International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.gaexcellence.com/ijirev
GLOBAL ACADEMIC EXCELLENCE

PRELIMINARY DESIGN: INTEGRATION OF ELECTROLYSIS AND THIN-FILM SOLAR TECHNOLOGY FOR ONBOARD HYDROGEN PRODUCTION IN FUEL CELL VEHICLE (FCV)

Fatin Nadzirah Zul Ariffin[1], Juliza Jamaludin[1*], Bushra Naeem[2], Marriam Manzoor[2]

[1] Faculty of Engineering and Built Environment, Universiti Sains Islam Malaysia (USIM), Bandar Baru Nilai, 71800 Nilai Negeri Sembilan
ftndzrh594@raudah.usim.edu.my https://orcid.org/0009-0002-3826-0206
juliza@usim.edu.my https://orcid.org/0000-0003-4693-2236

[2]Information Technology Department, Balochistan University of Information Technology, Engineering and Management Sciences (BUITEMS), Quetta, Pakistan
bushra.naeem@ymail.com https://orcid.org/0000-0002-5703-6413
engr.marriam@gmail.com https://orcid.org/0009-0005-6091-4829

[*]Corresponding Author

Article Info:

Article history:
Received date: 22.01.2026
Revised date: 12.02.2026
Accepted date: 25.03.2026
Published date: 31.03.2026

To cite this document:

Zul Ariffin, F. N., Jamaludin, J., Naeem, B., & Manzoor, M. (2026). Preliminary Design: Integration Of Electrolysis and Thin-Film Solar Technology for Onboard Hydrogen Production in Fuel Cell Vehicle (FCV). *International Journal of Innovation and Industrial Revolution, 8*(24), 528-541.

Abstract:

This research is focused on the integration of thin-film solar technology with electrolysis for onboard hydrogen production in fuel cell vehicles (FCVs). The study identifies electrolysis, driven by renewable solar energy, as a suitable method for producing high-purity hydrogen directly on the vehicle. This approach addresses some of the challenges faced by the existing infrastructure for hydrogen refueling stations, which is heavily reliant on the efficient and safe transportation of hydrogen. Currently, transportation primarily depends on tanker trucks that move hydrogen from production facilities to refueling stations. However, this method is constrained by truck capacity, limiting the volume of liquid hydrogen transported. By designing an integrated system that combines thin-film solar panels with a compact electrolyzer, the research will be able to demonstrate a feasible and efficient approach for continuous hydrogen generation, eliminating the need for external refueling infrastructure. The system's performance is investigated and evaluated based on previous literature and will be further assessed using experimental simulations. From the investigation and preliminary analysis, this proposed technology is able to provide a significant improvement in hydrogen production efficiency compared to conventional methods. The preliminary findings show that this

International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 8 Issue 24 (March 2026) PP. 528-541

proposed innovative integration offers a viable solution for sustainable and independent hydrogen production in FCVs, supporting the advancement of clean transportation technologies and contributing to the broader adoption of fuel cell vehicles.

DOI: 10.35631/IJIREV.824033

Keyword:

Efficiency, Hydrogen, Infrastructure, Onboard

© The authors (2026). This is an Open Access article distributed under the terms of the Creative Commons Attribution (CC BY NC) (http://creativecommons.org/licenses/by-nc/4.0/), which permits non-commercial re-use, distribution, and reproduction in any medium, provided the original work is properly cited. For commercial re-use, please contact ijirev@gaexcllence.com.

Introduction

The transportation sector plays a crucial role in Malaysia's economy and its people, like many other developing nations. However, it's contribution to air pollution is unavoidable, it also poses health concerns in large cities (Ong, Mahlia, & Masjuki, 2011). The alarming increase in emissions of combustible vehicles is a major contributor to air pollution and is considered as one of the major concerns regarding global warming. One of the basic hurdles faced by transportation sector is the finite availability of conventional fuel, prompting an urgent need for alternative and sustainable solution. As a response to this critical issue, powered vehicles such as Hydrogen Fuel Cell vehicle (FCV) is emerging as promising alternative. This innovative technology presents a viable path ahead, which offers cleaner and environmentally friendly mode of transportation. As part of ongoing research, the primary focus is towards exploring a viable path for powered vehicles as practical solution, so it can mitigate the adverse environmental impacts associated with conventional fuel-driven transportation. This research aims to pave the way for a more sustainable and eco-friendly future in the realm of transportation.

Hydrogen FCV presents a promising technology for clean energy, but their widespread adoption faces significant challenges; particularly in the category of infrastructure (Kolbe, Lechtenböhmer, & Fischedick, 2020; Pawelczyk, Łukasik, Wysocka, Rogala, & Gębicki, 2022; Wong, Ho, So, Tsang, & Chan, 2021). The infrastructure for hydrogen refuelling stations is heavily dependent on the efficient and safe transportation of hydrogen, regardless as a compressed gas or a cryogenic liquid. There are substantial energy losses (Hren et al., 2023) at each stage (from electrolysis production to compression and cooling), which requires considerable amount of electricity and reduce the overall efficiency of hydrogen as a fuel.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Right now, hydrogen transport relies primarily on tanker trucks carrying hydrogen from production facilities to refuelling stations. This method is restricted by the capacity of trucks, limiting the volume of liquid hydrogen (Lane, Shaffer, & Samuelsen, 2020). Additionally, cost of hydrogen production facilities is directly proportional to its demand (Greene, Ogden, & Lin, 2020). Overcoming these challenges is crucial to understand the full potential of hydrogen as a clean and sustainable energy source for transportation. One potential solution is to combine electrolysis and fuel cell technology by integrating thin-film solar panels to produce hydrogen directly within the vehicle.

