COMPARISON OF TECHNO-ECONOMIC ASSESSMENT OF CENTRALIZED AND DISTRIBUTED HYDROGEN PRODUCTION USING PROTON EXCHANGE ELECTROLYSIS IN MALAYSIA

MAS'UD IDRIS

A project report submitted in fulfilment of the
requirements for the award of the degree of
Master of Science

School of Chemical and Energy Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

JULY 2022

ACKNOWLEDGEMENT

I have consulted many people, including researchers, academicians, renewable energy experts, and contributed much to this research project. Especially, I wish to express my profound appreciation to my supervisor, Dr. Tuan Amran Abdullah, for his encouragement, guidance, critics, and friendship. This proposal would not have been achieved without his immense support and interest.

I want to thank the entire management team of the Nigerian Institute of transport technology for their excellent leadership which supported me to seeing the success of this program. Especially the Director-General/ chief executive of NITT, Dr. Bayero S. Farah, and the Director of Transport Technology Centre, Engr. Elkenah O. Ngbale for their words of encouragement and support throughout the study. I also express my deep appreciation to my dear colleague's student who supported me in one way or the other to see the completion of this program.

ABSTRACT

The global demand for sustainable and renewable energy resources as a substitute for fossil-based fuels is increasing in tandem with the advancement of renewable energy technologies. Therefore, hydrogen is a potential candidate for an efficient instrument for massive-scale energy production and storage. This study aim to quantify the techno-economic benefits of centralised and distributed hydrogen production using proton exchange membrane electrolysis in Malaysia. Malaysia wants to implement renewable energy, and hydrogen is one of the energy carriers. An assessment of the capital and operating cost of hydrogen production is required. In Malaysia, the hydrogen economy based on centralised and distributed hydrogen production via PEM electrolysis has yet to be computed. The research methodology used technical and financial input parameters were analyzed using the H2A model v3 2018 spreadsheet and discounted cash flow analysis for hydrogen production costs. The capital expenditure and operating, maintenance, and repair costs were calculated, and a solar PV system was installed to power the PEM electrolyzer system. The research findings show that the highest cost of electricity and capital costs of hydrogen production was recorded, while fixed operating and maintenance costs are found to be lower in centralised H2 production. For distributed H_2 production, it was found that the costs of electricity consumption for a kilogram of hydrogen are much higher, followed by the capital cost of hydrogen and lower fixed operating and maintenance costs were observed. The cost of a unit of hydrogen in centralised hydrogen production is lower than in distributed hydrogen production at RM19.94/kgH2 (USD4.48/kgH_2) and RM10.15/kgH2 (USD2.28/kgH_2), for the centralised and distributed, respectively. It is suggested that centralised H_2 hydrogen production is more promising and had a lower cost of production when implemented. The higher cost of hydrogen storage was recorded using tube trailer, which involves the higher capital cost and lower operating cost for the tube trailer storage at a rate of RM2,014,353/trailer (USD445,562/trailer) and RM31,963/trailer (USD7,181/trailer). Based on the two scales of production it concludes that, centralized H2 production had a lower cost of producing a kg of hydrogen than distributed H2 production. Installing a solar PV system greatly impacts the price of green hydrogen GH2.

TABLE OF CONTENTS

TITLE		PAGE
	DECLARATION	**ii**
	DEDICATION	**iii**
	ACKNOWLEDGEMENT	**iv**
	ABSTRACT	**v**
	TABLE OF CONTENTS	**ix**
	LIST OF TABLES	**vii**
	LIST OF FIGURES	**xiii**
	LIST OF ABBREVIATIONS	**ix**
	LIST OF SYMBOLS	**x**
CHAPTER 1	**INTRODUCTION**	**1**
	1.1 Background	1
	1.2 Research Problem	4
	1.3 Research Questions	4
	1.4 Research Objectives	4
	1.5 Scope	5
	1.6 Research Hypothesis	5
	1.7 Significance	6
CHAPTER 2	**LITERATURE REVIEW**	**7**
	2.1 Introduction	7
	2.2 Hydrogen production	7
	2.2.1 Proton Exchange Membranes Electrolysis	8
	2.2.2 Alkaline Electrolysis	11
	2.2.3 Solid Oxide Electrolysis	12
	2.2.4 Photoelectrochemical Electrolysis	13
	2.2.5 Steam Reforming	14

