UNIVERSITI PUTRA MALAYSIA

HIGH-TEMPERATURE ELECTROLYSIS OF COPPER CHLORIDE USING HYBRID PROTON EXCHANGE MEMBRANE FOR HYDROGEN PRODUCTION

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Chair : Nordin bin Hj Sabli, PhD
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Comprehensive utilisation of green hydrogen energy is an excellent pathway to reduce greenhouse gas emissions and simultaneously eliminate the carbon footprint released into the atmosphere. Meanwhile, hydrogen production via CuCl thermochemical cycle is an attractive process due to moderate-/low-temperature requirements and high efficiency. Therefore, there is a huge potential for producing hydrogen from the copper chloride (CuCl) thermochemical cycle by utilising the power plant's excess heat. Currently, the CuCl hydrogen electrolytic process is part of the CuCl thermochemical cycle. It produces hydrogen at low temperatures utilising the expensive Nafion and Nafion-based membranes. A high-temperature CuCl hydrogen electrolytic process using a hybrid membrane as the alternative membrane to Nafion for hydrogen production was performed in this study.

A polybenzimidazole/zirconium phosphate (PBI/ZrP) hybrid membrane was synthesized using the solution mixing method followed by phosphoric acid (PA) doping. It was then validated for water uptake, tensile strength, thermogravimetric analysis (TGA), copper (Cu) diffusion and ionic exchange capacity (IEC). The PBI/ZrP hybrid membrane was developed after the screening process of PBI and sulphated poly (ether ether ketone) (SPEEK) membrane with the advantage of having high tensile strength (85.17 MPa), high ionic exchange capacity (3.2×10^{-3} mol g^{-1}), low copper diffusion ($7.87 \times 10{-7}$ cm^2 s^{-1}), sufficient water uptake (40 – 50 wt.%), a four-fold increase in proton conductivity compared to pristine PBI. The scanning electron microscope (SEM) was executed to evaluate the surface morphology of the membrane while SEM-EDX detected the membrane's composition. For the parametric study, the CuCl hydrogen electrolytic system with PBI/ZrP (0.5 A cm^{-2}, 115 °C) produced 3.27 cm^3 cm^{-1} hydrogen (highest). At a higher CuCl flowrate, the PBI/ZrP showed a significant increment of 66% (up to 3.27 cm^3 min^{-1}) when the applied current

density was changed from 0.1 to 0.5 A cm^{-2}. The CuCl hydrogen electrolytic process at 0.05 M CuCl concentration produced 2.69 cm^3 min^{-1} and 2.15 cm^3 min^{-1} hydrogen for PBI/ZrP and Nafion 117, respectively. The operating temperature ($p = 0.026$) and current density ($p = 0.000$) were found statistically significant based on the p-value < 0.05. The CuCl hydrogen electrolytic process parameters were optimised using a response surface method (RSM) with a central composite design (CCD). The optimised parameter settings were temperature at 116 °C, current density at 0.773 A cm^{-2} and CuCl concentration at 0.075 M to get the optimum hydrogen yield of 0.7167 cm^3 min^{-1}. The actual hydrogen yield from the optimized parameter settings was 0.7709 cm^3 min^{-1} with a discrepancy of 7.56% from the predicted value.

The high-temperature CuCl hydrogen electrolytic process using a PBI/ZrP hybrid membrane for hydrogen has been performed and proven a good alternative to Nafion. At the same time, able to yield maximum hydrogen output with optimum operating parameters, thus minimizing the associated cost in the hydrogen production.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ELEKTROLISIS KUPRUM KLORIDA BERSUHU TINGGI MENGGUNAKAN MEMBRAN PERTUKARAN PROTON HIBRID UNTUK PENGELUARAN HIDROGEN

Oleh

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Penggunaan komprehensif tenaga hidrogen hijau ialah cara terbaik untuk mengurangkan pencemaran gas rumah hijau, pada masa yang sama menghapuskan jejak karbon yang dilepaskan ke atmosfera. Sementara itu, pengeluaran hidrogen melalui kitaran termokimia CuCl menarik kerana keperluan suhu sederhana / rendah dan kecekapan tinggi. Oleh sebab itu, terdapat potensi yang besar untuk menghasilkan hidrogen daripada kitaran termokimia kuprum klorida (CuCl) dengan menggunakan haba berlebihan dari loji kuasa. Pada masa ini, proses elektrolitik hidrogen CuCl ialah sebahagian daripada kitaran termokimia CuCl. Proses ini menghasilkan hidrogen pada suhu rendah menggunakan membran Nafion dan membran berasaskan Nafion yang mahal. Proses elektrolisis hidrogen kuprum klorida pada suhu tinggi menggunakan membran hibrid sebagai membran alternatif kepada Nafion untuk pengeluaran hidrogen dilakukan dalam kajian ini.

Membran hibrid polibenzimidazol/zirkonium fosfat (PBI/ZrP) telah disintesis menggunakan kaedah pencampuran larutan diikuti pengedopan asid fosforik (PA). Kemudian, membran disahkan untuk pengambilan air, kekuatan tegangan, analisis termogravimetri, peresapan ion kupum (Cu) dan kapasiti pertukaran ionik (IEC). Membran hibrid PBI/ZrP dibangunkan selepas proses saringan membran PBI dan poli (eter eter keton) tersulfat dengan kelebihan kekuatan tegangan yang tinggi (85.17 MPa), kapasiti pertukaran ionik yang tinggi (3.2×10^{-3} mol g^{-1}), resapan kuprum yang rendah (7.87×10^{-7} cm^2 s^{-1}), pengambilan air yang mencukupi (40 – 50 wt.%), empat kali ganda konduktiviti proton berbanding dengan PBI asal. Mikroskop elektron pengimbas (SEM) dijalankan untuk menilai morfologi permukaan membran sementara SEM-EDX mengesan komposisi membran. Bagi kajian parametrik, sistem elektrolitik hidrogen CuCl dengan PBI/ZrP (0.5 A cm^{-2}, 115 °C) menghasilkan 3.27 cm^3 min^{-1} gas hidrogen (tertinggi). Pada kadar alir CuCl yang lebih tinggi, PBI/ZrP menunjukkan

peningkatan ketara dengan 66% (sehingga 3.27 $cm^3\ min^{-1}$) apabila ketumpatan arus diubah daripada 0.1 ke 0.5 A cm^{-2}. Proses elektrolitik hidrogen CuCl pada kepekatan CuCl 0.05 M menghasilkan gas hidrogen sebanyak 2.69 $cm^3\ min^{-1}$ dan 2.15 $cm^3\ min^{-1}$, masing-masing untuk PBI/ZrP dan Nafion 117. Suhu operasi (p = 0.026) dan ketumpatan arus (p = 0.000) didapati signifikan secara statistik berdasarkan nilai $p < 0.05$. Parameter proses elektrolitik CuCl ini dioptimumkan dengan menggunakan kaedah tindak balas permukaan (RSM) dengan reka bentuk komposit berpusat (CCD). Ketetapan parameter yang dioptimumkan adalah suhu 116 °C, ketumpatan arus 0.773 A cm^{-2} dan kepekatan CuCl pada 0.075 M untuk mencapai hasil hidrogen optimum pada 0.7167 $cm^3\ min^{-1}$. Hasil hidrogen sebenar daripada tetapan parameter dioptimumkan adalah 0.7709 cm^3 min^{-1} dengan perbezaan sebanyak 7.56% daripada nilai jangkaan.

Proses elektrolitik hidrogen CuCl bersuhu tinggi menggunakan membran hibrid PBI/ZrP telah dijalankan dan terbukti sebagai alternatif yang baik selain Nafion. Pada masa yang sama boleh menghasilkan hidrogen maksimum dengan parameter operasi optimum seterusnya meminimumkan kos-kos berkaitan dengan pengeluaran hidrogen.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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This is to confirm that:

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- supervisory responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2015-2016) are adhered to.

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LIST OF ABBREVIATIONS

ADL	Acid doping level
ANOVA	Analysis of Variance
CCD	Central Composite Design
CCUS	Carbon capture, utilization & storage
CuCl	Copper chloride
DMAc	Dimethylacetamide
DOE	Design of Experiment
EDX	Energy dispersive x-ray
EIS	Electrochemical impedance spectroscopy
FCEV	Fuel cell electric vehicle
GC	Gas chromatography
GHG	Greenhouse gas
HCl	Hydrochloric acid
ICE	Internal combustion engine
IEC	Ionic exchange capacity
LOHC	Liquid organic hydrogen carrier
LSV	Linear sweep voltammetry
MEA	Membrane electrode assembly
PBI	Polybenzimidazole
PEM	Proton exchange membrane
SEM	Scanning electron microscopy
SMR	Steam methane reforming
SPEEK	Sulfonated poly(ether ether ketone)
TGA	Thermogravimetric analysis

UV-Vis	UV-Visible spectroscopy
PFSA	Perfluorosulfonic acid
PA	Phosphoric acid
RBD	Randomised block design
RSM	Response surface methodology

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The world's current population as of August 2021 is almost 7.9 billion, as reported by the United Nations, surpassing the earlier prediction of 7.5 billion in 2025 (da Silva Veras et al., 2017). The world needs enough staple food for the entire population, and to fulfil that, the world needs energy resources to move people around, powering the agricultural and agro-based industries as well as other activities (Abe et al., 2019; Midilli et al., 2021; Roeb et al., 2013). It is anticipated that the world's energy demand will be 600 to 1000 EJ by 2050 (Carey et al., 2020; Hosseini & Wahid, 2016; Kumar et al., 2020). A smart approach is essential to balance power demand and manage energy effectively (Ahmad et al., 2021; Awadallah et al., 2014). Due to the intense usage of conventional fuels to power the population activities, the depletion of ozone layers is now at an alarming level due to the effect of greenhouse gas (GHG) emissions like carbon dioxide and methane (Oladokun et al., 2016; Omoniyi et al., 2021; Owgi et al., 2021). As the world is united and committed to resolving GHG emissions, the Montreal Protocol (1987), Kyoto Protocol (1997) and Paris Agreement (2015) have been signed in the hope of recovering the ozone layers and reducing the impact of climate change by 2050 (Abdullah et al., 2019; Kimura & Li, 2019; Sanguesa et al., 2021; Stokes, 2020). Unlike two prior protocols that targeted only developed nations, Paris Agreement (2015) is more objective in reducing GHG emissions while targeting only a maximum of two degrees Celsius temperature increase by a collective commitment from all countries to cut their climate pollution (Baykara, 2018; Gielen et al., 2017).

One of the most promising clean and green energy without any GHG emission or zero carbon footprint is green hydrogen (Dawood et al., 2020; Shiva Kumar & Himabindu, 2019). Hydrogen is an energy-dense (weight basis) substance with a 120 MJ/kg higher heating value (HHV), a clean gas with very low density and high dispersibility (Bessarabov et al., 2016; Li et al., 2010). Although hydrogen does not exist in the gas form naturally, it constantly forms as a compound with other atoms such as water (H_2O), methane (CH_4), butane (CH_4H_{10}), other liquids and hydrocarbon gases (Nicoletti et al., 2015). There are many techniques to produce hydrogen, categorised as fossil fuels or renewable sources. The hydrogen can be produced from renewable sources such as the biomass process (Ren et al., 2020) and water splitting process (thermolysis, photolysis, electrolysis) (Baykara, 2018; Nikolaidis & Poullikkas, 2017).

Hydrogen produced from the electrolysis is categorised as green hydrogen only when the electrical energy is from renewable and sustainable sources. Other than that, there is also grey hydrogen which is produced from fossil fuels, mainly from steam methane reforming (SMR) and blue hydrogen, which is produced from fossil fuels but with carbon capture, utilisation and storage (CCUS) (Carey et al., 2020; Edwards et al., 2021; ESMAP, 2020; Kaddami & Mikou, 2017). Electrolysis is a water-splitting process where an external voltage is applied across a circuit which is connected via a solid proton exchange membrane (PEM) that separates the electrodes and electrolytes that produce the hydrogen gas (cathode via hydrogen evolution reaction (HER)) and the oxygen gas (anode via oxygen evolution reaction (OER)) (Babic et al., 2017; Bessarabov et al., 2016; Escorihuela, García-Bernabé, et al., 2019; Shiva Kumar & Himabindu, 2019). The electrolysis process occurs in the electrolyser setup that comprises end plates, serpentine flow plates, membrane electrode assembly, gas diffusion layers with catalyst and current collectors (cathode, anode) (Araya et al., 2016; Bessarabov et al., 2016; Esposito, 2017; Xiao Li et al., 2020; Vincent & Bessarabov, 2017).

Thermochemical water splitting is a highly efficient chemical conversion of water into hydrogen and oxygen production (Guban et al., 2020; Kim et al., 2019). Several cycles have been developed to manufacture hydrogen from thermochemical water splitting, but only a handful have been proved to be economically viable (Hall & Lvov, 2016; Ofelia Antonia Jianu, 2013). There are thermochemical cycles for hybrid sulfur (HyS) (Pingitore et al., 2019a), copper chloride (CuCl) (Dawood et al., 2020), cerium-chlorine (Ce-Cl) (Varin & Wronski, 2013), vanadium–chlorine (V–Cl) (Alfaifi et al., 2018), hybrid chlorine (Cobourn & Easton, 2017), copper-sulfate (Cu-SO_4) (Naterer et al., 2009a) and iron-chloride (Fe-Cl) (Naterer et al., 2009a). All these thermochemical cycles use intermediate mediums to catalyse the reaction sequences of physical and chemical processes for water splitting within a closed and controlled circuit without emitting any emissions into the atmosphere (Farsi et al., 2019; Zamfirescu et al., 2019). However, only a few thermochemical cycles have a promising output and are feasible for hydrogen production. Nevertheless, the CuCl thermochemical cycle has been giving a very good output and is feasible practically. Therefore, the electrolysis step in the CuCl thermochemical cycle is a promising process to get a decent hydrogen production output.

A decent PEM electrolysis requires a good PEM membrane as the membrane electrode assembly (MEA) for the electrolyser. A proton exchange membrane (PEM) functions as a membrane that separates the electrolytes in an electrolyser that acts as the proton conductor by allowing the movement of the proton from anode to cathode electrode for the production of hydrogen (Bessarabov et al., 2016; Ran et al., 2017; Zhang et al., 2016; Zhou et al., 2021). Currently, the PEM fuel cells and electrolysers are mainly dominated by the perfluoro sulfonic acid (PFSA) membranes as the main component for MEA that operate well in the low region temperature up to 90 °C (Aili et al., 2011a; Mossayebi et al., 2016; Villagra & Millet, 2019). However, due to Nafion's high price, unstable thermal properties, fuel crossover, reduction of conductivity at high temperatures and swelling problems, alternative membranes are being developed from polybenzimidazole, sulfonated polyether ether ketone, polysulfone and polyimide-based membranes (Gashoul et al., 2017; Iulianelli & Basile, 2012; Mossayebi et al., 2016; Shaari & Kamarudin, 2019). Therefore, this study investigates the high-temperature electrolysis of copper chloride in hydrochloric acid using a hybrid proton exchange membrane for hydrogen production.

1.2 Problem Statement

Hydrogen, the world’s most abundant element, is a reliable and renewable energy source. However, the main production methods for hydrogen, which include steam methane reforming and coal gasification, are still generating greenhouse gases along with hydrogen production. Today, over 90% of the world's hydrogen is produced by steam reforming of fossil fuels (natural gas and coal gasification) mainly due to lower cost of production and established methods (Chen et al., 2016; Edwards et al., 2021; Lei et al., 2019; Maggio et al., 2019; Zhaolin Wang & Naterer, 2014). As a result, greenhouse gasses are released into the atmosphere and contribute to the earth’s temperature increment. Carbon dioxides contributed 55% from the total percentage of greenhouse gases released into the atmosphere, followed by chlorofluorocarbon (CFC) 11&12 by 17%, methane by 15% and other CFCs and nitrogen oxides by 7% and 6%, respectively (Nicoletti et al., 2015; Sahin & Esen, 2022) It is expected that from 2017 to 2060 there will be a GHG emission of about 263,000 million tons of CO_2 being released to the atmosphere (Qiu et al., 2021). Apart from that, hydrogen production from fossil fuels also caused air pollution and threatened energy security (Ren et al., 2020). Therefore, a new approach to producing green and sustainable hydrogen should be investigated.

Currently, only 4% of hydrogen is produced from the water electrolysis process (Gandía et al., 2013; Koponen et al., 2015; Mah et al., 2019; Sim et al., 2015a). The novel electrolysis system is crucial due to its importance in replacing conventional steam methane reforming that still emits greenhouse gases during the hydrogen production process (Luo et al., 2018). Furthermore, the electrolysis process produces high purity hydrogen and requires less space, and the equipment is compact to produce the same amount of hydrogen yield.

The current CuCl–HCl polymer electrolyte membrane (PEM) electrolysis process used costly Nafion as its membrane and was only tested to operate at low temperature (< 90 °C) (Devrim et al., 2016; Seo et al., 2017; Shiva Kumar & Himabindu, 2019). Although Nafion is the most common membrane in PEM fuel cell applications, the conductivity of the Nafion membrane is heavily affected by membrane hydration due to the medium stage transformation from liquid to vapour, makes it unsuitable for high-temperature applications (Park et al., 2016; Sigwadi et al., 2019; Tahrim & Amin, 2019). Besides, the high permeability of copper for Nafion membrane in copper chloride (CuCl) electrolysis inhibits a longer electrolysis process, leading to less hydrogen production (Khurana et al., 2015; Naterer et al., 2014b, 2017b). Hence, the improvement gained from a hybrid membrane that combines the properties of high conductivity, low copper permeability and highly thermostable material is suitable to be a Nafion membrane-based replacement.