Literature Review

Current Hydrogen Refueling Station

Hydrogen refueling station plays a crucial role in the triumph of hydrogen fuel cell vehicles (FCVs), providing the necessary infrastructure for efficient and sustainable hydrogen fuel distribution. Currently, the components in hydrogen refueling stations include several fundamental technologies and equipment. Figure 1 illustrates the general subsystem of a hydrogen refueling station, providing an elaborating overview of the key components and their interconnections. The diagram typically includes several primary subsystems: hydrogen production or delivery, compression, storage, dispensing, and safety systems. Compressors are essential as they increase the pressure of hydrogen gas to the required level for vehicle refueling. Storage tanks are used to store hydrogen at high pressure, ensuring a steady supply is available for refueling. Dispensers: which function similarly to gasoline pumps; deliver hydrogen to the vehicle's tank and are equipped with safety features to handle high-pressure hydrogen. The refueling process involves connecting the dispenser to the vehicle's hydrogen tank and transferring hydrogen under high pressure, typically completing the process within a few minutes.

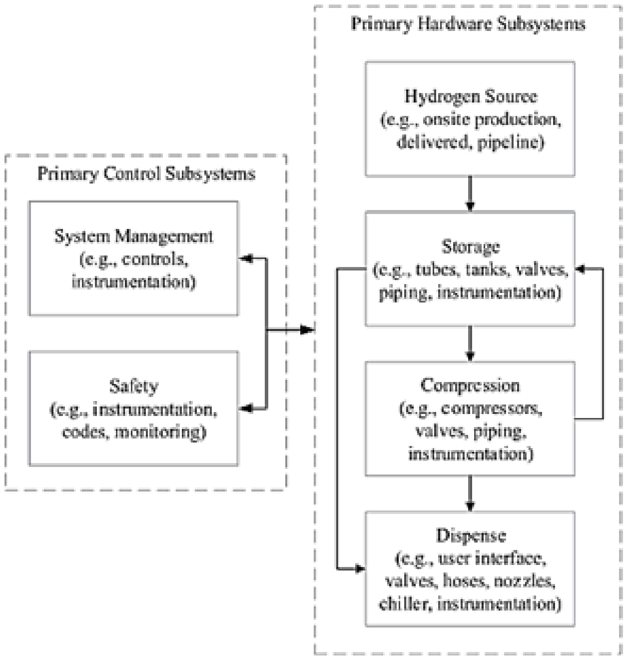

Figure 1: General Hydrogen Station Subsystems Diagram

Source: (Kurtz, Sprik, & Bradley, 2019)

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Globally, the deployment of hydrogen refueling station varies significantly. With key regions such as Japan, Germany, and California leading in infrastructure development (Genovese & Fragiacomo, 2023). Hydrogen stations come in various types, with the two primary categories being stations that receive hydrogen produced through steam methane reforming and those that produce hydrogen on-site via water electrolysis. Currently, most operational stations utilize the first method (Kurtz et al., 2019). Additionally, there are a few stations that use alternative hydrogen pathways, such as delivered hydrogen from renewable sources and hydrogen delivered through pipelines, although these are less common. The production model can be centralized with hydrogen produced at large facilities and transported to stations or distributed from onsite hydrogen production facilities.

Hydrogen refueling stations' environmental impact largely depends on the hydrogen production method. Stations using hydrogen produced from renewable sources, known as green hydrogen, have a significantly lower carbon footprint. Efforts to increase the use of green hydrogen are ongoing, aiming to enhance the sustainability of the hydrogen fuel supply chain. Despite these efforts, challenges such as the carbon footprint associated with hydrogen transportation and distribution persist.

Current Hydrogen Production Methods

Hydrogen production is a crucial aspect of advancing clean energy technologies and reducing reliance on fossil fuels. However, to achieve the goal of zero emission, the production of hydrogen must be carefully considered as it directly impacts the overall environmental footprint of hydrogen-powered vehicles. Colour-based classification is one of the primary methods used to describe hydrogen types, it depends heavily on how hydrogen is produced and what fuel is used to produce it as shown in Figure 2 (Singla, Gupta, Beryozkina, Safaraliev, & Singh, 2024). The main type of hydrogen is green, blue and grey. Green hydrogen is produced through the electrolysis of water, utilizing renewable energy such as wind or solar power. On the other hand, blue hydrogen is generated through steam methane reforming (SMR) or autothermal reforming (ATR), where natural gas is the primary feedstock. Blue hydrogen presents a lower-carbon alternative compared to traditional hydrogen production methods (Oni, Anaya, Giwa, Di Lullo, & Kumar, 2022). Grey hydrogen was differentiated into hydrogen derived from fossil fuel feedstock by hydrocarbon reaction processes such as steam reforming (Panić, Cuculić, & Ćelić, 2022).