2.3 Hydrogen Production Techno-Economics 15

2.4 Summary of Reviewed Literature 21

CHAPTER 3 RESEARCH METHODOLOGY 23

3.1 Introduction 23

3.2 Proposed Methodology 23

3.2.1 Summary of Methodology Flow Chart 24

3.2.2 Research Methodology Flow Chart 25

3.2.3 Hydrogen production Process & supply chain Diagram 26

3.3 Parameters for Hydrogen Production Analysis 27

3.3.1 PEM Electrolyzer System Capital Cost 28

3.3.2 Stack System Cost 28

3.3.3 Balance of Plant 28

3.3.4 Installation of Solar Energy system 31

3.4 Assumptions 32

3.5 Limitation 33

3.6 Data Analysis 33

CHAPTER 4 SIMULATION RESULTS AND DISCUSSION 34

4.1 Introduction 34

4.2 Estimation of Centralized PEM H2 Production Cost 34

4.2.1 Cost of 5MW Solar System 35

4.3 Estimation of Distributed PEM H2 Production Cost 37

4.3.1 Cost of 5.0KW Solar system 37

4.4 Comparison between Centralized and Distributed H2 Production Economics 41

4.5 Estimation the Cost of Tube Trailer H2 Storage 44

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS **46**

5.1 Conclusion 46

5.2 Recommendation 47

REFERENCES **48**

APPENDIX A **54**

APPENDIX B **59**

LIST OF TABLES

TABLE NO.	TITLE	PAGE
Table 3-1	Technical assumptions for calculation for both scenario (Centralised and decentralized H2 production)	29
Table 3-2	Financial assumptions for calculation for both scenario (Centralised and decentralized H2 production)	30
Table 3-3	Assumptions for tube trailer Hydrogen Storage	31
Table 3-4	Solar System Parameters	32
Table 4-1	Solar System Capital and Operating Cost	35
Table 4-2	Solar Panel Details Cost	38
Table 4.3	Capital cost of Solar System	39
Table 4.4	Hydrogen Production Cost Breakdown	42
Table 4.5	Cost of Tube Trailer Hydrogen Storage	45

LIST OF FIGURES

FIGURE NO.	TITLE	PAGE
Figure 1.1	System Design and Balance of Plant for PEM Electrolyzer (IREA, 2020)	2
Figure 1.2	A Trade-off between Efficiency, Durability and Cost of Electrolyzer	3
Figure 2.1	Schematic Flow Chart of Hydrogen Production Methods	8
Figure 2.2	Shows (a) Unipolar and (b) Bipolar Stack Design Of an Electricity	9
Figure 2.3	Challenges and Overviewed of Possible enabling Measures for Power to Hydrogen.	11
Figure 2.4	Illustration of Alkaline Water Electrolysis	12
Figure 2.5	Schematic Demonstration of solid Oxide Electrolysis	13
Figure 2.6	Demonstration of Industrial Hydrogen Production	15
Figure 2.7	Effect of Electricity cost and Capacity Factor on LCOH of Hydrogen Production for 4.2MW PEM Electrolysis	17
Figure 2.8	Blue Hydrogen and Worth of Managing CO2	17
Figure 2.9	PEM Water Electrolyzer	18
Figure 3.1	Summarized Methodology Flowchart diagram	24
Figure 3.2	Research Methodology Flowchart	25
Figure 3.3	Schematic Flow Chart of the Hydrogen Supply Chain from Generation to Distribution	26

Figure 4.1	Centralized PEM Hydrogen Production Cost	36
Figure 4.2	Distributed PEM Hydrogen Production Cost	40

LIST OF ABBREVIATIONS

A	-	Area
AEL	-	Alkaline Electrolysis
BOP	-	Balance of Plant
CCS	-	Carbon Capture Storage
CF	-	Plant Capacity Factor
CAPEX	-	Capital Expenditure
CPV	-	Coupled- Photovoltaic
DC	-	Direct Current
DCC	-	Direct Capital Cost
GH2	-	Green Hydrogen
GHG	-	Green House Gas
H2	-	Hydrogen
HHV	-	Higher Heating Value
ICC	-	Indirect Capital Cost
IC	-	Installation Cost
IEA	-	International Energy Agency
KIC	-	Key Industry Contributors
KgH2	-	Kilogram Hydrogen
KWh	-	Kilowatt-hour
KW	-	Kilowatt
KOH	-	Potassium Hydroxide
LHV	-	Lower Heating Value
LT	-	Life Time
LCH	-	Levelized Cost of Hydrogen
MWh	-	Megawatt Hour
MW	-	Megawatt
N2	-	Nitrogen