Many researchers have recently accomplished the investigation of producing a valuable product from CuCl electrolysis by using Nafion as the proton exchange membrane (Abdo & Bradley Easton, 2016; Giddey et al., 2019; Kim et al., 2019; Sathaiyan et al., 2015). The complete typical thermochemical cycle of the CuCl diagram is shown in **Figure 1**.

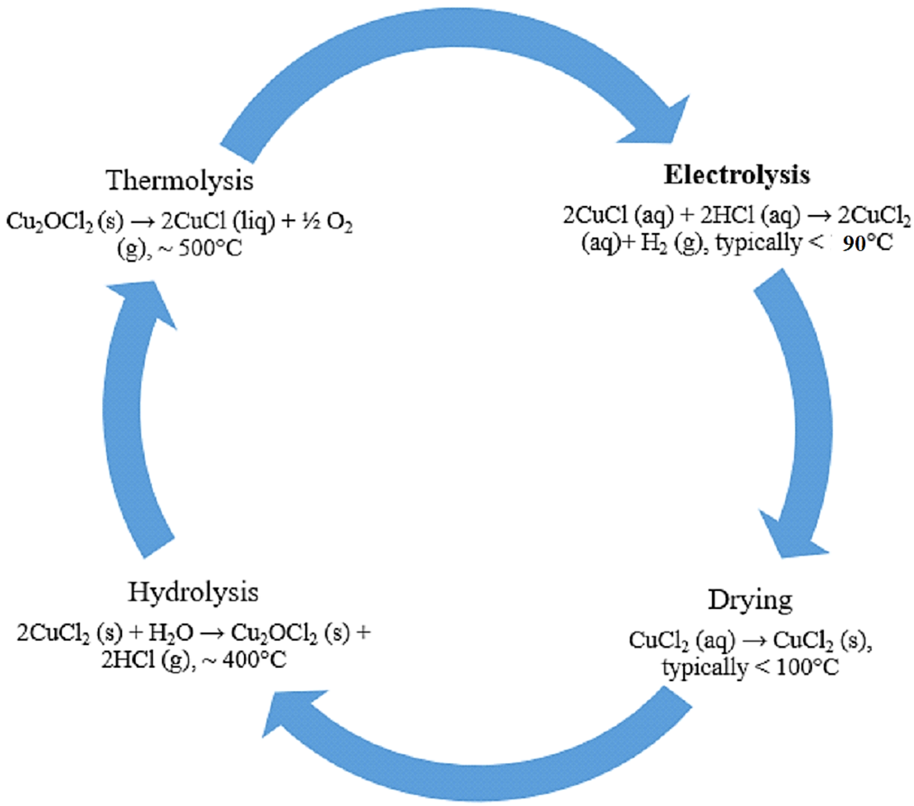

Figure 1: The typical complete thermochemical cycle of CuCl–HCl

The thermochemical cycle of the CuCl (**Figure 1**) starts with the electrolysis of CuCl and HCl electrolytes at ambient temperature and up to 90 °C for the Nafion-based membrane electrode assembly electrolyser. The process is followed by drying the $CuCl_2$ before proceeding with the hydrolysis process, which produces copper oxychloride (Cu_2OCl_2) and hydrogen chloride (HCl) gas at a reaction temperature around 400 °C. The thermolysis of Cu_2OCl_2 at 500 °C and the hydrolysis process can utilise the freely available excess heat from the nuclear or power plant to excite the reaction to produce CuCl and O_2. However, for this study, the focal point of research is the high temperature (100 to 130 °C) of CuCl electrolysis and the synthesised hybrid membrane that is more economical and performs better than the Nafion membrane. From previous studies, hydrogen has been the main output of the CuCl electrolysis process with copper (II) chloride ($CuCl_2$) as the by-product which is slightly hazardous with only rating 1 of the hazardous materials identification system (HMIS), rating 0 for normal material and rating 4 for deadly health hazards (Scholar Chemistry and Columbus Chemical Industries, 2009). In a CuCl thermochemical cycle, the $CuCl_2$ is produced after the electrolysis step. The reaction from the electrolysis stage converts CuCl into $CuCl_2$. No chlorine gas (Cl_2) is produced because the reaction produced $CuCl_2$ in an aqueous form and hydrogen in a gas form (Ghandehariun et al., 2012; Khalid, 2017). Still, the process is limited to low temperatures, which is up to 90 °C only (Abdo & Bradley Easton, 2016; Seyedali Aghahosseini, 2013; Balashov et al., 2011b; Edge, 2013; Naterer et al., 2015a; Zhou et al., 2021) and the cost to acquire the Nafion membrane is relatively high (USD 600 to 1200 per m^2; Euro 5000 per kg), which is up to four times costlier than PBI (Kraytsberg & Ein-Eli, 2014; Paidar et al., 2016b; Zhou et al., 2021; Zuo et al., 2012). Therefore, hydrogen production at high-temperature (above 100 °C and up to 200 °C) in the CuCl electrolysis has a considerable potential to be a sustainable source of producing green hydrogen. The novel electrolysis system is crucial due to its importance in replacing conventional steam methane reforming that still emits greenhouse gases during the hydrogen production process. Furthermore, the electrolysis process produces high purity hydrogen and requires less space, and the equipment is compact to produce the same amount of hydrogen yield. The Nafion membrane is a pioneer and widely used membrane for fuel cell applications. As for the fuel cell applications, it used hydrogen and air (oxygen) as the fuel to produce electrical energy and water as a by-product. As for the PEM electrolyser using the Nafion membrane, the reactants are acidic electrolytes and water. The electrolytes are subjected to the hydrogen evolution reaction (HER) at the cathode and oxygen evolution reaction (OER) at the anode. In previous studies, Nafion is used for hydrogen production from the CuCl–HCl electrolysis via a Nafion-based PEM electrolyser. However, Nafion has a high copper diffusion which can accumulate at the cathode electrode, thus inhibiting the formation of hydrogen via HER. By replacing the Nafion with another alternative membrane, the efficiency of the hydrogen production process via PEM CuCl electrolysis can be increased with the reduction in ion crossover. Therefore, necessary research should be performed to check the feasibility of using a hybrid membrane other than Nafion as the proton exchange membrane with an improvement in the conversion of CuCl–HCl electrolytes and the hydrogen yield.

1.3 Research Objectives

The focus of this study is to synthesise a functional hybrid membrane for the membrane electrode assembly (MEA) set up in an acid-based high-temperature CuCl PEM electrolyser and optimise the operating parameters for the copper chloride electrolytic system to achieve an optimised hydrogen output. This study is divided into four focused objectives as follows:

1. To develop and validate the PBI and SPEEK hybrid membrane component for membrane electrode assembly (MEA) preparation in CuCl–HCl electrolysis.

2. To evaluate the operating parameters on the performance of the hybrid membrane for CuCl–HCl electrolytic production.

3. To optimise and validate the operating parameters suitable for the PBI/ZrP hybrid membrane-based CuCl–HCl electrolysis.

1.4 Limitation of the Study

This study was conducted under several limitations that may greatly influence the output of the research if no necessary actions were taken:

1. Initially, the desired operating temperature was planned to range between 100 to 200 °C to fully exploit the high-temperature electrolysis. However, due to the limitation of the gasket material and pressure build-up inside the electrolyser, the operating temperature was revised to have a range between 100 to 130 °C.

2. The concentration of the electrolyte CuCl–HCl was limited to 0.2 M CuCl in 1 M HCl due to eroded peristaltic pump heads when applied a 1 M CuCl in 2 M HCl electrolyte. It has also caused pitting corrosion to the electrolyser block made of stainless steel. Therefore, the electrolyser blocks were changed to titanium.

3. The bipolar plate was changed from carbon graphite to titanium plate due to high-temperature vapours that can penetrate through the pores, which resulted in a drastic reduction in the hydrogen yield.

1.5 Scope of Research

The scopes of this study that determines the depth of the investigation to achieve the objectives mentioned above are:

1. The screening of PBI and SPEEK doped membranes with phosphoric acid at optimized immersion temperature (30–100 °C) and time (40 –960 min).

2. The development and validation of the PBI and SPEEK for hybrid membrane synthesis by dissolving the base membrane in dimethylacetamide (DMAc). This was performed via the addition of inorganic fillers: silicon dioxide (SiO_2), titanium dioxide (TiO_2) and zirconium oxide (ZrO_2) to the PBI and SPEEK membrane, followed by phosphoric acid (PA) doping. The best-synthesised hybrid membrane was selected for the characterisation of chemical and physical properties prior to the preparation of membrane electrode assembly (MEA).

3. The investigation of the performance of the selected hybrid membrane on a CuCl–HCl electrolytic hydrogen production system was applied by using two

levels of randomised block design (RBD). Operating parameters involved are electrolyte concentrations (CuCl and HCl), applied current density, temperature, and electrolyte flowrates. The significant parameters were ranked using a fractional factorial design (FFD).

4. Three of the most significant parameters obtained from Objective (iii) were used to optimise the CuCl–HCl electrolytic system towards hydrogen production using a response surface methodology (RSM) with central composite design (CCD), simulated using the Minitab 18 Software.

1.6 Significance of the Study

This research has a promising potential for promoting sustainable energy where the newly developed CuCl electrolysis PBI/ZrP hybrid membrane participates in hydrogen production. Furthermore, the current usage of perfluorosulfonic acid membranes such as Nafion or Nafion-based membranes—as the main membrane used in electrolysis—is expensive and only proven for low operating temperatures below 80 °C for the CuCl hydrogen electrolytic process. The newly synthesised and developed hybrid membrane has improved properties such as higher proton conductivity (increase 4-fold compared to pristine PBI), lower diffusivity of copper ion (better than Nafion), thermally stable (up to 900 °C while Nafion fully decomposed at 600 °C) and cheaper than existing Nafion-based membrane (cost one-fourth of the Nafion).

Additionally, the PBI/ZrP hybrid membrane was tested in high-temperature electrolysis (100–130 °C) of CuCl for the hydrogen production that was previously not tested or explored due to incompatibility of the Nafion membrane to operate at high-temperature. Furthermore, the Nafion membrane has high copper ion diffusion. The synthesis cost for PBI/ZrP hybrid membrane is RM10.78 per piece (49 cm^2 for MEA preparation & electrolyser fitting. This has included all related costs for the addition of inorganic filler ZrO_2 5wt% of PBI, chemicals DMAc & phosphoric acid, while the pristine Nafion 117 cost is RM24.34 per piece (49 cm^2). This has included all related costs for the addition of inorganic filler ZrO_2 5wt% of PBI, chemicals DMAc & phosphoric acid, while the pristine Nafion 117 cost is RM24.34 per piece (49 cm^2). PBI/ZrP is estimated to be 56% cheaper than Nafion 117, with the additional benefit of lower copper diffusion across the membrane that can prolong the hydrogen evolution reaction (HER) at the cathode. By utilising the excess heat from the industrial powerplant, the cost for elevating the electrolysis temperature is basically zero. The main operating cost to run the high-temperature CuCl–HCl hydrogen electrolytic system is the fee required to pay the power supplier or generated from renewable energy resources such as solar, geothermal, and wind. Therefore, the PBI/ZrP hybrid membrane-based high-temperature CuCl–HCl hydrogen electrolytic system is very economical to operate at an industrial powerplant having excess heat. The excess energy can be tapped to produce green hydrogen with zero carbon footprint while simultaneously saving the heating energy required to elevate the operating temperature of the electrolysis process.

1.7 Organization of Thesis

The following chapters are dedicated to carefully explain, discuss, and analyse their respective topic related to the high-temperature CuCl–HCl electrolysis using a hybrid membrane for hydrogen production. Chapter 2 reviews the hydrogen source, hydrogen technologies, polymer electrolyte membrane, thermochemical cycle of CuCl, and CuCl electrolysis.

Chapter 3 describes the methodology of the experiment. A research methodology flow chart is attached to the commencement of the chapter and offers a summary of the flow of the research. The research plan is performed vigilantly and considers every part of membrane synthesis, characterisation, and testing.

Chapter 4 highlights the membrane screening procedure to find a better alternative membrane than Nafion using polybenzimidazole (PBI) and sulfonated poly (ether ether ketone) (SPEEK) membranes. Two alternative membranes and eight modes of acid doping were used to screen the best membrane before incorporating the PBI or SPEEK for the metal-organic framework by introducing inorganic fillers like TiO_2, SiO_2 and ZrO_2. PBI/ZrP hybrid membrane emerged as the best performing membrane. The optimisation was further refined with the top three significant parameters. The accuracy of the models, the behaviour and the interaction between the independent variables have been analysed.

Finally, Chapter 5 summarises the principal conclusion of the present work, established from the results and findings. From the knowledge and experience gained in the present work, a list of useful recommendations is proposed to improve future work and its opportunities for research continuation.

REFERENCES

Abdo, N. (2015). *Modified Nafion Membranes for Hydrogen Production in Cu-Cl Thermochemical Cycle*. University of Ontario Institute of Technology.

Abdo, N., & Bradley Easton, E. (2016). Nafion/Polyaniline composite membranes for hydrogen production in the Cu-Cl thermochemical cycle. *International Journal of Hydrogen Energy*, *41*(19), 7892–7903. https://doi.org/10.1016/j.ijhydene.2015.11.180

Abdo, N., & Bradley Easton, E. (2015). Polyaniline Composite Membranes for Hydrogen Production in Cu-Cl Thermochemical Cycle. *6th International Conference on Hydrogen Production May 3-6, 2015 UOIT—Oshawa, Ontario, Canada*, 244–253. https://doi.org/10.1016/-j.ijhydene.2015.11.180

Abdullah, W. S. W., Osman, M., Kadir, M. Z. A. A., & Verayiah, R. (2019). The potential and status of renewable energy development in Malaysia. *Energies*, *12*(12). https://doi.org/10.3390/en12122437

Abe, J. O., Popoola, A. P. I., Ajenifuja, E., & Popoola, O. M. (2019). Hydrogen energy, economy and storage: Review and recommendation. *International Journal of Hydrogen Energy*, *44*(29), 15072–15086. https://doi.org/10.1016/j.ijhydene.2019.04.068

Abouzari-Lotf, E., Ghassemi, H., Mehdipour-Ataei, S., & Shockravi, A. (2016). Phosphonated polyimides: Enhancement of proton conductivity at high temperatures and low humidity. *Journal of Membrane Science*, *516*, 74–82. https://doi.org/10.1016/j.memsci.2016.06.009

Abouzari-Lotf, E., Nasef, M. M., Ghassemi, H., Zakeri, M., Ahmad, A., & Abdollahi, Y. (2015). Improved Methanol Barrier Property of Nafion Hybrid Membrane by Incorporating Nanofibrous Interlayer Self-Immobilized with High Level of Phosphotungstic Acid. *ACS Applied Materials and Interfaces*, *7*(31), 17008–17015. https://doi.org/10.1021/-acsami.5b02268

Abraham, J., Thomas, J., Hafusa, A., George, S. C., & Thomas, S. (2018). Liquid Transport Through Polymer Nanocomposites. *Transport Properties of Polymeric Membranes*, 191–215. https://doi.org/10.1016/B978-0-12-809884-4.00011-2

Acar, C., & Dincer, I. (2018). Hydrogen Energy. *Comprehensive Energy Systems*, *1–5*, 568–605. https://doi.org/10.1016/B978-0-12-809597-3.00113-9

Acar, C., Dincer, I., & Naterer, G. F. (2016). Review of photocatalytic water-splitting methods for sustainable hydrogen production. *International Journal of Energy Research*, *41*(August 2007), 7892–7903. https://doi.org/10.1002/er

Agata Godula-Jopek. (2015). *Hydrogen Production by Electrolysis* (D. H. In & g. A. Godula-Jopek (eds.)). Wiley-VCH.

Aghahosseini, S., Dincer, I., & Naterer, G. F. (2013). Linear sweep voltammetry measurements and factorial design model of hydrogen production by HCl/CuCl electrolysis. *International Journal of Hydrogen Energy*, *38*(29), 12704–12717. https://doi.org/10.1016/j.ijhydene.2013.07.105

Aghahosseini, S, Dincer, I., & Naterer, G. F. (2013). Process integration of hydrolysis and electrolysis processes in the Cu e Cl cycle of hydrogen production. *International Journal of Hydrogen Energy*, *38*(23), 9633–9643. https://doi.org/10.1016/j.ijhydene.2013.05.108

Aghahosseini, Seyedali. (2013). *System Integration and Optimization of Copper-Chlorine Thermochemical Cycle with Various Options for Hydrogen Production* (Issue August). University of Ontario Institute of Technology.