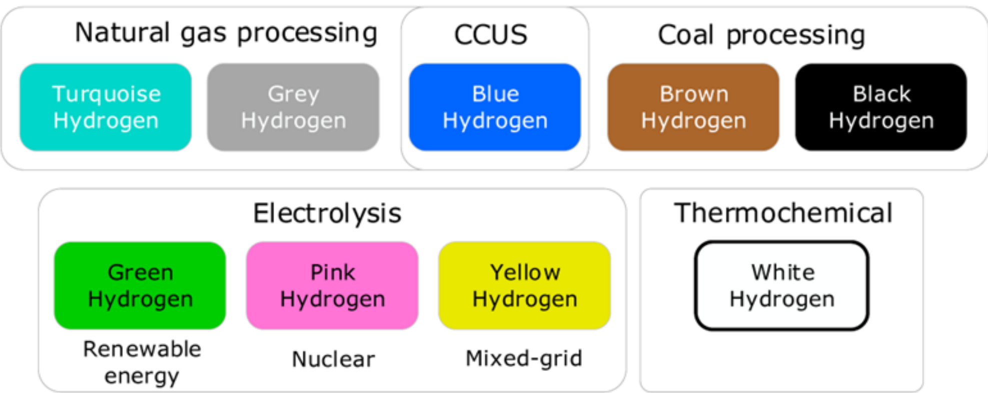

Figure 2: Hydrogen Colour-Based Classification Methodology

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Table 1 shows the current Hydrogen production methods. Electrolysis (Ahad, Bhuiyan, Sakib, Becerril Corral, & Siddique, 2023; Akac, Tsiatsiou, & Angelakakis, 2022; De Wolf & Smeers, 2023; Dulău, 2023; Habib & Arefin, 2022; Hoque, Biswas, Mazhar, & Howard, 2020; Szałek, Pielecha, & Cieslik, 2021; N. Wang & Tang, 2022; Xiaoxin, Qigong, & Yuan, 2023; Yazdi, Moradi, Pirbalouti, Zarei, & Li, 2023) is a chemical process that uses electrical energy to drive a non-spontaneous reaction, splitting water into hydrogen and oxygen. While it offers a clean method for hydrogen production, its high cost and challenges related to storage and transportation (Kumar & Himabindu, 2019) are significant. Steam reforming of methane (Ahad et al., 2023; De Wolf & Smeers, 2023; Dulău, 2023) involves reacting natural gas with steam to produce hydrogen and carbon dioxide. Although it is a widely used method, it contributes to greenhouse gas emissions through the release of carbon dioxide and increases the demand for natural gas, which could deplete reserves.

Partial oxidation of hydrocarbons (Ahad et al., 2023; De Wolf & Smeers, 2023; Wang & Tang, 2022) generates synthesis gas (syngas) through the partial oxidation of hydrocarbons. This method also produces carbon dioxide as a byproduct, contributing to greenhouse gas emissions, like steam reforming. Gasification of biomass (Ahad et al., 2023; Dulău, 2023) converts organic materials from plants or wastes into a gaseous mixture containing hydrogen. While this method utilizes renewable resources, it faces challenges including carbon dioxide emissions, the need for a hydrogen separation process from the gas mixture, variable results depending on catalysts, and high capital costs. Coal gasification (Ahad et al., 2023; Szałek et al., 2021) transforms coal into a gas mixture primarily composed of hydrogen and carbon monoxide. This method, however, results in carbon dioxide emissions, suffers from feedstock impurities, and involves high reactor costs, which are significant drawbacks. Each of these methods has its unique advantages and limitations, reflecting the complexities and trade-offs involved in hydrogen production.

Table 1: Current Hydrogen Production Methods

Methods	Concept	Limitation
Electrolysis	A chemical process that uses electrical energy to drive a non-spontaneous chemical reaction.	High cost, Storage and Transportation problem.
Steam reforming of methane	The natural gas reacted with steam to produce hydrogen and carbon dioxide.	Release Carbon dioxide as greenhouse gases and the increased demand for natural gas to produce hydrogen would deplete natural gas reserves.
Partial oxidation of hydrocarbons	The process of partial oxidation leads to the generation of synthesis gas (syngas).	Release Carbon dioxide as greenhouse gases
Gasification of biomass	A process that involves converting biomass, such as organic materials from plants or waste, into a gaseous mixture containing hydrogen.	Release Carbon dioxide as greenhouse gases, need H_2 separation process from mixture gas, variable results depend on the catalysts and high capital cost.

International Journal of Innovation and Industrial Revolution IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Coal gasification	A process that converts coal into a gas mixture primarily composed of hydrogen and carbon monoxide.	Release Carbon dioxide as greenhouse gases, feedstock impurities and high reactor cost.

Electrolysis

Water electrolysis is a well-known technique to produce hydrogen by using electrical energy to split water into hydrogen and oxygen. Electrolysis technologies are categorized based on the operating temperature and electrolyte employed. Electrochemical water splitting is an effective and clean method to produce high-purity hydrogen by using renewable energy, which has ignited new interests in the past decades (Wang, Cao, & Jiao, 2022).

Electrolysis is a chemical process that uses electrical energy to drive the non-spontaneous decomposition of water (H_2O) into hydrogen (H_2) and oxygen (O_2) gases. This process occurs in an electrolyzer, which consists of two electrodes—an anode and a cathode—immersed in an electrolyte solution. At the cathode (negative electrode), water molecules gain electrons to produce hydrogen gas and hydroxide ions. Conversely, at the anode (positive electrode), water molecules lose electrons to form oxygen gas and hydrogen ions. This results in the overall reaction where water is split into hydrogen and oxygen gases. There are several types of electrolyzers used (as shown in Table 2), including alkaline electrolyzers (ALK), which use a liquid alkaline electrolyte; proton exchange membrane (PEM) electrolyzers, which use a solid polymer (SO) electrolyte and offer high efficiency and compactness; and solid oxide electrolyzers, which operate at high temperatures and are known for their high efficiency.