NREL	-	National Renewable Energy Laboratory
OPEX	-	Operating and Maintenance Expenditure
O &M	-	Operating and Maintenance
PEC	-	Photoelectrochemical
PEM	-	Proton Exchange Membrane
PTLs	-	Porous Transport Layers
PV	-	Photovoltaic
SMR	-	Steam Methane Reforming
SR	-	Steam Reforming
SOE	-	Solid Oxide Electrolysis
W	-	Watt

LIST OF SYMBOLS

MA/Cm2	-	Mega Ampere/ centimetre
A	-	Electrode surface Area
H2O	-	Water
€	-	Euro
$	-	US dollar
Nm^{-3}	-	Newton meter cube
CO2 e	-	Carbon Dioxide equivalent
%	-	Percentage
RM	-	Malaysian Ringgit
Mt	-	Metric tonne
V3	-	Version 3
MPa	-	Metric Pascal
CMBOP	-	Cost of Mechanical Balance of Plant
CBOP	-	Cost of Balance of Plant
CEBOP	-	Cost of Electricity Balance of Plant
MJ	-	Megajoule
GJ	-	Gigajoule

CHAPTER 1

INTRODUCTION

1.1 Problem Background

Hydrogen (H2) is a desirable fuel and will be future energy source. Interest in hydrogen energy has increased in recent years due to global worries over fossil fuels' role in greenhouse gas (GHG) emissions that have harmed the environment. Hydrogen can be generated using renewable energy sources more promising than today's traditional fossil fuels. Hydrogen energy can be used in a variety of applications, including transportation, combined heat and power systems, and home utilities (Boudries, 2016).

Hydrogen is plentiful in nature, primarily in mixed states, and can be created through a various conversion processes, including water electrolysis, fossil fuel combustion via natural gas steam reforming, biomass gasification, pyrolysis, and biological fermentation. Other methods are proton-electron membrane electrolysis (PEM), alkaline electrolysis (AEL), solid oxide electrolyzer cell (SOEC), and photo-electrochemical electrolyzer (PEC). However, steam reforming and water electrolysis are the most mature and marketed technologies among the ways of producing hydrogen. Hydrogen production can be powered by either conventional or renewable energy sources (Schnuelle et al., 2020).

IREA (2020) reported that the PEM lifetime of an electrolyzer is affected by several factors, including operating conditions, variable load, gas permeation, and anode dissolution. Poor water quality is one of the primary causes of stack failure in PEM electrolyzers. As a result of impurities, such as membranes, and ionomers in the catalyst, layer, catalysts, and PTLs rapidly degrade. PEMs have one of the smallest and simplest system designs but are susceptible to calcination and water impurities such as iron, copper, chromium, and sodium.