Ahmad, H., Kamarudin, S. K., Hasran, U. A., & Daud, W. R. W. (2010). Overview of hybrid membranes for direct-methanol fuel-cell applications. *International Journal of Hydrogen Energy*, *35*(5), 2160–2175. https://doi.org/10.1016/j.ijhydene.2009.12.054

Ahmad, M. S., Ali, M. S., & Rahim, N. A. (2021). Hydrogen energy vision 2060: Hydrogen as energy Carrier in Malaysian primary energy mix – Developing P2G case. *Energy Strategy Reviews*, *35*, 100632. https://doi.org/10.1016/j.esr.2021.100632

Aili, D., Hansen, M. K., Pan, C., Li, Q., Christensen, E., Jensen, J. O., & Bjerrum, N. J. (2011a). Phosphoric acid doped membranes based on Nafion®, PBI and their blends - Membrane preparation, characterization and steam electrolysis testing. *International Journal of Hydrogen Energy*, *36*(12), 6985–6993. https://doi.org/10.1016/j.ijhydene.2011.03.058

Aili, D., Hansen, M. K., Pan, C., Li, Q., Christensen, E., Jensen, J. O., & Bjerrum, N. J. (2011b). Phosphoric acid doped membranes based on Nafion®, PBI and their blends - Membrane preparation, characterization and steam electrolysis testing. *International Journal of Hydrogen Energy*, *36*(12), 6985–6993. https://doi.org/10.1016/j.ijhydene.2011.03.058

Alfaifi, B. Y., Ullah, H., Alfaifi, S., Tahir, A. A., & Mallick, T. K. (2018). Photoelectrochemical solar water splitting: From basic principles to advanced devices. *Veruscript Functional Nanomaterials*, *2*, BDJOC3. https://doi.org/10.22261/fnan.bdjoc3

Ambrose, A. F., Al-Amin, A. Q., Rasiah, R., Saidur, R., & Amin, N. (2017). Prospects for introducing hydrogen fuel cell vehicles in Malaysia. *International Journal of Hydrogen Energy*, *42*(14), 9125–9134. https://doi.org/10.1016/j.ijhydene.2016.05.122

Anwar, M., Victor, B., Kui, C., & Khan, R. (2019). Optimization of renewable hydrogen-rich syngas production from catalytic reforming of greenhouse gases (CH4 and CO2) over calcium iron oxide supported nickel catalyst. *Journal of the Energy Institute*, *92*(1), 177–194. https://doi.org/10.1016/-j.joei.2017.10.010

Apak, S., Atay, E., & Tuncer, G. (2012). Renewable hydrogen energy regulations, codes and standards: Challenges faced by an EU candidate country. *International Journal of Hydrogen Energy*, *37*(7), 5481–5497. https://doi.org/10.1016/j.ijhydene.2012.01.005

Araya, S. S., Zhou, F., Liso, V., Sahlin, S. L., Vang, J. R., Thomas, S., Gao, X., Jeppesen, C., & Kær, S. K. (2016). A comprehensive review of PBI-based high temperature PEM fuel cells. *International Journal of Hydrogen Energy*, *41*(46), 21310–21344. https://doi.org/10.1016/-j.ijhydene.2016.09.024

Arico, A. S., Sebastian, D., Schuster, M., Bauer, B., D'Urso, C., Lufrano, F., & Baglio, V. (2015). *Selectivity of Direct Methanol Fuel Cell Membranes*. 793–809. https://doi.org/10.3390/membranes5040793

Arunbabu, D., Sannigrahi, A., & Jana, T. (2008). Blends of polybenzimidazole and poly(vinylidene fluoride) for use in a fuel cell. *Journal of Physical Chemistry B*, *112*(17), 5305–5310. https://doi.org/10.1021/jp711860v

Avramov, S. G., Lefterova, E., Penchev, H., Sinigersky, V., & Slavcheva, E. (2016). *Comparative study on the proton conductivity of perfluorosulfonic and polybenzimidazole based polymer electrolyte membranes*. *48*, 43–50.

Awadallah, A. E., Mostafa, M. S., Aboul-Enein, A. A., & Hanafi, S. A. (2014). Hydrogen production via methane decomposition over Al2O3–TiO2 binary oxides supported Ni catalysts: Effect of Ti content on the catalytic efficiency. *Fuel*, *129*, 68–77. https://doi.org/10.1016/j.fuel.2014.03.047

Awang, N., Ismail, A. F., Jaafar, J., Matsuura, T., Junoh, H., Ismail, A. F., Jaafar, J., Matsuura, T., Junoh, H., & Rahman, M. A. (2014). *Accepted Manuscript*.

Aydar, A. Y. (2018). Utilization of Response Surface Methodology in Optimization of Extraction of Plant Materials. *IntechOpen*, 157–168. https://www.intechopen.com/books/advanced-biometric-technologies/liveness-detection-in-biometrics

Ayers, K. E., Renner, J. N., Danilovic, N., Wang, J. X., Zhang, Y., Maric, R., & Yu, H. (2016). Pathways to ultra-low platinum group metal catalyst loading in proton exchange membrane electrolyzers. *Catalysis Today*, *262*, 121–132. https://doi.org/10.1016/j.cattod.2015.10.019

Babic, U., Suermann, M., Büchi, F. N., Gubler, L., & Schmidt, T. J. (2017). Critical Review—Identifying Critical Gaps for Polymer Electrolyte Water Electrolysis Development. *Journal of The Electrochemical Society*, *164*(4), F387–F399. https://doi.org/10.1149/2.1441704jes

Bakangura, E., Wu, L., Ge, L., Yang, Z., & Xu, T. (2016). Mixed matrix proton exchange membranes for fuel cells: State of the art and perspectives. *Progress in Polymer Science*, *57*, 103–152. https://doi.org/10.1016-/j.progpolymsci.2015.11.004

Balashov, V. N., Schatz, R. S., Chalkova, E., Akinfiev, N. N., Fedkin, M. V., & Lvov, S. N. (2011a). CuCl Electrolysis for Hydrogen Production in the Cu–Cl Thermochemical Cycle. *Journal of The Electrochemical Society*, *158*(3), B266–B275. https://doi.org/10.1149/1.3521253

Balashov, V. N., Schatz, R. S., Chalkova, E., Akinfiev, N. N., Fedkin, M. V, & Lvov, S. N. (2011b). *CuCl Electrolysis for Hydrogen Production in the Cu–Cl Thermochemical Cycle*. 266–275. https://doi.org/10.1149-/1.3521253

Ball, M., & Weeda, M. (2015a). *The hydrogen economy: Vision or reality ? 4*.

Ball, M., & Weeda, M. (2015b). The hydrogen economy - Vision or reality? *International Journal of Hydrogen Energy*, *40*(25), 7903–7919. https://doi.org/10.1016/j.ijhydene.2015.04.032

Banerjee, S., & Kar, K. K. (2017). Impact of degree of sulfonation on microstructure, thermal, thermomechanical and physicochemical properties of sulfonated poly ether ether ketone. *Polymer (United Kingdom)*, *109*, 176–186. https://doi.org/10.1016/j.polymer.2016.12.030

Baykara, S. Z. (2018). Hydrogen: A brief overview on its sources, production and environmental impact. *International Journal of Hydrogen Energy*, *43*(23), 10605–10614. https://doi.org/10.1016/j.ijhydene.2018.02.022

Berber, M. R., Fujigaya, T., Sasaki, K., & Nakashima, N. (2013). Remarkably Durable High Temperature Polymer Electrolyte Fuel Cell Based on Poly(vinylphosphonic acid)-doped Polybenzimidazole. *Scientific Reports*, *3*(1), 1764. https://doi.org/10.1038/srep01764

Bernardo, G., Araújo, T., da Silva Lopes, T., Sousa, J., & Mendes, A. (2020). Recent advances in membrane technologies for hydrogen purification. *International Journal of Hydrogen Energy*, *45*(12), 7313–7338. https://doi.org/10.1016/j.ijhydene.2019.06.162

Bessarabov, D., Wang, H., Li, H., & Zhao, N. (2016). PEM Electrolysis for hydrogen production: Principles and Applications. In D. Bessarabov, H. Wang, H. Li, & N. Zhao (Eds.), *CRC Press, Taylor & Francis Group*. Taylor & Francis. https://doi.org/10.1557/mrs.2019.210

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis - A review. *Journal of Cleaner Production*, *85*, 151–163. https://doi.org/10.1016/j.jclepro.2013.07.048

Bičáková, O., & Straka, P. (2012). Production of hydrogen from renewable resources and its effectiveness. *International Journal of Hydrogen Energy*, *37*(16), 11563–11578. https://doi.org/10.1016/j.ijhydene.-2012.05.047

Boongaling, C., Ian, K., Batac, T., Medrano, E., & Jr, R. (2022). Prospects and challenges for green hydrogen production and utilization in the Philippines. *International Journal of Hydrogen Energy*, *47*(41), 17859–17870. https://doi.org/10.1016/j.ijhydene.2022.04.101

Büchi, F. N., Schmidt, T. J., & Schmidt, T. J. (2017). *Critical Review — Identifying Critical Gaps for Polymer Electrolyte Water Electrolysis Development Review — Identifying Critical Gaps for Polymer Electrolyte Water*. *January*. https://doi.org/10.1149/2.1441704jes

Burgal, J. P. da S. (2016). Development of Poly (ether ether ketone) Nanofiltration Membranes for Organic Solvent Nanofiltration in Continuous Flow Systems. *A Thesis Submitted for the Degree of Doctor of Philosophy of Imperial College London and the Diploma of Imperial College London.*

Burton, N. A., Padilla, R. V., Rose, A., & Habibullah, H. (2021). Increasing the efficiency of hydrogen production from solar powered water electrolysis. *Renewable and Sustainable Energy Reviews*, *135*(August 2020), 110255. https://doi.org/10.1016/j.rser.2020.110255

Canan Acar1,*,†, I. D. and G. F. N. 1Faculty. (2016). Review of photocatalytic water-splitting methods for sustainable hydrogen production. *International Journal Of Energy Research*, *41*(19), 7892–7903. https://doi.org/10.1016/j.ijhydene.2015.11.180

Carbone, A., Pedicini, R., Saccà, A., Gatto, I., & Passalacqua, E. (2008). Composite S-PEEK membranes for medium temperature polymer electrolyte fuel cells. *Journal of Power Sources*, *178*(2), 661–666. https://doi.org/10.1016/j.jpowsour.2007.10.023

Carey, J., Kennedy, S., & Mastny, L. (2020). Global Renewables Outlook: Energy transformation 2050. In *International Renewable Energy Agency*. https://www.irena.org/publications/2020/Apr/Global-RenewablesOutlook2020

Carmo, M., Fritz, D. L., Mergel, J., & Stolten, D. (2013). A comprehensive review on PEM water electrolysis. *International Journal of Hydrogen Energy*, *38*(12), 4901–4934. https://doi.org/10.1016/j.ijhydene.2013.01.151

Carollo, A., Quartarone, E., Tomasi, C., Mustarelli, P., Belotti, F., Magistris, A., Maestroni, F., Parachini, M., Garlaschelli, L., & Righetti, P. P. (2006). Developments of new proton conducting membranes based on different polybenzimidazole structures for fuel cells applications. *Journal of Power Sources*, *160*(1), 175–180. https://doi.org/10.1016/j.jpowsour.-2006.01.081

Chen, H., Ginzburg, V. V., Yang, J., Yang, Y., Liu, W., Huang, Y., Du, L., & Chen, B. (2016). Thermal conductivity of polymer-based composites: Fundamentals and applications. *Progress in Polymer Science*, *59*, 41–85. https://doi.org/10.1016/j.progpolymsci.2016.03.001

Chen, J. C., Chen, P. Y., Lee, S. W., Liou, G. L., Chen, C. J., Lan, Y. H., & Chen, K. H. (2016). Synthesis of soluble polybenzimidazoles for high-temperature proton exchange membrane fuel cell (PEMFC) applications. *Reactive and Functional Polymers*, *108*, 122–129. https://doi.org/10.1016/j.reactfunctpolym.2016.05.006

Chen, L., Dong, X., Wang, Y., & Xia, Y. (2016). Separating hydrogen and oxygen evolution in alkaline water electrolysis using nickel hydroxide. *Nature Communications*, *7*(May), 1–8. https://doi.org/10.1038/ncomms11741

Cheng, Y., & Ping, S. (2015). *Advances in electrocatalysts for oxygen evolution reaction of water electrolysis-from metal oxides to carbon nanotubes*.

Cho, H., Hur, E., Henkensmeier, D., Jeong, G., Cho, E., Kim, H. J., Jang, J. H., Lee, K. Y., Hjuler, H. A., Li, Q., Jensen, J. O., & Cleemann, L. N. (2014). Meta-PBI/methylated PBI-OO blend membranes for acid doped HT PEMFC. *European Polymer Journal*. https://doi.org/10.1016/-j.eurpolymj.2014.06.019

Choi, S. W., Park, J. O., Pak, C., Choi, K. H., Lee, J. C., & Chang, H. (2013). Design and synthesis of cross-linked copolymer membranes based on poly(benzoxazine) and polybenzimidazole and their application to an electrolyte membrane for a high-temperature PEM fuel cell. *Polymers*, *5*(1), 77–111. https://doi.org/10.3390/polym5010077

Chong, H. Y., Dahari, M., Yap, H. J., & Loong, Y. T. (2013). Development of hazard assessment for hydrogen refueling station in Malaysia. *Applied Mechanics and Materials*, *315*, 121–127. https://doi.org/10.4028/-www.scientific.net/AMM.315.121

Cobourn, S. L., & Easton, E. B. (2017). The effect of copper contamination at the cathode of Cu-Cl/HCl electrolyzers. *International Journal of Hydrogen Energy*, *42*(47), 28157–28163. https://doi.org/10.1016/-j.ijhydene.2017.09.142

da Silva Veras, T., Mozer, T. S., da Costa Rubim Messeder dos Santos, D., & da Silva César, A. (2017). Hydrogen: Trends , production and characterization of the main process worldwide. *International Journal of Hydrogen Energy*, *42*(4), 2018–2033. https://doi.org/10.1016/-j.ijhydene.2016.08.219

Daud, W. R. W., Ahmad, A., Mohamed, A. B., Kamarudin, S. K., Koh, J. I. S., Rasid, N., Daud, Z. B., Hasran, U. A., Samuel, N., & Abdullah, M. I. (2017). *The Blueprint for Fuel Cell Industries in Malaysia*.

Dawood, F., Anda, M., & Shafiullah, G. M. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*, *45*(7), 3847–3869. https://doi.org/10.1016/j.ijhydene.2019.12.059

Deheri, C., & Acharya, S. K. (2022). Purified biohythane (biohydrogen+biomethane) production from food waste using CaO2+CaCO3 and NaOH as additives. *International Journal of Hydrogen Energy*, *47*(5), 2862–2873. https://doi.org/10.1016-/j.ijhydene.2021.10.232

Deimede, V., Labou, D., & Neophytides, S. G. (2014). Polymer electrolyte membranes based on blends of sulfonated polysulfone and PEO-grafted polyethersulfone for low temperature water electrolysis. *Journal of Applied Polymer Science*, *131*(4), 1–8. https://doi.org/10.1002-/app.39922

Devrim, Y., Devrim, H., & Eroglu, I. (2016). Polybenzimidazole/SiO2 hybrid membranes for high temperature proton exchange membrane fuel cells. *International Journal of Hydrogen Energy*, *41*(23), 10044–10052. https://doi.org/10.1016/j.ijhydene.2016.02.043

Di Noto, V., Zawodzinski, T. A., Herring, A. M., Giffin, G. A., Negro, E., & Lavina, S. (2012). Polymer electrolytes for a hydrogen economy. *International Journal of Hydrogen Energy*, *37*(7), 6120–6131. https://doi.org/10.1016/-j.ijhydene.2012.01.080

Díaz, M., Ortiz, A., & Ortiz, I. (2014). Progress in the use of ionic liquids as electrolyte membranes in fuel cells. *Journal of Membrane Science*, *469*, 379–396. https://doi.org/10.1016/j.memsci.2014.06.033

Dincer, I., & Naterer, G. F. (2014). Overview of hydrogen production research in the Clean Energy Research Laboratory (CERL) at UOIT. *International Journal of Hydrogen Energy*, *39*(35), 20592–20613. https://doi.org/10.1016/j.ijhydene.2014.06.074

Dincer, Ibrahim. (2012). Green methods for hydrogen production. *International Journal of Hydrogen Energy*, *37*(2), 1954–1971. https://doi.org/10.1016/j.ijhydene.2011.03.173

Dincer, Ibrahim, & Acar, C. (2015). Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, *40*(34), 11094–11111. https://doi.org/10.1016/-j.ijhydene.2014.12.035

Dincer, Ibrahim, & Acar, C. (2017). Innovation in hydrogen production. *International Journal of Hydrogen Energy*, *42*(22), 14843–14864. https://doi.org/10.1016/j.ijhydene.2017.04.107

Dupuis, A. (2011). Proton exchange membranes for fuel cells operated at medium temperatures: Materials and experimental techniques. *Progress in Materials Science*, *56*, 289–327. https://doi.org/10.1016-/j.pmatsci.2010.11.001

Dutta, S. (2014). A review on production, storage of hydrogen and its utilization as an energy resource. In *Journal of Industrial and Engineering Chemistry* (Vol. 20, Issue 4, pp. 1148–1156). https://doi.org/10.1016/-j.jiec.2013.07.037

Economic Planning Unit. (2021). A Prosperous, Inclusive, Sustainable Malaysia. *12th Malaysian Plan*, 532. https://rmke12.epu.gov.my/bm

Edge, P. (2013). The Production and Characterization of Ceramic Carbon Electrode Materials for CuCl - HCl Electrolysis. In *Master of Science, University of Ontario Institute of Technology* (Vol. 1, Issue July). University of Ontario Institute of Technology.

