DEVELOPMENT OF A SOLAR PV INTEGRATED WATER ELECTROLYZER SYSTEM FOR SOLID MUNICIPAL WASTE INCINERATOR

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INSTITUTE FOR ADVANCED STUDIES
UNIVERSITI MALAYA
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DEVELOPMENT OF A SOLAR PV INTEGRATED WATER ELECTROLYZER SYSTEM FOR SOLID MUNICIPAL WASTE INCINERATOR

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ABSTRACT

The drive towards sustainable future warrants deep decarburization of all the energy and non-energy sectors. In this regards, an attempt has been made to decarbonize municipal solid waste (MSW) management sector using green hydrogen. A systematic study has been conducted to investigate the feasibility of hydrogen as a primary combustion fuel for thermal treatment of MSW i.e., incineration. Various strategies i.e., (1) coupling of solar photovoltaics (PV) with battery and electrolyzer and (2) direct coupling of electrolyzer with PV have been tried and investigated to provide hydrogen to the incinerator. Furthermore, active on-demand electrical sparking mechanism (auto-ignition) and use of secondary electrolyzer with optimum battery storage approaches have also been identified and investigated. Moreover, comparative techno-economics of strategies have also been assessed.

A high reduction in weight percent of MSW i.e., 86-94%, and loss on ignition (1.74%-6.41%) have been observed for MSW containing 60-80% moisture content with the use of hydrogen as primary fuel. This is due to high flame temperature, uniform heat distribution and less radiation losses which is a characteristic property of hydrogen flame. In terms of energy consumption, PV + Battery system consumed 42.42% and 15.07% less energy compared to auto-ignition and PV + Secondary-Electrolyzer system. Moreover, in terms of energy required to remove moisture, PV + Battery system used 80% less energy, while auto-ignition and PV + Secondary-Electrolyzer showed 70.5% and 77.5% less energy respectively. However, the initial capital cost of PV + battery system has been calculated to be 15.4% and 11.8% more compared to auto-ignition and PV + Secondary-Electrolyzer system respectively. Further, in terms of cost benefit for longer run, PV +

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Battery system has been calculated to be 73.3% and 23.3% more expensive than auto-ignition and PV + Secondary electrolyzer method respectively assuming 30year of life span.

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ABSTRAK

Pengurusan sisa pepejal perbandaran (municipal solid waste, MSW) semakin mencabar dari hari ke hari disebabkan oleh peningkatannya yang pesat. MSW bukan sahaja berbahaya, malah kaedah rawatannya juga menjadi masalah kepada alam sekitar. Antara cara-cara pengurusan MSW yang digunakan, teknik insinerasi adalah teknik yang paling matang dan digunakan secara meluas untuk merawat bahan buangan. Tetapi, insinerasi biasanya memerlukan bahan api fosil yang menjurus kepada pelepasan gas rumah hijau (GHG). Kebelakangan ini, hydrogen telah muncul sebagai bahan api alternatif untuk aplikasi pembakaran. Penghasilan hidrogen daripada sumber boleh diperbaharui seperti solar, angin dan lain-lain bukan sahaja menjadikannya bahan api boleh diperbaharui tetapi juga boleh menjadi satu langkah ke arah persekitaran hijau dan mampan. Dalam projek ini, penggunaan hidrogen “on deamand” yang dihasilkan melalui elektroliser air alkaline untuk pembakarakn sisa pepejal perbandaran telah diterokai. Satu kajian sistematik telah dibentangkan untuk menyiasat kebolehlaksanaan hidrogen sebagai bahan api pembakaran utama untuk pembakaran sisa pepejal perbandaran (MSW). Selepas itu, insinerator jenis aci menegak telah direka bentuk dengan keupayaan untuk beroperasi dengan hidrogen yang dihasilkan oleh elektrolisis. Dengan membekalkan gas campuran hidrogen dan oksigen (dalam nisbah stoikiometri) melalui system penunu khas yang direka, suhu pembakaran maksima setinggi 850oC telah direkodkan dalam insinerator. Pengurangan yang tinggi dalam peratus berat iaitu, 86-94%, dan kehilangan pada penyalaan (1.74%-6.41%) telah diperhatikan. Tambahan pula, elektroliser ini telah disepadukan dengan panel solar photovoltaic (PV) untuk menjadikannya sistem yang berdiri sendiri dan mampan sendiri. Teknik kawalan telah dibangunkan untuk mendapatkan arus maksima daripad PV untuk menjalankan elektroliser. Tiga pendekatan berbeza untuk menyuapkan hidrogen kepada incinerator telah diterokai, iaitu (i) PV+Bat (mod Hibrid); (ii) penyalaan automatik (Gandingan langsung) dan (iii) PV+Sec-ELE

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(Gandingan langsung) dikaji berdasarkan aspek teknikal dan ekonominya. Dihasilkan bahawa PV+Bat menggunakan 42.42% dan 15.07% kurang tenaga daripada kaedah pencucuhan automatik dan PV+sec-ELE tetapi kos masing-masing 15.4% dan 11.8% lebih tinggi dari segi pelaburan modal. Begitu juga, kaedah PV+Bat ialah 80% digunakan kurang tenaga bersamaan dengan keperluan untuk kandungan lembapan sisa manakala pencucuhan automatik dan PV+sec-ELE masing-masing menunjukkan 70.5% dan 77.5% kurang tenaga. Selanjutnya pendekatan ini menunjukkan perbezaan yang besar dari segi manfaat kos untuk jangka masa yang lebih lama. PV+Bat diramalkan 73.3% dan 23.3% lebih mahal daripada kaedah pencucuhan automatik dan PV+sec-ELE masing-masing selepas 30 tahun jangka hayat. Kajian ini bukan sahaja menentukan sistem berasaskan hidrogen sebagai sistem hijau dan bersih tetapi juga menjanjikan kemampanannya.

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LIST OF ABBREVIATIONS

PV	Photovoltaic
ELE	Electrolyzer
GHG	Greenhouse Gases
MSW	Municipal Solid Waste
LOI	Loss on Ignition
HHO	Oxyhydrogen
KOH	Potassium hydroxide
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
DC	Direct Current
RE	Renewable Energy
LPM	Liter per minute
FLIR	Forward Looking InfraRed
SOEC	Solid Oxide Electrolyzer Cell
PEM	Proton Exchange Membrane Electrolyzer

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CHAPTER 1: INTRODUCTION

1.1 Background

The industrialized modernization and energy hungry civilization pose a major threat to global ecosystem. The high dependence on fossil fuels without mitigation plans for associated greenhouse gas (GHG) emissions put the humanity on the edge of climatic disaster (Welsby, Price, Pye, & Ekins, 2021). Fossil fuels are considered to be the biggest contributor of GHG emission among all the emission activities shown in table 1.1 (Olivier & Peters, 2020) with 36.7 billion tons in 2019 and increasing (Ritchie & Roser, 2020). This increase in emission is also responsible for global increase in temperature to 0.95°C more than average (Olivier & Peters, 2020), which is why, the year 2019 was recorded to be the second warmest year in 140 years. Recently, various policy statements and roadmaps from both the developed and developing countries have been put forward, emphasizing more on alternative, clean, green and sustainable energy sources to fight against the ever increasing associated climatic risks and strategies to reduce their GHG emissions (Althor, Watson, & Fuller, 2016). Daily thermal applications like steamers, combustions engines, boilers, thermal incinerator etc. are needed to be replaced from use of fossil fuel (Butt, Ahmad, Che, & Rahim, 2021).

Table 1.1 Sources of CO_2 emissions in 2019

Sources	**Share (%)**
Electricity and heat generation	35.8
Manufacturing industries	16.7
Road transport	15.9
Buildings (houses, offices, etc.)	8.7
Other national fuel combustion	7.9
International transport (by air & water)	3.6
fossil-fuel combustion ➢ Coal = 43.8% ➢ Oil = 34.6% ➢ Natural Gas = 21.6	88.6

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Various renewable energy sources such as solar, wind, tidal, biomass etc are available, however, solar energy is by far the most abundant and easily available source of clean and sustainable energy on the earth. According to a report, the solar energy supplied to the earth is approximately 9600 times more than the global daily total energy consumption in 2017 which was around 17.91TW (Thakur, Ghosh, Devi, Kim, & Kumar, 2020),. In recent years, solar energy has emerged as one of the fastest growing source of green energy, however, efficient harness of energy from sunlight, storage and its utilization is still a challenge to meet real-world energy demand. Various storage options, i.e., battery, pumped hydro, compressed air, hydrogen etc are available with their associated advantages and limitation. Recently, hydrogen has become one of the most appreciated option for solar energy storage and utilization due to its high energy density/mass property of 120-142 MJ/kg while having zero CO_2 emission (Thakur et al., 2020). Till now maximum theoretical efficiency of 'Solar to Hydrogen' (STH) in a lab scale experiment was reported to be 29.7% (Q. Chen, Fan, Fu, Li, & Zou, 2018). For large scale system, hydrogen production from solar has been considered an efficient way with an overall energy and exergy efficiencies of 16.95% and 17.45% respectively (Ishaq & Dincer, 2021). In a recent study (Idriss, 2020), it was estimated that cost of hydrogen production from solar can be between \$1.5 - \$2/kg of hydrogen (price of electricity was kept @ \$0.02/kWh).

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1.2 Hydrogen as a 'green fuel'

The practicality of hydrogen as energy carrier has now been widely admitted through the scientific and policy maker's circles due to its clean combustion, ease in transportation, distribution and utilization (Tolod, Hernández, & Russo, 2017). Furthermore, hydrogen has been considered one of the most suitable energy carrier for deep decarburization of hard-to-abate energy sectors. (Liao, Huang, & Wu, 2012).

Hydrogen can be produced through various methods i.e.,, namely steam reformation, gasification and electrolysis (Nikolaidis & Poullikkas, 2017). Hydrogen produced from fossil fuel via gasification or steam reformation has been considered “grey hydrogen” due to the inherent associated carbon emissions (Diab, Fulcheri, Hessel, Rohani, & Frenklach, 2022). With the increasing awareness on sustainability, the industry is actively exploring the production of “green hydrogen”, i.e. hydrogen that can be produced without using fossil fuels. Electrolysis technology is the most mature technology to produce green hydrogen. It is being used commercially in many small and large scale applications.

Various studies suggested the possibility of blending hydrogen with other fuels as an efficient and cost effective way to reduce the carbon footprint and improve the thermal efficiency of combustion-related applications (Krishna, 2018; Ozcanli, Akar, Calik, & Serin, 2017; Park et al., 2011; D. Sharma, Pathak, & Chhikara, 2015; Thangaraj & Govindan, 2018; Uludamar et al., 2017). Combustion engines in particular show promising results towards increased efficiency of brake power and brake thermal efficiency by 5% and 7%, respectively, while reducing HC, NOx and smoke by 88, 94 and 18% respectively. Hydrogen gas can be used as a fuel to power catalytic boilers, gas powered heat pumps and direct flame combustion boilers that are more-or-less the same as natural gas boilers. A large variety of district heating techniques can be repurposed to employ hydrogen in a cost effective way. The use of hydrogen gas is not limited to combustion engines and industrial applications, but is also applicable for house heating purposes. It is a beneficial substitute during thermal coating processes. It can be an alternative of plasma gas or can be mixed as an additive gas during thermal spray processes for depositing metallic or nonmetallic materials in a molten or semi-molten condition (Klein, 2008).

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In this study, an attempt has been made to use hydrogen as primary combustion fuel for MSW incineration. Various strategies have been identified, investigated and compared for cost effective and efficient production and utilization of green hydrogen to decarbonize MSW management sector.

1.2.1 Issues related to waste management

MSW management has always been a challenge for the community impacting environmental sustainability. Around 2.01 billion tons of waste has been generated annually and is expected to increase to 3.4 billion tons by 2050 (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018). The anticipated reasons include an increase in population and prosperity. East Asia and the Pacific region contribute to 23% followed by Europe and the South Asian region (20% and 17% respectively). Approximately 50% of the waste collected is not properly managed. Instead, it is openly burned or dumped in landfills which contributes to more than 3% of GHG emissions (Gautam & Agrawal, 2021). Only methane (produced by the decomposition of MSW in the open air) accounts for 1-2% of GHG emissions.

