382.05	ZAR	Calculated loan principal.

This result is consistent with the online data provided by Huawei. This falls within the expected pricing range for solar PV systems in South Africa. For consistency in comparisons, the conservative (upper limit) purchase price (R140 000.00) of the 5 kW solar PV system plus installation (R20 000.00) is used.

- The initial investment represents the upfront cost of acquiring and installing the solar PV system. For the 5 kW solar PV system, this cost is:

$$Initial\ Investment = R160\ 000.00$$

For this calculation, all costs will be computed in ZAR to maintain accuracy throughout the process. The final value will then be converted to US$, ensuring minimal loss of precision during currency conversion.

- To ensure the system functions optimally over its 25-year lifespan, it is assumed that the inverter and battery will need replacement after year 10 and year 20. The replacement costs were estimated, using the AC DIRECT online store (DIRECT, 2025) and is given as:

$$Replacement\ cost = R80\ 000.00$$

- The Total Cost of Ownership (TCO) is calculated by summing the initial investment and the replacement cost. Since no recurring operational costs were assumed (fuel and maintenance), the TCO formula is simplified as follows:

$$TCO\ (ZAR) = Initial\ Investment + Replacement\ Cost = 160\ 000 + 80\ 000$$
$$= R240\ 000.00$$

Converting this value to US$,

$$TCO\ (US\$) = \frac{R240\ 000.00}{US\$18.00} = US\$13\ 333.33$$

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iv) Total Cost of Ownership (TCO) for Grid-Tied Solar PV System

- Electricity tariff (Block 1: 0 – 600 kWh/month): R3.292 per kWh (Town, 2024)

- Annual cost (lower bound – 10% efficiency):

$$7\ 543.50 \times 3.292 = R24\ 833.20$$

- Annual cost (Upper Bound – 25% efficiency):

$$5\ 781.00 \times 3.292 = R19\ 031.05$$

- **Total grid cost over 25-year system lifespan:**

$$\text{Lower bound – R24 833.20} \times 25 = \text{R620 830.00}$$
$$\text{Upper bound – R19 031.00} \times 25 = \text{R475 775.00}$$

Adjusted Total Cost of Ownership (TCO) for Grid-Tied Solar PV System:

Base costs:

- Solar PV system (5 kW): R171 000.00 (US$9 500.00)

- Battery and inverter replacement cost: R36 000.00

TCO – lower bound:

$$TCO_{lower} = \mathrm{C_{pv}} + C_{bat} + C_{grid}$$

Where:

$\mathrm{C_{pv}}$ = Initial cost of the 5 kW solar PV system (R160 000.00)

C_{bat} = Battery and inverter replacement cost (R80 000.00)

C_{grid} = Total grid cost over 25 years (ZAR) for lower and upper bounds.

- Lower Bound TCO = 160 000.00 + 80 000.00 + 620 830.05 = R860 830.05 = **US$47 823.89**
- Upper Bound TCO = 160 000.00 + 80 000.00 + 475 776.30 = R715 776.30 = **US$39 765.35**

---

v) TCO Scaling of Ene-Farm to 5 kW

- Using the rule of two-thirds, assuming that the Ene-Farm system is modular and scalable. The calculation for the 5 kW scaled-up system is given as:

$TCO_{5kW} = TCO_{1kW} \times (\frac{5}{1})^{\frac{2}{3}} = 15\,083.54 \times 5^{(\frac{2}{3})} = \mathrm{US\$44\,103.54}$ estimated over 10 years.

For a lifespan of 25 years, a 5kW Ene-Farm system would need to be replaced at year 10 and year 20, thus:

$$TCO_{5kW}(25\ years) = TCO_{5kW} \times 3\ replacements = \mathrm{US\$132\,310.63}$$

Scaling Solar PV to Meet Water Heating Needs

The energy required is given by:

- Baseline household demand: 18.55 kWh/day.
- Water heating energy demand: 11.6 kWh/day.
- Battery charging demand: 5 kWh/day.

To provide a fair comparison between the Ene-Farm and the solar PV system, the solar PV system must be scaled-up to meet the total energy demand of 35.15 kWh/day.

The solar system outputs 25 kWh/day which gives a deficit of 10.15 kWh/day.

- To meet the 10.15 kWh/day deficit, the additional capacity required is given by:

$$Additional\ capacity\ required = \frac{Defecit}{Sunlight\ hours} = \frac{10.15}{5} = 2.03\ kW.$$

Which implies that the solar system will need to have a capacity of (5 + 2.03) kW = 7.03 kW.

The TCO of the 7.03 kW solar PV system can be estimated by using a component-specific scaling approach as described in (Ramasamy, 2020). Different components of a solar PV system scale at different rates due to economies of scale. Typical scaling exponents for solar system components is taken from NREL's cost benchmark document (Ramasamy, 2020).