Edwards, R. L., Font-Palma, C., & Howe, J. (2021). The status of hydrogen technologies in the UK: A multi-disciplinary review. *Sustainable Energy Technologies and Assessments*, *43*(November 2020), 100901. https://doi.org/10.1016/j.seta.2020.100901

Epelle, E. I., Desongu, K. S., Obande, W., Adeleke, A. A., Ikubanni, P. P., Okolie, J. A., & Gunes, B. (2022). A comprehensive review of hydrogen production and storage : A focus on the role of nanomaterials. *International Journal of Hydrogen Energy*, *47*(47), 20398–20431. https://doi.org/10.1016/j.ijhydene.2022.04.227

Escorihuela, García-Bernabé, Montero, Andrio, Sahuquillo, Giménez, & Compañ. (2019). Proton Conductivity through Polybenzimidazole Composite Membranes Containing Silica Nanofiber Mats. *Polymers*, *11*(7), 1182. https://doi.org/10.3390/polym11071182

Escorihuela, J., Narducci, R., Compañ, V., & Costantino, F. (2019). Proton Conductivity of Composite Polyelectrolyte Membranes with Metal-Organic Frameworks for Fuel Cell Applications. In *Advanced Materials Interfaces*. https://doi.org/10.1002/admi.201801146

Escorihuela, J., Olvera-Mancilla, J., Alexandrova, L., del Castillo, L. F., & Compañ, V. (2020). Recent progress in the development of composite membranes based on polybenzimidazole for high temperature proton exchange membrane (PEM) fuel cell applications. *Polymers*, *12*(9). https://doi.org/10.3390/POLYM12091861

Escorihuela, J., Sahuquillo, Ó., García-Bernabé, A., Giménez, E., & Compañ, V. (2018). Phosphoric acid doped polybenzimidazole (PBI)/Zeolitic imidazolate framework composite membranes with significantly enhanced proton conductivity under low humidity conditions. *Nanomaterials*, *8*(10), 1–13. https://doi.org/10.3390/nano8100775

Esmaeili, N., Gray, E. M. A., & Webb, C. J. (2019). Non-Fluorinated Polymer Composite Proton Exchange Membranes for Fuel Cell Applications – A Review. *ChemPhysChem*, *20*(16), 2016–2053. https://doi.org/10.1002/-cphc.201900191

ESMAP. (2020). *Green Hydrogen in Amsterdam*.

Esposito, D. V. (2017). Membraneless Electrolyzers for Low-Cost Hydrogen Production in a Renewable Energy Future. *Joule*, *1*(4), 651–658. https://doi.org/10.1016/j.joule.2017.07.003

Fabian, F. M. (2012). *Application of Response Surface Methodology and Central Composite Design for 5P12-RANTES Expression in the Pichia pastoris System*.

Farsi, A., Zamfirescu, C., Dincer, I., & Naterer, G. F. (2019). Thermodynamic assessment of a lab-scale experimental copper-chlorine cycle for sustainable hydrogen production. *International Journal of Hydrogen Energy*, *44*(33), 17595–17610. https://doi.org/10.1016/-j.ijhydene.2019.04.177

Ferrandon, M. S., Lewis, M. A., Alvarez, F., & Shafirovich, E. (2010). Hydrolysis of CuCl2 in the Cu-Cl thermochemical cycle for hydrogen production: Experimental studies using a spray reactor with an ultrasonic atomizer. *International Journal of Hydrogen Energy*, *35*(5), 1895–1904. https://doi.org/10.1016/j.ijhydene.2009.12.034

Gagliardi, G. G., Ibrahim, A., Borello, D., & El-Kharouf, A. (2020). Composite polymers development and application for polymer electrolyte membrane technologies-a review. *Molecules*, *25*(7). https://doi.org/10.3390/molecules25071712

Gandía, L. M., Arzamendi, G., Diéguez, P. M., Roeb, M., Monnerie, N., Houaijia, A., Thomey, D., & Sattler, C. (2013). Chapter 4 – Solar Thermal Water Splitting. In *Renewable Hydrogen Technologies* (pp. 63–86). https://doi.org/10.1016/B978-0-444-56352-1.00004-0

Gao, C., Hu, M., Wang, L., & Wang, L. (2020). Synthesis and properties of phosphoric-acid-doped polybenzimidazole with hyperbranched cross-linkers decorated with imidazolium groups as high-temperature proton exchange membranes. *Polymers*, *12*(3). https://doi.org/10.3390/-polym12030515

Garbe, S., Futter, J., Schmidt, T. J., & Gubler, L. (2021). Insight into elevated temperature and thin membrane application for high efficiency in polymer electrolyte water electrolysis. *Electrochimica Acta*, *377*, 138046. https://doi.org/10.1016/j.electacta.2021.138046

Garrick, T. R., Wilkins, C. H., Pingitore, A. T., Mehlhoff, J., Gulledge, A., Benicewicz, B. C., & Weidner, J. W. (2017). Characterizing Voltage Losses in an SO_2 Depolarized Electrolyzer Using Sulfonated Polybenzimidazole Membranes. *Journal of The Electrochemical Society*, *164*(14), F1591–F1595. https://doi.org/10.1149/2.1061714jes

Garsany, Y., Gould, B. D., Baturina, O. A., & Swider-Lyons, K. E. (2009). Comparison of the Sulfur Poisoning of PBI and Nafion PEMFC Cathodes. *Electrochemical and Solid-State Letters*, *12*(9), B138–B140. https://doi.org/10.1149/1.3168516

Gashoul, F., Parnian, M. J., & Rowshanzamir, S. (2017). A new study on improving the physicochemical and electrochemical properties of SPEEK nanocomposite membranes for medium temperature proton exchange membrane fuel cells using different loading of zirconium oxide nanoparticles. *International Journal of Hydrogen Energy*, *42*(1), 590–602. https://doi.org/10.1016/j.ijhydene.2016.11.132

Ghandehariun, S., Wang, Z., Rosen, M. A., & Naterer, G. F. (2012). Reduction of hazards from copper(I) chloride in a Cu-Cl thermochemical hydrogen production plant. *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2012.05.057

Ghelich, R., Jahannama, M. R., Abdizadeh, H., Torknik, F. S., & Vaezi, M. R. (2019). Central composite design (CCD)-Response surface methodology (RSM) of effective electrospinning parameters on PVP-B-Hf hybrid nanofibrous composites for synthesis of HfB 2 -based composite nanofibers. *Composites Part B: Engineering*, *166*(January), 527–541. https://doi.org/10.1016/j.compositesb.2019.01.094

Giddey, S., Badwal, S. P. S., & Ju, H. (2019). Polymer electrolyte membrane technologies integrated with renewable energy for hydrogen production. In *Current Trends and Future Developments on (Bio-) Membranes* (pp. 235–259). Elsevier Inc. https://doi.org/10.1016/B978-0-12-813545-7.00010-6

Giddey, S., Badwal, S. P. S., & Ju, H. K. (2018). Polymer electrolyte membrane technologies integrated with renewable energy for hydrogen production. *Current Trends and Future Developments on (Bio-) Membranes: Renewable Energy Integrated with Membrane Operations*, 235–259. https://doi.org/10.1016/B978-0-12-813545-7.00010-6

Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. *Energy Strategy Reviews*, *24*(January), 38–50. https://doi.org/10.1016/j.esr.2019.01.006

Gielen, D., Saygin, D., & Rigter, J. (2017). Renewable Energy Prospects: Indonesia. In *International Renewable Energy Agency (IRENA)* (Issue March). http://www.irena.org/remap

Gnanapragasam, N. V., Reddy, B. V., & Rosen, M. A. (2010). Hydrogen production from coal gasification for effective downstream CO2 capture. *International Journal of Hydrogen Energy*, *35*(10), 4933–4943. https://doi.org/10.1016/j.ijhydene.2009.07.114

Gong, Y., Chalkova, E., & Akinfiev, N. (2010). Development of CuCl-HCl electrolysis for hydrogen production via Cu-Cl thermochemical cycle. In *Nuclear Production of Hydrogen, Fourth Information Exchange Meeting, Oakbrook, Illinois, USA , 14-16 April 2009* (Issue April 2009, pp. 251–257). OECD Publishing.

Gong, Y., Chalkova, E., Akinfiev, N. N., Balashov, V., Fedkin, M., & Lvov, S. N. (2019). CuCl-HCl Electrolyzer for Hydrogen Production via Cu-Cl Thermochemical Cycle. *ECS Transactions*, *19*(10), 21–32. https://doi.org/10.1149/1.3237105

Guban, D., Muritala, I. K., Roeb, M., & Sattler, C. (2020). Assessment of sustainable high temperature hydrogen production technologies. *International Journal of Hydrogen Energy*, *45*(49), 26156–26165. https://doi.org/10.1016/j.ijhydene.2019.08.145

Guzmán, C., Alvarez, A., Godínez, L. A., Ledesma-García, J., & Arriaga, L. G. (2012). Evaluation of ZrO2 composite membrane operating at high temperature (100 °C) in direct methanol fuel cells. *International Journal of Electrochemical Science*, *7*(7), 6106–6117.

Hall, D. M., Akinfiev, N. N., Larow, E. G., Schatz, R. S., & Lvov, S. N. (2014). Thermodynamics and Efficiency of a CuCl (aq)/ HCl (aq) Electrolyzer. *Electrochimica Acta*, *143*, 70–82. https://doi.org/10.1016/-j.electacta.2014.08.018

Hall, D. M., & Lvov, S. N. (2016). Modeling a CuCl(aq)/HCl(aq) Electrolyzer using Thermodynamics and Electrochemical Kinetics. *Electrochimica Acta*, *190*, 1167–1174. https://doi.org/10.1016/j.electacta.2015.12.184

Han, B., Mo, J., Kang, Z., Yang, G., Barnhill, W., & Zhang, F. Y. (2017). Modeling of two-phase transport in proton exchange membrane electrolyzer cells for hydrogen energy. *International Journal of Hydrogen Energy*, *42*(7), 4478–4489. https://doi.org/10.1016/j.ijhydene.2016.12.103

Han, B., Steen, S. M., Mo, J., & Zhang, F.-Y. (2015). Electrochemical performance modeling of a proton exchange membrane electrolyzer cell for hydrogen energy. *International Journal of Hydrogen Energy*, *40*(22), 7006–7016. https://doi.org/10.1016/j.ijhydene.2015.03.164

Handayani, S., Dewi, E. L., Hardy, J., & Christiani, L. (2012). Influence of Composite Electrolyte Membrane for Proton Exchange Membrane Fuel Cells. *Procedia Chemistry*, *4*, 123–130. https://doi.org/10.1016/-j.proche.2012.06.018

Hanna Rosli, N. A., Loh, K. S., Wong, W. Y., Mohamad Yunus, R., Khoon Lee, T., Ahmad, A., & Chong, S. T. (2020). Review of chitosan-based polymers as proton exchange membranes and roles of chitosan-supported ionic liquids. *International Journal of Molecular Sciences*, *21*(2), 1–53. https://doi.org/10.3390/ijms21020632

Hansen, M. K. (2012). *PEM Water Electrolysis at Elevated Temperatures*. Technical University of Denmark.

Hansen, M. K., Aili, D., Christensen, E., Pan, C., Eriksen, S., Jensen, J. O., Von Barner, J. H., Li, Q., & Bjerrum, N. J. (2012). PEM steam electrolysis at 130°C using a phosphoric acid doped short side chain PFSA membrane. *International Journal of Hydrogen Energy*, *37*(15), 10992–11000. https://doi.org/10.1016/j.ijhydene.2012.04.125

Haque, M. A., Sulong, A. B., Loh, K. S., Majlan, E. H., Husaini, T., & Rosli, R. E. (2017). Acid doped polybenzimidazoles based membrane electrode assembly for high temperature proton exchange membrane fuel cell: A review. *International Journal of Hydrogen Energy*, *42*(14), 9156–9179. https://doi.org/10.1016/j.ijhydene.2016.03.086

Haron, R., Mat, R., Tuan Abdullah, T. A., & Rahman, R. A. (2018). Overview on utilization of biodiesel by-product for biohydrogen production. *Journal of Cleaner Production*, *172*, 314–324. https://doi.org/10.1016/-j.jclepro.2017.10.160

Harvey, R., Abouatallah, R., & Cargnelli, J. (2016). *PEM Electrolysis for Hydrogen Production: Principles and Applications*.

Hassan, N. S., Jalil, A. A., Khusnun, N. F., Ahmad, A., Abdullah, T. A. T., Kasmani, R. M., Norazahar, N., Kamaroddin, M. F. A., & Vo, D. V. N. (2021). Photoelectrochemical water splitting using post-transition metal oxides for hydrogen production: a review. *Environmental Chemistry Letters*. https://doi.org/10.1007/s10311-021-01357-x

He, L., Yang, J., & Chen, D. (2013). Hydrogen from Biomass: Advances in Thermochemical Processes. *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*, 111–133. https://doi.org/10.1016/B978-0-444-56352-1.00006-4

He, R., Li, Q., Xiao, G., & Bjerrum, N. J. (2003). Proton conductivity of phosphoric acid doped polybenzimidazole and its composites with inorganic proton conductors. *Journal of Membrane Science*, *226*(1–2), 169–184. https://doi.org/10.1016/j.memsci.2003.09.002

He, S., Lin, Y., Ma, H., Jia, H., Liu, X., & Lin, J. (2016). Preparation of sulfonated poly(ether ether ketone) (SPEEK) membrane using ethanol/water mixed solvent. *Materials Letters*, *169*, 69–72.

Hinkley, J., Hayward, J., Mcnaughton, R., Gillespie, R., Matsumoto, A., Watt, M., & Lovegrove, K. (2016). *Cost assessment of hydrogen production from PV and electrolysis*. *March*, 1–35. http://arena.gov.au/files/2016/05/-Assessment-of-the-cost-of-hydrogen-from-PV.pdf

Holladay, J. D., Hu, J., King, D. L., & Wang, Y. (2009). An overview of hydrogen production technologies. *Catalysis Today*, *139*(4), 244–260. https://doi.org/10.1016/j.cattod.2008.08.039

Hooshyari, K., Javanbakht, M., & Adibi, M. (2016). Novel composite membranes based on PBI and dicationic ionic liquids for high temperature polymer electrolyte membrane fuel cells. *Electrochimica Acta*, *205*. https://doi.org/10.1016/j.electacta.2016.04.115

Hooshyari, K., Javanbakht, M., Shabanikia, A., & Enhessari, M. (2015). Fabrication BaZrO3/PBI-based nanocomposite as a new proton conducting membrane for high temperature proton exchange membrane fuel cells. *Journal of Power Sources*, *276*, 62–72. https://doi.org/-10.1016/j.jpowsour.2014.11.083

Hosseini, S. E., & Wahid, M. A. (2016). Hydrogen production from renewable and sustainable energy resources : Promising green energy carrier for clean development. *Renewable and Sustainable Energy Reviews*, *57*, 850–866. https://doi.org/10.1016/j.rser.2015.12.112

Hosseini, S. E., & Wahid, M. A. (2020). Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy. *International Journal of Energy Research*, *44*(6), 4110–4131. https://doi.org/10.1002/er.4930

Hwang, K., Kim, J. H., Kim, S. Y., & Byun, H. (2014). Preparation of polybenzimidazole-based membranes and their potential applications in the fuel cell system. *Energies*, *7*(3), 1721–1732. https://doi.org/-10.3390/en7031721

Ishaq, H., Dincer, I., & Naterer, G. F. (2018). Development and assessment of a solar, wind and hydrogen hybrid trigeneration system. In *International Journal of Hydrogen Energy* (Vol. 43, Issue 52, pp. 23148–23160). https://doi.org/10.1016/j.ijhydene.2018.10.172

Iulianelli, A., & Basile, A. (2012). Sulfonated PEEK-based polymers in PEMFC and DMFC applications: A review. *International Journal of Hydrogen Energy*, *37*(20), 15241–15255. https://doi.org/10.1016/j.ijhydene.-2012.07.063

Ivy, J. (2004). Summary of Electrolytic Hydrogen Production Milestone Completion Report. *Small*. https://doi.org/10.1126/science.1066771

Javad Parnian, M., Rowshanzamir, S., & Gashoul, F. (2017). Comprehensive investigation of physicochemical and electrochemical properties of sulfonated poly (ether ether ketone) membranes with different degrees of sulfonation for proton exchange membrane fuel cell applications. *Energy*, *125*, 614–628. https://doi.org/10.1016/j.energy.2017.02.143

Jianu, O.A., Wang, Z., Rosen, M. A., & Naterer, G. F. (2013). Shadow imaging of particle dynamics and dissolution rates in aqueous solutions for hydrogen production. *Experimental Thermal and Fluid Science*, *51*, 297–301. https://doi.org/10.1016/j.expthermflusci.2013.08.012

Jianu, Ofelia Antonia. (2013). *Mass Transfer and Particle Dissolution in Liquid-Gas and Solid-Liquid Flows : Application to Hydrogen Production Processes by* (Issue October). University of Ontario Institute of Technology.

Jois, H. S. S., & Bhat, D. K. (2013). Miscibility, water uptake, ion exchange capacity, conductivity and dielectric studies of poly(methyl methacrylate) and cellulose acetate blends. *Journal of Applied Polymer Science*, *130*(5), 3074–3081. https://doi.org/10.1002/app.39535

Ju, H. K., Badwal, S., & Giddey, S. (2018). A comprehensive review of carbon and hydrocarbon assisted water electrolysis for hydrogen production. In *Applied Energy* (Vol. 231, pp. 502–533). https://doi.org/10.1016/-j.apenergy.2018.09.125

Kaddami, M., & Mikou, M. (2017). *Effect of operating parameters on hydrogen production by electrolysis of water*. *2*, 1–8.