There are various waste management techniques such as thermal, biological conversion, or landfill which not only address municipal waste problems but can also be a potential source for energy generation (Bajić, Dodić, Vučurović, Dodić, & Grahovac, 2015). These technologies depend upon the composition and characteristics of the waste that is available. However, the focus of the current research is towards thermal treatment, the advantages and disadvantages of thermal waste management strategies i.e. incineration, gasification, and pyrolysis have been presented in table 1.2 and compared with landfill practice (Liu, Xing, & Liu, 2017).

Among all the commercially available thermal processes, incineration is the most widely used thermal conversion technique for processing MSW (Shi, Mahinpey, Aqsha,

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& Silbermann, 2016) due to its ease in operation, lower cost, and ability to process a wide variety of feed. In 2021, the global market size of incinerators has reached 14.35 billion USD and is expected to surpass 18.87 billion USD by 2027 (*Incinerator Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2022-2027*, 2021).

Landfilling is not always a viable solution for waste. As in UAE landfilling is not an option due to hydrological reasons. In a recent study, the potential of waste incineration and power production has been studied (Paleologos, Caratelli, & El Amrousi, 2016) Similarly in Hyderabad, one of the cities of Pakistan, there is a maximum potential available in biochemical and thermo-chemical methods for power generation (Korai, Mahar, & Uqaili, 2016). Moreover, incineration generates less GHG emissions compared to landfills. Incineration of the waste in the UK has a lesser impact on the environment than landfill and could easily meet up to 2.3% of the UK's total electricity demand which eventually saves almost 2 to 2.6 million tons of GHG emission (Jeswani & Azapagic, 2016). Different European countries such as Sweden, Denmark, Finland, and Estonia are global leaders and incinerating at least 50% of MSW which in turn reduce their landfill to 10%. Landfilling results in 34.8% in reduction of waste with a rate of 87.8% stabilization while emitting a significant amount of emissions (116.7 to 192.2 Kg-CO2Eq/t). Incineration is advantageous compared to landfills in terms of volume reduction of waste (up to 90%) with controlled emission (124.3 Kg-CO2Eq/t). It is also advantageous for recovering 1163.1 MJ/t of electricity at the same time (Liu et al., 2017). In western part of Europe, 35% to 80% of the waste produced has been incinerated yearly. Similarly, USA convert 40% of MSW to electrical energy by incineration method (Reddy, 2011).

Waste to energy has become a vibrant industry of approximately worth USD 37.6 million in 2020 which is expected to raise about USD 44 million by 2024 (Makarichi,

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Jutidamrongphan, & Techato, 2018). By 2015, 1179 incinerators were built globally with a capacity of 700000 MT/d out of which 80 WtE incinerators plants working in the USA alone that were generating 2769 MWh electricity for the grid by processing 96000 tons of MSW per day (Makarichi et al., 2018). Till now China has the largest capacity of incineration MSW with more than 240000 MT/d. Alone in China, WtE incineration plants have grown rapidly from 3.70 to 133.08 million metric tons of designed capacity between 2003 and 2018, respectively. This has increased the percentage for incineration in China that was 14.66% in 2010 to 44.67% in 2018. A typical WtE plant in China with a capacity of 1000 t/d and a life expectancy of 25 years, expects relevant margins and stable profit with a payback period of 11.3 years (X.-g. Zhao, Jiang, Li, & Wang, 2016). In 2012, a projection was made by the world bank that WtE will have the potential to provide 11 Exajoules of energy globally by 2050 (Makarichi et al., 2018). Despite WtE available potential and different incentives, still, 75% of the global MSW is landfilled. Different European countries like Sweden, Denmark, Finland, and Estonia are global leaders in this industry by incinerating at least 50% of municipal solid waste which result reduce their landfill to 10%.

In principle, an incinerator is a furnace that takes MSW as feed and uses fuel to burn it. Oxygen in the form of air has been provided through blowers to achieve near-complete and clean burning. Various design modifications and fuel types have been tried to improve the efficiency of the incineration process. There are different types of the incinerators that are being tested based on their working design. In a recent study, a rocket-engine-based incinerator has been designed by adopting design concepts of swirl flow and nozzle shape applied to a furnace of power plants and a rocket combustor (Son, Kim, & Sohn, 2014). From the study, it was found that the shape and location of flame can affect the temperature of the incinerator by the flow rate of fuel, deflection and incline angles of nozzles, and dimensional size of the chamber. The other two most commonly

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used technologies are (i) grated fire incinerator (GFI) and (ii) Fluidized bed incinerator (FBI). In both technologies, coal is normally used as an auxiliary fuel for the low heating value of waste. On the other hands, GFI works at higher net power generation from the combustion of MSW itself (D. Chen & Christensen, 2010). However, both technologies are still a major source of GHG emissions due to the use of coal as fuel.

The requirement of fossil-based fuels for incineration has been the biggest challenge for a sustainable future. According to a study, the global average MSW generation was approximately 2017 MT/year in 2016 which is predicted to rise to 2586 MT/year in 2025 and subsequently 3399 MT/year by 2050 (K. D. Sharma & Jain, 2020). Considering these statistics, it can be calculated that approximately 129.30MJ energy will be required to incinerate waste by 2025 (*THE INCINERATOR GUIDEBOOK*, 2010; Komitov, Rasheva, & Binev, 2019). To address this issue, the electrification of thermal processes (i.e., incineration) has been conceptualized and emerging technologies such as plasma, microwave, and resistance heating have been widely investigated with promising results.

Plasma technology is one of the leading example to effectively electrify the MSW management sector. It is more environment friendly and clean technology (Inaba & Iwao, 2000). However, the current capital and operational cost of plasm incineration is prohibitively high, (Ducharme, 2010) accounting to more than USD 65 – 200 million with 500 tons MSW/day capacity (Munir, Mardon, Al-Zuhair, Shawabkeh, & Saqib, 2019) and only a plasma source assembly alone can cost more than $50000 (Wilson, Williams, Liss, & Wilson, 2013). Plasma is a thermal method, normally used for the safe disposal of health care waste. In this process, an extremely high temperature of approximately 5000 – 14000 °C has been created using various gases (N2, Ar, H2) (Munir et al., 2019). There are two plasma waste incineration plants named Plasco in Canada and Euro-Plasma in the USA and their operational cost is close to 149 USD/ton of waste

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treatment(Ramos & Rouboa, 2018). Expensive high power DC supply required to power up plasma source makes it more costly in terms of maintenance (Change, 2014). Microwave technology is another emerging technology to treat MSW in an environment friendly way. However, this technology suffers from up-scaling. Although the capital cost is comparable with an effective and efficient incineration technology, it cannot work at a large scale (Pellerin, 1994). Also, microwave technology it is not suitable for all types of wastes because the dielectric properties of the waste streams are not same. (Appleton, Colder, Kingman, Lowndes, & Read, 2005). Normally microwave technology is used for vitrified bottom ash of incinerated waste, requiring approximately 3300kJ/kg of energy (Flesoura, Dilissen, Dimitrakis, Vleugels, & Pontikes, 2021). The advantages and disadvantages of thermal waste management strategies i.e. incineration, gasification and pyrolysis have been presented in table 1.2 and compared with landfill practice (Liu et al., 2017).

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Table 1.2 Summary of different waste management technologies (Beyene, Werkneh, & Ambaye, 2018; El Haggar, 2010; Ghasemi & Yusuff, 2016; A. Kumar & S. R. Samadder, 2017; Nema & Ganeshprasad, 2002)

Waste Management Technologies	*Incineration*	*Pyrolysis*	*Landfilling*	*Microwave*	*Plasma*
Advantages	• Use for variety of wastes • No pre-treatment required • Significant reduction in weight & volume • Easy energy recovery	• Clean Technology • Effectively decompose waste • Much energy efficient	• Easy to handle • Most Cheap process	• Easy to use • Can reduce waste up to significant volume (80%) • Environmental friendly • Minimum emissions	• Consume less space • Suitable for almost all types of waste • Negligible toxic residue • Environmental friendly • Reduce volume up to 99% • Easy for energy recovery

Disadvantages	• Emission of pollutants • Can be a source of dioxin emission • Heavy metals is residue	• Special Environment required in absence of oxygen • Pre-treatment of waste required • Expensive than other combustion technique	• Cause surrounded soil, water and environment polluted • Required access to sanitary landfill • Require large amount of land.	• High capital cost • Pre-treatment of waste required • Not suitable for all type of waste • Not commercially viable for large scale	• Very High capital and operating cost • Not commercially viable for large scale • Required technical assistance for operation

1.2.2 Potential of hydrogen for MSW management

Recently, hydrogen has attracted huge attention as an alternative fuel in many combustion applications due to its clean-burning, ease in utilization, and transportation (Ahmad, Ali, & Abd Rahim, 2021; Butt, Saeed, et al., 2021). It is considered to be environment friendly and believe to be zero-emission future green fuel as it contains only water vapor as by product (Butt, Ahmad, Che, & Rahim, 2021; Cellek & Pınarbaşı, 2018). The need of hour is to find a solution for MSW thermal treatment for sustainable deep decarburization of society. Use of hydrogen as fuel for incineration produced by electrolysis of water can be a potentially alternative and clean fuel (Butt, Ahmad, Che, & Rahim, 2021). Eventually this technology can a way forward to reduce air pollution and action toward the UN Sustainable Development Goals 12 and 13. This study can help in achieving these UNSDGs by investing in low-carbon development for disposal of waste and pollutants which results in controlling greenhouse gas emission.

In this study, hydrogen has been employed as a green alternative to thermal MSW management. A systematic study has been conducted by providing a pre-mix mixture of hydrogen and oxygen in stoichiometric ratio to the combustion chamber as the primary

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fuel to incinerate MSW. Moreover, an attempt has been made to measure the amount of hydrogen required for simulated waste with high moisture content and random MSW from various restaurants.

A DC-DC convertor has been designed to directly couple the electrolyzer with solar PV to produce hydrogen gas. Finally, different strategies have been investigated to cater the intermittency problem faced by on-demand hydrogen based incinerator system. Different technical and economic aspects were studied based on experimental facts. The objective of the study was to develop system as stand-alone and scalable green hydrogen based waste incinerator.

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1.3 Problem Statement

Growth in urbanization and technologies tends to increase in the generation of the waste. Different techniques like landfill, incineration, biological conversion are being used from decades to treat this waste. Incineration technology for MSW is advantageous due technological maturity, ease in operation and low cost. However, the fuel assisted thermal treatment of MSW is not sustainable. Moreover, the electrification of MSW management sector is prohibitively costly. Also complete recycling of all waste generated is not possible. Herein, in an attempt to integrate the MSW management sector with renewable energy in an efficient and cost effective way, on-demand green hydrogen as combustion fuel for incineration has been proposed. This approach will help deep decarburization of this hard-to-abate sector and could be a possible alternative for other combustion applications of industries.

1.4 Objectives of the research

The following objectives have been set in the present research work for developing an incinerator for municipal solid waste management

- To develop a standalone solar PV integrated water electrolysis system for feeding hydrogen as a fuel to incinerator
- To evaluate performance of hydrogen based waste incineration
- To develop strategies for coupling of PV based electrolyzer with incinerator to realize the behavior of incineration
- To analyze techno-economical study for strategies used in coupling ELE-PV with incinerator

1.5 Scope of the research

This study is based on two parts, (i) coupling of electrolyzer with solar PV without any other source to attain its standalone ability and (ii) to use hydrogen as auxiliary fuel for incinerator to incinerate municipal solid waste. Electrolyzer has been coupled with solar PV with a DC-DC convertor to control the production of hydrogen depending upon the solar PV. Furthermore, different strategies have been studied for cost effective and efficient waste incineration.