Table 2: Types Of Electrolyzers

Type of electrolyzers	Proton Exchange Membrane (PEM)	Alkaline Electrolysis (ALK)	Solid Oxide Electrolysis (SO)
Electrodes and catalyst	an: Ti + Ti/RuO2, IrO2 cat: Ti + Pt	an: Ni, Fe cat: Ni/Ni-Co + Pt	an: ceramic (Mn, La, Cr), Ni cat: Zr + Ni/CeOx
Separator	Polymeric membrane	Diaphragm (usually Zirfon)	Ceramic membrane
Electrolyte	Usually, Nafion	KOH or NaOH	Usually, YSZ
H2 Production perMW ((kgH2/h)/MW)	17-19	16–19	24-25
Nominal power (kW)	2.4 -1250	0.5 - 7000	150 - 2700
Cell voltage (V)	2-2.2	2.1-2.3	1.5-1.6
Advantages	- High current density. - Smaller volume. - Heat recovery from cooling.	- Well-tested technology. - Lower costs. - Condensation recovery.	- Higher electrical efficiency. - RES- or industrial waste-heat usable - Reversible devices.
Disadvantages	- Higher costs to ALK.	- Corrosive liquid electrolyte.	- Thermal energy needed (steam). - Long warming up.

	- Greater water requirement - Smaller application - experience.	- H2 purification necessary. - Bigger volume.	- Limited lifetime

Source: (Sapountzi, Gracia, Fredriksson, & Niemantsverdriet, 2017)

Thin Film Solar

Table 3 shows the comparison between the type of absorber materials. The efficiency of different types of thin film solar cells varies significantly. CIGS solar cells typically achieve an efficiency of around 12.0% (Noufi & Zweibel, 2006), while CdTe cells often exceed 15% (Wu, 2004). In contrast, a-Si solar cells generally have an efficiency range of 6-8%. This variation reflects the different performance characteristics and applications suited to each type of solar cell technology. The bandgap range of different thin film solar cells varies, influencing their efficiency and application. CIGS solar cells have a bandgap range of 1.0 eV to 1.6 eV, which provides a balance between absorbing various parts of the solar spectrum and achieving high efficiency. CdTe cells have a bandgap of approximately 1.44 eV, optimized for efficient energy conversion in practical solar applications. In contrast, a-Si cells have a higher bandgap of around 1.75 eV, which affects their performance by limiting their ability to absorb lower-energy photons but makes them suitable for certain low-power applications.

Table 3: Comparison Between Type of Absorber Materials

Type of absorber materials	**CIGS**	**CdTe**	a-Si
Efficiency	12.0%	>15%	6-8%
Bandgap range	1.0 eV – 1.6 eV	1.44 eV	1.75 eV
Thickness range	1-2 µm	3-5 µm	1 µm
Temperature coefficient	-0.26%/C	-0.25%/C	-0.3%/C
Advantages	Higher durability and has wide absorption spectrum	Good performance in low light and has high efficiency in large-scale production	Abundant and non-toxic material
Disadvantages	expensive	Toxity of cadmium	Shorter lifespan and degradation over time.

The thickness of various thin film solar cells varies according to their material. CIGS solar cells typically range from 1 to 2 micrometers in thickness, while CdTe cells are thicker, ranging from 3 to 5 micrometers. On the other hand, a-Si solar cells are generally thinner, with a typical thickness of around 1 micrometer. This difference in thickness impacts the manufacturing process and the overall performance of the solar cells. The temperature coefficient, which indicates how a solar cell's efficiency changes with temperature, varies among different thin film technologies. CIGS solar cells have a temperature coefficient of -0.26% per degree Celsius, while CdTe cells have a slightly lower coefficient of -0.25% per degree Celsius. In comparison, a-Si solar cells exhibit a higher temperature coefficient of -0.3% per degree Celsius. This means that a-Si cells experience a greater reduction in efficiency as temperatures rise compared to CIGS and CdTe cells (Lee & Ebong, 2017).

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541
CIGS (Copper Indium Gallium Selenide) solar cells offer significant advantages, including a wide absorption spectrum, which allows them to capture a broader range of sunlight and convert more energy into electricity. They are also known for their higher durability, making them suitable for various environmental conditions. On the other hand, CdTe (Cadmium Telluride) solar cells excel in low-light conditions, ensuring reliable performance even when sunlight is limited. Additionally, they demonstrate high efficiency in large-scale production, making them a cost-effective choice for extensive solar installations. Each type of thin film solar cell comes with its own set of disadvantages. CIGS solar cells are relatively expensive, making them less accessible for some applications. CdTe cells, while efficient, face concerns about the toxicity of cadmium, which can pose environmental and health risks. On the other hand, a-Si solar cells have a shorter lifespan and tend to degrade over time, which can impact their long-term performance and durability. These disadvantages highlight the trade-offs involved in selecting the most suitable solar technology for specific needs.