Kaippamangalath, N., & Gopalakrishnapanicker, U. (2018). Transport Properties Through Polymer Membranes. In *Transport Properties of Polymeric Membranes*. https://doi.org/10.1016/B978-0-12-809884-4.00008-2

Kalamaras, C. M., & Efstathiou, A. M. (2013). Hydrogen Production Technologies: Current State and Future Developments. *Conference Papers in Energy*, *2013*, 1–9. https://doi.org/10.1155/2013/690627

Kalathil, A., Raghavan, A., & Kandasubramanian, B. (2019). Polymer Fuel Cell Based on Polybenzimidazole Membrane: A Review. *Polymer-Plastics Technology and Materials*, *58*(5), 465–497. https://doi.org/10.1080/-03602559.2018.1482919

Kar, S. K., Harichandan, S., & Roy, B. (2022). Bibliometric analysis of the research on hydrogen economy: An analysis of current findings and roadmap ahead. *International Journal of Hydrogen Energy*, *47*(20), 10803–10824. https://doi.org/10.1016/j.ijhydene.2022.01.137

Khalid, F. (2017). *Development and analysis of a high temperature electrolyser for the Cu-Cl cycle for hydrogen production*. PhD Thesis. https://ir.library.dc-uoit.ca/handle/10155/820

Khan, M. U., Lee, J. T. E., Bashir, M. A., Dissanayake, P. D., Ok, Y. S., Tong, Y. W., Shariati, M. A., Wu, S., & Ahring, B. K. (2021). Current status of biogas upgrading for direct biomethane use: A review. *Renewable and Sustainable Energy Reviews*, *149*(June), 111343. https://doi.org/-10.1016/j.rser.2021.111343

Khurana, S., Hall, D. M., Schatz, R. S., & Lvov, S. N. (2015). *Effect of Clamping Pressure and Temperature on the Performance of a CuCl (aq)/ HCl (aq) Electrolyzer*. *4*(4). https://doi.org/10.1149/2.0011504eel

Kim, D. J., Choi, D. H., Park, C. H., & Nam, S. Y. (2016). Characterization of the sulfonated PEEK/sulfonated nanoparticles composite membrane for the fuel cell application. *International Journal of Hydrogen Energy*, *41*(13), 5793–5802. https://doi.org/10.1016/j.ijhydene.2016.02.056

Kim, D. J., Park, C. H., & Nam, S. Y. (2016). Molecular dynamics simulations of modified PEEK polymeric membrane for fuel cell application. *International Journal of Hydrogen Energy*, *41*(18), 7641–7648. https://doi.org/10.1016/j.ijhydene.2015.12.220

Kim, S., Schatz, R., Khurana, S., Fedkin, M., Wang, C., & Lvov, S. (2019). Advanced CuCl Electrolyzer for Hydrogen Production via the Cu-Cl Thermochemical Cycle. *ECS Transactions*, *35*(32), 257–265. https://doi.org/10.1149/1.3655709

Kimura, S., & Li, Y. (2019). Demand and Supply Potential of Hydrogen Energy in East Asia. In *Economic* (Vol. 01). https://www.g20karuizawa.-go.jp/assets/pdf/Demand and Supply Potential of Hydrogen Energy in East Asia.pdf

Koponen, J. (2015). Review of water electrolysis technologies and design of renewable hydrogen production systems. *Neo-Carbon Energy*, 1–22.

Koponen, J., Kosonen, A., & Ahola, J. (2015). Review of water electrolysis technologies and design of renewable hydrogen production systems [Lappeenranta University of Technology]. In *Neo-Carbon Energy*. https://lutpub.lut.fi/bitstream/handle/10024/104326/MScThesis_JKK.pdf?sequence=2&isAllowed=y%0D

Kraytsberg, A., & Ein-Eli, Y. (2014). Review of advanced materials for proton exchange membrane fuel cells. *Energy and Fuels*, *28*(12), 7303–7330. https://doi.org/10.1021/ef501977k

Krishnan, N. N., Lee, S., Ghorpade, R. V., Konovalova, A., Jang, J. H., Kim, H. J., Han, J., Henkensmeier, D., & Han, H. (2018). Polybenzimidazole (PBI-OO) based composite membranes using sulfophenylated TiO2 as both filler and crosslinker, and their use in the HT-PEM fuel cell. *Journal of Membrane Science*, *560*(May), 11–20. https://doi.org/10.1016/-j.memsci.2018.05.006

Krüger, A.J., Kerres, J., Kerres, J., Krieg, H. M., & Bessarabov, D. (2017). Electrochemical Hydrogen Production from SO2 and Water in a SDE Electrolyzer. *Hydrogen Production Technologies*, 277–303. https://doi.org/10.1002/9781119283676.ch7

Krüger, Andries J., Kerres, J., Bessarabov, D., & Krieg, H. M. (2015). Evaluation of covalently and ionically cross-linked PBI-excess blends for application in SO2 electrolysis. *International Journal of Hydrogen Energy*, *40*(29), 8788–8796. https://doi.org/10.1016/j.ijhydene.2015.05.063

Kumar, R., Kumar, A., & Pal, A. (2020). An overview of conventional and non-conventional hydrogen production methods. *Materials Today: Proceedings*, *xxxx*. https://doi.org/10.1016/j.matpr.2020.08.793

Kumar, V., Arthanareeswaran, G., Ismail, A. F., Jaafar, J., & Das, D. B. (2017). Nanocomposite membranes prepared from sulfonated polyether ether ketone (SPEEK) and nanocaly for enhancement of fuel cell properties. *International Journal of Hydrogen Energy*, 1–9. https://doi.org/10.1016/-j.ijhydene.2017.06.128

Kumari, M., & Gupta, S. K. (2019). Response surface methodological (RSM) approach for optimizing the removal of trihalomethanes (THMs) and its precursor's by surfactant modified magnetic nanoadsorbents (sMNP) - An endeavor to diminish probable cancer risk. *Scientific Reports*, *9*(1), 1–11. https://doi.org/10.1038/s41598-019-54902-8

Laberty-Robert, C., Vallé, K., Pereira, F., & Sanchez, C. (2011). Design and properties of functional hybrid organic–inorganic membranes for fuel cells. *Chemical Society Reviews*, *40*(2), 961–1005. https://doi.org/-10.1039/c0cs00144a

Lade, H., Kumar, V., Arthanareeswaran, G., & Ismail, A. F. (2017). Sulfonated poly(arylene ether sulfone) nanocomposite electrolyte membrane for fuel cell applications: A review. *International Journal of Hydrogen Energy*, *42*(2), 1063–1074. https://doi.org/10.1016/j.ijhydene.-2016.10.038

Lei, Q., Wang, B., Wang, P., & Liu, S. (2019). Hydrogen generation with acid/alkaline amphoteric water electrolysis. *Journal of Energy Chemistry*, *38*, 162–169. https://doi.org/10.1016/j.jechem.2018.12.022

Lettenmeier, P., Wang, R., Abouatallah, R., Helmly, S., Morawietz, T., Hiesgen, R., Kolb, S., Burggraf, F., Kallo, J., Gago, A. S., & Friedrich, K. A. (2016). Durable Membrane Electrode Assemblies for Proton Exchange Membrane Electrolyzer Systems Operating at High Current Densities. *Electrochimica Acta*, *210*, 502–511. https://doi.org/10.1016/-j.electacta.2016.04.164

Li, D. B., Hui, H. W., & Zhao, N. (2016). PEM Electrolysis Production for Hydrogen: Principles and Applications. In *CRC Press, Taylor & Francis Group*. https://doi.org/10.1557/mrs.2019.210

Li, F., Mao, Z., Li, J., Li, G., Zhu, G., Zhang, L., Meng, D., & Wang, Z. (2017). *Porous polybenzimidazole membranes doped with phosphoric acid : Preparation and application in high temperature PEM fuel cells*. 2–7.

Li, Q. F., Rudbeck, H. C., Chromik, A., Jensen, J. O., Pan, C., Steenberg, T., Calverley, M., Bjerrum, N. J., & Kerres, J. (2010). Properties, degradation and high temperature fuel cell test of different types of PBI and PBI blend membranes. *Journal of Membrane Science*, *347*(1–2), 260–270. https://doi.org/10.1016/j.memsci.2009.10.032

Li, Qingfeng, He, R., Berg, R. W., Hjuler, H. A., & Bjerrum, N. J. (2004). Water uptake and acid doping of polybenzimidazoles as electrolyte membranes for fuel cells. *Solid State Ionics*, *168*(1–2), 177–185. https://doi.org/10.1016/j.ssi.2004.02.013

Li, Qingfeng, Jensen, J. O., Savinell, R. F., & Bjerrum, N. J. (2009). High temperature proton exchange membranes based on polybenzimidazoles for fuel cells. *Progress in Polymer Science*, *34*(5), 449–477. https://doi.org/10.1016/j.progpolymsci.2008.12.003

Li, Qingfeng, Pan, C., Jensen, J. O., Noye, P., & Bjerrum, N. J. (2007). Cross-Linked Polybenzimidazole Membranes for Fuel Cells. *Chemistry of Materials*. *19*(21), 350–352.

Li, Qingshan, Zheng, Y., Guan, W., Jin, L., Xu, C., & Wang, W. G. (2014). Achieving high-efficiency hydrogen production using planar solid-oxide electrolysis stacks. *International Journal of Hydrogen Energy*, *39*(21), 10833–10842. https://doi.org/10.1016/j.ijhydene.2014.05.070

Li, X., Qian, G., Chen, X., & Benicewicz, B. C. (2013). Synthesis and characterization of a new fluorine-containing polybenzimidazole (PBI) for proton-conducting membranes in fuel cells. *Fuel Cells*, *13*(5), 832–842. https://doi.org/10.1002/fuce.201300054

Li, X, Qian, G., Chen, X., & Benicewicz, B. C. (2013). Synthesis and Characterization of a New Fluorine-Containing Polybenzimidazole (PBI) for Proton-Conducting Membranes in Fuel Cells. *Fuel Cells*, *13*(5), 832–842. https://doi.org/10.1002/fuce.201300054

Li, Xiao, Zhao, L., Yu, J., Liu, X., Zhang, X., Liu, H., & Zhou, W. (2020). Water Splitting: From Electrode to Green Energy System. *Nano-Micro Letters*, *12*(1), 1–29. https://doi.org/10.1007/s40820-020-00469-3

Li, Y., Guo, L., Zhang, X., Jin, H., & Lu, Y. (2010). Hydrogen production from coal gasification in supercritical water with a continuous flowing system. *International Journal of Hydrogen Energy*, *35*(7), 3036–3045. https://doi.org/10.1016/j.ijhydene.2009.07.023

Lian, Z., Wang, Y., Zhang, X., Yusuf, A., Famiyeh, Lord, Murindababisha, D., Jin, H., Liu, Y., He, J., Wang, Y., Yang, G., & Sun, Y. (2021). Hydrogen Production by Fluidized Bed Reactors: A Quantitative Perspective Using the Supervised Machine Learning Approach. *J*, *4*(3), 266–287. https://doi.org/10.3390/j4030022

Liu, H., & Liu, S. (2021). Life cycle energy consumption and GHG emissions of hydrogen production from underground coal gasification in comparison with surface coal gasification. *International Journal of Hydrogen Energy*, *46*(14), 9630–9643. https://doi.org/10.1016/j.ijhydene.2020.12.096

Lobato, J., Cañizares, P., Rodrigo, M. A., Úbeda, D., & Pinar, F. J. (2011). A novel titanium PBI-based composite membrane for high temperature PEMFCs. *Journal of Membrane Science*, *369*(1–2), 105–111. https://doi.org/10.1016/j.memsci.2010.11.051

Lui, J., Chen, W. H., Tsang, D. C. W., & You, S. (2020). A critical review on the principles, applications, and challenges of waste-to-hydrogen technologies. *Renewable and Sustainable Energy Reviews*, *134*(September), 110365. https://doi.org/10.1016/j.rser.2020.110365

Luo, M., Yi, Y., Wang, S., Wang, Z., Du, M., Pan, J., & Wang, Q. (2018). Review of hydrogen production using chemical-looping technology. *Renewable and Sustainable Energy Reviews*, *81*(April 2017), 3186–3214. https://doi.org/10.1016/j.rser.2017.07.007

Mack, F., Laukenmann, R., Galbiati, S., Kerres, J. A., & Zeis, R. (2015a). Electrochemical Impedance Spectroscopy as a Diagnostic Tool for High-Temperature PEM Fuel Cells. *ECS Transactions*, *69*(17), 1075–1087. https://doi.org/10.1149/06917.1075ecst

Mack, F., Laukenmann, R., Galbiati, S., Kerres, J. A., & Zeis, R. (2015b). Electrochemical Impedance Spectroscopy as a Diagnostic Tool for High-Temperature PEM Fuel Cells. *ECS Transactions*, *69*(17), 1075–1087. https://doi.org/10.1149/06917.1075ecst

Mader, J., Xiao, L., Schmidt, T. J., Fuel, B., & Ave, V. (2008). Polybenzimidazole / Acid Complexes as High-Temperature Membranes A New Approach : *Advanced Computer Simulation Approaches For Soft Matter Sciences I*, *February*, 63–124. https://doi.org/10.1007/12

Maggio, G., Nicita, A., & Squadrito, G. (2019). How the hydrogen production from RES could change energy and fuel markets: A review of recent literature. *International Journal of Hydrogen Energy*, *44*(23), 11371–11384. https://doi.org/10.1016/j.ijhydene.2019.03.121

Mah, A. X. Y., Ho, W. S., Bong, C. P. C., Hassim, M. H., Liew, P. Y., Asli, U. A., Kamaruddin, M. J., & Chemmangattuvalappil, N. G. (2019). Review of hydrogen economy in Malaysia and its way forward. *International Journal of Hydrogen Energy*, *44*(12), 5661–5675. https://doi.org/10.1016/j.ijhydene.2019.01.077

Maharana, T., Sutar, A. K., Nath, N., Routaray, A., Negi, Y. S., & Mohanty, B. (2014). Polyetheretherketone (PEEK) Membrane for Fuel Cell Applications. *Advanced Energy Materials*, *9781118686*, 433–464. https://doi.org/10.1002/9781118904923.ch11

Mahmoud, M., & Fujigaya, T. (2016). Enhancement of performance of pyridine modified polybenzimidazole fuel cell membranes using zirconium oxide nanoclusters and optimized phosphoric acid doping level. *International Journal of Hydrogen Energy*, *41*(16), 6842–6854.

Maier, M., Smith, K., Dodwell, J., Hinds, G., Shearing, P. R., & Brett, D. J. L. (2022). Mass transport in PEM water electrolysers: A review. *International Journal of Hydrogen Energy*, *47*(1), 30–56. https://doi.org/10.1016/j.ijhydene.2021.10.013

Maity, S., & Jana, T. (2013). Soluble polybenzimidazoles for PEM: Synthesized from efficient, inexpensive, readily accessible alternative tetraamine monomer. *Macromolecules*, *46*(17), 6814–6823. https://doi.org/10.1021/ma401404c

Malek, B. A. (2017). *National Green Technology Masterplan with Special Focus on Energy Sector* (Issue November 2017).