1.6 Significance of the study

The integration of MSW management sector with clean energy sources and development of cost effective modular incineration systems has the potential to reduce the GHG emissions and minimize the MSW transportation issues. The proposed approach would play a significant role towards the sustainable and clean environment. Followings are some of the significant features of the proposed technology:

- It is a standalone and scale able system which can be easily employed to remote areas.
- It can handle waste of more than 60-70% moisture.
- Eliminate the need of fossil fuel as auxiliary fuel (oil/diesel previously used)

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- Incineration system can be easily powered from any intermittent source or connected directly to the grid

1.7 Organization of the thesis

This thesis comprises of five chapters with the content as follows: (i) Chapter 1 includes the background of the research, aim of research, objectives and the significance of the study. (ii) Chapter 2 presents an in depth literature review on the topic of research. It briefly describes the issues related to the fuel and its effect on environment due to GHG emission. Also a detailed overview has been presented on the challenges related to waste management technique and their effect on environment. An attempt has been made to discuss how hydrogen maybe considered as an alternative green fuel and its potential towards different thermal applications. (iii) Chapter 3 explains the methodology used for this research work. Details have been provided for fabrication of incinerator and data logging setup. Also direct and battery assisted PV coupling as well as auto-ignition and secondary electrolyzer approach have been detailed. All characterization techniques involved in this study are briefly explained which include operational parameters (voltage, current, temperature) of electrolyzer, incineration efficiency i.e., weight reduction and loss on ignition for waste. (iv) Chapter 4 is dedicated to theoretical as well as experimental investigation. This chapter presents experimental results for fabrication of burners used for incinerator. Operational results of DC-DC convertor made-up for PV electrolyzer coupling. Also performance parameters of incinerator have been discussed here. Furthermore, a comparative techno-economic analysis has been presented. (v) Chapter 5 presents conclusions, recommendations and recent trends in the field of hydrogen.

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CHAPTER 2: LITERATURE REVIEW

This chapter describes hydrogen as green alternative fuel for different combustion and thermal applications. Also different technologies for production of hydrogen are been discussed. A study on literature is done related to the challenges for municipal solid waste management and different technologies that are used to treat them. Further in this chapter, it was discussed about the potential use of hydrogen as a fuel for incineration technology.

2.1 Issues related to usage of fossil fuel

The excessive dependency on fossil fuels result in an alarming increase in pollution levels, which stimulates research community to search for new sustainable and environment friendly fuels. Current perspective of the use of green technology shows a footstep towards reducing global warming and dependency on fossil fuels. Over the years, various approaches have been put forwarded to reduce fossil fuels consumption from various sectors of society. For example, introduction of electric vehicles in transportation sector, efficient utilization of building energy, replacement of various gas/wood fired household appliances with electrical appliances etc. which leads to reduction in harmful exhaust emissions from combustion of conventional hydrocarbon fuel (Dincer & Acar, 2017). According to a report of Nathanial Gronewold, a total carbon emission is approximately 43.1 billion tons out of which 36.8 billion metric tons is only due to industrial activities and burning of fossil fuels. It is now an hour of need to find new and renewable alternatives that replaces the fossil fuel burning.

2.2 Use of different green fuels

Today, green fuels for combustion engines are point of focus of researchers due to current global warming and air pollution. Different researchers investigated in blending

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of alcohols including ethanol and methanol with diesel and other fossil fuels to form biofuels (N. Yilmaz, Donaldson, & Johns, 2005; N. Yilmaz & Sanchez, 2012; N. Yilmaz & Vigil, 2014; N. Yilmaz, Vigil, Benalil, Davis, & Calva, 2014). This attempt of blending was a successful in reducing emission of NOx and SOx during combustion of fuel (N. Yilmaz, Vigil, Donaldson, & Darabseh, 2014). One of the most common green fuel is known as biodiesel. It is produced by using oil extracted from fruits seeds or plants. This is oil is different in combustion properties and much thicker than conventional diesel. So transesterification of triacylglycerol or esterification of free fatty acid is done to reduce the viscosity of vegetable oil (Soccol, Brar, Faulds, & Ramos, 2016). This crude oil is than passes through distillation for final product. A complete process of producing biodiesel from vegetable oil is shown in figure 2.1.

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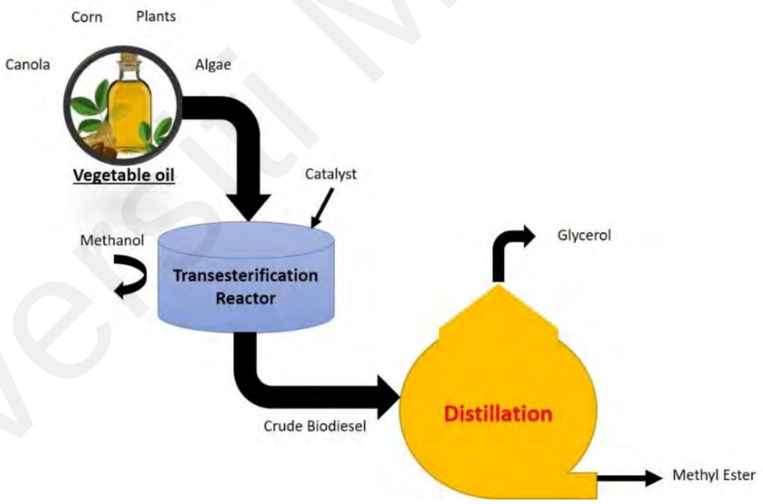

Figure 2.1 Schematic diagram for production of biodiesel from vegetable oil

Cellulosic ethanol is known as second generation of bio fuel compose of ethanol and other oxygenated compounds. It is formed from cellulose of fruits or vegetables instead of seeds. This method comprises of four major steps which includes i) biomass pretreatment; ii) enzymatic hydrolysis; iii) monosaccharide; iv) ethanol distillation. There are different processes as shown in figure 2.2 to produce cellulosic ethanol.

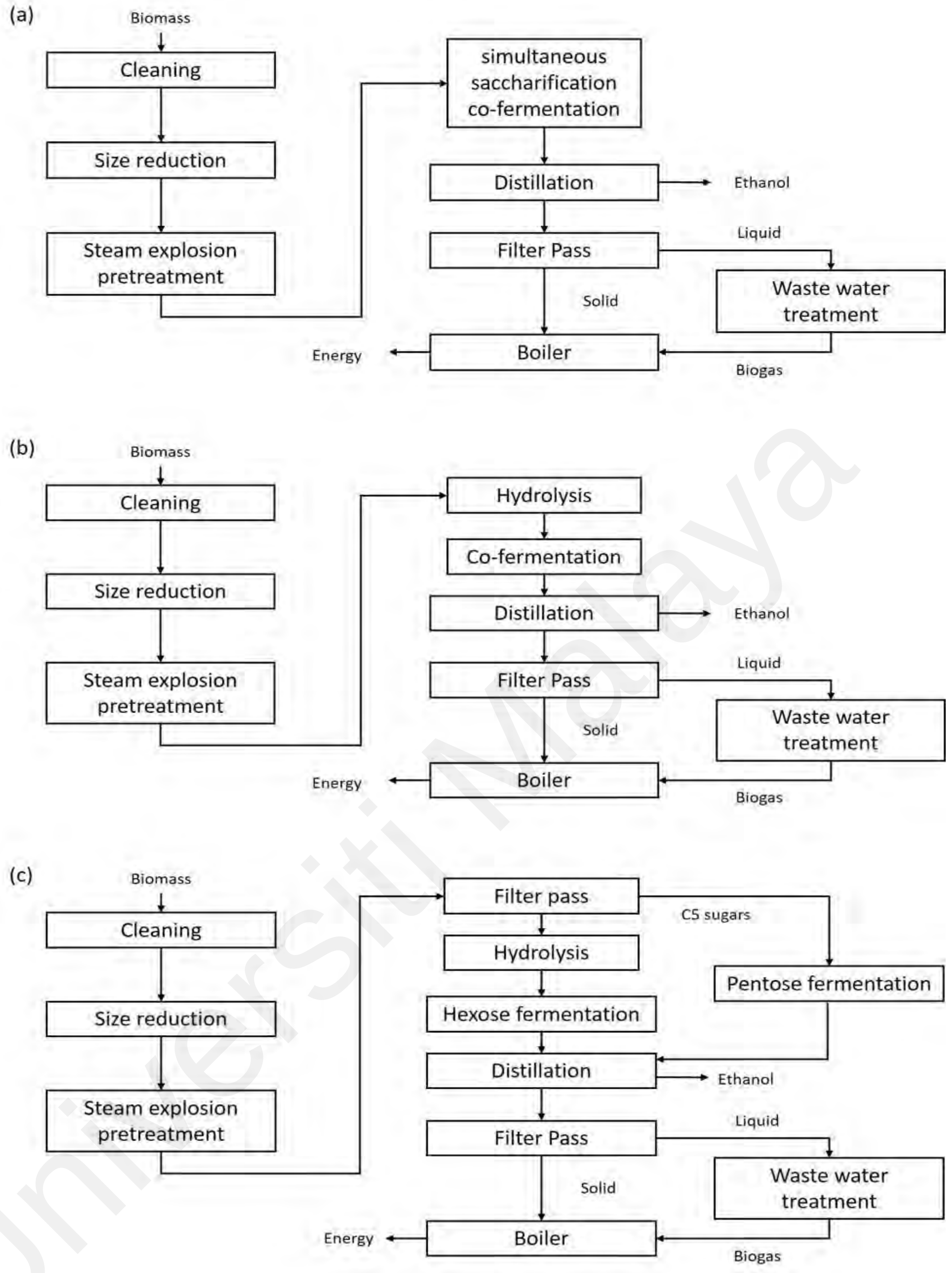

Figure 2.2 Flow diagram of producing cellulosic ethanol a) simultaneous scarification and co-fermentation b) separated hydrolysis and co-fermentation c) separated hydrolysis and fermentation

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2.3 Hydrogen as an emerging fuel

Environmental aspects, global climatic change and depletion of fossil fuel lead towards hydrogen as an alternative fuel technology. Depletion of fossil fuels is not only the issue but one of the major issues is atmospheric damage due to their combustion. Result of burning fossil fuel such as crude oil, coal or natural gas has become a concern for the environmentalist. Research is being focused on the new green and renewable sources as an alternative. It is hour of need for mitigation of harmful environmental effect and reducing GHG emission by substituting carbon based energy sources with carbon free resources. Recently, hydrogen has attracted the attention of researcher to be used as an alternative fuel in many applications. It has showed a promising approach for de-carbonization in energy intensive utilizing sectors such as industry and transport (Ausfelder & Bazzanella, 2016). It is considered to be a renewable synthetic fuel. Hydrogen is considered to be the most popular green fuel with a promising future. Hence, hydrogen fuel can be most effective replacement of carbon-based fuels to prevent hazardous emissions of pollutants like carbon dioxide, carbon mono oxide, sulphur oxide and organic acids (Sandalcı & Karagöz, 2014). Due to low emission of pollutants especially carbon contents, hydrogen may be consider as a promising alternative fuel burners (Ilbas, Yılmaz, Veziroglu, & Kaplan, 2005). Hydrogen itself has a greater combustion efficiency and calorific value compared to currently available fossil fuels (Sudarmanta, Darsopuspito, & Sungkono, 2016). Other parameters of hydrogen includes high specific heat (Higher heating value as 142.18MJ/kg and 120.21MJ/kg as lower heating value), high flammability limit (4% to 75% volume in air), low ignition energy (0.02mJ), auto ignition temperature (585°C), quenching distance and heat of combustion (Pakale, Pawar, Patil, & Patel, 2015; A. C. Yilmaz, Uludamar, & Aydin, 2010). Hydrogen as fuel is an attraction for researchers as a green step. This is due to non-pollutant and sustainable properties of hydrogen. Hydrogen can be term as ‘grey’, ‘blue’ or ‘green’ hydrogen depending upon ways of their production. Production of hydrogen by splitting of water through an electro-chemical process is consider as ‘green’ hydrogen. This method can be step towards green and environmental friendly if the electricity is sourced

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renewably, such as hydro, wind or solar. In 2017 only 4% of total hydrogen production is produce by this method which is predicted to be 22% by 2050 through rapid advancement in technology (Cornell, 2017).

