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Modeling of On-Shore Facility for Fuel Cell Refueling to Improve TEMESA Ferries

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Abstract

This study focuses on designing and developing an onshore hydrogen refueling facility for TEMESA ferries, with a specific pilot project targeting ferry operations between Magogoni and Kigamboni in Tanzania. The transition to hydrogen fuel cell technology is motivated by the need to mitigate greenhouse gas emissions and improve the overall environmental impact of maritime operations, particularly addressing Tanzania's heavy reliance on fossil fuels for ferry propulsion.

The proposed hydrogen refueling facility will produce green hydrogen via water electrolysis using a Proton Exchange Membrane (PEM) electrolyzer. The generated hydrogen will be stored, compressed, and dispensed to the ferries, creating a fully integrated and efficient refueling system. The research methodology combines site selection analysis, system modeling, and equipment specification to optimize the design. Through detailed calculations, the daily hydrogen demand for the TEMESA ferries was determined to be approximately 1,534.28 kg/day, necessitating a power input of 2.97 MW for hydrogen production. Key system components include an onshore low-pressure storage tank, sized at 17,070 m³, and onboard high-pressure storage tanks designed to store hydrogen at 350 bars, ensuring sufficient capacity to meet daily operational requirements. Additionally, the study outlines the necessary specifications for compressors, cooling systems, and dispensers to ensure safe and efficient hydrogen transfer from storage to the ferries.

By focusing on the technical and operational aspects of the hydrogen refueling system, this study provides a blueprint for implementing hydrogen fuel cell technology in Tanzania's maritime sector. The successful completion of this pilot project has the potential to pave the way for broader adoption of clean hydrogen technologies in other ferry operations across the country, contributing to the decarburization of Tanzania's transport infrastructure. Moreover, the study highlights opportunities for future scalability, optimization, and integration of renewable energy sources in the hydrogen production process, thereby enhancing the long-term sustainability of the sector.

Keywords: Alternative Fuel; Hydrogen Refueling System; Fuel Cell Fer; Modelling; Onshore Infrastructure

Introduction

The maritime industry is critical in global transportation, facilitating the movement of goods and people across vast distances (Ferry Fuel & Propulsion Feasibility Study Final Report | 2022, 2022). However, it is also a significant contributor to environmental pollution, with fossil fuel-powered vessels emitting large quantities of greenhouse gases and other harmful pollutants (Peng et al., 2020).

As the world shifts towards more sustainable and environmentally friendly energy sources in Tanzania an impetus to develop a technology for environmentally friendly energy has emerged as a promising solution for reducing emissions in the maritime sector (Laasma et al., 2022). Current research efforts Worldwide increasingly focused on the use of hydrogen fuel cell that generates electricity through an electrochemical reaction process between hydrogen and oxygen, producing water and heat as byproducts (D. Wang et al., 2021). Such a source of energy technology is believed to offer some advantages such as zero Carbon emissions, and hence, may be considered a feasible alternative use of fossil fuel in maritime applications (Bach et al., 2020,Feng et al., 2022).

In third developing countries, energy security is another pressing issue. Tanzania's reliance on imported fossil fuels makes the ferry operations vulnerable to global fuel market fluctuations and geopolitical tensions. (Transport & Environment, 2020). This dependence on external sources for fuel can lead to shortages and price spikes, impacting the stability and affordability of ferry operations. Ensuring a stable and secure fuel supply is essential for the continuous and efficient operation of the ferries.

Amid these challenges, hydrogen fuel cell refueling technology emerges as a promising solution. Hydrogen fuel cells offer a clean, efficient, and sustainable alternative to fossil fuels. (Hydrogen Delivery Hydrogen Storage Technologies Technical Team Roadmap Roadmap, 2013). They produce electricity through a chemical reaction between hydrogen and oxygen, with water as the only byproduct. (Klop et al., 2023). This technology significantly reduces emissions and can help meet stringent environmental regulations. (Whitepaper, 2021). However, the current infrastructure in Tanzania is not equipped to support the widespread adoption of hydrogen fuel cells for maritime applications.

The ongoing reliance on diesel fuel for TEMESA ferry operations on the Magogoni-Kigamboni route presents several challenges, including high emissions, operational costs, and potential adverse environmental impacts. There is a need to develop a renewable energy-based solution to support TEMESA's operational requirements and environmental goals. This study addresses the gap by designing an onshore hydrogen refueling facility and identifying hydrogen's specific needs, challenges, and benefits as a clean fuel alternative in maritime public transportation.

The transition to hydrogen fuel cell-powered ferries presents an opportunity for Tanzania to enhance its transportation infrastructure, reduce environmental impact, and align with global clean energy sustainability goals. However, the successful implementation of this technology requires the development of dedicated on-shore Fuel Cell refueling facilities. (Laursen et al., 2023)Ghamrawi, 2018).

2.0 Review of the paper

Hydrogen is a promising energy carrier recognized for its potential to contribute to a cleaner, sustainable energy future. As the most abundant element in the universe, it can be produced through various methods such as electrolysis (using renewable electricity to split water) and steam methane reforming (using natural gas) (Giddey et al., 2012). Hydrogen reacts with oxygen in a fuel cell to produce only water, making it a zero-emission fuel compared to fossil fuels that emit carbon dioxide (CO_2) and other pollutants (Brown, 2019).

Hydrogen is particularly attractive in hard-to-electrify sectors, such as long-haul transportation, aviation, and heavy industry, where battery-based solutions may be less feasible (Wu et al., 2019). Recent technological advancements have improved the efficiency and cost-effectiveness of hydrogen production and fuel cell systems, making hydrogen a vital player in achieving global sustainability goals. Some key literature in this field was reviewed.

2.1 Determination of initial data for hydrogen production and handling for fuel cells in marine vessels.

The successful integration of hydrogen fuel cells into marine vessels begins with collecting and analyzing critical data concerning hydrogen production, hydrogen storage, fuel cell efficiency, and operational requirements. Various researchers have contributed to understanding these aspects, providing foundational insights for designing effective hydrogen-powered marine systems. (Kumar & Himabindu, 2019).

For hydrogen production processes, imagine a device that can turn water into powerful, clean fuel hydrogen using nothing but electricity. This device is called an electrolyze, and when it employs advanced Proton Exchange Membrane (PEM) technology, it becomes a PEM electrolyze. This technology is at the heart of a future where we can produce hydrogen sustainably, offering a glimpse into a world powered by clean energy.

2.2 The magic behind PEM Electrolyzes

At its core, a PEM electrolyze is a sophisticated piece of equipment designed to split water molecules (H_2O) into their basic components of hydrogen (H_2) and oxygen (O_2). This process, known as electrolysis, is driven by electricity. When the electricity comes from renewable sources like National grid power, wind, or solar power, the hydrogen produced is entirely green, meaning it’s generated with no carbon emissions (Kumar & Himabindu, 2019). Here’s how it works in a step-by-step process;

Water enters the system: the journey begins as water is fed into the electrolyze. Water is a simple molecule, composed of two hydrogen atoms and one oxygen atom, bound together.

Water electrolysis is a process that splits water (H_2O) into hydrogen (H_2) and oxygen (O_2) using electricity. This method is recognized for its ability to produce very high-purity hydrogen, often achieving levels as high as 99.999%, making it an ideal source of hydrogen for various industrial applications, fuel cells, and other energy systems.