Malinowski, M., Iwan, A., Paściak, G., Parafiniuk, K., & Gorecki, L. (2014). Synthesis and characterization of para- and meta-polybenzimidazoles for high-temperature proton exchange membrane fuel cells. *High Performance Polymers*, *26*(4), 436–444. https://doi.org/10.1177/-0954008313517909

Mallick, D., Mahanta, P., & Moholkar, V. S. (2017). Co-gasification of coal and biomass blends: Chemistry and engineering. *Fuel*, *204*, 106–128. https://doi.org/10.1016/j.fuel.2017.05.006

Marshall, A. Ã., Børresen, B., Hagen, G., Tsypkin, M., & Tunold, R. (2007). *Hydrogen production by advanced proton exchange membrane (PEM) water electrolysers — Reduced energy consumption by improved electrocatalysis*. *32*, 431–436. https://doi.org/10.1016/j.energy.-2006.07.014

Martinez-Burgos, W. J., de Souza Candeo, E., Pedroni Medeiros, A. B., Cesar de Carvalho, J., Oliveira de Andrade Tanobe, V., Soccol, C. R., & Sydney, E. B. (2021). Hydrogen: Current advances and patented technologies of its renewable production. *Journal of Cleaner Production*, *286*. https://doi.org/10.1016/j.jclepro.2020.124970

Martínez-Merino, V., Gil, M. J., & Cornejo, A. (2013a). Biological Hydrogen Production. *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*, 171–199. https://doi.org/10.1016/B978-0-444-56352-1.00008-8

Martínez-Merino, V., Gil, M. J., & Cornejo, A. (2013b). Biomass Sources for Hydrogen Production. *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*, 87–110. https://doi.org/10.1016/B978-0-444-56352-1.00005-2

Martino, M., Ruocco, C., Meloni, E., Pullumbi, P., & Palma, V. (2021). Main hydrogen production processes: An overview. *Catalysts*, *11*(5). https://doi.org/10.3390/catal11050547

Mazloomi, K., & Gomes, C. (2012). Hydrogen as an energy carrier: Prospects and challenges. *Renewable and Sustainable Energy Reviews*, *16*(5), 3024–3033. https://doi.org/10.1016/j.rser.2012.02.028

Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S. J., & Ulgiati, S. (2018). Life cycle assessment and water footprint of hydrogen production methods: From conventional to emerging technologies. *Environments - MDPI*, *5*(2), 1–19. https://doi.org/10.3390/-environments5020024

Mekhilef, S., Safari, A., Mustaffa, W. E. S., Saidur, R., Omar, R., & Younis, M. A. A. (2012). Solar energy in Malaysia: Current state and prospects. *Renewable and Sustainable Energy Reviews*, *16*(1), 386–396. https://doi.org/10.1016/j.rser.2011.08.003

Melchior, J., & Kreuer, K. (2017). Why do proton conducting polybenzimidazole. *Physical Chemistry Chemical Physics*, *19*(1), 601–612. https://doi.org/10.1039/c6cp05331a

Midilli, A., Kucuk, H., Topal, M. E., Akbulut, U., & Dincer, I. (2021). A comprehensive review on hydrogen production from coal gasification: Challenges and Opportunities. *International Journal of Hydrogen Energy*, *46*(50), 25385–25412. https://doi.org/10.1016/-j.ijhydene.2021.05.088

Millet, P., Mbemba, N., Grigoriev, S. A., Fateev, V. N., Aukauloo, A., & Etiévant, C. (2011). Electrochemical performances of PEM water electrolysis cells and perspectives. *International Journal of Hydrogen Energy*, *36*(6), 4134–4142. https://doi.org/10.1016/j.ijhydene.2010.06.105

Millet, Pierre. (2015). Fundamentals of Water Electrolysis. *Hydrogen Production: By Electrolysis*, *2*, 33–62. https://doi.org/10.1002/9783527676507.ch2

Millet, Pierre, & Grigoriev, S. (2013a). Chapter 2 - Water Electrolysis Technologies. In *Renewable Hydrogen Technologies* (pp. 19–41). https://doi.org/http://dx.doi.org/10.1016/B978-0-444-56352-1.00002-7

Millet, Pierre, & Grigoriev, S. (2013b). Water Electrolysis Technologies. In *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety* (pp. 19–41). https://doi.org/10.1016/B978-0-444-56352-1.00002-7

Mishra, A. K., Bose, S., Kuila, T., Kim, N. H., & Lee, J. H. (2012). Silicate-based polymer-nanocomposite membranes for polymer electrolyte membrane fuel cells. *Progress in Polymer Science*, *37*(6), 842–869. https://doi.org/10.1016/j.progpolymsci.2011.11.002

Miyake, T., & Rolandi, M. (2016). Grotthuss mechanisms: from proton transport in proton wires to bioprotonic devices. *Journal of Physics: Condensed Matter*, *28*(2), 023001. https://doi.org/10.1088/0953-8984/28/2/023001

Mo, J., Dehoff, R. R., Peter, W. H., Toops, T. J., Green, J. B., & Zhang, F.-Y. (2016). Additive manufacturing of liquid/gas diffusion layers for low-cost and high-efficiency hydrogen production. *International Journal of Hydrogen Energy*, *41*(4), 3128–3135. https://doi.org/10.1016/-j.ijhydene.2015.12.111

Mohd Zahri, N. A., Md Jamil, S. N. A., Abdullah, L. C., Jia Huey, S., Nourouzi Mobarekeh, M., Mohd Rapeia, N. S., & Shean Yaw, T. C. (2020). Central composite design of heavy metal removal using polymer adsorbent. *Journal of Applied Water Engineering and Research*, *0*(0), 1–14. https://doi.org/10.1080/23249676.2020.1831978

Mohsen, S., Ehteshami, M., & Chan, S. H. (2014). The role of hydrogen and fuel cells to store renewable energy in the future energy network – potentials and challenges. *Energy Policy*, *73*, 103–109. https://doi.org/10.1016/-j.enpol.2014.04.046

Mollá, S., & Compañ, V. (2014). Polymer blends of SPEEK for DMFC application at intermediate temperatures. *International Journal of Hydrogen Energy*, *39*(10), 5121–5136. https://doi.org/10.1016/j.ijhydene.2014.01.085

Moradi, M., Moheb, A., Javanbakht, M., & Hooshyari, K. (2016). Experimental study and modeling of proton conductivity of phosphoric acid doped PBI-Fe2TiO5 nanocomposite membranes for using in high temperature proton exchange membrane fuel cell (HT-PEMFC). *International Journal of Hydrogen Energy*, *41*(4), 2896–2910. https://doi.org/10.1016/-j.ijhydene.2015.12.100

Mori, M., & Jensterle, M. (2014). *Life-cycle assessment of a hydrogen-based uninterruptible power supply system using renewable energy*. 1810–1822. https://doi.org/10.1007/s11367-014-0790-6

Mossayebi, Z., Saririchi, T., Rowshanzamir, S., & Parnian, M. J. (2016). Investigation and optimization of physicochemical properties of sulfated zirconia/sulfonated poly (ether ether ketone) nanocomposite membranes for medium temperature proton exchange membrane fuel cells. *International Journal of Hydrogen Energy*, *41*(28), 12293–12306. https://doi.org/10.1016/j.ijhydene.2016.05.017

Najjar, Y. S. H. (2013). Hydrogen safety : The road toward green technology. *International Journal of Hydrogen Energy*, *38*(25), 10716–10728. https://doi.org/10.1016/j.ijhydene.2013.05.126

Nambi Krishnan, N., Konovalova, A., Aili, D., Li, Q., Park, H. S., Jang, J. H., Kim, H. J., & Henkensmeier, D. (2019). Thermally crosslinked sulfonated polybenzimidazole membranes and their performance in high temperature polymer electrolyte fuel cells. *Journal of Membrane Science*, *588*(June). https://doi.org/10.1016/j.memsci.2019.117218

Nasef, M. M., Fujigaya, T., Abouzari-Lotf, E., Nakashima, N., & Yang, Z. (2016). Enhancement of performance of pyridine modified polybenzimidazole fuel cell membranes using zirconium oxide nanoclusters and optimized phosphoric acid doping level. *International Journal of Hydrogen Energy*, *41*(16), 6842–6854. https://doi.org/10.1016/j.ijhydene.2016.03.022

Naterer, G. F., Suppiah, S., Rosen, M. A., Gabriel, K., Dincer, I., Jianu, O. A., Wang, Z., Easton, E. B., Ikeda, B. M., Rizvi, G., Pioro, I., Pope, K., Mostaghimi, J., & Lvov, S. N. (2017a). Advances in unit operations and materials for the Cu–Cl cycle of hydrogen production. *International Journal of Hydrogen Energy*, *42*(24), 15708–15723. https://doi.org/-10.1016/j.ijhydene.2017.03.133

Naterer, G. F., Suppiah, S., Rosen, M. A., Gabriel, K., Dincer, I., Jianu, O. A., Wang, Z., Easton, E. B., Ikeda, B. M., Rizvi, G., Pioro, I., Pope, K., Mostaghimi, J., & Lvov, S. N. (2017b). Advances in unit operations and materials for the CuCl cycle of hydrogen production. *International Journal of Hydrogen Energy*, *42*(24), 15708–15723. https://doi.org/10.1016/j.ijhydene.2017.03.133

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Ahmed, S., Wang, Z., Rosen, M. A., Dincer, I., Gabriel, K., Secnik, E., Easton, E. B., Lvov, S. N., Papangelakis, V., & Odukoya, A. (2014a). Progress of international program on hydrogen production with the copper–chlorine cycle. *International Journal of Hydrogen Energy*, *39*(6), 2431–2445. https://doi.org/10.1016/j.ijhydene.2013.11.073

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Ahmed, S., Wang, Z., Rosen, M. A., Dincer, I., Gabriel, K., Secnik, E., Easton, E. B., Lvov, S. N., Papangelakis, V., & Odukoya, A. (2014b). Progress of international program on hydrogen production with the copper-chlorine cycle. *International Journal of Hydrogen Energy*, *39*(6), 2431–2445.

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Ferrandon, M., Wang, Z., Dincer, I., Gabriel, K., Rosen, M. A., Secnik, E., Easton, E. B., Trevani, L., Pioro, I., Tremaine, P., Lvov, S., Jiang, J., Rizvi, G., Ikeda, B. M., Lu, L., … Avsec, J. (2011). Clean hydrogen production with the Cu–Cl cycle – Progress of international consortium, II: Simulations, thermochemical data and materials. *International Journal of Hydrogen Energy*, *36*(24), 15486–15501. https://doi.org/10.1016/j.ijhydene.2011.08.013

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Daggupati, V., Gabriel, K., Dincer, I., Rosen, M. A., Spekkens, P., Lvov, S. N., Fowler, M., Tremaine, P., Mostaghimi, J., Easton, E. B., Trevani, L., Rizvi, G., Ikeda, B. M., Kaye, M. H., … Avsec, J. (2010). Canada's program on nuclear hydrogen production and the thermochemical Cu–Cl cycle. *International Journal of Hydrogen Energy*, *35*(20), 10905–10926. https://doi.org/10.1016/j.ijhydene.2010.07.087

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Dincer, I., Rosen, M. A., Gabriel, K., Secnik, E., Easton, E. B., Pioro, I., Lvov, S., Jiang, J., Mostaghimi, J., Ikeda, B. M., Rizvi, G., Lu, L., Odukoya, A., Spekkens, P., … Avsec, J. (2013). Progress of international hydrogen production network for the thermochemical Cu–Cl cycle. *International Journal of Hydrogen Energy*, *38*(2), 740–759. https://doi.org/10.1016/-j.ijhydene.2012.10.023

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Rosen, M. A., Dincer, I., Gabriel, K., Odukoya, A., Secnik, E., Easton, E. B., & Papangelakis, V. (2015a). Progress in thermochemical hydrogen production with the copper-chlorine cycle. *International Journal of Hydrogen Energy*, *40*(19), 6283–6295. https://doi.org/10.1016/-j.ijhydene.2015.02.124

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Rosen, M. A., Dincer, I., Gabriel, K., Odukoya, A., Secnik, E., Easton, E. B., & Papangelakis, V. (2015b). Progress in thermochemical hydrogen production with the copper–chlorine cycle. *International Journal of Hydrogen Energy*, *40*(19), 6283–6295. https://doi.org/10.1016/-j.ijhydene.2015.02.124

Naterer, G., Suppiah, S., Lewis, M., Gabriel, K., Dincer, I., Rosen, M. A., Fowler, M., Rizvi, G., Easton, E. B., Ikeda, B. M., Kaye, M. H., Lu, L., Pioro, I., Spekkens, P., Tremaine, P., Mostaghimi, J., Avsec, J., & Jiang, J. (2009a). Recent Canadian advances in nuclear-based hydrogen production and the thermochemical Cu-Cl cycle. *International Journal of Hydrogen Energy*, *34*(7), 2901–2917. https://doi.org/10.1016/-j.ijhydene.2009.01.090

Naterer, G., Suppiah, S., Lewis, M., Gabriel, K., Dincer, I., Rosen, M. A., Fowler, M., Rizvi, G., Easton, E. B., Ikeda, B. M., Kaye, M. H., Lu, L., Pioro, I., Spekkens, P., Tremaine, P., Mostaghimi, J., Avsec, J., & Jiang, J. (2009b). Recent Canadian advances in nuclear-based hydrogen production and the thermochemical Cu–Cl cycle. *International Journal of Hydrogen Energy*, *34*(7), 2901–2917. https://doi.org/10.1016/-j.ijhydene.2009.01.090

Natural Resources Canada (NRCan). (2020). *Seizing the Opportunities for Hydrogen*.

Navarro, R. M., Guil, R., & Fierro, J. L. G. (2015). 2 – Introduction to hydrogen production. In *Compendium of Hydrogen Energy*. https://doi.org/-10.1016/B978-1-78242-361-4.00002-9

Naya, T. (2010). *Conductivity of Ion Exchange Materials*. *May*, 14–22. https://doi.org/10.1016/j.memsci.2005.05.002

Ng, L. Y., Mohammad, A. W., Leo, C. P., & Hilal, N. (2013). Polymeric membranes incorporated with metal/metal oxide nanoparticles: A comprehensive review. *Desalination*, *308*, 15–33. https://doi.org/10.1016/j.desal.2010.11.033

Nguyen, T., Abdin, Z., Holm, T., & Mérida, W. (2019). Grid-connected hydrogen production via large-scale water electrolysis. *Energy Conversion and Management*, *200*(June), 112108. https://doi.org/10.1016/j.enconman.-2019.112108

Nicoletti, G., Arcuri, N., Nicoletti, G., & Bruno, R. (2015). A technical and environmental comparison between hydrogen and some fossil fuels. *Energy Conversion and Management*, *89*, 205–213. https://doi.org/10.1016/j.enconman.2014.09.057

Nicotera, I., Kosma, V., Simari, C., Angioni, S., Mustarelli, P., & Quartarone, E. (2015). Ion dynamics and mechanical properties of sulfonated polybenzimidazole membranes for high-temperature proton exchange membrane fuel cells. *Journal of Physical Chemistry C*, *119*(18), 9745–9753. https://doi.org/10.1021/acs.jpcc.5b01067

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews*, *67*(January), 597–611. https://doi.org/10.1016/j.rser.2016.09.044

Nnabuife, S. G., Ugbeh-Johnson, J., Okeke, N. E., & Ogbonnaya, C. (2022). Present and Projected Developments in Hydrogen Production: A Technological Review∗. *Carbon Capture Science & Technology*, *3*(January), 100042. https://doi.org/10.1016/j.ccst.2022.100042

Norasyiqin, S., Latif, A., Chiong, M. S., Rajoo, S., Takada, A., Chun, Y., Tahara, K., & Ikegami, Y. (2021). The Trend and Status of Energy Resources and Greenhouse Gas Emissions in the Malaysia Power Generation Mix. *Energies*, *14*(2200), 1–26.

Noto, V. Di, Piga, M., Giffin, G. A., Quartarone, E., Righetti, P., Mustarelli, P., & Magistris, A. (2011). Structure-property interplay of proton conducting membranes based on PBI5N, SiO2-Im and H3PO4 for high temperature fuel cells. *Physical Chemistry Chemical Physics*, *13*(26), 12146–12154. https://doi.org/10.1039/c1cp20902g

Odukoya, A., & Naterer, G. F. (2011). Electrochemical mass transfer and entropy generation of cuprous chloride electrolysis. *International Journal of Hydrogen Energy*, *36*(17), 11345–11352. https://doi.org/10.1016/-j.ijhydene.2010.11.092

Odukoya, A., Naterer, G. F., Roeb, M., Mansilla, C., Mougin, J., Yu, B., Kupecki, J., Iordache, I., & Milewski, J. (2016). Progress of the IAHE Nuclear Hydrogen Division on international hydrogen production programs. *International Journal of Hydrogen Energy*, *41*(19), 7878–7891. https://doi.org/10.1016/j.ijhydene.2015.09.126

Ogawa, T., Takeuchi, M., & Kajikawa, Y. (2018). Analysis of trends and emerging technologies in water electrolysis research based on a computational method: A comparison with fuel cell research. *Sustainability (Switzerland)*, *10*(2). https://doi.org/10.3390/su10020478

Olabi, A. G., bahri, A. saleh, Abdelghafar, A. A., Baroutaji, A., Sayed, E. T., Alami, A. H., Rezk, H., & Abdelkareem, M. A. (2021). Large-vscale hydrogen production and storage technologies: Current status and future directions. *International Journal of Hydrogen Energy*, *46*(45), 23498–23528. https://doi.org/10.1016/j.ijhydene.2020.10.110

Oladokun, O., Ahmad, A., Abdullah, T. A. T., Nyakuma, B. B., Kamaroddin, M. F. A., Ahmed, M., & Alkali, H. (2016). Sensitivity analysis of biohydrogen production from Imperata cylindrica using stoichiometric equilibrium model. *Jurnal Teknologi*, *78*(8–3), 137–142. https://doi.org/-10.11113/jt.v78.9577

Omoniyi, O., Bacquart, T., Moore, N., Bartlett, S., Williams, K., Goddard, S., Lipscombe, B., Murugan, A., & Jones, D. (2021). Hydrogen gas quality for gas network injection: State of the art of three hydrogen production methods. *Processes*, *9*(6), 1–9. https://doi.org/10.3390/pr9061056

Oono, Y., Sounai, A., & Hori, M. (2009). Influence of the phosphoric acid-doping level in a polybenzimidazole membrane on the cell performance of high-temperature proton exchange membrane fuel cells. *Journal of Power Sources*, *189*(2), 943–949. https://doi.org/10.1016/j.jpowsour.-2008.12.115

Orhan, M. F., Dincer, I., & Rosen, M. A. (2013). *Design and simulation of a copper – chlorine cycle for hydrogen production*. *June 2012*, 1160–1174. https://doi.org/10.1002/er

Orhan, M. F., Dincer, I., Rosen, M. A., & Kanoglu, M. (2012). Integrated hydrogen production options based on renewable and nuclear energy sources. *Renewable and Sustainable Energy Reviews*, *16*(8), 6059–6082. https://doi.org/10.1016/j.rser.2012.06.008

Ortiz, A., Vilas, M., Tojo, E., Dı, M., & Ortiz, I. (2013). *Performance of PEMFC with new polyvinyl-ionic liquids based membranes as electrolytes*. *9*, 0–7. https://doi.org/10.1016/j.ijhydene.2013.04.155

Osman, A. I., Mehta, N., Elgarahy, A. M., Hefny, M., Al-Hinai, A., Al-Muhtaseb, A. H., & Rooney, D. W. (2022). Hydrogen production, storage, utilisation and environmental impacts: a review. In *Environmental Chemistry Letters* (Vol. 20, Issue 1). Springer International Publishing. https://doi.org/10.1007/s10311-021-01322-8

Otero, J., Sese, J., Michaus, I., Santa Maria, M., Guelbenzu, E., Irusta, S., Carrilero, I., & Arruebo, M. (2014). Sulphonated polyether ether ketone diaphragms used in commercial scale alkaline water electrolysis. *Journal of Power Sources*, *247*(2014), 967–974. https://doi.org/10.1016/j.jpowsour.2013.09.062

Owgi, A. H. K., Jalil, A. A., Hussain, I., Hassan, N. S., Hambali, H. U., Siang, T. J., & Vo, D. V. N. (2021). Catalytic systems for enhanced carbon dioxide reforming of methane: a review. *Environmental Chemistry Letters*, *19*(3), 2157–2183. https://doi.org/10.1007/s10311-020-01164-w

Özdemir, Y., Özkan, N., & Devrim, Y. (2017). Fabrication and Characterization of Cross-linked Polybenzimidazole Based Membranes for High Temperature PEM Fuel Cells. *Electrochimica Acta*, *245*, 1–13. https://doi.org/10.1016/j.electacta.2017.05.111

Özdemir, Y., Üregen, N., & Devrim, Y. (2017). Polybenzimidazole based nanocomposite membranes with enhanced proton conductivity for high temperature PEM fuel cells. *International Journal of Hydrogen Energy*, *42*(4), 2648–2657. https://doi.org/10.1016/j.ijhydene.2016.04.132

Paddison, S. J. (2009). *Proton Conduction in PEMs : Complexity , Cooperativity*. https://doi.org/10.1007/978-0-387-78691-9

Paidar, M., Fateev, V., & Bouzek, K. (2016a). Membrane electrolysis—History, current status and perspective. *Electrochimica Acta*, *209*, 737–756. https://doi.org/10.1016/j.electacta.2016.05.209

Paidar, M., Fateev, V., & Bouzek, K. (2016b). *Membrane electrolysis — History, current status and perspective*. *209*, 737–756.