Transportation industry in one of the biggest consumer of fossil fuel. According to IEA, alone USA's 26% of total energy consumption in 2020 was for transportation (EIA, 2021). For more than decades, studies are being done to replace fuels with hydrogen in transportation sector. Pure hydrogen was being used in spark ignition engine for higher efficiency and higher power output (Naber & Siebers, 1998). Hydrogen is being used and studied in different manners in combustion engines as fuel. Usage of hydrogen in a combustion engine is through air enriched hydrogen injected directly into the intake system of CI engine (Ravi, Rao, Ramaswamy, & Jagadeesan, 1992). A non-storage scheme in four stroke 4-cylinder and two stroke 1-cylinder was studied in order to avoid extra fuel tanks and without any structural changes (Aydin & Kenanoğlu, 2018). Also hydrogen from dry cell HHO reactor was studied as a fuel additive with different stoichiometric and volumetric flow rates in a diesel and bio-diesel (Arat, Baltacioglu, Özcanli, & Aydin, 2016; Aydin & Kenanoğlu, 2018). In another study compressed natural gas (CNG) was hydrogenated with different amounts of HHO-CNG fuel without any structural changing of combustion engine. CI engine under test resulted in improvement of its power, torque and Brake specific fuel consumption (BSFC) with 4.7%, 6.75% and 17.2% respectively (Arat et al., 2016). Still challenge of using pure hydrogen for spark ignition engine is knocking, pre-ignition and NOx emission (Lee, Kim, Lee, & Caton, 2001).

Many high-grade heat industrial processes can be benefited from hydrogen. This include power catalytic boilers, gas powered heat pumps and direct flame combustion boilers. District heating, water desalination, thermal coatings, cutting and welding

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applications are the prominent industrial application for hydrogen usage (Butt, Ahmad, Che, & Rahim, 2021). Steam generation for thermal application can also be aided by hydrogen fuel (DeWitt, 2014). Now-a-days waste management incinerator are showed potential of using hydrogen for incineration purposes (Butt, Ahmad, Che, & Abd Rahim, 2021). Combustion of hydrogen-rich coal gas gives a uniform temperature distribution inside the combustor and produce almost zero emission in result (Karyeyen & Ilbas, 2020). Storage of energy is always an issue to focus for researchers. Efforts are made to store excess electricity in the form of hydrogen by transporting hydrogen in gas pipelines to increase production volume. Renewable hydrogen can be promising way to reduce major greenhouse gases (GHG) while displacing these natural gas pipelines. But due to the different characteristics of hydrogen and natural gas in terms of flame speed, stability limits and adiabatic flame temperature, pure hydrogen or highly enriched natural gas with hydrogen can affect the combustion performance. But in a study it was determine that cooktop burner didn't significantly affect up to the 15% by volume of hydrogen blending with natural gas (Y. Zhao, McDonell, & Samuelsen, 2019). This showed feasibility of using hydrogen on exciting system and appliance without any modification. Energy exporter countries can be advantageous from this method. Already Netherlands is likely to develop a carbon-free hydrogen economy by investing EUR17.5–25 billion by 2025 (van Wijk, 2017). Hydrogen has also attracted to be an alternative for lithium ion batteries to power Unmanned Aerial Vehicles (UAVs). It can provide more range to UAV given its magnitude increase in mass and volume specific energy over Li-ion batteries (Depcik et al., 2020). Further, more proton exchange membrane fuel cell PEMFC has a lower power density than combustion engines which helps in making a small design and can provide power directly to UAV without a complex design (Depcik et al., 2020).

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2.3.1 Potential use of hydrogen as fuel

Depletion of fossil fuels is one of the major concern of energy. Burning emissions of fossil fuel such as crude oil, coal or natural gas has become issue for the environmentalist. Research is being focused on the new green and renewable sources as an alternative. Recently, hydrogen has attracted the attention of researcher to be used as an alternative fuel in many applications. It is considered to be a renewable synthetic fuel. hydrogen is a potential option for renewable energy and quite clean in regard to carbon dioxide and carbon monoxide emission. It is considered to be environmental friendly and believe to be zero emission future green fuel as it contains only water vapor as combustion emission upon burning with oxygen unlike fossil fuels (Cellek & Pınarbaşı, 2018). Another factor which dominates hydrogen upon other fuels is its calorific value. This is the value of heat produced on burning of fuel. Calorific value of fuels helps to decide fuel to be used. Normally, fuel with high calorific value is considered to be good. In recent decades, a lot of research is being focused on its potential and usage of hydrogen gas for industrial as well as domestic applications (shown in figure 2.3). These applications include soldering, welding, jewelry working, industrial boilers, furnaces, heating, waste incinerators, automobile industry etc. In a study, different sources of energy were analyzed and an economical comparison was deduced and summarized in table 2.1 along their calorific values (Komitov et al., 2019). The following section has been dedicated to discuss demonstrated applications of hydrogen has primary/secondary fuel with advantages and limitations.

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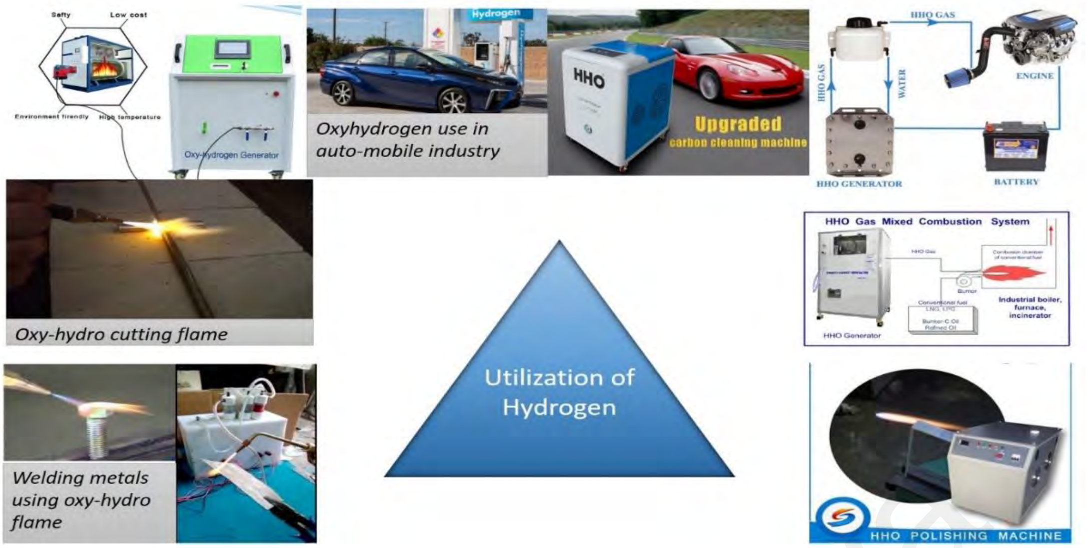

Figure 2.3 Potential use of hydrogen in different industrial and domestic applications (Butt, Ahmad, Che, & Rahim, 2021)

Table 2.1 Calorific value of different types of fuel (Komitov et al., 2019; Soares, 2011)

No.	Energy sources	Calorific Value	Price of energy source
1	Hydrogen gas	6.26 Wh/l	0.11 €/kWh
2	Electricity	1.00 kWh	0.11 €/kWh
3	Wood pellets	5.28 kWh/kg	0.26 €/kg
4	Agro pellets	3.33 kWh/kg	0.13 €/kg
5	Natural gas- CNG	9.89 kWh/m3	0.44 €/m3
6	LPG	13.9 kWh/kg	1.12 €/kg
7	Gas oil	11.63 kWh/l	1.09 €/l

2.3.2 Combustion Engines

Due to the scarcity of fossil fuel and its stringent emission norms, there is an hour of need to find alternatives for automotive industry to shift its research in developing engines that can use alternative fuel with high fuel efficiency and low emissions (Verhelst & Wallner, 2009). Hydrogen gas is also economical with respect to “price of energy” of other fossil fuel but it is an expensive investment as required more capital cost than other energy sources. From the study it was seen that there is a huge potential of use of

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oxyhydrogen gas as an alternative fuel is available in the transport sector. It can easily reduce 30% to 40% of carbon emission that is about 20% of the total carbon emission. As industrial sector is responsible of more than 70% of total greenhouse gas emission, so use of the oxyhydrogen gas in different industrial application provides a green opportunity to decrease emission of this major GHG contributor. Potential of hydrogen is not only limited towards vehicles but also for locomotives. Different models were establishing to incorporate hydrogen as an alternate to power locomotives. On maturing hydrogen as fuel, it can provide limitless green fuel for the need of mankind.

Now-a-days oxyhydrogen is considering as a promising alternative for fossil fuel for combustion engines. The potential of on-demand oxyhydrogen generation has been explored recently with high optimism and enthusiasm due to its better and clean combustion properties compared to conventional fuels. In a recent study, addition of oxyhydrogen gas was tested and it was seen there was increase in brake power ranging and brake thermal efficiency from 2% to 5.7% and 10.26% to 34.9% respectively. Also a significant decrease of 20% to 30% in fuel consumption was also observed while a decrease of 18% and 14% in CO and HC emissions respectively (Arjun et al., 2019). In another study (Nabil & Dawood, 2019) fuel consumption was controlled while increasing the millage of car. This was done by mixing of oxyhydrogen gas with gasoline for its combustion engine as shown in figure 2.4.

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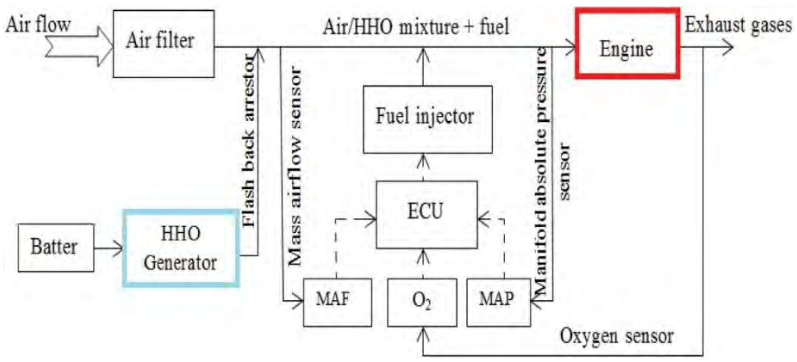

Figure 2.4 Schematic drawing of modern gasoline engine with oxyhydrogen generator(Nabil & Dawood, 2019)

Chiriac et al. (Chiriac, Apostolescu, & Dica, 2006) passed oxyhydrogen gas through a mixing chamber by controlling temperature and pressure. It helps increasing brake thermal efficiency up to 3% while dropping hydrocarbon, carbon monoxide and carbon dioxide to 67%, 54% and 18% respectively. Yilmaz et al. (A. C. Yilmaz et al., 2010) supplied oxyhydrogen gas to intake manifold after water separator which not only increase engine torque by 19% and decrease fuel consumption by 14% but also reduce CO and HC by 13.5% and 5% respectively. Musmar and Al-Rousan (Sa'ed & Al-Rousan, 2011) observed improvements in thermal efficiency by introducing oxyhydrogen gas mixed with gasoline along with air in the intake manifold of a gasoline spark ignition engine as shown in figure 2.5.