The following equation can describe the overall chemical reaction for water electrolysis;

H_2O + Electricity (237.2 kJ/mol) +Heat (48.6 kJ/mol) → $H_2 + \frac{1}{2} O_2$

Explanation of the equation

- **Water (H_2O)**; the reactant in the process, water molecules are split into components.
- **Electricity**; energy input required to drive the electrolysis reaction. The energy provided is primarily in the form of electrical energy.
- **Heat**; additional energy is required in the form of heat to sustain the reaction, though the amount is less compared to the electrical energy.

Products:

Hydrogen (H_2); the main product, which is produced in its pure form, and Oxygen (O_2), a byproduct of the reaction, is often released into the atmosphere or captured for industrial use.

1. **The anode reaction**, inside the electrolyzer, water molecules encounter the anode, a positively charged electrode made from special materials like iridium oxide. At the anode, electricity splits the water molecules into oxygen gas, positively charged hydrogen ions (protons), and electrons. The oxygen gas is released as a byproduct, often vented away or captured for industrial uses.
2. **Proton exchange membrane (PEM)**; the key innovation in PEM electrolyzers is the membrane that sits between the anode and the cathode (the negative electrode). This membrane is a special polymer that allows only protons those positively charged hydrogen ions to pass through it. The PEM is crucial because it keeps the two sides of the reaction separate while allowing the necessary particles to move where they need to go.

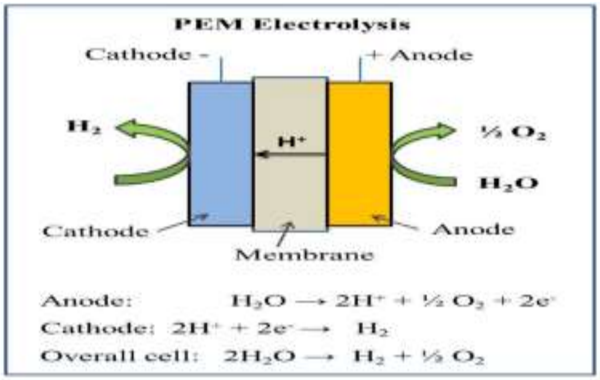

Figure 2.1 Schematic illustration of PEM Electrolyzer. Source: (Ogden et al. 2018).

3. **The cathode reaction**; on the other side of the membrane, at the cathode, the protons combine with the electrons that have traveled through an external circuit to produce pure hydrogen gas. This hydrogen can then be collected and stored for various uses, such as fuel for hydrogen-powered vehicles, industrial processes, or even for generating electricity when needed.
4. **The external circuit**; the electrons, which cannot pass through the membrane, flow through an external circuit from the anode to the cathode. This flow of electrons creates an electrical current, and it's this current that drives the entire process of electrolysis.

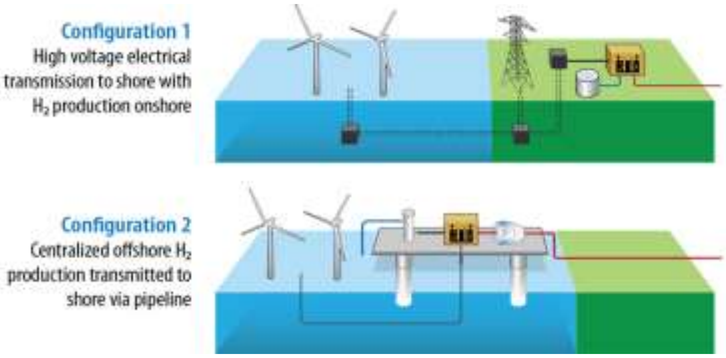

Figure 2.2 Schemes of on-shore and offshore hydrogen production systems. Source:

(Ogden et al. 2018).

Hydrogen storage requirements, Hydrogen storage is a central concern due to its low energy density per unit volume at ambient conditions. Researchers like (Ogden et al. 2018) have highlighted the importance of selecting appropriate storage technologies, such as compressed hydrogen tanks, liquid hydrogen, or metal hydrides, depending on the vessel's operational profile. Compressed hydrogen storage at 350 bar is a viable option for short to medium-range vessels, providing a balance between storage volume and energy capacity.

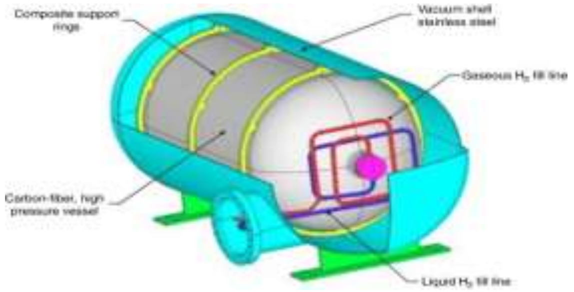

Figure 2.3 pressure storage tank. (Source: Zhang et al.2020)

Fuel Cell Efficiency and Power Requirements, the efficiency of hydrogen fuel cells and their power output are critical for determining the energy needs of marine vessels. Research by Ballard and Lessen (2020) indicates that proton exchange membrane (PEM) fuel cells, with efficiencies ranging from 45% to 60%, are suitable for marine applications due to their rapid start-up times and high power density. These characteristics are essential for the stop-start nature of ferry operations.

Operational Data Collection, the collection of operational data, including fuel consumption patterns, voyage durations, and energy requirements, is vital for designing a refueling system that meets the demands of marine vessels. According to Wang et al. (2021), accurate data collection and analysis allow for the optimization of fuel cell system design, ensuring that the hydrogen supply meets the vessel's energy demands without excess capacity, which could lead to unnecessary costs.

Methodology

3.1Research method design

This study's methodology was created to methodically handle every research goal, guaranteeing an organized approach to modeling, design, and data gathering. The methods used to accomplish each particular goal are summarized in detail in Table 3.1 below, which also lists the instruments, procedures, and evaluations carried out to make the development of a hydrogen fuel cell refueling facility model for TEMESA ferries easier.

Table 3.1: Show Methodology Overview; approaches for achieving research objectives in designing a hydrogen Fuel Cell Refueling Facility for TEMESA Ferries

Objective	**Methodology**	**Application**
I. Determining the initial data for hydrogen production and handling for fuel cells in ferries.	Data was gathered from technical specifications, ferry operation records, and literature on hydrogen fuel cell technology. Interviews with TEMESA engineers provided insights into the current diesel system, operational demands, and projected benefits of hydrogen adoption. Additionally, industry reports were reviewed to	Data on operational efficiency and fuel consumption for TEMESA ferries was collected through interviews and operation records, allowing for a detailed comparison with the projected performance of the hydrogen fuel cell system.

	identify optimal hydrogen fuel cell specifications.	
II. Developing a facility model for fuel cell refueling of ferries.	MATLAB Simulink software was used to model the hydrogen fuel cell system's components. The model incorporated electrolysis for hydrogen production, storage tank capacities, pressure management through compressors, and cooling needs.	

3.2 Initial design data collection

As part of the initiative to establish a hydrogen fuel cell refueling facility for the ferries' operation, a thorough and strategic approach was taken to ensure the optimal location and functionality of the facility. The key objective was to ensure the facility's onshore placement along the ferry route for easy access.

The Magogoni-Kigamboni route was chosen to serve as a pilot project, reflecting the overall plan and providing a model for future refueling stations around the Country.

3.2.1 Site selection process

(i) Initial assessment and identification of site selection

The first step involved identifying potential sites along the ferry channel between Magogoni and Kigamboni. It was crucial that these sites were onshore to allow easy docking and refueling of the ferries. The locations considered included areas near the Magogoni terminal, the Kigamboni terminal, and potential midway points along the route that could offer strategic advantages see Figure 3.1.