Pal, D. B., Singh, A., & Bhatnagar, A. (2022). A review on biomass based hydrogen production technologies. *International Journal of Hydrogen Energy*, *47*(3), 1461–1480. https://doi.org/10.1016/j.ijhydene.-2021.10.124

Parnian, M. J., Rowshanzamir, S., & Gashoul, F. (2017). Comprehensive investigation of physicochemical and electrochemical properties of sulfonated poly (ether ether ketone) membranes with different degrees of sulfonation for proton exchange membrane fuel cell applications. *Energy*, *125*, 614–628. https://doi.org/10.1016/j.energy.2017.02.143

Parthasarathy, P., & Narayanan, K. S. (2014). Hydrogen production from steam gasification of biomass: Influence of process parameters on hydrogen yield - A review. *Renewable Energy*, *66*, 570–579. https://doi.org/10.1016/j.renene.2013.12.025

Pathway, A. S., The, F. O. R., & Transition, E. E. (2019). *Europe Hydrogen*. https://doi.org/10.2843/249013

Peng, X., & Jin, Q. (2022). Molecular simulation of methane steam reforming reaction for hydrogen production. *International Journal of Hydrogen Energy*, *47*(12), 7569–7585. https://doi.org/10.1016/j.ijhydene.-2021.12.105

Perry, K. A., More, K. L., Payzant, E. A., Meisner, R. A., Sumpter, B. G., & Benicewicz, B. C. (2014). A comparative study of phosphoric acid-doped m-PBI membranes. *Journal of Polymer Science, Part B: Polymer Physics*, *52*(1), 26–35. https://doi.org/10.1002/polb.23403

Phoumin, H., Kimura, F., & Arima, J. (2020). Potential renewable hydrogen from curtailed electricity to decarbonize asean's emissions: Policy implications. *Sustainability (Switzerland)*, *12*(24), 1–15. https://doi.org/10.3390/su122410560

Pinar, F. J., Cañizares, P., Rodrigo, M. A., Ubeda, D., & Lobato, J. (2012). Titanium composite PBI-based membranes for high temperature polymer electrolyte membrane fuel cells. Effect on titanium dioxide amount. *RSC Advances*, *2*(4), 1547–1556. https://doi.org/10.1039/-c1ra01084k

Pingitore, A. T., Molleo, M., Schmidt, T. J., & Benicewicz, B. C. (2019a). Fuel Cells and Hydrogen Production. In *Fuel Cells and Hydrogen Production*. https://doi.org/10.1007/978-1-4939-7789-5

Pingitore, A. T., Molleo, M., Schmidt, T. J., & Benicewicz, B. C. (2019b). Polybenzimidazole Fuel Cell Technology: Theory, Performance, and Applications Andrew. In *Fuel Cells and Hydrogen Production* (pp. 477–514). Springer Nature. https://doi.org/10.1007/978-1-4939-7789-5

Pinsky, R., Sabharwall, P., Hartvigsen, J., & O'Brien, J. (2020). Comparative review of hydrogen production technologies for nuclear hybrid energy systems. *Progress in Nuclear Energy*, *123*(March), 103317. https://doi.org/10.1016/j.pnucene.2020.103317

Qiu, S., Lei, T., Wu, J., & Bi, S. (2021). Energy demand and supply planning of China through 2060. *Energy*, *234*, 121193. https://doi.org/10.1016/j.energy.2021.121193

Quartarone, E., Magistris, A., Mustarelli, P., Grandi, S., Carollo, A., Zukowska, G. Z., Garbarczyk, J. E., Nowinski, J. L., Gerbaldi, C., & Bodoardo, S. (2009). Pyridine-based PBI composite membranes for PEMFCs. *Fuel Cells*, *9*(4), 349–355. https://doi.org/10.1002/fuce.200800149

Quartarone, Eliana, Angioni, S., & Mustarelli, P. (2017). Polymer and Composite Membranes for Proton-Conducting, High-Temperature Fuel Cells: A Critical Review. *Materials*, *10*(687), 1–17. https://doi.org/10.3390/-ma10070687

Qyyum, M. A., Dickson, R., Ali Shah, S. F., Niaz, H., Khan, A., Liu, J. J., & Lee, M. (2021). Availability, versatility, and viability of feedstocks for hydrogen production: Product space perspective. *Renewable and Sustainable Energy Reviews*, *145*(March), 110843. https://doi.org/10.1016/j.rser.-2021.110843

Rahim, A. H. A., Salami, A., Kamarudin, S. K., & Hanapi, S. (2016). *An overview of polymer electrolyte membrane electrolyzer for hydrogen production : Modeling and mass transport*. *309*, 56–65.

Ran, J., Wu, L., He, Y., Yang, Z., Wang, Y., Jiang, C., Ge, L., Bakangura, E., & Xu, T. (2017). Ion exchange membranes: New developments and applications. *Journal of Membrane Science*, *522*, 267–291. https://doi.org/10.1016/j.memsci.2016.09.033

Rashid, M. M., Mesfer, M. K. Al, Naseem, H., & Danish, M. (2015). Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis. *International Journal of Engineering and Advanced Technology*, *3*, 2249–8958.

Razykov, T. M., Ferekides, C. S., Morel, D., Stefanakos, E., Ullal, H. S., & Upadhyaya, H. M. (2011). Solar photovoltaic electricity: Current status and future prospects. *Solar Energy*, *85*(8), 1580–1608. https://doi.org/10.1016/j.solener.2010.12.002

Reichelstein, S., & Yorston, M. (2013). The prospects for cost competitive solar PV power. *Energy Policy*, *55*, 117–127. https://doi.org/10.1016/j.enpol.-2012.11.003

Ren, X., Dong, L., Xu, D., & Hu, B. (2020). Challenges towards hydrogen economy in China. *International Journal of Hydrogen Energy*, *45*(59), 34326–34345. https://doi.org/10.1016/j.ijhydene.2020.01.163

Roeb, M., Monnerie, N., Houaijia, A., Thomey, D., & Sattler, C. (2013). *Solar Thermal Water Splitting*. 63–86.

Romano, S. M. (2015). *Application of Nanofibres in Polymer Composite Membranes for Direct Methanol Fuel Cells*. *July*.

Rosen, M. A., & Koohi-Fayegh, S. (2016). The prospects for hydrogen as an energy carrier: an overview of hydrogen energy and hydrogen energy systems. *Energy, Ecology and Environment*, *1*(1), 10–29. https://doi.org/10.1007/s40974-016-0005-z

Roy, S., & Singha, N. R. (2017). Polymeric nanocomposite membranes for next generation pervaporation process: Strategies, challenges and future prospects. *Membranes*, *7*(3). https://doi.org/10.3390/-membranes7030053

Saba, S. M., Müller, M., Robinius, M., & Stolten, D. (2018). The investment costs of electrolysis – A comparison of cost studies from the past 30 years. *International Journal of Hydrogen Energy*, *43*(3), 1209–1223. https://doi.org/10.1016/j.ijhydene.2017.11.115

Sahin, H., & Esen, H. (2022). The usage of renewable energy sources and its effects on GHG emission intensity of electricity generation in Turkey. *Renewable Energy*, *192*, 859–869. https://doi.org/10.1016/-j.renene.2022.03.141

Salarizadeh, P., Javanbakht, M., Pourmahdian, S., & Beydaghi, H. (2016). Influence of amine-functionalized iron titanate as filler for improving conductivity and electrochemical properties of SPEEK nanocomposite membranes. *Chemical Engineering Journal*, *299*, 320–331. https://doi.org/10.1016/j.cej.2016.04.086

Sana, B., & Jana, T. (2018). Polymer electrolyte membrane from polybenzimidazoles: Influence of tetraamine monomer structure. *Polymer*, *137*, 312–323. https://doi.org/10.1016/j.polymer.2018.01.029

Sana, B., Koyilapu, R., Dineshkumar, S., Muthusamy, A., & Jana, T. (2019). High temperature PEMs developed from the blends of Polybenzimidazole and poly(azomethine-ether). *Journal of Polymer Research*, *26*(2). https://doi.org/10.1007/s10965-019-1716-6

Sanguesa, J. A., Torres-Sanz, V., Garrido, P., Martinez, F. J., & Marquez-Barja, J. M. (2021). A Review on Electric Vehicles: Technologies and Challenges. *Smart Cities*, *4*(1), 372–404. https://doi.org/10.3390/-smartcities4010022

Sannigrahi, A., Ghosh, S., Maity, S., & Jana, T. (2010). Structurally isomeric monomers Directed copolymerization of polybenzimidazoles and their properties. *Polymer*, *51*(25), 5929–5941. https://doi.org/10.1016/-j.polymer.2010.10.013

Sapountzi, F. M., Gracia, J. M., Weststrate, C. J. (Kee. J., Fredriksson, H. O. A., & Niemantsverdriet, J. W. (Hans. (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

Sarabia, L. A., & Ortiz, M. C. (2009). Response Surface Methodology. *Comprehensive Chemometrics*, *1*, 345–390. https://doi.org/10.1016/-B978-044452701-1.00083-1

Sarafrazi, M., Hamadanian, M., & Ghasemi, A. R. (2019). Optimize epoxy matrix with RSM/CCD method and influence of multi-wall carbon nanotube on mechanical properties of epoxy/polyurethane. *Mechanics of Materials*, *138*(August), 103154. https://doi.org/10.1016/j.mechmat.2019.103154

Sarrai, A. E., Hanini, S., Merzouk, N. K., Tassalit, D., Szabó, T., Hernádi, K., & Nagy, L. (2016). Using central composite experimental design to optimize the degradation of Tylosin from aqueous solution by Photo-Fenton reaction. *Materials*, *9*(6). https://doi.org/10.3390/ma9060428

Sathaiyan, N., Nandakumar, V., Sozhan, G., Packiaraj, J. G., Devakumar, E. T., Parvatalu, D., Bhardwaj, A., & Prabhu, B. N. (2015). *Hydrogen generation through cuprous chloride-hydrochloric acid electrolysis*. *4*(1), 15–22. https://doi.org/10.11648/j.ijepe.20150401.13

Sazali, N. (2019). A Short Review on Developing Technologies by Hydrogen. *Journal of Advanced Research in Materials Science*, *59*(1), 14–23.

Sazali, N., Salleh, W. N. W., Jamaludin, A. S., & Razali, M. N. M. (2020). New perspectives on fuel cell technology: A brief review. *Membranes*, *10*(5). https://doi.org/10.3390/membranes10050099

Schatz, R., Kim, S., Khurana, S., Fedkin, M., & Lvov, S. N. (2013). High Efficiency CuCl Electrolyzer for Cu-Cl Thermochemical Cycle. *ECS Transactions*, *50*(49), 153–164. https://doi.org/10.1149/05049.0153ecst

Schatz, R. S. (2013). *Cu-Cl Electrolysis for Cu-Cl Thermochemical Cycle* (Issue December) [The Pennsylvania State University]. https://etda.-libraries.psu.edu/files/final_submissions/8212

Scholar Chemistry and Columbus Chemical Industries, I. (2009). *Material Safety Data Sheet of Copper (II) Chloride Solution, 0.1M*. https://ehslegacy.unr.edu/msdsfiles/23498.pdf

Seetharaman, S., Raghu, S. C., & Mahabadi, K. A. (2016). Enhancement of current density using effective membranes electrode assemblies for water electrolyser system. *Journal of Energy Chemistry*, *25*(1), 77–84. https://doi.org/10.1016/j.jechem.2015.08.010

Selamet, Ö. F., Becerikli, F., Mat, M. D., & Kaplan, Y. (2011). Development and testing of a highly efficient proton exchange membrane (PEM) electrolyzer stack. *International Journal of Hydrogen Energy*, *36*(17), 11480–11487. https://doi.org/10.1016/j.ijhydene.2011.01.129

Seo, K., Seo, J., Nam, K.-H., & Han, H. (2017). Polybenzimidazole/inorganic composite membrane with advanced performance for high temperature polymer electrolyte membrane fuel cells. *Polymer Composites*, *38*(1), 87–95. https://doi.org/10.1002/pc.23563

Shaari, N., & Kamarudin, S. K. (2019). Recent advances in additive-enhanced polymer electrolyte membrane properties in fuel cell applications: An overview. *International Journal of Energy Research*, *43*(7), 2756–2794. https://doi.org/10.1002/er.4348

Shao, Z., Sannigrahi, A., & Jannasch, P. (2013). Poly(tetrafluorostyrenephosphonic acid)-polysulfone block copolymers and membranes. *Journal of Polymer Science, Part A: Polymer Chemistry*, *51*(21), 4657–4666. https://doi.org/10.1002/pola.26887

Shi, D., Guo, Z., Bedford, N., Shi, D., Guo, Z., & Bedford, N. (2015). 10 – Nanoenergy Materials. In *Nanomaterials and Devices* (pp. 255–291). https://doi.org/10.1016/B978-1-4557-7754-9.00010-X

Shin, D. W., Guiver, M. D., & Lee, Y. M. (2017). Hydrocarbon-Based Polymer Electrolyte Membranes: Importance of Morphology on Ion Transport and Membrane Stability. *Chemical Reviews*, *117*(6), 4759–4805. https://doi.org/10.1021/acs.chemrev.6b00586

Shiva Kumar, S., & Himabindu, V. (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

Sigwadi, R., Dhlamini, M. S., Mokrani, T., Ṋemavhola, F., Nonjola, P. F., & Msomi, P. F. (2019). The proton conductivity and mechanical properties of Nafion®/ ZrP nanocomposite membrane. *Heliyon*, *5*(8), e02240. https://doi.org/10.1016/j.heliyon.2019.e02240

Sim, U., Jin, K., Oh, S., Jeong, D., Moon, J., Oh, J., & Nam, K. T. (2015a). Hydrogen Production by Electrolysis and Photoelectrochemical System. In *Handbook of Clean Energy Systems*. https://doi.org/10.1002/-9781118991978.hces223

Sim, U., Jin, K., Oh, S., Jeong, D., Moon, J., Oh, J., & Nam, K. T. (2015b). Hydrogen Production by Electrolysis and Photoelectrochemical System. In *Handbook of Clean Energy Systems*. https://doi.org/10.1002/-9781118991978.hces223

Singh, R., Mishra, P. K., Srivastava, N., Shrivastav, A., & Srivastava, K. R. (2021). Biomethane Production and Advancement. *Bioenergy Research*, 245–260. https://doi.org/10.1002/9781119772125.ch11

Smolinka, T., & Ojong, E. T. (2015). Chapter 8 – Hydrogen Production from Renewable Energies—Electrolyzer Technologies. In *Electrochemical Energy Storage for Renewable Sources and Grid Balancing* (pp. 103–128). https://doi.org/10.1016/B978-0-444-62616-5.00008-5

Soboleva, T., Xie, Z., Shi, Z., Tsang, E., Navessin, T., & Holdcroft, S. (2008). *Investigation of the through-plane impedance technique for evaluation of anisotropy of proton conducting polymer membranes*. *622*, 145–152. https://doi.org/10.1016/j.jelechem.2008.05.017

Soltani, R., Dincer, I., & Rosen, M. A. (2016). Electrochemical analysis of a HCl(aq)/CuCl(aq) electrolyzer: Equilibrium thermodynamics. *International Journal of Hydrogen Energy*, *41*(19), 7835–7847. https://doi.org/10.1016/j.ijhydene.2016.01.026

Soltani, R., Dincer, I., & Rosen, M. A. (2019). Kinetic and electrochemical analyses of a CuCI/HCl electrolyzer. *International Journal of Energy Research*, *December 2018*, er.4703. https://doi.org/10.1002/er.4703

Song, M., Lu, X., Li, Z., Liu, G., Yin, X., & Wang, Y. (2016). Compatible ionic crosslinking composite membranes based on SPEEK and PBI for high temperature proton exchange membranes. *International Journal of Hydrogen Energy*, *41*(28), 12069–12081. https://doi.org/10.1016/-j.ijhydene.2016.05.227

Staiti, P., Minutoli, M., & Hocevar, S. (2000). Membranes based on phosphotungstic acid and polybenzimidazole for fuel cell application. *Journal of Power Sources*, *90*(2), 231–235. https://doi.org/10.1016/-S0378-7753(00)00401-8

Stiegel, G. J., & Ramezan, M. (2006). Hydrogen from coal gasification: An economical pathway to a sustainable energy future. *International Journal of Coal Geology*, *65*(3–4), 173–190. https://doi.org/10.1016/-j.coal.2005.05.002

Stokes, I. (2020). Technology Roadmap. *Training for Project Management*, 241–246. https://doi.org/10.4324/9781315264783-86

Su, H., Bladergroen, B. J., Pasupathi, S., Linkov, V., & Ji, S. (2012). Performance investigation of membrane electrode assemblies for hydrogen production by solid polymer electrolyte water electrolysis. *International Journal of Electrochemical Science*, *7*(5), 4223–4234.