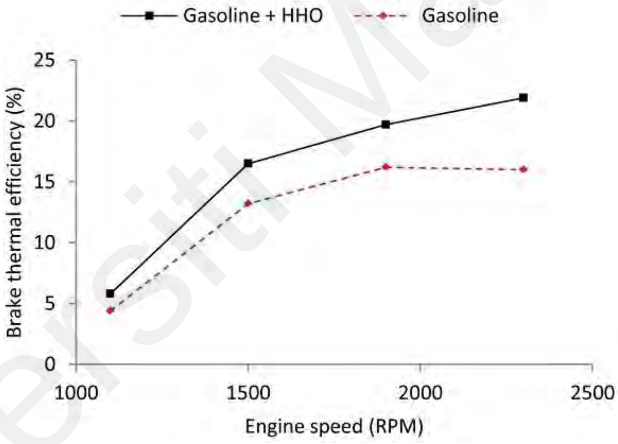

Figure 2.5 Effect of oxyhydrogen mixed with gasoline on brake thermal efficiency (Sa'ed & Al-Rousan, 2011)

Leelakrishnan et al.(Leelakrishnan, Lokesh, & Suriyan, 2013) inducted oxyhydrogen gas along with air-fuel mixture after carburetor with gasoline. This increase efficiency of brake power and brake thermal by 5% and 7% respectively while reducing HC, NOx and smoke by 88%, 94% and 18% respectively. El-Kassaby used oxyhydrogen gas in IC engines based on gasoline by passing through a separation tank with two flashback arrestors as safety and then introduced into intake manifold. Thermal efficiency was

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checked at various speed which results in 10% increase in thermal efficiency while decreasing CO, HC and NOx by 18%, 14% and 15% respectively. Use of oxyhydrogen gas was not confined to gasoline engine but was also studied for diesel based engine. Milind et al. (Sawant, 2011) used oxyhydrogen gas into IC engine after air filter which passed through bubbler. This blending increase the brake thermal efficiency and volumetric efficiency by 10%. In another study (EL-Kassaby, Eldrainy, Khidr, & Khidr, 2016) oxyhydrogen gas was mixed with bio diesel. It was preheated and then introduced inti intake manifold which increase in brake power, torque and thermal efficiency while decreasing hydrocarbon, carbon monoxide, carbon dioxide and nitrogen oxide emission.

An investigation was done by blending of oxyhydrogen gas with compressed natural gas (CNG) and diesel. Arat (Arat et al., 2016) introduce oxyhydrogen gas through bubbler into mixing chamber after filtrate at rate of 5.14 L/min as shown in figure 2.6. Two modes were studied in this research: mode A as oxyhydrogen + diesel and mode B 25% oxyhydrogen + 75 % CNG + diesel. It has been observed that brake torque, brake power and thermal efficiency was improved by 2.7 %, 3.18% and 3.4% in mode A, while for mode B this increment was 4.75%, 6.85% and 6.28% respectively. Carbon dioxide was decrease by 9% and 9.65% for mode A and B respectively while NOx reduces to 11.76% and 28.4%. Carbon monoxide reduced to 15% for mode A, however increased for mode B by 16%. Similar mixing of oxyhydrogen was done by Masjuki (Masjuki et al., 2016) with diesel and 20% palm biodiesel blend on test bed as shown in figure 2.7. oxyhydrogen gas was introduced at flow rate of 4 x 10-6m3/s with air. This increased 2% average in brake power while drop in injected fuel consumption by 5%. This method decreases CO and HC by 20% and 10% respectively however when oxyhydrogen was introduced with biodiesel blend, it increased NO by 25%.

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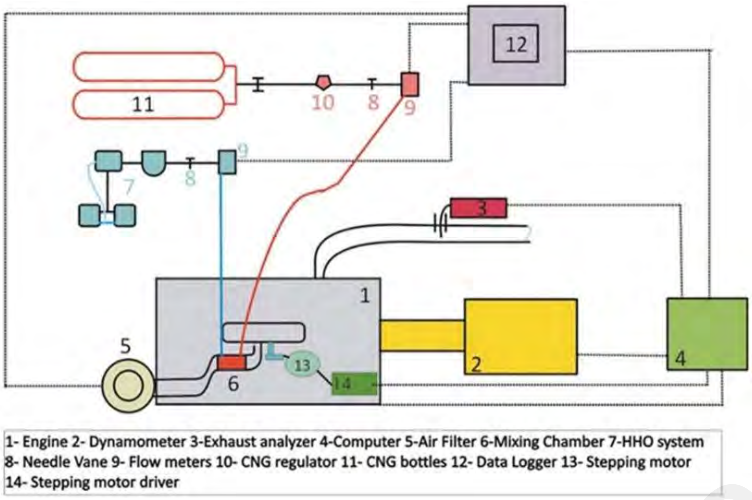

Figure 2.6 Experimental setup for mixing oxyhydrogen + CNG + diesel in IC engine (Arat et al., 2016)

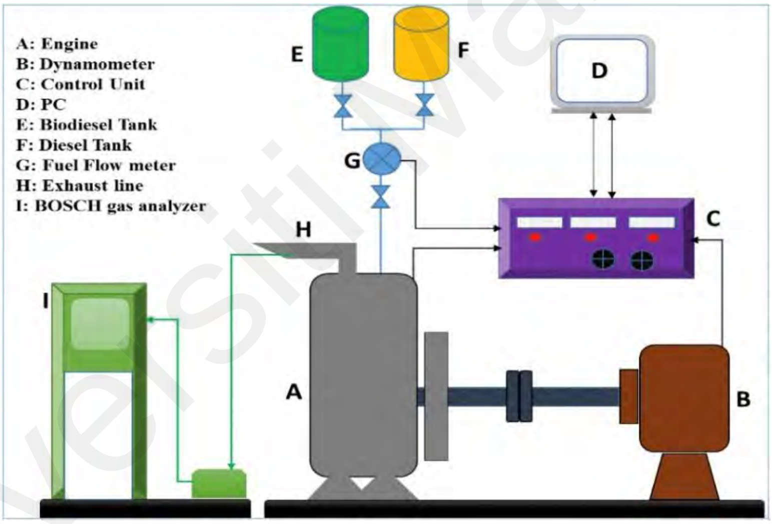

Figure 2.7 Test bed for testing oxyhydrogen gas with biodiesel blend in IC engine (Masjuki et al., 2016)

A comparative study between pure hydrogen and oxyhydrogen enriched biodiesel fuel for diesel engine was done by Mustafa (Baltacioglu, Arat, Özcanli, & Aydin, 2016). It was concluded from study that engine performance values were increased when oxyhydrogen was used as compared to pure hydrogen at standard diesel fuel operating conditions. It was also observed that pure hydrogen produces low exhaust gas emissions than oxyhydrogen. A comparison is shown in the table 2.2.

Table 2.2 Comparison of experimental results oxyhydrogen + B10 versus H2 + B10(Baltacioglu et al., 2016)

Output		**Preference (Oxyhydrogen + B10/H2 + B10)**	**Effect (%)**
Emissions	CO (ppm)	H2 + B10	5.80 less
	CO2 (%)	H2 + B10	8.72 less
	NOX (ppm)	H2 + B10	9.70 less
Performance	Brake Power (kW)	Oxyhydrogen + B10	4.33 more
	Brake Torque (Nm)	Oxyhydrogen + B10	2.15 more
	BSFC (g/kWh)	Oxyhydrogen + B10	7.60 less

Oxyhydrogen is not only used as a fuel for combustion engine but can also be used for removal of carbon deposits from combustion engine (Turgeon & Van Tiggelen, 2016). oxyhydrogen generated hydrogenates solid carbon deposits into liquid and gaseous hydrocarbons in the exhaust of combustion engine. Discharge of the hydrogen to the exhaust system also reacts with NOx in the exhaust gas to reduce the NOx. The oxyhydrogen may be discharged to a plurality of locations to clean solid carbon and reduce NOx emissions from a diesel engine (Rodrigues, Brunelli, & Oliveira, 2018). A summary of different fuel blending with oxyhydrogen gas in IC engines has been summarized in table 2.3.

Table 2.3 Detailed summery of OXYHYDROGEN utilization in IC engines

Sr. No	Fuel blend technique	Remarks	Reference
1.	low sulphur diesel (D100) 20% and 40% sunflower biodiesel – low sulphur diesel fuel blend (SB20 and SB40, respectively) 20% and 40% canola biodiesel – low sulphur diesel fuel blend (CaB20 and CaB40, respectively)	All biodiesel blends helped in improvement of vibration up to 5.98% except CaB20	(Uludamar et al., 2017)

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	20% and 40% corn biodiesel – low sulphur diesel fuel blend (CoB20 and CoB40, respectively)		
2.	Diesel fuel is replaced with biodiesel and blended with oxyhydrogen	Reduces the maximum brake torque by 2.6–2.7% CO concentrations fall to 50% HC concentrations fall to 40% Smoke levels fall to 85% Increases CO2 concentrations by up to 6% NOx concentrations by up to 10% in exhaust gas.	(Rimkus, Matijošius, Bogdevičius, Bereczky, & Török, 2018)
3.	Diesel engine fueled with blending of oxyhydrogen in 20% volumetric ratio of Castor oil methyl ester (CME)	Average improvement of 4.3% CO emission reductions 21% NOx emissions were increased	(Ozcanli et al., 2017)
4.	Oxyhydrogen gas is added into the intake air of the industrial diesel engine and tested on 0%, 50% and 100% loading at an engine speed of 700 to 900 rpm	Fuel consumption was decreased Smoke emissions were decreased CO emissions were decreased NOx emission level was remained same	(Park et al., 2011)
5.	Oxyhydrogen addition at a rate of 18 L/h into gasoline fueled engine	Thermal efficiency increased by 10% Fuel consumption decreased by 34%	(EL-Kassaby et al., 2016)

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		CO emission reduction by 18% HC reduction by 14% NOx emission reduction by 15%	
6.	Biodiesel fuel (KOME obtained from transesterification of karanja oil) blended with oxyhydrogen	Brake specific fuel consumption decreased by 2.41% and 17.53% at no load and full load respectively Brake thermal efficiency increased by 2.61% and 21.76% at no load and full load respectively	(Thangaraj & Govindan, 2018)
	Bio-diesohol (biodiesel + Ethanol) EN590 and EN14214 blended with oxyhydrogen at a rate of 1L/m for a single cylinder diesel engine	Fuel brake power increased by 11.33% Exhaust emissions were reduced by 8 – 12% NOx emission was increased	(Baltacioglu, Kenanoglu, & Aydın, 2019)
7.	Oxyhydrogen gas was added to the air which is being drawn into the spark ignition engine (4-stroke single cylinder).	Mileage was improved from 7.69% to 11.42% at speed of 2000 to 6000rpm of engine	(Krishna, 2018)
8.	Oxyhydrogen gas added with petrol in combustion engine with two different concentrations of electrolyte. 6 g/L of KOH 4 g/L of NaOH	6 g/L of KOH gave better performance Thermal efficiency increased by 10% Fuel consumption decrease by 34% NOx, CO and HC emission decreased by 15%, 18% and 14% respectively	(EL-Kassaby et al., 2016)

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9.	Hydroxyl gas addition in four stroke multi-cylinder SI engine	Brake power increased by 11.5% Fuel consumption decreased by 6.35% Thermal efficiency increased by 10.26% NOx emission decreased Temperature of exhaust gas decreased by 4%	(D. Sharma et al., 2015)
10.	Brown gas was introduced into petrol engine	With increase in air to fuel ratio combustion duration increased while a delay occurs in ignition Exhaust HC and CO2 concentration increase at high engine load	(Bhardwaj, Verma, & Sharma, 2014)
11.	Oxyhydrogen gas was mixed with a fresh air before entering the carburetor of Honda G 200 engine	NO & NOx reduced by 50% CO emission decreased by 20% Fuel consumption decreased by 20% to 30%	(Musmar & Al-Rousan, 2011)
12.	Oxyhydrogen gas was introduced in a four stroke single cylinder S.I engine without any modifications and storage tanks	HC emission reduced by 6.7% 16.3% of average gain in Specific fuel consumption	(Putha & Babu, 2015)
13.	Oxyhydrogen was blended with oxyhydrogen in a gasoline engine	Power output of engine increases around 5.7% Thermal efficiency increased by 5%	(Tiwari, Yadav, Singh, & Patel)
14.	Oxyhydrogen was blended with natural gas by ratio of 0%, 5%, 10%, 15% and 20%	CO and HC emission decreased with	(Sandhu, 2013)

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		increasing percentage of oxyhydrogen NOx emission increased with increase percentage of hydrogen component	
15.	Oxyhydrogen gas was blended in both petrol and diesel engine by using of different electrolytes (KOH, NaOH , NaCl) for electrolysis	Engine power increased by 27% as compared to pure gasoline 19.1% in engine torque was gained for compression ignition engine	(A. C. Yilmaz, 2010)
16.	Oxyhydrogen gas was introduced into the inlet air of a direct injection diesel engine.	Specific fuel consumption was decreased (about 20%) at low loads but remain constant for higher loads	(Rashad, 2014)
17.	Oxyhydrogen and Compressed Natural Gas (CNG)was blended and introduced into engine without making any modification	Fuel consumption decreased by 2.7% Brake torque was improved by 4.75%	(Arat et al., 2016)
18.	Two water alkaline electrolyzers (WAEs) with an efficiency of 50% and 60% were connected with IC engine in a combined parallel-series arrangement by mean of a control unit. Engine parameters were investigated at nominal speed of 1000 to 2000 rpm.	Gasoline consumption was reduced about 0.41 mLmin-1 to 0.79 mLmin-1 as speed was increased from 1000 to 2000 rpm CO2 emission was reduced about 2.17%	(Horcasitas-Verdiguel, Sandoval-Pineda, Grunstein-Ramírez, Terán-Balaguer, & Gonz lez-Huerta, 2016)

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a. Control of oxyhydrogen production for Combustion engines

Engine control unit (ECU) is brain of engine which control fuel flow and efficiency of high performance vehicles. For converting engine from standard fuel to oxyhydrogen gas required to consider additional factors such as oxyhydrogen burn rates, flow, temperature, and production rates. When vehicle engine is running on hybrid fuel (i-e fossil fuel and oxyhydrogen) it must able to compensate and revert back to fossil fuel operating status. If it fails to do so it can cause mechanical damage to engine. To overcome this problem, dual ECU system was introduced that allow vehicle engine to work continuously under all types of conditions while using hybrid fuel (Bailey & Bethurem, 2010). It was able to revert back automatically to fossil fuel parameters that ECU was mapping in the account when oxyhydrogen system may have failed to deliver the required volume of oxyhydrogen gas to the vehicle engine.