Methodology

Flowchart

Figure 3 presents a comprehensive flowchart of the research process. The initial step involves identifying the most suitable method for producing onboard hydrogen for fuel cell vehicles (FCV). This requires a thorough investigation and comparison of various hydrogen production techniques to determine the most efficient and feasible option. Following this, the research focuses on exploring different thin film solar technologies to select the one that best complements the hydrogen production method. Once the appropriate solar technology is identified, the next phase involves designing an integrated system that combines thin-film solar panels with an electrolysis unit to produce hydrogen directly onboard the FCV. This integrated system design is then simulated using Aspen software to predict its performance and efficiency. The simulation results are crucial for evaluating and validating the system's hydrogen production efficiency, comparing it to the current methods. The research objective is met if the integrated system achieves an efficiency exceeding 0.6, indicating that the design is effective and surpasses existing methods in producing hydrogen efficiently for FCV.

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

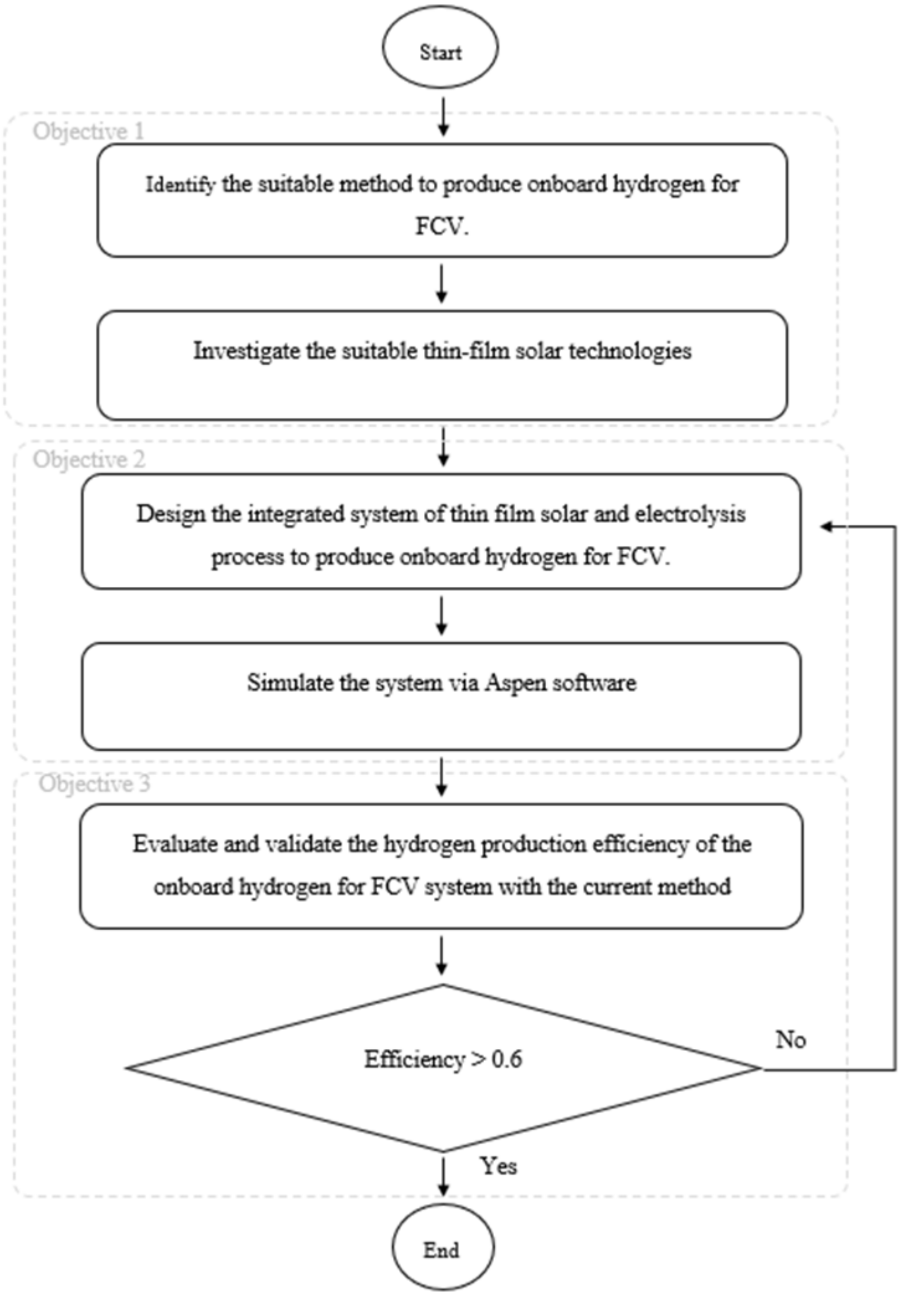

Figure 3: Flowchart

Design of the Integrated System

The primary objective of integrating thin-film solar panels with electrolysis technology is to enable FCVs to produce their own hydrogen fuel onboard, leveraging renewable solar energy. Figure 4 shows the proposed design outlines an innovative approach to onboard hydrogen production in fuel cell vehicles (FCVs) through the integration of electrolysis and thin-film solar technology. This integration is intended to provide a more sustainable and efficient alternative to conventional hydrogen refueling methods, aligning with the broader goals of reducing greenhouse gas emissions and improving energy independence in transportation.