Suhaimi, H. S. M., Leo, C. P., & Ahmad, A. L. (2017). Hydrogen Purification Using Polybenzimidazole Mixed-Matrix Membranes with Stabilized Palladium Nanoparticles. *Chemical Engineering and Technology*, *40*(4), 631–638. https://doi.org/10.1002/ceat.201600457

Suleman, F. (2014). *Comparative Study of Various Hydrogen Production Methods for Vehicles* (Issue December) [University of Ontario Institute of Technology]. http://ubc.summon.serialssolutions.com/-2.0.0/link/0/NwTWneagTriZfUGhLugaKdB0K_RODWYGViMDYM0P2v2L3B6Cd9-BnTBDUGI1hZ7CA-cbYhTK4JrGTYABNukAW2GCtgEQ4-xRHsh0vyMDjgjQZL8T

Sun, P., Li, Z., Wang, S., & Yin, X. (2018). Performance enhancement of polybenzimidazole based high temperature proton exchange membranes with multifunctional crosslinker and highly sulfonated polyaniline. *Journal of Membrane Science*, *549*(October 2017), 660–669. https://doi.org/10.1016/j.memsci.2017.10.053

Sun, X., Simonsen, S. C., Norby, T., & Chatzitakis, A. (2019). Composite Membranes for High Temperature PEM Fuel Cells and Electrolysers: A Critical Review. *Membranes*, *9*(7), 1–46. https://doi.org/10.3390/-membranes9070083

Suryani, Chang, Y.-N., Lai, J.-Y., & Liu, Y.-L. (2012). Polybenzimidazole (PBI)-functionalized silica nanoparticles modified PBI nanocomposite membranes for proton exchange membranes fuel cells. *Journal of Membrane Science*, *403*, 1–7. https://doi.org/10.1016/-j.memsci.2012.01.043

Suryani, & Liu, Y.-L. (2009). Preparation and properties of nanocomposite membranes of polybenzimidazole/sulfonated silica nanoparticles for proton exchange membranes. *Journal of Membrane Science*, *332*(1–2), 121–128. https://doi.org/10.1016/j.memsci.2009.01.045

Tahrim, A. A., & Amin, I. N. H. M. (2019). *Advancement in Phosphoric Acid Doped Polybenzimidazole Membrane for High Temperature PEM Fuel Cells : A Review*. *23*(1), 37–62.

Tan, R. S., Tuan Abdullah, T. A., Abdul Jalil, A., & Md Isa, K. (2020). Optimization of hydrogen production from steam reforming of biomass tar over Ni/dolomite/La2O3 catalysts. *Journal of the Energy Institute*, *93*(3), 1177–1186. https://doi.org/10.1016/j.joei.2019.11.001

The International Renewable Energy Agency (IRENA). (2019). Hydrogen: a Renewable Energy Perspective. In *Irena* (Issue September). https://irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective

Tian, D., Gu, T., Yellamilli, S. N., & Bae, C. (2020). Phosphoric acid-doped ion-pair coordinated PEMs with broad relative humidity tolerance. *Energies*, *13*(8), 1–14. https://doi.org/10.3390/en13081924

Tijani, A. S., & Rahim, A. H. A. (2016). Numerical Modeling the Effect of Operating Variables on Faraday Efficiency in PEM Electrolyzer. *Procedia Technology*, *26*, 419–427. https://doi.org/10.1016/-j.protcy.2016.08.054

Timilsina, G. R., Kurdgelashvili, L., & Narbel, P. A. (2012). Solar energy: Markets, economics and policies. *Renewable and Sustainable Energy Reviews*, *16*(1), 449–465. https://doi.org/10.1016/j.rser.2011.08.009

Toghyani, S., Afshari, E., Baniasadi, E., Atyabi, S. A., & Naterer, G. F. (2018). Thermal and electrochemical performance assessment of a high temperature PEM electrolyzer. *Energy*, *152*, 237–246. https://doi.org/10.1016/j.energy.2018.03.140

Toghyani, Somayeh, Fakhradini, S., Afshari, E., Baniasadi, E., Abdollahzadeh Jamalabadi, M. Y., & Safdari Shadloo, M. (2019). Optimization of operating parameters of a polymer exchange membrane electrolyzer. *International Journal of Hydrogen Energy*, *44*(13), 6403–6414. https://doi.org/10.1016/j.ijhydene.2019.01.186

Tufa, R. A., Rugiero, E., Chanda, D., Hnàt, J., van Baak, W., Veerman, J., Fontananova, E., Di Profio, G., Drioli, E., Bouzek, K., & Curcio, E. (2016). Salinity gradient power-reverse electrodialysis and alkaline polymer electrolyte water electrolysis for hydrogen production. *Journal of Membrane Science*, *514*, 155–164. https://doi.org/10.1016/-j.memsci.2016.04.067

Tung, S. P., & Hwang, B. J. (2005). Synthesis and characterization of hydrated phosphor-silicate glass membrane prepared by an accelerated sol-gel process with water/rapor management. *Journal of Materials Chemistry*, *15*(34), 3532–3538. https://doi.org/10.1039/b505918f

Udagawa, J., Aguiar, P., & Brandon, N. P. (2007). Hydrogen production through steam electrolysis: Model-based steady state performance of a cathode-supported intermediate temperature solid oxide electrolysis cell. *Journal of Power Sources*. https://doi.org/10.1016/j.jpowsour.2006.12.081

Unnikrishnan, L., Mohanty, S., & Nayak, S. K. (2013). Proton exchange membranes from sulfonated poly(ether ether ketone) reinforced with silica nanoparticles. *High Performance Polymers*, *25*(7), 854–867. https://doi.org/10.1177/0954008313487392

Üregen, N., Pehlivanoğlu, K., Özdemir, Y., & Devrim, Y. (2017). Development of polybenzimidazole/graphene oxide composite membranes for high temperature PEM fuel cells. *International Journal of Hydrogen Energy*, *42*(4), 2636–2647. https://doi.org/10.1016/j.ijhydene.2016.07.009

Ursua, A., Gandia, L. M., & Sanchis, P. (2012). Water Electrolysis : Current Status and Future Trends. *Proceedings of the IEEE*, *100*(2), 410–426. https://doi.org/10.1109/JPROC.2011.2156750

Valtcheva, I. (2016). *Polybenzimidazole membranes for organic solvent nanofiltration: formation parameters and applications*. http://hdl.handle.net/10044/1/32357

Vancoillie, J., Demuynck, J., Sileghem, L., Van De Ginste, M., & Verhelst, S. (2012). Comparison of the renewable transportation fuels, hydrogen and methanol formed from hydrogen, with gasoline - Engine efficiency study. *International Journal of Hydrogen Energy*, *37*(12), 9914–9924. https://doi.org/10.1016/j.ijhydene.2012.03.145

Varin, R. A., & Wronski, Z. S. (2013). Progress in Hydrogen Storage in Complex Hydrides. In *Renewable Hydrogen Technologies: Production, Purification, Storage, Applications and Safety*. Elsevier. https://doi.org/10.1016/B978-0-444-56352-1.00013-1

Vilčiauskas, L., Tuckerman, M. E., Bester, G., Paddison, S. J., & Kreuer, K. D. (2012). The mechanism of proton conduction in phosphoric acid. *Nature Chemistry*, *4*(6), 461–466. https://doi.org/10.1038/nchem.1329

Villagra, A., & Millet, P. (2019). An analysis of PEM water electrolysis cells operating at elevated current densities. *International Journal of Hydrogen Energy*, *44*(20), 9708–9717. https://doi.org/10.1016/j.ijhydene.2018.11.179

Vincent, I., & Bessarabov, D. (2017). *Low cost hydrogen production by anion exchange membrane electrolysis : A review*. *May*.

Volkov, V. V, Federation, R., & Deville, S. (2016). Encyclopedia of Membranes. In *Encyclopedia of Membranes*. Springer. https://doi.org/10.1007/978-3-662-44324-8

Wan Mohd Noral Azman, W. N. E., Jaafar, J., Salleh, W. N. W., Ismail, A. F., Othman, M. H. D., Rahman, M. A., & Rasdi, F. R. M. (2020). Highly selective SPEEK/ENR blended polymer electrolyte membranes for direct methanol fuel cell. *Materials Today Energy*, *17*, 100427. https://doi.org/10.1016/j.mtener.2020.100427

Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011). A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research. *Applied Energy*, *88*(4), 981–1007. https://doi.org/10.1016/j.apenergy.2010.09.030

Wang, Z., Roberts, R. R., Naterer, G. F., & Gabriel, K. S. (2012). Comparison of thermochemical, electrolytic, photoelectrolytic and photochemical solar-to-hydrogen production technologies. *International Journal of Hydrogen Energy*, *37*(21), 16287–16301. https://doi.org/10.1016/-j.ijhydene.2012.03.057

Wang, Zhaolin, & Naterer, G. F. (2014). Integrated fossil fuel and solar thermal systems for hydrogen production and CO2 mitigation. *International Journal of Hydrogen Energy*, *39*(26), 14227–14233. https://doi.org/10.1016/j.ijhydene.2014.01.095

Woo, J.-Y., Lee, K.-M., Jee, B.-C., Ryu, C.-H., Yoon, C.-H., Chung, J.-H., Kim, Y.-R., Moon, S.-B., & Kang, A.-S. (2010). Electrocatalytic characteristics of Pt–Ru–Co and Pt–Ru–Ni based on covalently cross-linked sulfonated poly(ether ether ketone)/heteropolyacids composite membranes for water electrolysis. *Journal of Industrial and Engineering Chemistry*, *16*(5), 688–697. https://doi.org/10.1016/j.jiec.2010.07.017

Wu, X., He, G., Li, X., Nie, F., Yan, X., Yu, L., & Benziger, J. (2014). *Improving proton conductivity of sulfonated poly (ether ether ketone) proton exchange membranes at low humidity by semi- interpenetrating polymer networks preparation*. *246*, 482–490. https://doi.org/10.1016/-j.jpowsour.2013.07.108

Xiang, C., Papadantonakis, K. M., & Lewis, N. S. (2016). Principles and implementations of electrolysis systems for water splitting. *Materials Horizons*, *3*(3), 169–173. https://doi.org/10.1039/c6mh00016a

Xiao, L., Zhang, H., Scanlon, E., Ramanathan, L. S., Choe, E.-W., Rogers, D., Apple, T., & Benicewicz, B. C. (2005). High-Temperature Polybenzimidazole Fuel Cell Membranes via a Sol - Gel Process. *Chem. Mater.*, *17*(21), 5328–5333. https://doi.org/10.1021/cm050831+

Yadav, D., & Banerjee, R. (2020a). Net energy and carbon footprint analysis of solar hydrogen production from the high-temperature electrolysis process. *Applied Energy*, *262*(January), 114503. https://doi.org/10.1016/j.apenergy.2020.114503

Yadav, D., & Banerjee, R. (2020b). Net energy and carbon footprint analysis of solar hydrogen production from the high-temperature electrolysis process. *Applied Energy*, *262*(December 2019), 114503. https://doi.org/10.1016/j.apenergy.2020.114503

Yang, C., Srinivasan, S., Bocarsly, A. B., Tulyani, S., & Benziger, J. B. (2004). A comparison of physical properties and fuel cell performance of Nafion and zirconium phosphate/Nafion composite membranes. *Journal of Membrane Science*, *237*(1–2), 145–161. https://doi.org/10.1016/-j.memsci.2004.03.009

Ying, Y. P., Kamarudin, S. K., & Masdar, M. S. (2018). Silica-related membranes in fuel cell applications: An overview. *International Journal of Hydrogen Energy*, 1–17. https://doi.org/10.1016/J.IJHYDENE.2018.06.171

Yodwong, B., Guilbert, D., Phattanasak, M., Kaewmanee, W., Hinaje, M., & Vitale, G. (2020a). AC-DC converters for electrolyzer applications: State of the art and future challenges. *Electronics (Switzerland)*, *9*(6), 1–30. https://doi.org/10.3390/electronics9060912

Yodwong, B., Guilbert, D., Phattanasak, M., Kaewmanee, W., Hinaje, M., & Vitale, G. (2020b). Faraday's efficiency modeling of a proton exchange membrane electrolyzer based on experimental data. *Energies*, *13*(18), 1–14. https://doi.org/10.3390/en13184792

Yu, Y. L., Li, Y. N., Zhang, Y., Sun, R. N., Tu, J. S., & Shen, Y. (2018). Optimization and characterization of deoxypodophyllotoxin loaded mPEG-PDLLA micelles by central composite design with response surface methodology. *Chinese Journal of Natural Medicines*, *16*(6), 471–480. https://doi.org/10.1016/S1875-5364(18)30081-5

Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, *146*(May), 111180. https://doi.org/10.1016/j.rser.2021.111180

Yue, Z., Cai, Y. Ben, & Xu, S. (2016). Phosphoric acid-doped organic-inorganic cross-linked sulfonated poly(imide-benzimidazole) for high temperature proton exchange membrane fuel cells. *International Journal of Hydrogen Energy*, *41*(24). https://doi.org/10.1016/j.ijhydene.2015.10.057

Yuzer, B., Selcuk, H., Chehade, G., Demir, M. E., & Dincer, I. (2019). Evaluation of hydrogen production via electrolysis with ion exchange membranes. *Energy*, 116420. https://doi.org/10.1016/j.energy.2019.116420

Zamfirescu, C., Dincer, I., & Naterer, G. F. (2019). Kinetic and hydrodynamic analyses of chemically reacting gas-particle flow in cupric chloride hydrolysis for the Cu-Cl cycle. *International Journal of Hydrogen Energy*, *4*(44), 26783–26793. https://doi.org/10.1016/j.ijhydene.2019.08.142

Zeng, K., & Zhang, D. (2010). Recent progress in alkaline water electrolysis for hydrogen production and applications. *Progress in Energy and Combustion Science*, *36*(3), 307–326. https://doi.org/10.1016/-j.pecs.2009.11.002

Zhai, Y., Zhang, H., Xing, D., & Shao, Z. G. (2007). The stability of Pt/C catalyst in H3PO4/PBI PEMFC during high temperature life test. *Journal of Power Sources*, *164*(1), 126–133. https://doi.org/10.1016/-j.jpowsour.2006.09.069

Zhang, Bei, Cao, Y., Jiang, S., Li, Z., He, G., & Wu, H. (2016). Enhanced proton conductivity of Na fi on nanohybrid membrane incorporated with phosphonic acid functionalized graphene oxide at elevated temperature and low humidity. *Journal of Membrane Science*, *518*, 243–253. https://doi.org/10.1016/j.memsci.2016.07.032

Zhang, Bing, Zhang, S.-X., Yao, R., Wu, Y.-H., & Qiu, J.-S. (2021). Progress and prospects of hydrogen production: Opportunities and challenges. *Journal of Electronic Science and Technology*, *September 2020*, 100080. https://doi.org/10.1016/j.jnlest.2021.100080

Zhang, J., Tang, Y., Song, C., & Zhang, J. (2007). Polybenzimidazole-membrane-based PEM fuel cell in the temperature range of 120-200 °C. *Journal of Power Sources*, *172*(1), 163–171. https://doi.org/10.1016/-j.jpowsour.2007.07.047

Zhang, Q., Liu, H., Li, X., Xu, R., Zhong, J., Chen, R., & Gu, X. (2016). Synthesis and characterization of polybenzimidazole/α-zirconium phosphate composites as proton exchange membrane. *Polymer Engineering and Science*, *56*(6), 622–628. https://doi.org/10.1002/pen.24287

Zhang, X., Chan, S. H., Ho, H. K., Tan, S.-C., Li, M., Li, G., Li, J., & Feng, Z. (2015). Towards a smart energy network: The roles of fuel/electrolysis cells and technological perspectives. *International Journal of Hydrogen Energy*, *40*(21), 6866–6919. https://doi.org/10.1016/-j.ijhydene.2015.03.133

Zhou, Z., Zholobko, O., Wu, X.-F., Aulich, T., Thakare, J., & Hurley, J. (2021). Polybenzimidazole-Based Polymer Electrolyte Membranes for High-Temperature Fuel Cells: Current Status and Prospects. *Energies*, *14*(1), 135. https://doi.org/10.3390/en14010135

Zuo, Z., Fu, Y., & Manthiram, A. (2012). Novel blend membranes based on acid-base interactions for fuel cells. *Polymers*, *4*(4), 1627–1644. https://doi.org/10.3390/polym4041627

Züttel, A., Remhof, A., Borgschulte, A., & Friedrichs, O. (2010). Hydrogen: The future energy carrier. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *368*(1923), 3329–3342. https://doi.org/10.1098/rsta.2010.0113