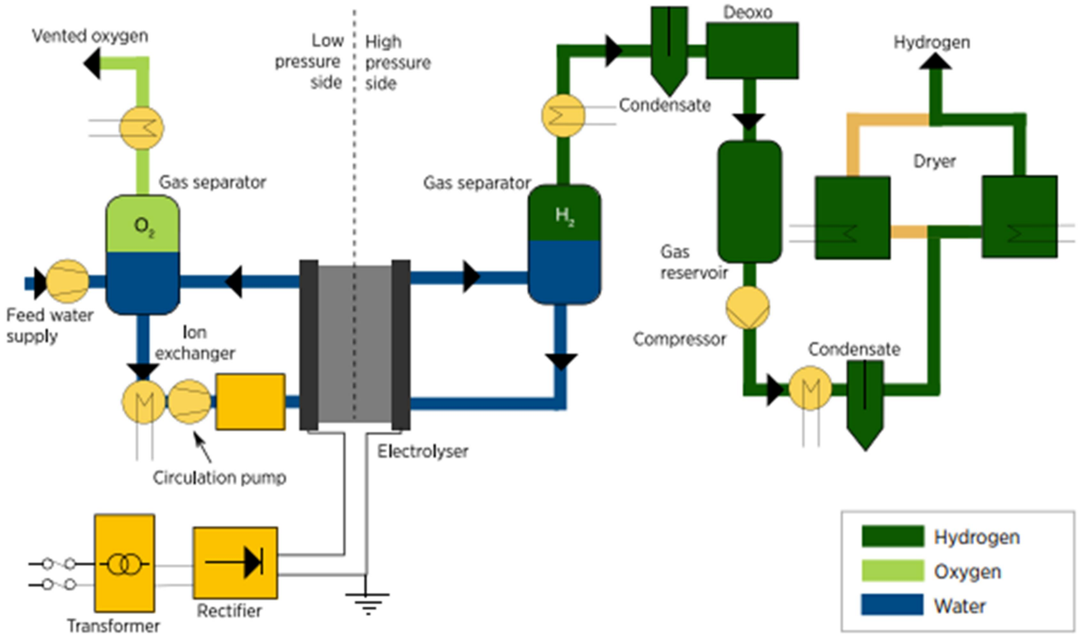

Figure 1-1 Illustration of System Design and Balance of plant for PEM electrolyzer (IREA, 2020)

Nonetheless, techno-economic analysis is critical in the hydrogen manufacturing process; for large-scale implementation, renewable hydrogen must become economically viable in comparison to traditional hydrogen produced from fossil fuels, such as natural gas steam reforming (SMR). The cost of power determines the cost of hydrogen generation, the cost of operating services, and the cost of capital. The cost of hydrogen production can be determined in broadly using technical and economic data (Schnuelle et al, 2020). The trade-off between efficiency, durability, and cost of the electrolyzer is shown in Figure 1.2.

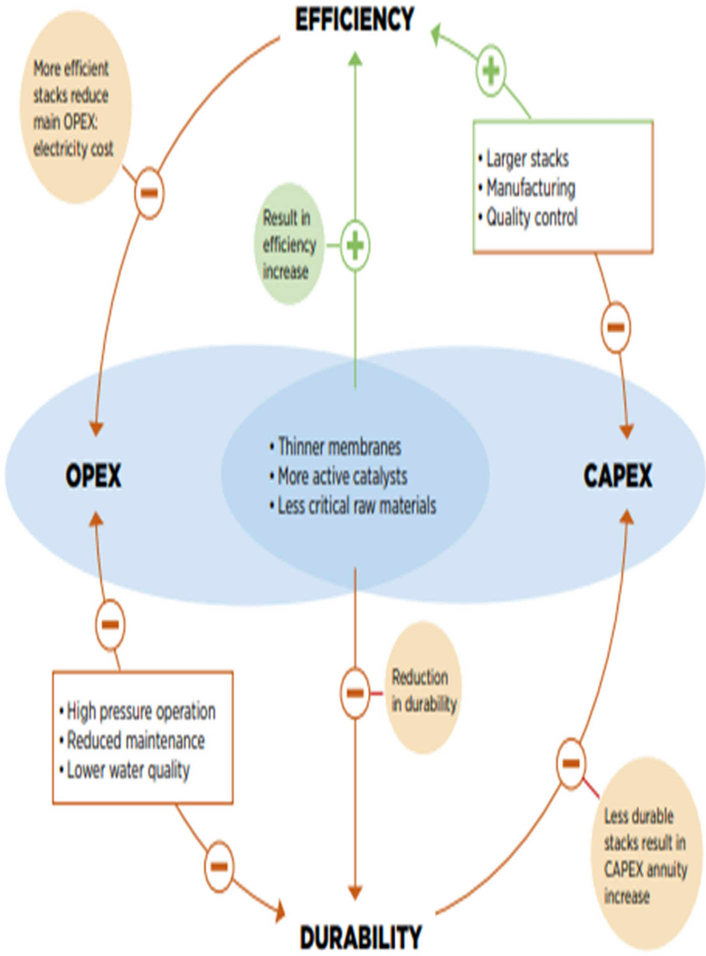

Figure 1.2 Trade-off between efficiency, durability, and cost of electrolyzer (IREA, 2020)

1.2 Research Problem

Hydrogen (H_2) is a clean energy source and the ideal fuel for the future; worldwide, interest in hydrogen energy is expanding. Hydrogen production has made enormous strides worldwide; however, large-scale hydrogen generation, primarily through steam reforming, has been commercialized; water electrolysis has also been commercialized, although at a considerable cost.