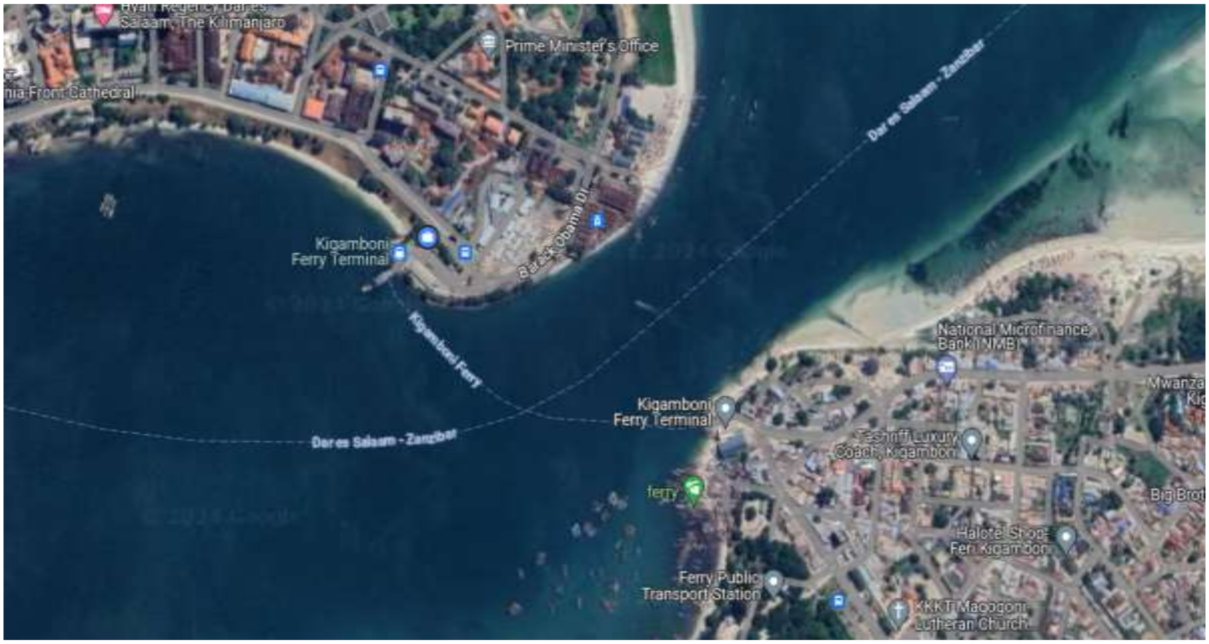

Figure 3.1: Picture shows the channel between Magogoni Kigamboni Area (Source: Google Maps).

(ii) Identification of potential locations

(a) Magogoni Area; Investigation of potential sites near the Magogoni terminal.

(b) Kigamboni Area; Explore sites near the Kigamboni terminal.

(c) Mid-Route Locations; Consideration of any viable sites midway that offer easy access from both terminals.

(iii) Evaluation of each location based on criteria

Evaluation of each location in Magogoni, Kigamboni, and Mid route are shown in Table 3.2

Table 3.2: Show evaluation based on Criteria

Criterion	**Magogoni area**	**Kigamboni area**	**Mid-route locations**
Proximity to Ferry Route	Excellent	Excellent	Good
Land Availability	Not available	Excellent	Good
Safety and Regulations	To be assessed	To be assessed	To be assessed
Utility Access	Excellent	Excellent	To be assessed

Environmental Impact	To be assessed	To be assessed	To be assessed
Expansion Potential	Not available	Excellent	Not available

- **Magogoni area**

This location was assessed for its proximity to the ferry route and utility access, which were both deemed excellent. However, land availability and expansion potential were significant constraints, making it less favorable despite its strategic advantages.

- **Kigamboni area**

Sites near the Kigamboni terminal emerged as highly promising. They offered excellent proximity to the ferry route, ample land availability, and strong potential for future expansion. The availability of necessary utilities was also rated excellent, though safety and environmental impact assessments were pending.

Figure 3.2: Proposed area for Hydrogen fuel cell Refueling facility for TEMESA ferries

Kigamboni side.

- **Mid-route locations**

While these sites provided good accessibility from both terminals, land availability was a limiting factor. Furthermore, these locations required thorough safety and environmental impact evaluations to ensure compliance with regulatory standards and minimal disruption to local ecosystems.

Through this rigorous evaluation process, it became evident that the Kigamboni area offered the most balanced advantages for establishing the hydrogen fuel cell refueling facility. The combination of excellent land availability, utility access, and expansion potential made it the optimal choice, provided that subsequent safety and environmental assessments confirmed its suitability.

With the site selected, the next step involves the detailed design and specification of the equipment necessary to meet the daily hydrogen consumption requirements of the ferries. This phase was focused on ensuring that the facility is equipped with the appropriate production, storage, and dispensing systems to support efficient and safe operations.

Findings and Discussion

This presents the study's findings, focusing on the design and performance analysis of the hydrogen refueling system for TEMESA ferries. The results include detailed simulations of hydrogen production, storage, and distribution processes, using site-specific data and system modeling to optimize the system’s efficiency and safety.

4.1 Ferries specification

The specifications of the ferries Mv Magogoni, Kazi, and Kigamboni were collected to establish a baseline for the design. These included dimensions, engine specifications, fuel consumption, and operational parameters are shown in Table 4.1.

Table 4.1: Specification of the Diesel Ferries Mv. Magogoni, Kazi and Kigamboni

Main Dimensions	**Mv. Magogoni**	**Mv. Kazi**	**Mv. Kigamboni**
Length	74.1M	52.25M	52.23M
Breadth	17.44M	12.60M	12.50M
Depth	5M	2.40M	2.4/2.00M
Gross Tonnage	500T	170T	150T
Service Speed (knots)	45.6 knots	44 knots	48 knots

Capacity			
Private cars	60	22	22
Passengers	2000	800	800
Engines	The mechanically governed **CAT 3406C** marine propulsion engine rating of 400 bhp (298 kW)	Marine propulsion engine rating output (B.H.P) PS(kW)/rpm 320(235)/2,000 **MD196TI**	Marine propulsion engine rating of Power output as per ISO 14396 Kw/hp 300/402 **BF6M1015**
Propellers			
Schottel Pump Jet	Pump JET SPJ 82 RD	Pump JET SPJ 57 RDL	Pump JET SPJ 57 RDL
Storage Tank			
	Two Main Tanks Capacity of 30,000 L each	Two Main Tanks Capacity of 15,000 L each	Two Main Tanks Capacity of 5,500 L each
	Two Daily Service Tank Capacity of 15,000 L each	Four Daily Service Tank Capacity of 1,500 L each	Four Daily Service Tank Capacity of 200 L each
Fuel consumptions Total fuel consumption per year **864,000L**	8,000L per week	6,000L per week	4,000L per week

4.2 Energy consumption data

To calculate the capacity of the fuel cells needed for the ferries in comparison to the current diesel power,

(i) **Total energy provided by diesel (per week);**

Then,

(a) Energy (MJ) =Fuel Consumption (L) ×Energy Density of Diesel (MJ/L) **(4.1)**

There for,

Mv. Magogoni: 8,000L/week×35.8 MJ/L= 286,400 MJ/week

Mv. Kazi: 6,000 L/week×35.8 MJ/L=214,800 MJ/week

Mv. Kigamboni: 4,000 L/week×35.8 MJ/L=143,200 MJ/week

(b) Determine fuel cell efficiency

Assuming a fuel cell efficiency of 50%, the energy required from hydrogen would be;

Required Energy from Hydrogen (MJ) $= \frac{Energy\ Provided\ by\ Diesel\ (MJ)}{Fuel\ Cell\ Efficiency}$ **(4.2)**