International Journal of Innovation and Industrial Revolution IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

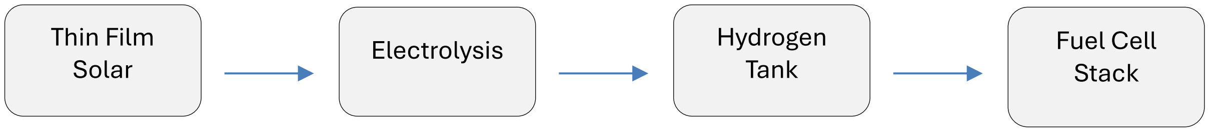

Figure 4: Block Diagram of the Proposed Design

Preliminary calculations are pivotal in assessing the feasibility of integrating thin-film solar technology with electrolysis for onboard hydrogen production in fuel cell vehicles (FCVs). These calculations are essential for ensuring that the integrated system operates efficiently and meets the vehicle’s performance and range requirements. Initially, estimating the energy requirements for the electrolyzer involves determining the amount of electrical power needed to drive the electrolysis process, which splits water into hydrogen and oxygen. This estimation is based on the power output of the thin-film solar panels installed on the vehicle. By evaluating the energy generation capabilities of these panels, one can ascertain whether they provide sufficient electricity to continuously support the electrolyzer’s operation.

Aspen software plays a crucial role in modeling and simulating these energy needs. It enables detailed simulations of chemical processes and energy systems, offering accurate assessments of the electrolyzer's energy consumption and performance under various conditions. The software facilitates predictions on the amount of hydrogen that can be produced based on the available solar energy and the electrolyzer's efficiency. The rate of hydrogen production is a crucial factor to ensure that the system will generate adequate hydrogen to meet the vehicle’s operational needs. This involves analyzing the electrolyzer’s efficiency and the solar energy available. Aspen software supports this by simulating different scenarios and optimizing parameters to achieve the desired hydrogen production rate.

Moreover, determining the appropriate hydrogen storage capacity is vital. The storage system must be capable of holding enough hydrogen to ensure the vehicle has a sufficient driving range and meets performance expectations. Aspen software will be used to model the storage system, and this software will help to evaluate the overall system efficiency and vehicle range. In summary, Aspen software plays a critical role in conducting this preliminary design by providing simulations and analysis of energy requirements, hydrogen production rates, and storage capacities. This will ensure that the proposed integrated system by combining thin-film solar technology and electrolysis is feasible, efficient, and capable of meeting the performance and range needs of the FCV.

Efficiency of Hydrogen Production

The efficiency of an electrolysis system will indicate the effectiveness of the electrical energy when it converts into chemical energy. Efficiency can be calculated as the heating value of the hydrogen produced divided by the electrical energy input. In this research, the efficiency of the electrolysis process is calculated using the higher heating value (HHV) of the produced hydrogen, while the lower heating value (LHV) is typically used for calculating efficiency in fuel cells (Harrison, Remick, Martin, & Hoskin, 2010). The equation is shown in (1).

$$Efficiency = \frac{HHV\ of\ H_2\ produced}{Electricity\ used} \tag{1}$$

International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Where, HHV of H_2 produced refers to the energy content of the hydrogen generated, measured in units like megajoules (MJ) or kilowatt-hours (kWh). Electricity used is the amount of electrical energy consumed during the electrolysis process, also measured in units like megajoules (MJ) or kilowatt-hours (kWh).

The efficiency of hydrogen production can be accurately determined through simulations using Aspen software. This advanced simulation tool allows for a comprehensive analysis of the hydrogen production process, providing detailed insights into various operational parameters. By using Aspen software, we can model the entire production system, including the electrolysis unit, energy inputs, and potential losses; to optimize and evaluate the efficiency of the process. The simulation will generate crucial data on parameters such as energy consumption, hydrogen yield, and overall system performance. These insights enable us to identify areas for improvement, optimize the process, and ensure that the hydrogen production system operates at its maximum efficiency.

Results

Proposed Design

Figure 5 illustrates the concept of integrated system onboard the vehicle. In this model, thin-film solar panels capture energy from the sun, which powers the electrolysis process. During electrolysis process, water is split into hydrogen and oxygen. The produced hydrogen will be stored in a hydrogen tank. The stored hydrogen then will be combined with the oxygen. The final product will be directed to the fuel cell stack. In the fuel cell stack, a chemical reaction will occur, producing electricity that powers the vehicle's motor system, thereby driving the vehicle forward. This innovative design leverages renewable solar energy to produce clean hydrogen fuel, highlighting a sustainable approach to powering vehicles.