Malaysia wishes to deploy renewable energy, and as hydrogen is one of the energy carriers, an assessment of the capital and operating costs of hydrogen production and distribution is required. PEM electrolysis is one of the technologies for producing hydrogen using renewable energy (from solar farms) that is considered green hydrogen. The hydrogen economy for Malaysia is not well-calculated; the article has no data on proton exchange membrane electrolysis for the Malaysia scenario. Malaysia has not yet investigated centralized and distributed hydrogen production by proton exchange membrane electrolysis.

1.3 Research Question

Which hydrogen production method using PEM electrolysis is economically viable in Malaysia?

1.4 Research Objectives

This research aims to quantify and compare the techno-economic benefits of centralized and distributed hydrogen production in Malaysia.

The detailed objectives of the study are as follows:

1. To estimate the centralized hydrogen production from PEM electrolysis
2. To calculate the distributed hydrogen production from PEM electrolysis

3. To compare hydrogen production economics between centralized and distributed hydrogen production.
4. To estimate tube trailer hydrogen storage cost

1.5 Scope

This study used hydrogen production model that was built by United Stated National Renewable Energy Laboratory (H2A model v3 2018 spread sheet and discounted cash flow analysis), the input data are based on Malaysian scenario includes price of water, land cost, production technician salary, truck driver salary, truck fuel consumption, number of staff, legal requirements, natural gas price, site preparation or construction cost, engineering and design cost. Other technical inputs are the price of electrolyzer system, solar system, auxiliary and installation cost, price of tube vessel, trailer cost, steel containment structure cost and balance of a system.

The study estimated hydrogen production from PEM electrolysis using a 5-megawatt solar power source. The study assessed the CAPEX and OPEX of hydrogen synthesis from PEM using electricity generated by a 5KWatt solar energy source. The investment cost covered the original capital (CAPEX) and operating expenses (OPEX), as well as CAPEX and OPEX of tube trailer hydrogen storage.

1.6 Research Hypothesis

By giving the option of generating hydrogen via PEM power by PV solar, centralized hydrogen production is significantly more cost-effective in a small country like Malaysia than distributed (small) hydrogen production.

1.7 Research Significance

Malaysia has an abundance of renewable energy resources that it wishes to adopt, and hydrogen is one of the energy carriers. The research study contributes to the academic community's understanding of the economic viability of centralized and distributed hydrogen production by PEM electrolysis. The study aids in implementing of renewable energy policies in Malaysia by assessing financial viability and safety risks.

REFERENCE

Adam, C. (2020). Assessment of Hydrogen Production Costs from Electrolysis: United State and Europe. *International Council on Clean Transportation*, 1-62.

Aghil S, Hamed M. H, Sopian K. (2013). E.d (David Worrall). New Formulation for the Estimation of Monthly Average Daily Solar Irradiation for the Tropics. A Case Study of Peninsular Malaysia. International Journal of Photoenergy. Pp 1.

Agriculture Land For Sale @ Batu 12 Gambang, Kuantan - Land for sale in Kuantan, Pahang (mudah.my)

Ayers K.(2010). Research advances towards low-cost, high-efficiency PEM. ECS Transactions 33:3–15.

Ayers K., M. H. (2020). Peer reviewed of Hydrogen Production Cost From PEM Electrolysis. *Department of Energy, United State of America*, 1-15.

Azham Vsc. (2014, January 31). *SEDA Malaysia: Kumpulan Melaka Berhad Solar Farm.* Retrieved from http://azhamvosovic.blogspot.com /2014/01/seda-malaysia-kumpulan- melaka-berhad.html.

Bechrakis, D. A. (2006). Solar water splitting by photovoltaic-electrolysis with a solar-to-hydrogen efficiency of over 30%. *Energy Communications*, 47(1), 46-59.

Boreum Lee, J. H. (2018). Economic feasibility studies of high-pressure PEM water electrolysis for distributed H2 refuelling stations. *Energy Conversion.* , 162, 139–144.