Generally, 12 Volt or 24-volt DC source has been used for electrolyzer. Current fed to the electrolyzer is controlled to regulate the production of the oxyhydrogen gas. In a recent study, a novel constant current power system for oxyhydrogen cell operation was develop to reduce the fuel consumption in combustion engines (K. P. Kumar, Arora, & Mahesh, 2016). System was able to monitor the current requirement and regulate with help of pulse width modulation by using metal-oxide semiconductor field effect transistors (MOSFETs). These MOSFETs were driven by mean of an embedded system. In another study, solar powered oxyhydrogen system has been designed and demonstrated with the intention to illustrate potential oxyhydrogen generation using renewable energy (W.-C. Lin, 2007). A Solar-powered oxyhydrogen generating system is shown in figure 2.8. A similar system was proposed by Jamoshid et al. (Jamoshid, Hashim, Ali, & Saudin, 2013) to reduce the consumption of vehicle's fuel. A 50W PV panel was suggested to energize the electrolyzer that can assist a 1000cc car engine. It has been claimed that 11.34% to 14.6% of fuel consumption can be reduced by using this system. In another study, a comparative study has been conducted between model predictive controller (MPC) and proportional integral derivative (PID) to control on-demand production of oxyhydrogen by using alkaline electrolyzer. A mathematical model was formed (shown in below equation 2.1) to obtain linearity of the electrolyzer for the control of system

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(Cervantes-Bobadilla, Escobar-Jiménez, Gómez-Aguilar, García-Morales, & Olivares-Peregrino, 2018).

$$H\ (z) = \frac{0.01822z^{-1} + 0.01587^{-2}}{1-1.627z^{-1} + 0.6604z^{-2}} \tag{2.1}$$

A complete control mechanism is shown in figure 2.9. It was concluded from the study that MPC controller perform slightly better than the PID controller, as it had a shorter set-up time, lower error rates, and lower sensitivity to measurement noise (Cervantes-Bobadilla et al., 2018).

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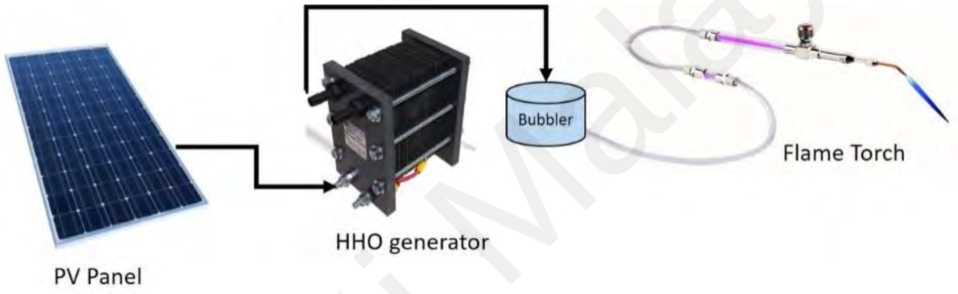

Figure 2.8 Solar-powered oxyhydrogen generating system

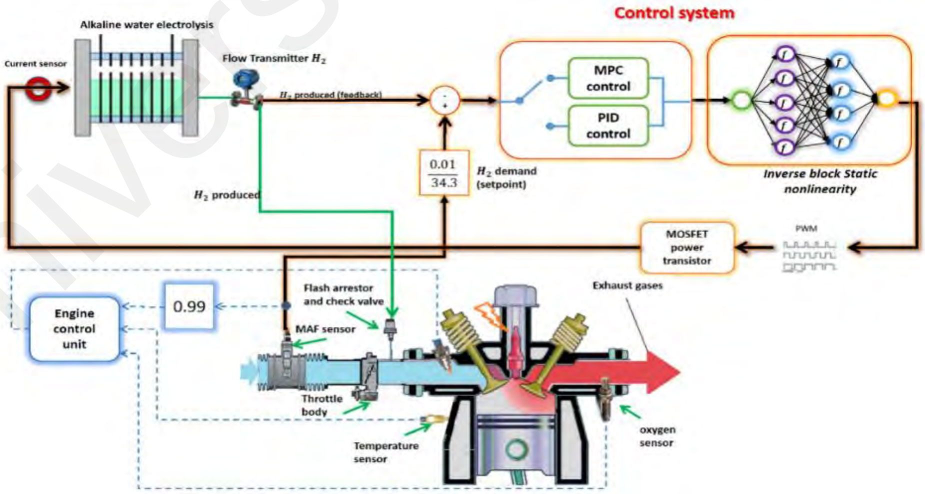

Figure 2.9 Control system for MPC and PID (Cervantes-Bobadilla et al., 2018)

Mustafa (Baltacıoğlu, 2019) used pulse width modulation (PWM) technique by using micro-controller to regulate the production of oxyhydrogen gas for car engines (show in figure 2.10). In this study, eight different duty cycles (0 – 80%) were generated for which different corresponding amperes were set for the electrolyzer for producing respective oxyhydrogen. Selection of the duty cycle was set automatically by mean of sensor according the volume and requirement of the engine.

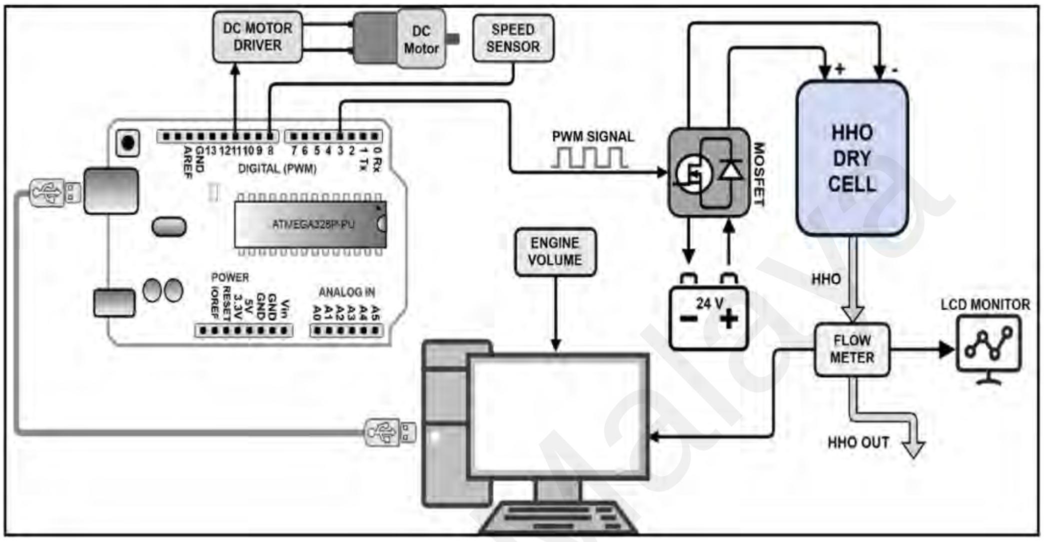

Figure 2.10 Schematic diagram of oxyhydrogen reactor control system using PWM (Baltacıoğlu, 2019)

Another PWM based technique to control oxyhydrogen production has been shown in figure 2.11 (Ç. Conker, 2019). In this study, a fuzzy logic based programming was developed for the selection of the duty cycle of the PWM. A complete Simulink block diagram for fuzzy logic based control system is shown in figure 2.12. As there were no static marking for selection of duty cycle so it efficiently produces the oxyhydrogen by keeping the temperature of cell in safe zone. His studies further reveal in figure 2.12 that, regardless of the control settings oxyhydrogen production by using fuzzy logic technique is more efficient than fixed PWM. From the figure 2.11, it was clear that in fixed PWM case hydrogen was efficiently produce in first half only but not in second due to overheating. On the other hand, the FL based controller operates the system while taking the necessary precautions, the oxyhydrogen generator system runs without overheating.

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A self-adaptive fuzzy PID controller technique has also been recently used to control the production of oxyhydrogen (C. Conker & Baltacioglu, 2020). This self-adaptive approach showed better performance than conventional control technique.

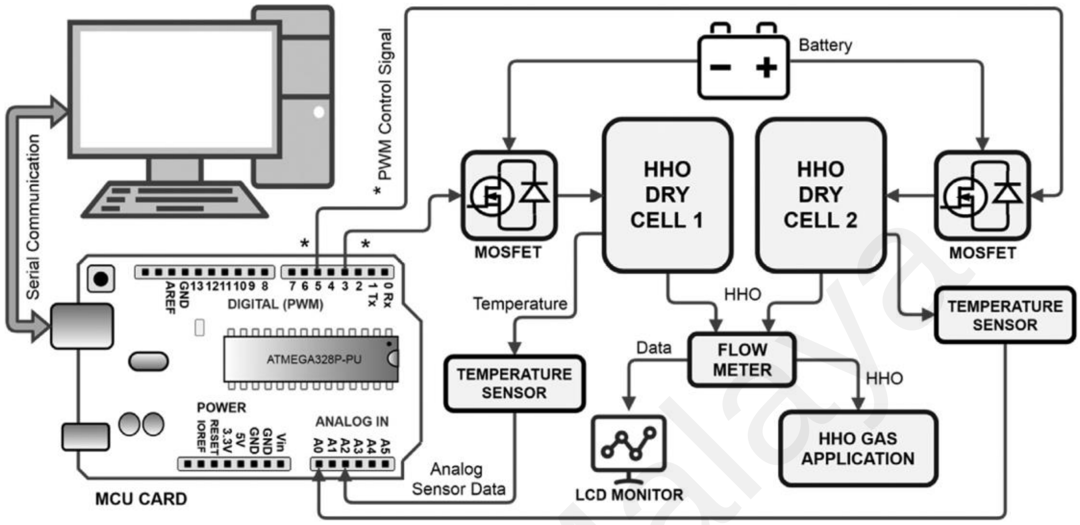

Figure 2.11 Schematic diagram of oxyhydrogen reactor control system by controlling temperature (Ç. Conker, 2019)