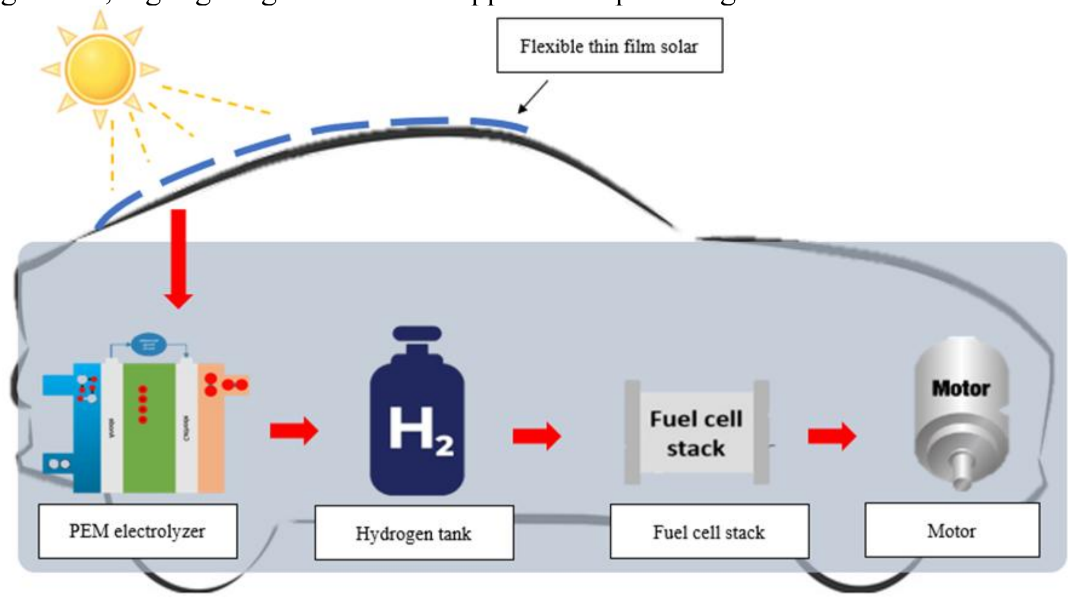

Figure 5: The Concept of The Integrated System Onboard the Vehicle

International Journal of Innovation and Industrial Revolution IJIREV
EISSN: 2637-0972
Volume 8 Issue 24 (March 2026) PP. 528-541

Conclusion and Future Works

In conclusion, this research will effectively address the key objectives related to the onboard hydrogen production for fuel cell vehicles (FCVs). From the previous literature and preliminary design, it shows that the integration of electrolysis with thin-film solar technology is a suitable advanced technology for onboard applications to produce hydrogen for sustainable transportation. Electrolysis, powered by renewable solar energy, offers a clean and efficient means of producing high-purity hydrogen, making it an ideal choice for reducing emissions and avoiding reliance on external refueling infrastructure. The successful preliminary proposed design of an integrated thin-film solar panels with an electrolysis process had demonstrated the feasibility of harnessing solar energy directly on the vehicle for continuous hydrogen production. This design leverages the flexibility and lightweight nature of thin-film solar technology to enhance system efficiency and practicality. Further experiments and analysis to evaluate and validate the proposed preliminary design is required to confirm that it meets the operational requirements of the current specification of FCV. The integrated system efficiently transforms solar energy into hydrogen, achieving lower energy consumption and enhanced performance metrics. This proposed preliminary design is believed to support the advancement of fuel cell technology (FCV) and contributing to the development of sustainable transportation solutions.

Acknowledgements:	The authors would like to express their sincere gratitude to Universiti Sains Islam Malaysia for providing the necessary resources and support throughout the course of this research. Special appreciation is extended to colleagues and peers who contributed valuable insights and constructive feedback, which greatly enhanced the quality of this paper.
Funding Statement:	No Funding
Conflict of Interest Statement:	The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV).
Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
Author Contribution Statement:	All authors contributed significantly to the development of this manuscript. Juliza Jamaludin was responsible for the conceptualization, methodology, and overall supervision of the study. Fatin Nadzirah Zul Ariffin handled data collection, analysis, and interpretation of results. Bushra Naeem and Marriam Manzoor contributed to the literature review, drafting, and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

References

Ahad, M. T., Bhuiyan, M. M. H., Sakib, A. N., Becerril Corral, A., & Siddique, Z. (2023). An overview of challenges for the future of hydrogen. *Materials*, *16*(20), 1–28.

Akac, A., Tsiatsiou, K., & Angelakakis, A. (2022). A review on best practices using hydrogen fuel-cell electric vehicles in public transport. *IOP Conference Series: Earth and Environmental Science*, *1123*(1), 1–10. IOP Publishing. doi:10.1088/1755-1315/1123/1/012055

De Wolf, D., & Smeers, Y. (2023). Comparison of battery electric vehicles and fuel cell vehicles. *World Electric Vehicle Journal*, *14*(9), 1–13.

Dulău, L.-I. (2023). CO2 emissions of battery electric vehicles and hydrogen fuel cell vehicles. *Clean Technologies*, *5*(2), 696–712. https://doi.org/10.3390/cleantechnol5020035

Genovese, M., & Fragiacomo, P. (2023). Hydrogen refueling station: Overview of the technological status and research enhancement. *Journal of Energy Storage*, *61*, 1–22. https://doi.org/10.1016/j.est.2023.106758

Greene, D. L., Ogden, J. M., & Lin, Z. (2020). Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. *ETransportation*, *6*, 1–22. https://www.sciencedirect.com/science/article/pii/S2590116820300436

Habib, M. S., & Arefin, P. (2022). Adoption of Hydrogen Fuel Cell Vehicles and Its Prospects for the Future. *Oriental Journal Of Chemistry*, *38*(3), 621–631. https://bit.ly/393tE5b

Harrison, K. W., Remick, R., Martin, G. D., & Hoskin, A. (2010). Hydrogen Production: Fundamentals and Case Study Summaries. In *Hydrogen and Fuel Cells: Fundamentals, Technologies and Applications* (pp. 207–226). John Wiley & Sons.