Borgschulte A. (2016). The hydrogen grand challenge. *Front. Energy Res.*, 4, 11, https://doi.org/10.3389/fenrg.2016.00011.

Boudries R. (2016). Techno-economic assessment of solar hydrogen production using CPV- electrolysis systems. Journal Energy Procedia. Vol. 93, Pp 96-101 http://dx.doi.org/10.1016/j.egypro.2016.07

Brian James, W. C. (2013). PEM Electrolysis H2A Production Cased Study documentation. *Strategis Analysis*, 1-27.

Burnat D., Schlupp M., & Wichser A. (2015). Composite membranes for alkaline electrolysis based on polysulfone and mineral fillers, J. Power Sources 291, 163– 172.

Burne, S. (2012). The future of fuel: The future of hydrogen. *Fuel Cells Bulletin*, 2012 (1), 12-15.

Carmo M., D. F. (2013). , A comprehensive review on PEM water electrolysis. *Int. J. Hydrogen Energy*, 38, 4901–4934.

Gas Malaysia: Natural gas selling price for 3Q at RM30.03 per MMBtu | The Star

David F., R.M. (2020). Solar Industry update. National renewable Energy Laboratory.1-43. Retrieved: Q4 2019/Q1 2020

Dimitri B. (2016). PEM electrolysis for hydrogen production, Principle and application, 4-206

Dönitz W., E. E. (1985). High-temperature electrolysis of water vapour-status of development and perspectives for application. *Int. J. Hydrogen Energy*, 10, 291–295.

Energy, U. S. (2015). Hydrogen Production. *Fuel Cell Technologies Office Multi-Year Research, Development and Demonstration Plant*, 11007, 1-44.

Foteini Sapountzi M., M. J.-J. (2017). Electrocatalysts for the generation ofhydrogen, oxygen and synthesis gas. *Prog. Energy Combust. Sci.*, 58, 1–35.

Garland, N. M. (2019). Recent Advances in Hydrogen and Fuel Cell Technology. *ECS Transactions*, 17(1), 223–232.

Grimm, A. d., Grimm, A., de Jong, W. A., & Kramer, G. J. (2020). . *Hydrogen Energy*, 45(43), 22545-22555.

Houchins (PI) Cassidy, B. D. (2020). Hydrogen Storage Cost Analysis (ST100). *Strategic Analysis*, 1-24.

https://us.sunpower.com/products/solar-panels

https://www.pv-tech.org/sunpower-goes-large-with-new-a-series-ibc-module-using-
ngt technology/

https://news.energysage.com/how-much-does-the-average-solar-panel-installation-cost-in-the-u-s/

https://www.solarharmonics.com/solar-inverters-how-much-do-solar-inverters-cost/

https://www.solarharmonics.com/solar-inverters-how-much-do-solar-inverters-cost/

https://www.nst.com.my/news/nation/2020/02/562532/higher-water-tariff-necessary-upgrade-infrastructure

https://www.globalpetrolprices.com/Malaysia/natural_gas_prices/

West Port 38500sf (malaysialand.com)

https://www.salaryexpert.com/salary/job/production-technician/malaysia

https://letsavelectricity.com/how-many-solar-panels-i-can-install-in-100-sq-ft-area/

https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis
_ 2 019.pd

International Energy agency. (2019). The Future of Hydrogen. Report Prepared by the IEA for the G20, Japan. Tech. rep. Paris, URL: https://www.iea.org/reports/the-future-of- hydrogen.

IRENA. (2019). A Renewable Energy Perspective: https://www.irena.org/-/media/Files/IRENA/ Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf.

International Standard ISO 22734-1, Hydrogen generators using water electrolysis process Part 1 Industrial and commercial applications.

Jim Hinkley, J. H. (2016). Cost Assessment of Hydrogen Production from PV and electrolysis. *CSIRO Energy*, 1-39.

Koponen J. (2017). Control and energy efficiency of PEM water electrolyzers in Renewable energy systems. Int. Journal of Hydrogen Energy, (42), 29648-29660

Krosposki B., J. L. (2006). Electrolysis: Information opportunities. National Renewable energy Laboratory. Wetse://www.osti.gov./bridge. *National Renewable energy Laboratory.*

Kumar S., H. V. (2019). Hydrogen Production by PEM water electrolysis. a Review. *Material Science for Energy Technologies*, 442-454.