1) Mv. Magogoni $= \frac{286{,}400\ MJ/week}{0.50} = 572{,}800\ MJ/week$
2) Mv. Kazi $= \frac{214{,}800\ MJ/week}{0.50} = 429{,}600\ MJ/week$
3) Mv. Kigamboni $= \frac{143{,}200\ MJ/week}{0.50} = 286{,}400\ MJ/week$

(c) Calculation of hydrogen required

Hydrogen required $= \frac{Required\ Energy\ from\ Hydrogen(MJ)}{Energy\ density\ of\ Hydrogen\ (MJ/kg)}$ **(4.3)**

1. Mv Magogoni $= \frac{572{,}800\ MJ/week}{120\ MJ/kg} = 4{,}773.33\ kg/week$
2. Mv. Kazi $= \frac{429{,}600\ MJ/week}{120\ MJ/kg} = 3{,}580\ kg/week$
3. Mv. Kigamboni $= \frac{286{,}400\ MJ/week}{120\ MJ/kg} = 2{,}386.67\ kg/week$

Since these values are for one week, we can find the daily requirement by dividing by 7 (the number of days in a week);

Daily Hydrogen Requirement $= \frac{weekly\ Hydrogen\ Requirement}{7}$ **(4.4)**

1. Mv. Magogoni $\frac{4{,}773.33\ kg/week}{7} = 681.90\ kg/day$
2. Mv. Kazi $\frac{3{,}580\ kg/week}{7} = 511.43\ kg/day$
3. Mv. Kigamboni $\frac{2{,}386.67\ kg/week}{7} = 340.95\ kg/day$

Therefore, the total daily hydrogen requirement for all three ferries is **1,534.28 kg/day.**

To find the annual hydrogen usage, multiply the daily usage by the number of days in a year. Assuming a year has 365 days;

Annual Hydrogen Usage = 1,534.28 kg/day x 365 days/year **(4.5)**

Therefore,

Annual Hydrogen Usage = 560,051.2kg/year

4.3 Initial design parameters determination

The general assumptions simplifying and constraining the design process, ensuring a manageable and accurate representation of the system dynamics, are as follows

(a) Neglect of pressure losses;

In the design of the hydrogen refueling system, pressure losses in pipelines and across heat exchangers are disregarded. This assumption simplifies calculations and

assumes efficient transfer of gases and heat throughout the system, thereby focusing on the core functionality without complex pressure loss considerations.

(b) Neglect of gravitational potential energy;

Given the design's horizontal layout, there is no height difference between components of the station. Consequently, gravitational potential energy is neglected, simplifying energy calculations by excluding gravitational effects. This approach assumes that all components are on the same elevation, ensuring uniform energy distribution.

(c) Neglect of kinetic energy;

The velocities within the hydrogen refueling system are assumed to be minimal, allowing for the neglect of kinetic energy. This simplification aids in dynamic modeling by excluding kinetic effects, which are considered negligible for the system's operation.

(d) Uniform distribution of hydrogen in tanks;

It is assumed that hydrogen within storage tanks is well-stirred, leading to a uniform distribution. Tanks are modeled as lumped capacities, simplifying spatial considerations and ensuring consistent pressure and temperature throughout each tank.

(e) Ambient temperature at start of refueling;

At the beginning of each refueling process, the hydrogen mass within the storage tank at the station and the vehicle tank is assumed to be at ambient temperature.

This assumption simplifies initial conditions for temperature calculations, providing a standardized starting point for each refueling cycle.

4.3 The PEM electrolyzer design

4.3.1 Hydrogen production rate

Given;

Desired Hydrogen Production 1,534.28 kg/day, Molar Mass of Hydrogen H_2 Is 2.02g/mol

Formula;

$$\text{Moles of } H_2 \text{ required per day} = \frac{\boldsymbol{Desired\ hydrogen\ production\ (g/day)}}{\boldsymbol{Molar\ Mass\ of\ H_2\ (g/mol)}} \qquad \mathbf{(4.6)}$$

Calculation,

$$\text{Moles of } H_2 = \frac{1{,}534.280\ g/day}{2.02\ g/mol} = \mathbf{759.545\ mol/day}$$

4.3.2 Electrical power requirement

Given:

The theoretical Energy for Water Electrolysis is 237.2 kJ/mol, and Efficiency is 70% (or 0.70)

Formula;

$$\text{Actual Energy Requirement (kJ/mol } H_2) = \frac{\boldsymbol{Theoretical\ Energy\ (kJ/molH_2)}}{\boldsymbol{Efficiency}} \qquad \mathbf{(4.7)}$$

Calculation;

$$\text{Actual Energy Requirement} = \frac{237.2kJ/mol}{0.70} = \mathbf{338.86\ kJ/molH_2}$$

4.3.3 Power requirement

$$\text{Power Requirement } \mathbf{(MW)} = \frac{\boldsymbol{Actual\ Energy\ Requirement\ (kJ/molH_2)\ x\ Moles\ of H_2}}{\boldsymbol{86{,}400_s/day}} \qquad \mathbf{(4.8)}$$

$$\text{Power Requirement } = \frac{338.86kJ/mol\ x\ 759.545\ mol/day}{86{,}400_s/day} = \mathbf{2.97MW}$$

The power requirement for the system to produce hydrogen of 1,534.28 kg/day is **2.97 MW.**

4.3.4 Water flow rate

Given;

Water Consumption per Mole of H_2 is 1 mol H_2O

Formula;

$$\text{Water Flow Rate (L/day)} = \frac{\boldsymbol{Moles\ of\ H_2\ per\ day\ x\ Molar\ mass\ of\ H_2O\ (g/mol)}}{\mathbf{1000}\ \boldsymbol{g/L}} \qquad \mathbf{(4.9)}$$

Calculation;

$$\text{Water Flow Rate} = \frac{759.545\ mol/day\ x\ 18.02g/mol}{1000g/L} = 13.68\ L/day$$

4.3.5 Cell size

Given;

Current density 1.5 A/cm^2, Cell voltage 1.8 V

Formula;

$$\text{Cell Area per cell } cm^2 = \frac{\boldsymbol{Total\ Power\ Requirement\ (MW)}}{\boldsymbol{Current\ Density\ (A/cm^2)\ x\ Cell\ Voltage\ (V)}} \qquad \mathbf{(4.10)}$$

Calculation:

$$\text{Cell Area per cell} = \frac{2.97\ MW}{1.5\ A/cm^2)\ x\ 1.8\ V)} = \frac{2.97\ x\ 10^6 W}{1.5\ A/cm^2)\ x\ 1.8\ V)} = 1.1\ x10^6\ cm^2$$

So, the cell area per cell is approximately. $\mathbf{1.1\ x10^6\ cm^2\ or\ 110\ m^2}$

4.3.6 Number of cells required

Given

Cell size = *62 cm x 62 cm = 3,844* cm^2 *per cell* (**Note:** the cell size of 62 cm x 62 cm, which equal to 3,844 cm^2Per cell is a commonly assumed value for large-scale PEM (Proton Exchange Membrane) electrolyzer cells.

Formula;

$$\text{Number of Cells} = \frac{\boldsymbol{Total\ Cell\ Area\ (cm^2)}}{\boldsymbol{Area\ of\ Each\ Cell\ (cm^2)}} \qquad \mathbf{(4.11)}$$

Calculation,

$$\text{Number of Cells} = \frac{1.1\ x10^6\ cm^2}{3{,}844cm^2/cell} = \frac{1{,}100{,}000\ cm^2}{3{,}844cm^2/cell} = \mathbf{286\ Cell}$$

So, the number of cells required is approximately **286 cells**

4.3.7 Storage Tanks (Onshore and Onboard)

a) Onshore low-pressure storage tank;

Let, V_{LP} Be the volume of the low-pressure storage tank.