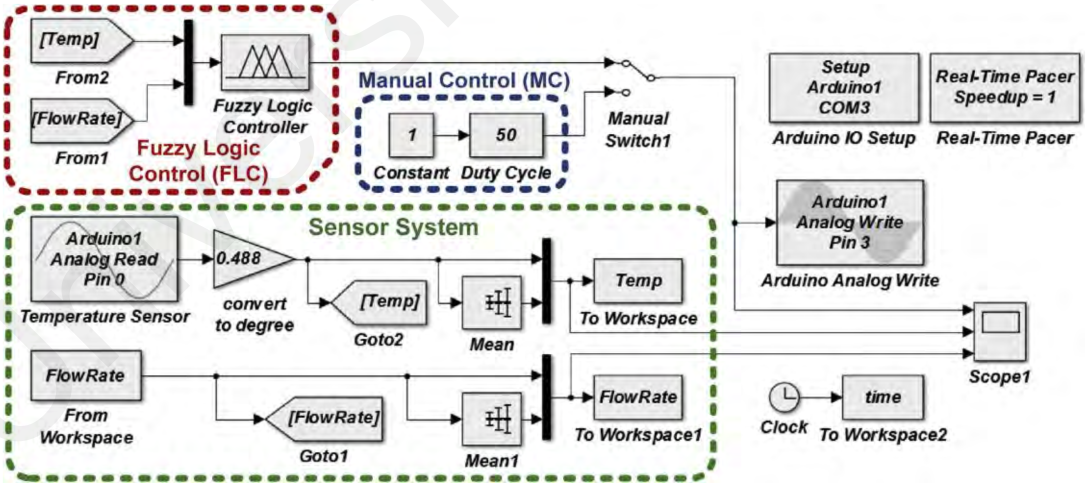

Figure 2.12 Simulink block diagram of the Fuzzy Logic based control system(Ç. Conker, 2019)

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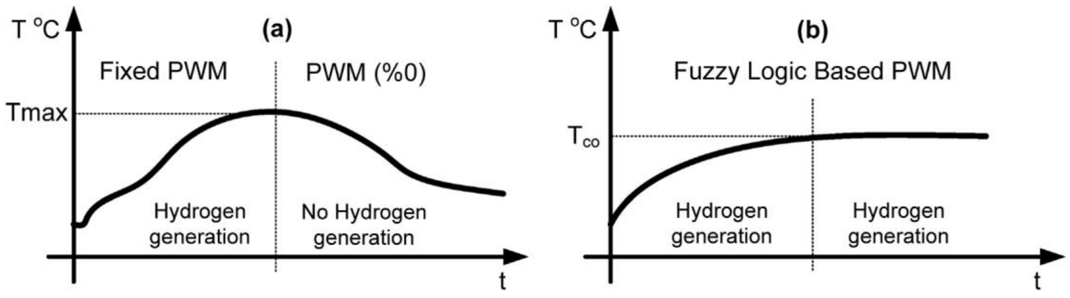

Figure 2.13 oxyhydrogen Reactor system (a) using fixed PWM signal (b) using fuzzy logic based PWM (Ç. Conker, 2019)

Another PWM control system was proposed by Worawat & Apinan (Worawat & AURASOPON, 2015) that can constantly regulate the output current of oxyhydrogen dry cell. This PWM control system was meant for the use of oxyhydrogen dry cell in combustion engine. It could protect from overvoltage as well as limiting the maximum current in order to maintain the temperature of cell. This system was even able to control variation occurs in DC supply (battery) or a change in the internal resistance of dry cell.

2.3.3 Thermal Applications

2.3.3.1 Boilers

Hydrogen gas can be used as a fuel to power catalytic boilers, gas powered heat pumps and direct flame combustion boilers that are similar to boilers of natural gas. A large variety of district heating techniques can be redesign that can use oxyhydrogen as fuel (Chiesa, Lozza, & Mazzocchi, 2005). In a study oxyhydrogen burner was used as a combined source of heat and water vapor to attain high temperature for hydrolysis of fluorides (Hoel, Fanale, & Clark, 1960). It was concluded that materials with higher fluoride contents can also be treated in the same way. Hydrogen fuel was also been a promising technique to be used for steam generation for thermal related application (DeWitt, 2014). If stoichiometric properties of oxyhydrogen are exploited well they can be an alternative fuel for thermal applications. An identical natural gas based boiler to

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hydrogen based direct flame combustion boiler is already installed in Europe and North America for residential heating (Palmer & Cooper, 2013). So, it encourages researchers to replace different industrial heating process like cement kiln that use natural gas with hydrogen. Even hydrogen gas can be used with existing large scale boilers and industrial furnaces that use fossil fuel like LNG, LPG or diesel. Hydrogen gas can be blend with these conventional fuels to run the boilers and furnaces (as shown in figure 2.14). Heat from the boiler than can be used for different heating purposes.

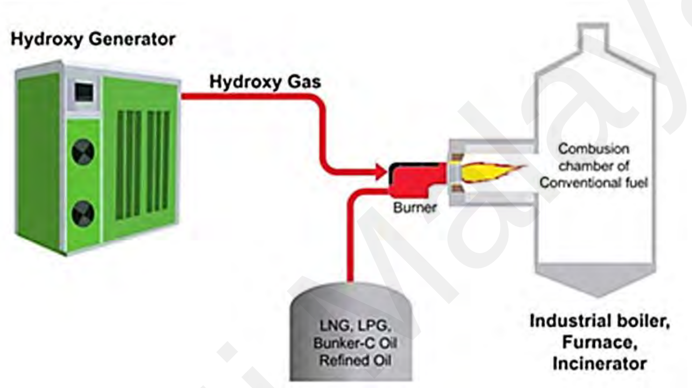

Figure 2.14 Oxyhydrogen gas mixed combustion system for boiler (Butt, Ahmad, Che, & Rahim, 2021)

2.3.3.2 Heating in domestic applications

Hydrogen gas is not limited for use in combustion engines and industrial applications. It can also be used for house heating purposes. Komitov et al (Komitov et al., 2019) determines the cost of building heating using different energy sources. It was summarized in table 2.4. It was concluded from the study that hydrogen gas has potential to be used for heating purpose of building. From data in table 2.4, it is established that hydrogen cheapest energy source for building heating. No hazardous emission is involved during hydrogen combustion. It only cost water and necessary electricity for decomposition of water. Thus, hydrogen is feasible for heating purpose of buildings but required a separate boiler room for electrolyzer and boiler chambers.

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Table 2.4 Value of heating per hour at different energy sources(Komitov et al., 2019)

No.	Energy sources	Energy requirement	Cost of heating
1	Hydrogen gas	1.49kWh	0.16 €/h
2	Electricity	9.29 kWh	1.00 €/h
3	Wood pellets	1.76 kg	0.45 €/h
4	Agro pellets	2.79 kg	0.36 €/h
5	Natural gas- CNG	0.94 m3	0.41 €/h
6	LPG	0.67 kg	0.73 €/h
7	Gas oil	0.70 l	0.77 €/h

2.3.3.3 Water desalination

As shortage of fresh water has been predicated in near future. One of the way to obtain fresh water is by solar desalination (Qiblawey & Banat, 2008). Use of active and/or passive solar still is the simplest one. A solar still is a similar process of natural hydrologic cycle of evaporation and condensation. Heat from the sun rays is passed through glass cover of the basin filled with impure water. This heat energy results in evaporation of water. Different modifications in solar still can be done to increase the productivity. Use of hydrogen gas for water desalination in solar still is a new concept (Nabil & Dawood, 2019). In this technique hydrogen gas is applied for burning in conventional system which results in fresh water quality. A conventional solar still can be integrated with photovoltaic panels and oxy-hydrogen generator as shown in figure 2.15.

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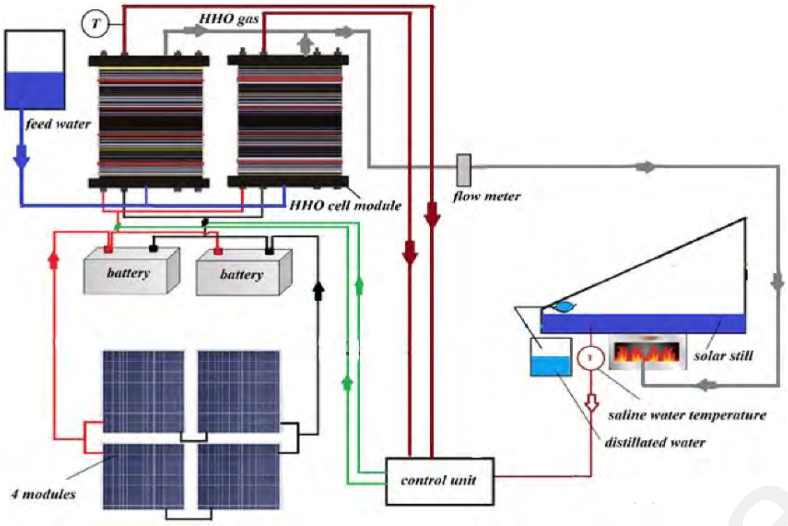

Figure 2.15 Schematic diagram of proposed solar desalination system (Nabil & Dawood, 2019)

Efficiency of this hybrid method of water desalination was 25%. This efficiency is less than the conventional system which is 29% (Kabeel & El-Agouz, 2011). This is because of more energy consumed along with the time. Also the cost of 1 liter of distilled water is higher for the new system as compared to conventional. Although new hybrid system with hydrogen is not much more efficient and cost effective but it has showed a potential for usage of hydrogen in different applications.

2.3.3.4 Thermal Coating

Due to the stoichiometric properties of oxyhydrogen, it can be used dynamically in thermal applications. It is a beneficial substitute during thermal coating process. Oxyhydrogen can be an alternative of plasma gas or can be mixed as an additive gas during thermal spray process for depositing metallic or nonmetallic materials in a molten or semi-molten condition (Klein, 2008). This coating process can be seen in figure 2.16. In another study, oxyhydrogen gas was used for gas flame of powder coating applications (Barsukov, Barabash, Rodichev, & Kozhus, 2017). It was established in the study that oxyhydrogen flame has a potential of adhesive strength on spraying modes of powder.

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On the other hand, oxyhydrogen does not produce harmful contents as organic fuel produce during combustion of gas-flame spraying for coating.

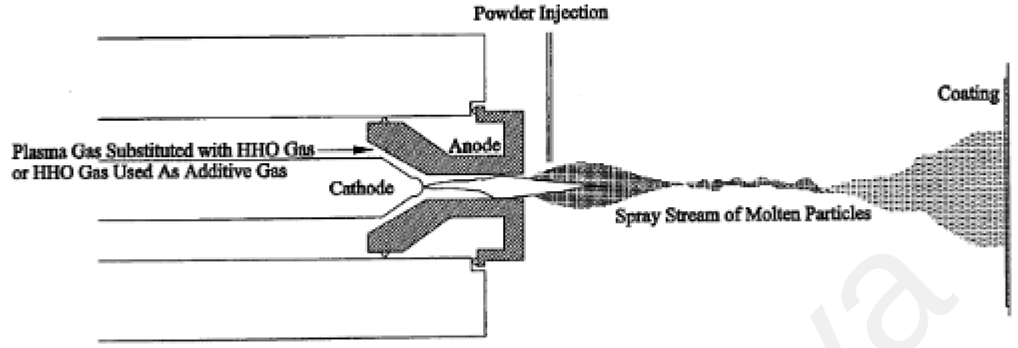

Figure 2.16 Thermal spray process using oxyhydrogen for coating (Klein, 2008)

2.3.3.5 Cutting and welding application

Ordinary gas cutter commonly known as oxy-acetylene fuel cutting has several demerits. They are limited only to mild or low alloy steels or cast iron but not much suitable for aluminum or stainless steel and have a wide heat affected zone, which causes brittleness. Also most of the times these cutters form a thin and brittle layer at the edges of the cut (Borse, Chavan, Ingale, Jejure, & Bakal, 2017). Oxyhydrogen flame pressurized gradually from low towards high for punching and cutting process of metal (Brown, 1978). Similarly, gas welding has also disadvantages such as low temperature of gas flame, slow rate of heating, not suitable for heavy sections and carbon steel. Combustion advantages of oxyhydrogen gas made it a promising alternative for welding and cutting applications. Temperature of oxyhydrogen gas is 2800°C with a straight, high speed flame and concentrated flame (R. K. M. A. N. Kumar). Oxy-hydrogen cutter can cut the face straighter and smother while heat affected zone is much smaller with high cutting speed and able to cut even thicker materials (Prisecaru et al., 2004). This method has low running cost and much more environmental friendly. Cutting and welding by using

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oxyhydrogen gas is shown in figure 2.17. Also welding by using oxyhydrogen gas has promise to be environmental friendly. As it has neutral flame so it does not required oxygen from external source. This helps in prevention of emitting harmful gasses during welding and reduce the risk of indoor welding (R. K. M. A. N. Kumar).