Landman Avigail, D. H. (2017). Photoelectrochemical water splitting in separate oxygen and hydrogen cells. *Science.gov (United States)*, 1-26.

Layzell D.B., C. Y. (2020). Towards Net-Zero Energy Systems in Canada: A Key Role For Hydrogen. *Transition Accerator Reports.* , Vol. 2, 1-52. Retrieved

Lee s., K. H. (2021). Scenario-Based Techno-economic Analysis of Steam Methane Reforming Process for Hydrogen Production. *Applied Science*, 1-14.

Liang M., B. Y. (2019). Preparation of LSM-YSZ composite powder for the anode of solid oxide electrolysis cell and its activation mechanism. *J. Power Source*, 190, 341-345.

M.A, L.-B. (2012). Recent advances in high-temperature electrolysis using solid oxide fuel cells: a review. *J. Power Sources*, 203, 4–16.

Markos, M (2016). Potential of Solar Energy in Kota Kinabalu, Sabah: An Estimate Using a Photovoltaic System Model. *Journal of Physics: Conference Series*, *710*, 7. Retrieved from https://doi.org/10.1088/1742-6596/710/1/012032

Moçoteguy P., B. A.-N. (2013). A review and comprehensive analysis of degradation mechanisms of solid oxide electrolysis cells. *Int. J. Hydrogen Energy*, 38,15887–15902.

PEM Electrolysis Cases published at: http://www.hydrogen.energy.gov/h2a_prod_studies.htm

Peterson, D.; Vickers, J.; DeSantis, D. (2020). "Hydrogen Production Cost From PEM Electrolysis – 2019 ". Record #19009.

Power, M. (2001). *Solar Power Installation Requirements: What You Need To Know*. Retrieved from https://stellarsolar.net/2018/11/14/solar-power-installation-requirements- what-you- need-to- know/

Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., and Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. Int. J. Hydrogen Energy 42, 30470–30492

Schnuelle C., T. W. (2020). Dynamic Hydrogen Production from PV and wind direct electricity supply -Modelling and techno-economic assessment. *Int. J. Hydrogen Energy,* 45 (55), 29938-29952.

Seetharamana S., Balaji R., Ramya R.K, & Dhathathreyan S. (2013). Graphene oxide modified non- noble metal electrode for alkaline anion exchange membrane water electrolyzers, Int. J. Hydrogen Energy 38, 14934– 14942.

Shaner, M.R et al.,. (2016). A comparative techno economic analysis of renewable hydrogen Production using solar energy. Energy & Environ. Sci. 9 (7), 2354–2371.

Suresh B., S. (2004) "Chemical Economics Handbook Marketing Research Report," SRI Consulting, 4-13

Trasatti S et al.,. (1999). Water electrolysis: who first, J. Electrochemical. 479, 90– 91

Ursua A et al.,. (2012). Hydrogen production from water electrolysis: current status and future trends, Proc. IEEE 100 (2) 410–426.

Xu W., K. S. (2010). The effects of ionomer Content on PEM Water Electrolyzer Membrane Electrode Assembly Performance. *Int. J. Hydrogen Energy*, 35, 12029-12037.

Yates J., Rahman D. et al.,. (2020). Techno-economic Analysis of Hydrogen Electrolysis from off-Grid Stand- Alone Photovoltaic Incorporating Uncertainty Analysis. *Cell Report Physical Science*, 1-15. Retrieved: https://doi.org/10.1016/j.xcrp.2020.100209

Yukesh Kannah, R. K.-V. (2021). Techno-economic assessment of various hydrogen production methods – A reviewed. *Bioresource Technology*, 319, 1241.

Zainul Abdin, C. T. (2021). Large-scale stationary hydrogen storage via liquid organic hydrogen carriers. *iscience*, 15.

Zeng, K. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications, Prog. Energy Combust. Sci. 36, 307–326.

E4tech, Element Energy. (2014). Study on development of water electrolysis in the EU.

Fuel Cells and Hydrogen Joint Undertaking. *Wetse://www.osti.gov./bridge*, 4-20.