P_{LP} = 10 bars (assumed for low-pressure storage)

Given,

Annual hydrogen requirement is 560,051.2kg, Daily hydrogen requirement is **1,534.28** kg, Density of hydrogen at 10 bar (low pressure),$\rho LP = 0.08988\ kg/m^3$, Density of hydrogen at 350 bar (high pressure) $\rho LP = 24.15\ kg/m^3$

Therefore,

The volume flow Pressure storage tank is $\boldsymbol{V_{LP} = \frac{m_{daily}}{\rho LP}}$ $\quad$ **(4.12)**

$$\boldsymbol{V_{LP} = \frac{1,534.28kg}{0.08988\ kg/m^3} = 17,070m^3}$$

b) Onshore high-pressure storage tank;

Let, V_{HP_i} Be the volume of each high-pressure storage tank (where *I* = *1, 2, 3*)

P_{LP} = 350 bars

Volume of low Pressure storage tank is $\boldsymbol{V_{HP_i} = \frac{m_{daily}}{3\ x\ \rho LP}}$ $\quad$ **(4.13)**

Therefore,

$$\boldsymbol{V_{HP_i} = \frac{1{,}534.28\ kg}{3\ x\ 24.15\ kg/m^3}\ 21.177m^3}$$

Each of the three high-pressure storage tanks should have a volume of approximately 21.177 m³.

c) Onboard high-pressure storage tank;

Let, V_{ON} = be the volume of the onboard high-pressure storage tank.

P_{ON} = 350 bars

$\boldsymbol{m_{daily}}$ = Daily hydrogen requirement, $\boldsymbol{\rho ON = 24.15\frac{kg}{m^3}}$

The volume of Onboard High-Pressure Tank is $\boldsymbol{V_{ON}} = \frac{m_{daily}}{\rho ON}$ $\quad(\mathbf{4.14})$

Table 4.2: show the volume, Density, and daily hydrogen requirement of onboard High-pressure tank after Calculation

	Mv. Magogoni	**Mv. Kazi**	**Mv. Kigamboni**
$\boldsymbol{m_{daily}}$	**681.90 kg**	**511.43 kg**	**340.95 kg**
$\boldsymbol{\rho ON}$	**24.14 kg/m^3**	**24.14 kg/m^3**	**24.14 kg/m^3**
$\boldsymbol{V_{ON}}$	**28.236m^3**	**21.177m^3**	**14.188m^3**

d) Compressor

The compressor must be capable of compressing hydrogen to 350 bar. We need to calculate the power requirement.

Let,

Inlet pressure = 1 bar (atmospheric pressure), Outlet pressure = 350 bar, Flow rate = 1534.28 kg/day (approx. 63.93 kg/hour), Hydrogen specific heat ratio **(γ)** = 1.41, Molecular weight of H_2 = 2.016 g/mol, Universal gas constant (R) = 8.314 J/ (mol·K), Temperature = Assume 300 K

Then,

$$\boldsymbol{P} = \frac{\dot{m}\boldsymbol{RT}}{\boldsymbol{\eta_m}(\boldsymbol{\gamma} - \mathbf{1})}\left[\left(\frac{\boldsymbol{P_2}}{\boldsymbol{P_1}}\right)^{\frac{\gamma-1}{1}} - \mathbf{1}\right] \qquad (\mathbf{4.15})$$

Where,

ṁ = mass flow rate (kg/s), $\boldsymbol{P_2}$ = inlet pressure (Pa), $\boldsymbol{P_1}$ = outlet pressure (Pa), $\boldsymbol{\eta_m}$ = mechanical efficiency (assume 0.85).

First, convert pressures;

$\boldsymbol{P_1} = \mathbf{1}\, bar = 100{,}000\, Pa$, $\boldsymbol{P_2} = 350\, bar = 35{,}000{,}000\, Pa$

To calculate the mass flow rate

$$\dot{m} = \frac{\mathbf{1{,}534.28}\, \boldsymbol{kg}}{\mathbf{24 \times 3600}_s} = \mathbf{0.01775}\, \boldsymbol{kg/s} \qquad (\mathbf{4.16})$$

To calculate the compressor power;

$$\boldsymbol{P} = \frac{\mathbf{0.01775 \times 8.314 \times 300}}{\mathbf{0.85 \times (1.41 - 1)}} \left[\left(\frac{\mathbf{35,000,000}}{\mathbf{100,000}} \right) \wedge^{\frac{\mathbf{0.41}}{\mathbf{1.41}}} - \mathbf{1} \right] \qquad (\mathbf{4.17})$$

$$\boldsymbol{P} = \frac{\mathbf{44.27}}{\mathbf{0.35}} \left[(\mathbf{350})^{\mathbf{0.29}} - \mathbf{1} \right]$$

$$\boldsymbol{P} = 127.036\ [6.12 - 1]$$

$$\boldsymbol{P} = 127.036\ \times 5.12$$

Therefore, the required Compressor to run in the facility must have a power of $\boldsymbol{P} = \mathbf{650}\ \boldsymbol{kW}$

e) Throttling valves, pre-cooler and dispensers

(a) Dispenser

The dispenser flow rate can be modeled using the continuity equation and the ideal gas law for compressible flow;

$$\dot{\mathrm{m}} = \boldsymbol{C_d} \cdot \boldsymbol{A} \cdot \sqrt{\mathbf{2} \cdot \boldsymbol{\rho} \cdot (\boldsymbol{P_1} - \boldsymbol{P_2})} \qquad (\mathbf{4.18})$$

Where,

$\boldsymbol{C_d}$ Is a discharged coefficient**,** $\boldsymbol{A}$ is a cross-sectional area of the nozzle, $\boldsymbol{\rho}$ is a density of hydrogen, $\boldsymbol{P_1}$and $\boldsymbol{P_2}$ Are the pressure before and after the nozzle, respectively?

Given data and assumptions;

The daily hydrogen requirement is 1534.28 kg/day, Assuming 24-hour operation for simplicity,

$\dot{\boldsymbol{m}} = \mathbf{0.01775}\ \boldsymbol{kg/s}$**,** Inlet, and outlet temperatures for pre-cooler = $\boldsymbol{T_{in}} = \mathbf{300}\ \boldsymbol{K}, \boldsymbol{T_{out}} = \mathbf{280}\ \boldsymbol{K}$ (assumed value), Pressure drop for throttling valve = $\boldsymbol{K}$ = 1, Pressures before and

after the dispenser $\boldsymbol{P_1} = \mathbf{350}\ \boldsymbol{bar}, \boldsymbol{P_2} = \mathbf{10}\ \boldsymbol{bar}$, $\boldsymbol{C_d} = \mathbf{0.85}$ (typical value for gas), **A = 0.0001** $\boldsymbol{m^2}$ **(**Eichman et al., 2014)**,** $\boldsymbol{\rho}$ **= 0.08375 kg/m³ (**typical density for hydrogen**)**

$$\dot{\mathrm{m}} = \mathbf{0.85} \cdot \mathbf{0.0001} \cdot \sqrt{\mathbf{2}\ \boldsymbol{x}\ \mathbf{0.08375}\ \boldsymbol{x}\ (\mathbf{350} - \mathbf{10})\boldsymbol{bar}}$$