Hoque, N., Biswas, W., Mazhar, I., & Howard, I. (2020). Life cycle sustainability assessment of alternative energy sources for the Western Australian transport sector. *Sustainability*, *12*(14), 1–32. https://doi.org/10.3390/su12145565

Hren, R., Vujanović, A., Van Fan, Y., Klemeš, J. J., Krajnc, D., & Čuček, L. (2023). Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. *Renewable and Sustainable Energy Reviews*, *173*, 1–18. https://doi.org/10.1016/j.rser.2022.113113

Kolbe, K., Lechtenböhmer, S., & Fischedick, M. (2020). Hydrogen derived from algae and cyanobacteria as a decentralized fueling option for hydrogen powered cars: Size, space, and cost characteristics of potential bioreactors. *International Journal of Sustainable Transportation*, *14*(5), 325–334. https://doi.org/10.1080/15568318.2018.1547935

Kumar, S. S., & Himabindu, Vjms. (2019). Hydrogen production by PEM water electrolysis–A review. *Materials Science for Energy Technologies*, *2*(3), 442–454. https://doi.org/10.1016/j.mset.2019.03.002

Kurtz, J., Sprik, S., & Bradley, T. H. (2019). Review of transportation hydrogen infrastructure performance and reliability. *International Journal of Hydrogen Energy*, *44*(23), 12010–12023. https://doi.org/10.1016/j.ijhydene.2019.03.027

Lane, B., Shaffer, B., & Samuelsen, S. (2020). A comparison of alternative vehicle fueling infrastructure scenarios. *Applied Energy*, *259*, 1–17. https://doi.org/10.1016/j.apenergy.2019.114128

Lee, T. D., & Ebong, A. U. (2017). A review of thin film solar cell technologies and challenges. *Renewable and Sustainable Energy Reviews*, *70*, 1286–1297. https://doi.org/10.1016/j.rser.2016.12.028

Noufi, R., & Zweibel, K. (2006). High-efficiency CdTe and CIGS thin-film solar cells: highlights and challenges. *2006 IEEE 4th World Conference on Photovoltaic Energy Conference*, *1*, 317–320. IEEE. 10.1109/WCPEC.2006.279455

Ong, H. C., Mahlia, T. M. I., & Masjuki, H. H. (2011). A review on emissions and mitigation strategies for road transport in Malaysia. *Renewable and Sustainable Energy Reviews*, *15*(8), 3516–3522. https://doi.org/10.1016/j.rser.2011.05.006

Oni, A. O., Anaya, K., Giwa, T., Di Lullo, G., & Kumar, A. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Conversion and Management*, *254*, 1–17. https://doi.org/10.1016/j.enconman.2022.115245

Panić, I., Cuculić, A., & Ćelić, J. (2022). Color-coded hydrogen: Production and storage in maritime sector. *Journal of Marine Science and Engineering*, *10*(12), 1–31. https://doi.org/10.3390/jmse10121995

Pawelczyk, E., Łukasik, N., Wysocka, I., Rogala, A., & Gębicki, J. (2022). Recent progress on hydrogen storage and production using chemical hydrogen carriers. *Energies*, *15*(14), 1–34. https://doi.org/10.3390/en15144964

Sapountzi, F. M., Gracia, J. M., Fredriksson, H. O. A., & Niemantsverdriet, J. W. H. (2017). Electrocatalysts for the generation of hydrogen, oxygen and synthesis gas. *Progress in Energy and Combustion Science*, *58*, 1–35. https://doi.org/10.1016/j.pecs.2016.09.001

Singla, M. K., Gupta, J., Beryozkina, S., Safaraliev, M., & Singh, M. (2024). The colorful economics of hydrogen: Assessing the costs and viability of different hydrogen production methods-A review. *International Journal of Hydrogen Energy*, *61*, 664–677. https://doi.org/10.1016/j.ijhydene.2024.02.255

Szałek, A., Pielecha, I., & Cieslik, W. (2021). Fuel cell electric vehicle (FCEV) energy flow analysis in real driving conditions (RDC). *Energies*, *14*(16), 1–17. https://doi.org/10.3390/en14165018

Wang, N., & Tang, G. (2022). A review on environmental efficiency evaluation of new energy vehicles using life cycle analysis. *Sustainability*, *14*(6), 1–35. https://doi.org/10.3390/su14063371

Wang, T., Cao, X., & Jiao, L. (2022). PEM water electrolysis for hydrogen production: fundamentals, advances, and prospects. *Carbon Neutrality*, *1*(1), 1–19. https://link.springer.com/article/10.1007/s43979-022-00022-8

Wong, E. Y. C., Ho, D. C. K., So, S., Tsang, C.-W., & Chan, E. M. H. (2021). Life cycle assessment of electric vehicles and hydrogen fuel cell vehicles using the greet model—A comparative study. *Sustainability*, *13*(9), 1–14. https://doi.org/10.3390/su13094872

Wu, X. (2004). High-efficiency polycrystalline CdTe thin-film solar cells. *Solar Energy*, *77*(6), 803–814. https://doi.org/10.1016/j.solener.2004.06.006

Xiaoxin, Z., Qigong, C., & Yuan, G. (2023). Optimal scheduling of integrated energy systems including hydrogen electrolyzers, HFCVs, and electric vehicles. *Energy Science & Engineering*, *11*(1), 347–356. https://doi.org/10.1002/ese3.1336

Yazdi, M., Moradi, R., Pirbalouti, R. G., Zarei, E., & Li, H. (2023). Enabling safe and sustainable hydrogen mobility: circular economy-driven management of hydrogen vehicle safety. *Processes*, *11*(9), 1–29. https://doi.org/10.3390/ma16206680