Component	Scaling Exponent (n)	Explanation
Solar Panels	0.9 – 1.0	Modular and linear in cost increase.
Inverters	0.7 – 0.8	Economies of scale due to higher capacities.
Battery Storage	0.6 – 0.7	Significant cost reduction for larger systems.
Soft Costs	0.9 – 1.0	The assumption is that this value will scale in a similar way to the panels, due to the panel installation being the most labour intensive. In South Africa, soft costs mainly include labour and certifications which isn't cost intensive in comparison to the system components (Labuschagne, 2023).

Calculation:

Based on industry reports from NREL's cost benchmark document (Ramasamy, 2020), the following assumptions are made:

- Solar panels ~40% of TCO.
- Inverter ~20% of TCO.
- Battery storage ~20% of the TCO.
- Soft cost such as labour and certifications ~20% of TCO.

Using the lower limit of the scaling components, the scaled cost can be calculated using the equation below:

$$C_{scale} = C_{base} \times \left(\frac{New\ Capacity}{Base\ capacity}\right)^{n}$$

- Solar panels:

$$C_{scale} = 5\ 333.33 \times \left(\frac{7.03}{5}\right)^{0.9} = US\$7\ 247.45$$

- Inverter:

$$C_{scale} = 2\ 666.66 \times \left(\frac{7.03}{5}\right)^{0.7} = US\$3\ 385.00$$

- Battery:

$$C_{scale} = 2\ 666.66 \times \left(\frac{7.03}{5}\right)^{0.6} = US\$3\ 271.60$$

- Soft costs:

$$C_{scale} = 2\ 666.66 \times \left(\frac{7.03}{5}\right)^{0.9} = US\$3\ 623.73$$

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vi) Cost Scaling for a 7 kW Grid-Tied Solar PV System (Worst-Case 10% Output)

Below is an explicit equation-based calculation that re-uses the same replacement costs and electricity tariff as previously established for the 5 kW system. All cost figures are scaled to 7 kW using the component-specific approach, and the cloudy day output is assumed to be 10% of peak capacity, matching the worst-case scenario.

- Household Demand (E_{house}) $= 18.55\ kWh/day$
- Water Heating Demand (E_{water}) $= 12.89\ kWh/day$

- Total Daily Requirement (E_{Total}) $= 31.44 kWh/day$
- Minimum V Capacity: $\frac{31.44\ kWh\ /\ day}{5h\ /\ day} \approx 6.288\ kW{\sim}7\ kW\ for\ design\ margin.$

The capital cost for the 7 kW system is US$17 527.77, using the scaling ratios.

Grid Electricity Cost for the Worst-Case 10 % Output on Cloudy Days:

- Cloudy Day PV Output:

$$E_{cloudy} = 7\ kW\ \times 5h \times 0.10 = 3.5 \frac{kWh}{day}$$

- Daily shortfall:

$$\Delta E_{daily} = E_{Total} - E_{cloudy} = 31.44 - 3.5 = 27.94\ kWh/day$$

- Cloudy Days per Year (assumed): 55
- Annual Shortfall: $27.94 \frac{kWh}{day} \times 55\ \approx 1\ 537 \frac{kWh}{year}$.
- Tariff: R3.292 / kWh ≈ US$0.18 / kWh (US$1 = R18.00)
- Annual Grid Cost:

$$1\ 537 \frac{kWh}{year} \times \frac{0.18\ USD}{kWh} \approx 277 \frac{US\$}{year}.$$

- 25-year grid cost: $277\ \times 25 \approx US\$6\ 925.00$.

Final TCO:

- Capital Cost (7 kW): ~US$17 527.77.
- Grid Imports (25 years) (worst-case 10% output): US$6 925.00

Combining:

$$TCO_{7kW,grid-tied} \approx 17\ 527.77 + 6\ 925.00 = US\$24\ 452.77$$

APPENDIX C

The table below summarizes the key indicators that is used for the analytical comparison between South Africa and Japan taken from (WorldData.info, 2025).

Table to analyse factors that contributed to adoption of hydrogen fuel cell technology in Japan

Category	Japan	South Africa
Population Density	329.4 inhabitants/km²	63.2 inhabitants/km²
Climate	Average daytime temperature: 19.4 °C Cold winters with snow in many regions.	Average daytime temperature: 26.1 °C Mild winters; no significant snowfall.
Technological	The residential Ene-Farm PEMFC fuel cell system generates both electricity and heat, which improves energy efficiency and reduces transmission losses (Nyangon & Darekar, 2024) and these systems reduce household CO_2 emissions by around 30% (Bhandari & Adhikari, 2024, Open reference preview (Bhandari & Adhikari, 2024).	The primary driver for the adoption of solar PV technology has been the need to mitigate the impacts of frequent load-shedding, rather than a direct effort to reduce CO_2 emissions.
Socio-Economic Indicators	GDP: US$33.77 million. Average income: US$39 350.00/year; unemployment: 2.6%.	GDP: US$6.02 million. Average income: US$6 480.00/year; unemployment: 28%.

Energy Balance	Production capacity: 3 065 474 GWh; CO_2 emissions: 1.01 bn t.	Production capacity: 555 480 GWh; CO_2 emissions: 393.24 m t.