Convert pressure to Pascal’s (1 bar = 100,000 Pa);

$$\dot{\mathrm{m}} = \mathbf{0.85} \cdot \mathbf{0.0001} \cdot \sqrt{\mathbf{2} \cdot \mathbf{0.08375} \cdot (\mathbf{350,000} - \mathbf{10,000})\boldsymbol{Pa}}$$

$$\dot{\mathrm{m}} = \mathbf{0.85} \cdot \mathbf{0.0001} \cdot \sqrt{\mathbf{61,132}}$$

$$\dot{\mathrm{m}} = \mathbf{0.85} \cdot \mathbf{0.0001} \cdot \mathbf{247.2489}$$

$$\dot{\mathrm{m}} = \mathbf{0.0210}\ \boldsymbol{kg/s}$$

(b) Pre-cooler model

The formula to calculate the heat removed **(**$\boldsymbol{Q}$**)** by pre-cooler is;

$$\mathbf{Q} = \dot{\mathrm{m}}.\boldsymbol{c_p}.(\boldsymbol{T_{in}} - \boldsymbol{T_{out}}) \qquad (\mathbf{4.19})$$

Where,

$\dot{m}$ is the mass flow rate of hydrogen gas, c_p Is the specific heat capacity of hydrogen gas and is approximately 14.3 kJ/kg·K (or 14,300 J/kg·K) around room temperature. , T_{in} Is the inlet temperature, T_{out} Is the outlet temperature?

Given,

$\dot{m}$ is 0.01775 kg/s (as calculated above), we assume, T_{in} 300K and T_{out} **280 K**

From,

$Q = \dot{\mathrm{m}}.c_p.(T_{in} - T_{out})$, substitute the value into the formula

Q = $\mathbf{0.01775}$ kg/s x 14,300 J/kg·K x (300 K - 280 K)

Q **= 5,076.5 W**

Therefore, the heat removed by the pre-cooler would be approximately **5,076.5 W** (or 5.0765 kW).

(c) Throttling valve model

Since the pressure losses are neglected and the valve maintains constant enthalpy ($h_1 = h_2$), the pressure drop calculation for the throttling valve,

The formula of the Throttling valve is $\Delta P = K \cdot \frac{\dot{m}^2}{\rho}$ $\quad (\mathbf{4.20})$

Given,

$\dot{m}$ = 0.01775 kg/s, ρ = 0.0899 kg/m^3, Assume K = 1 (hypothetical value for simplicity)

$\Delta P = K \cdot \frac{\dot{m}^2}{\rho}$ Substitute the value into the formula,

$\Delta P = 1\mathrm{x}\, \frac{(0.01775)^2}{0.0899\ kg/m^3}$

ΔP **= 0.003505bar** (350.5Pa)

Table 4.3 Calculated requirements for the hydrogen fuel cell refueling components.

SN	COMPONENTS	PARAMETERS		UNITS
1.	PEM Power Requirement	2.97		MW
	Water Requirement	13.68		L/day
	PEM Cell Size	10^6 or 110		cm^2/m^2
	Number of Cells Required	286		Cells
2.	Onshore low-pressure storage tank	17,070		m^3 at 10 bar
3.	Onshore High-Pressure Storage Tank	21.177		m^3 at 350 bar (three tanks)
4.	Onboard High-pressure Storage Tank	Mv. Magogoni	28.236	m^3 at 350 bar
		Mv. Kazi	21.177	m^3 at 350 bar
		Mv. Kigamboni	14.118	m^3 at 350 bar
5.	Compressor	650		kW
6.	Throttling Valves	0.003505/350.5		Bar/Pa
7.	Dispenser	0.0210		govoverss/s
8.	Pre-cooler	5,076.5 or 5.0765).		W /kW

4.4 Model development

The model development for the hydrogen fuel cell refueling facility involves several critical components, storage tanks, compressors, throttling valves, dispensers, and pre-coolers. These components must be accurately modeled to ensure the facility meets the hydrogen demand efficiently and safely.

(a) Components and their specifications

(a) PEM electrolyzer

- Power Requirement = 2.97 MW
- Water Requirement = 13.68 L/day

- PEM Cell Size = $1.1\ x\ 10^6\ cm^2\ or\ 110\ m^2$
- Number of Cells Required = 286 cells
- **Role;** The PEM electrolyzer is responsible for producing hydrogen through the electrolysis of water. The electrolyzer splits water into hydrogen and oxygen using electrical energy, providing a steady supply of hydrogen to the storage tanks. The efficiency and capacity of the electrolyzer are crucial to meet the daily hydrogen demand.

(b) **Onshore low-pressure storage tank**

- Volume = $17{,}070m^3$
- Pressure = 10 bar
- Hydrogen Capacity = 1,534.28 kg/day
- **Role;** Stores hydrogen at a lower pressure to provide a buffer before compression. This ensures a steady supply to the high-pressure system.

(c) **Onshore high-pressure storage tank**

- Volume = $21.177m^3$per tank (three tanks)
- Pressure = 350 bar
- Hydrogen Capacity = 1,534.28 kg/day
- **Role** = Stores hydrogen at high pressure, ready for dispensing. High-pressure storage is crucial for quick and efficient refueling.

(d) **Onboard high-pressure storage tank**

- Mv. Magogoni, Volume = $28.236\ m^3$, Hydrogen Capacity = 681.90 kg/day, Mv. Kazi Volume = $21.177\ m^3$, Hydrogen Capacity = 511.53kg/day, Mv. Kigamboni Volume = $14.188\ m^3$ Hydrogen Capacity =340.95 kg/day
- Pressure = 350 bar
- Role; Represents the storage on the ferry. Ensures that the hydrogen is stored safely at high pressure for operational use.

(e) **Compressor**

- Power Requirement = 650 kW

- **Role;** Increases the pressure of hydrogen from 10 bar to 350 bar. Efficient compression is vital for the transition from low-pressure storage to high-pressure storage.

(f) **Throttling valves**

- Pressure Drop = 0.003505bar, 35.5Pa
- **Role;** Regulates the flow and pressure of hydrogen between different stages of the refueling process. Ensures precise control over hydrogen dispensing.

(g) **Dispenser**

- Flow Rate = 0.0210 kg/s
- **Role;** Dispenses hydrogen into the vehicle or ferry. The flow rate must be sufficient to meet refueling speed requirements without causing excessive delays.

(h) **Pre-cooler**

- Heat Removed = 5,076.5 **W (or 5.0765 kW).**
- Role; Cools the hydrogen before high-pressure storage. Prevents overheating during compression, maintaining system efficiency and safety.

4.4.1 Model implementation in MATLAB Simulink

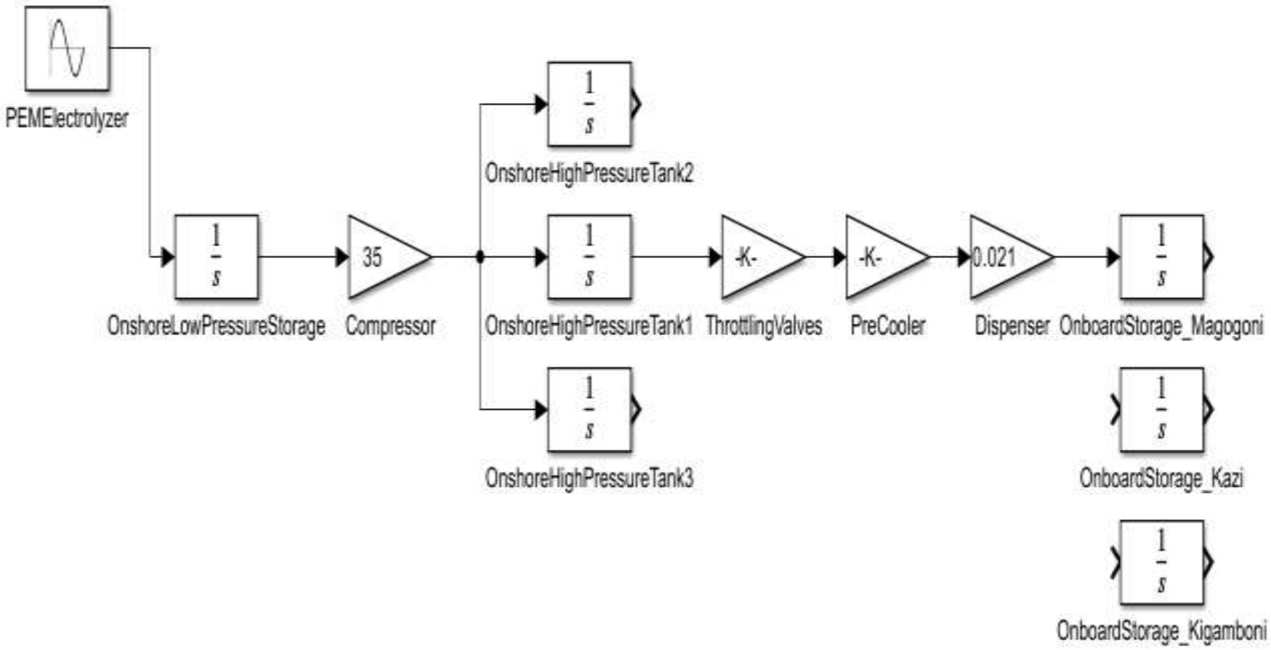

Figure 4.1 shows the hydrogen fuel cell refueling facility model

4.5 Filling process of onshore high-pressure storage tanks

The figure below shows the filling process of the high-pressure storage tanks, comparing the linear, exponential, and logarithmic filling behaviors over time.

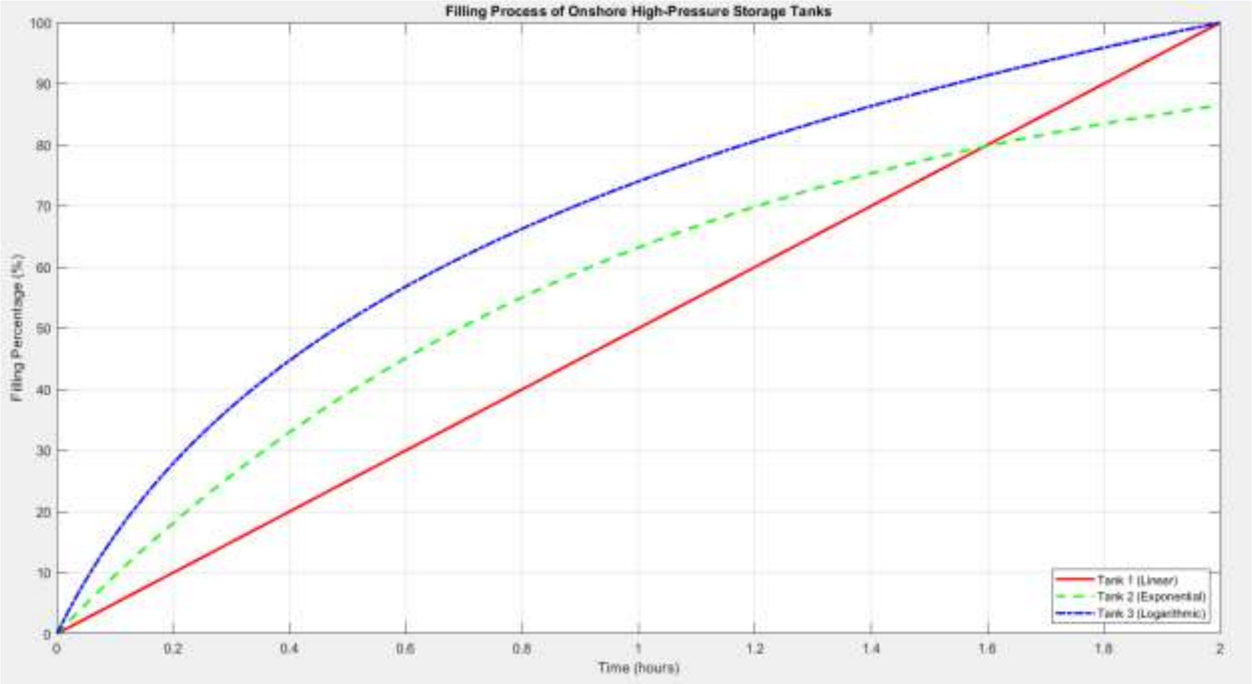

Figure 4.2 Filling processes of onshore high-pressure storage tanks

The filling process for the onshore high-pressure storage tanks was simulated with three different filling behaviors which are linear, exponential, and logarithmic. Each tank represents a different filling strategy based on flow rate and pressure dynamics, each tank reaches 100% capacity, but at different rates.

The graph comparing the filling processes of the three tanks shows distinct behaviors;

- **Tank 1 (Linear);** Fills steadily over the entire period, representing a controlled and predictable refueling process.
- **Tank 2 (Exponential);** Starts slowly and accelerates towards the end, showing how pressure builds up gradually.
- **Tank 3 (Logarithmic);** Fills quickly at first but slows down as it nears capacity, ensuring the system maintains safety by reducing flow rate as pressure increases.

This comparison highlights how different filling strategies can be used to optimize refueling based on operational needs, balancing speed, and safety.

The comparison of these three tanks demonstrates different filling dynamics, each with its advantages and disadvantages. Systems that require fast, safe, and efficient hydrogen refueling need to consider these different filling behaviors. **Linear filling** offers predictability, **exponential filling** offers efficiency as pressure builds, and **logarithmic filling** prioritizes safety by reducing the filling rate as capacity is approached. The results of this simulation can guide the design of high-pressure hydrogen storage systems, ensuring that they meet operational needs while maintaining safety and efficiency.

4.6 Filling process between onshore low-pressure and high-pressure storage tanks

The figure below compares the filling rates of the onshore low-pressure storage tanks and the high-pressure storage tanks, showing how the pressure requirements affect the filling dynamics.

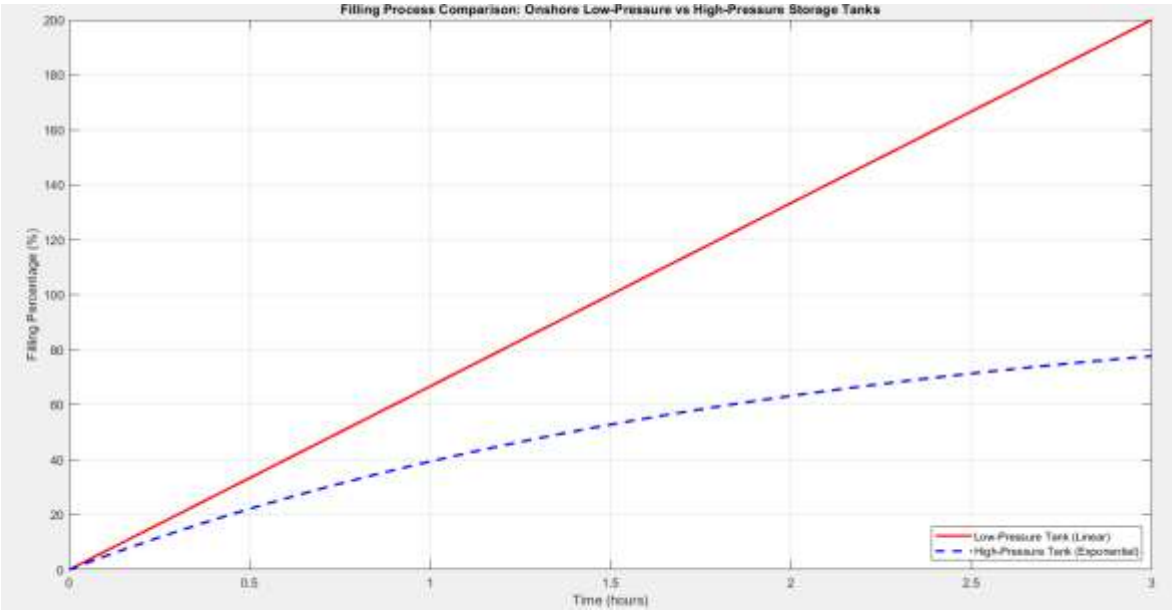

Figure 4.3 Filling process between onshore low-pressure and high-pressure storage tanks

The simulation results provide a comparative analysis of the filling processes for an onshore low-pressure storage tank and an onshore high-pressure storage tank over 3 hours. Each tank's filling rate is represented as a percentage of its total capacity, with time in hours shown on the x-axis and the filling percentage on the y-axis.

(a) Low-pressure storage tank; linear filling (red line)

- The low-pressure tank follows a linear filling process, indicated by a straight red line.
- The linear behavior suggests that there are no significant variations in the flow rate or pressure during the filling process. The hydrogen can be quickly stored in the low-pressure tank without requiring complex energy management or control mechanisms.

(b) High-pressure storage tank; non-linear filling (blue dashed line)

- The high-pressure tank, represented by the blue dashed line, follows a non-linear filling process. The curve shows an exponential filling pattern where the tank fills slowly at the beginning and then speeds up as time progresses.
- Even after 3 hours, the high-pressure tank does not reach 100% capacity, indicating that it requires more time to fill compared to the low-pressure tank.
- The slower initial filling rate reflects the difficulty in compressing hydrogen into the tank, especially as the internal pressure rises. As the tank nears full capacity, the flow rate begins to decelerate.
- Practical interpretation, shows the gradual filling process is typical of high-pressure tanks, where storing hydrogen at pressures as high as **350 bar** requires more energy and a controlled compression process. This prevents over-pressurization and ensures safe operation.

4.7 Dispenser flow rate

The hydrogen flow rate through the dispenser starts at **0.0210 kg/s** and decreases over time as the pressure in the onboard storage tanks approaches the source pressure. This controlled flow ensures a safe and efficient transfer of hydrogen during the refueling process.

The flow rate through the dispenser starts at **0.0210 kg/s** and decreases as the onboard storage tanks fill up, ensuring a safe and controlled hydrogen transfer.

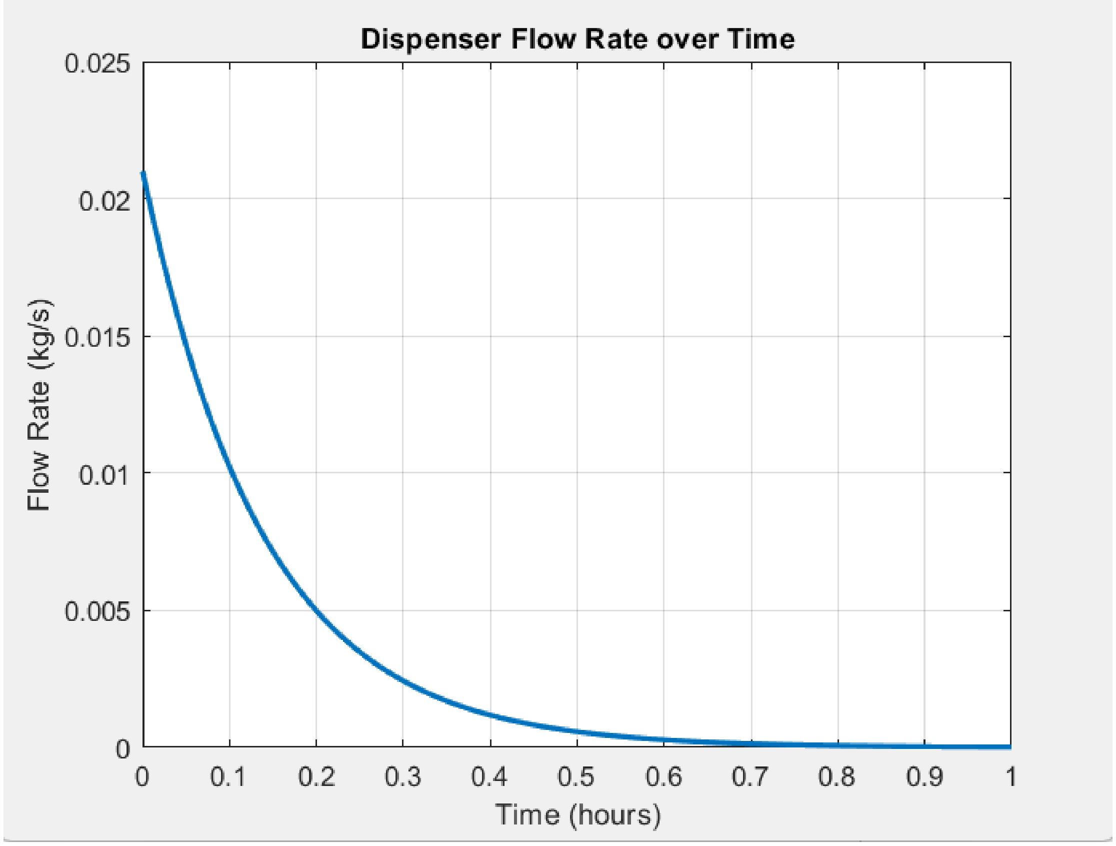

Figure 4.4 Show dispenser flow rate over time

4.8 Discussion

The onshore low-pressure storage tank serves as the main reservoir for hydrogen production, initially operating at 10 bars. The results indicate an exponential decrease in pressure as hydrogen is drawn into the refueling system. This gradual pressure reduction reflects the continuous consumption of hydrogen throughout the refueling process. The size of the low-pressure tank (17,070 m³) ensures sufficient supply to meet the daily hydrogen requirements of 1,534.28 kg. In contrast, the onboard high-pressure tanks for Mv. Magogoni, Mv. Kazi, and Mv. Kigamboni fills from 10 bar to 350 bar, with an initial rapid pressure rise that slows down as the tanks approach their full capacity. This behavior is a direct result of decreasing pressure differentials, which naturally regulate the hydrogen flow and ensure safe refueling operations.

Additionally, energy analysis indicates that the compressor is the most energy-intensive component, consuming the majority of the system's power. The pre-cooler, while essential for thermal regulation, consumes less energy in comparison. Optimizing the energy consumption of the compressor would have the greatest impact on improving the overall energy efficiency of the hydrogen refueling facility.

5 Conclusion

TEMESA ferries can be powered sustainably and effectively using this hydrogen refueling technology, to sum up. The architecture of the system guarantees dependable hydrogen generation, storage, and refueling while offering a foundation for future cost and energy efficiency optimization. Further advancements in electrolyzer performance, compression technology, and energy management will increase the viability of such systems for extensive maritime applications as hydrogen technology develops.

The current pilot project should serve as a model for scaling up hydrogen fuel cell use in other areas of Tanzania's maritime sector. A phased approach that gradually increases the number of hydrogen-powered ferries and refueling stations can ensure a smooth transition while addressing potential operational challenges.

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