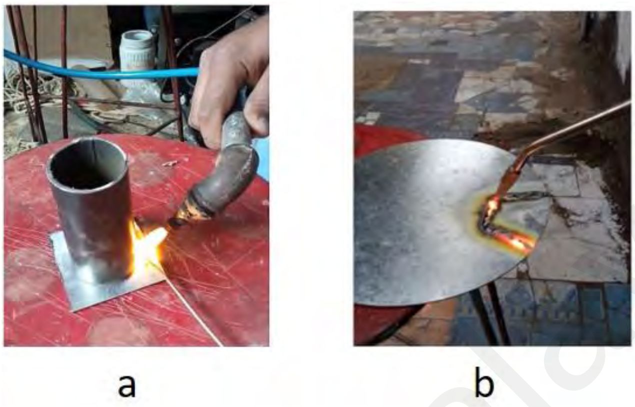

Figure 2.17 (a) Welding and (b) cutting by using oxyhydrogen gas (Nabil & Dawood, 2019)

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2.3.3.6 Waste incineration combustion

Particularly municipal solid waste is a heterogeneous feedstock for incineration. Its composition, characteristics or sometime whole waste stream can affect combustibility. This make difficult for incineration to maintain the minimum necessary level of temperature. For this reason, auxiliary burners are added which are feed by fossil fuel (natural gas, oil etc) to maintain the temperature of the furnace. These burners set to come on automatically when the temperature drops from the threshold point which is usually 850°C. These burners are used during startup, shutdown and upsets in system (*Waste Incineration and Public Health*, 2000).

Combustion is defined as a rapid exothermic reaction which takes place between a fuel and oxygen. Normally, waste is considered to be primary fuel for the incineration applications although fossil fuels co-fired with this waste in the presence of oxygen from air. In the result of the combustion process, same stable products are produce regardless of the fuel (natural gas, coal, gasoline etc) use for incineration (*Waste Incineration and Public Health*, 2000).

Incineration technology is depended upon combustion mechanism. It is a type of thermal plant that should be operated constantly and evenly on set point of temperature. Most of the reported studies are focused on fuels like gas, oil, coal etc. There are two types of combustion mechanism that are selected according to the waste that is to be incinerated i-e auto-combustion and fuel-assisted. In an auto combustion incinerator, additional fuel such as coal, wood or kerosene is used for the initial ignition. This auxiliary fuel is also then used for pre-heating purpose. At some optimum point, fuel intake is stop and waste it generates and maintains heat to continue combustion for disposal process. This technology is rather cheaper and required special arrangements and composition with secondary fuel (woo, charcoal etc.) for disposal of medical or hospital waste(*THE INCINERATOR GUIDEBOOK*, 2010). A fuel-assisted incinerator requires continuous supply of fossil fuel (diesel or gas) and electrical power to operate. Design of the fuel assisted incinerator is important for the control and supply of fuel to maintain a constant temperature for combustion and economize on fuel consumption. This type of incinerator normally has a capacity of destroying about 150Kg of waste in a day by consuming 5 to 8 liters of fuel per hour (4 to 6.5 kilogram of gas) (*THE INCINERATOR GUIDEBOOK*, 2010). It is possible to replace fossil fuel in fuel assisted incinerator with oxyhydrogen or brown gas will not only eliminate dependency of fossil fuel but also result in reducing greenhouse emission. This oxyhydrogen can be produce on site by water dissociation technology by oxyhydrogen gas generator. Waste stream get in contact with this oxyhydrogen-rich gas to get treated (Van Vliet, Campbell, & Chambers, 2007). Also due to high calorific value of hydrogen than other types of fuels, it is pondering that it could incinerate more efficiently and effectively than conventional

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fuels. An oxyhydrogen based incinerator system is shown in figure 2.18. An oxyhydrogen generator is coupled with an incinerator. Combustion chamber of incinerator is such designed that it can perform complete combustion condition of oxyhydrogen gas. Combustion heat of syngas and oxyhydrogen gas make synergy each other to create high temperature of 1400-1800˚C. This heat is able to melt anything and produce negligible ash. Flue gases from the incinerator plant can be further used for running steam power plant or district heating purposes.

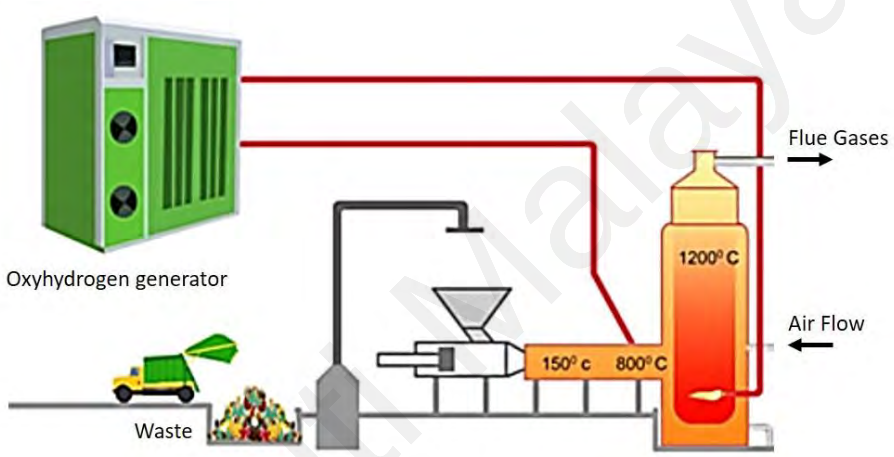

Figure 2.18 Oxyhydrogen based incinerator system

One of the popular method for treating waste water is through oxidation of organic matter by aerobic bacteria (Sillanpää, Ncibi, & Matilainen, 2018). In this process oxygen is supplied to bacteria. Compressors are used to inject pressurized air into aeration basin. These compressors have large motors are dependent on the availability of electrical power which need 20% to 30% of the total energy required by the water treatment plant. The availability of an energy-rich gas such as oxyhydrogen which can further be used to generate electricity on site (Van Vliet et al., 2007). This will help to control power costs and ensures an adequate supply of power available for the treatment plant.

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2.3.4 Methods for production of hydrogen

There are two main resources that are used in different technologies to produce hydrogen (shown in figure 2.19.)

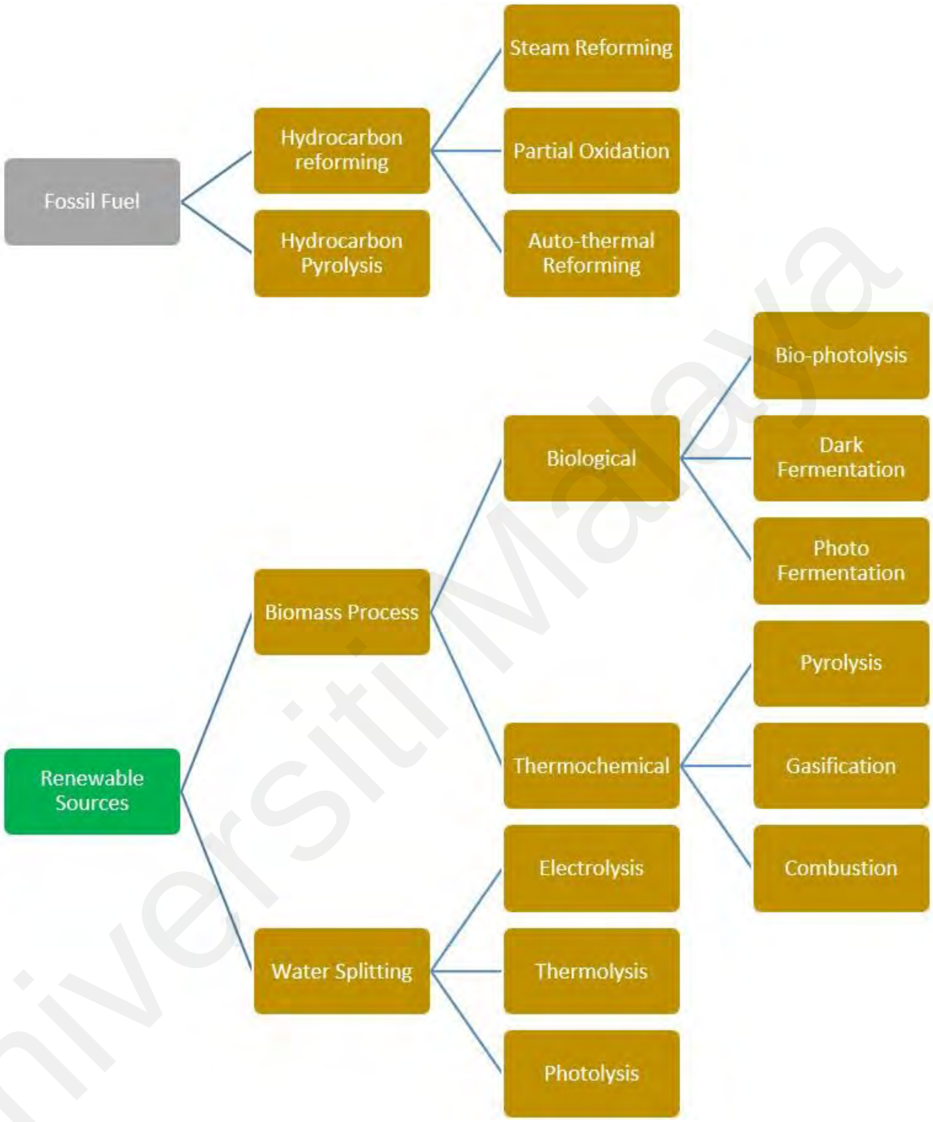

Figure 2.19 Different technologies to produce hydrogen

2.3.4.1 Steam Reforming

This method involves in catalytic conversion of hydrocarbon and steam which results in hydrogen and carbon dioxide. Natural gas, methane, ethane, propane, butane, pentane can be used as a raw material for this method. Desulphurization step is performed to avoid

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poisoning the reforming catalyst due to Sulphur particles. Reforming reaction is performed at high temperature with pressure up to 3.5MPa and steam-to-carbon ratio of 3.5 (Ersöz, 2008). After the reformer, the gas mixture passes through a heat recovery step and is fed into a reactor where the CO reacts with steam to produce additional hydrogen. A complete flow diagram of steam methane for producing hydrogen is shown in figure 2.20.

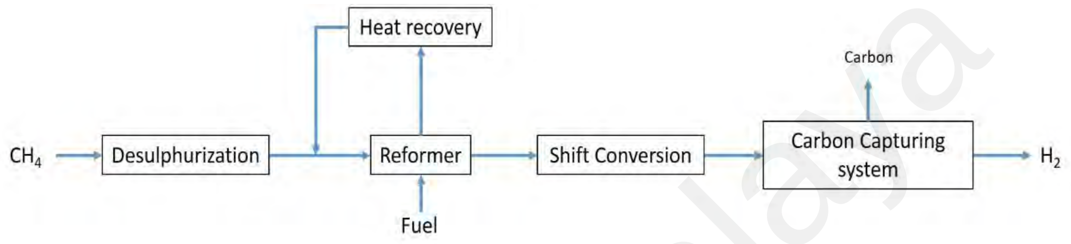

Figure 2.20 Flow diagram of steam methane method to produce hydrogen

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2.3.4.2 Partial Oxidation

This method involves conversion of steam, oxygen and hydrocarbon to hydrogen and carbon-oxides. Normally catalytic process occurred at 950°C with a large range of methane feedstock but non-catalytic process occurs on 1150 – 1315°C with hydrocarbons which includes methane, coal or oil (Steinberg & Cheng, 1989). Partial oxidation method is most suitable while using heavier feedstock (like heavy oil residue or coal) to produce hydrogen. In the same way as in steam reforming, Sulphur is removed and pure oxygen help in partial oxidizing the feedstock. Syngas produced in result, is further treated in the same way as in steam reforming. Due to lower hydrogen to carbon ratio, steam can be resulted in production of large quantity of hydrogen. This process is normally referred to coal gasification for production of hydrogen. Flow diagram for partial oxidation method is given in figure 2.21.

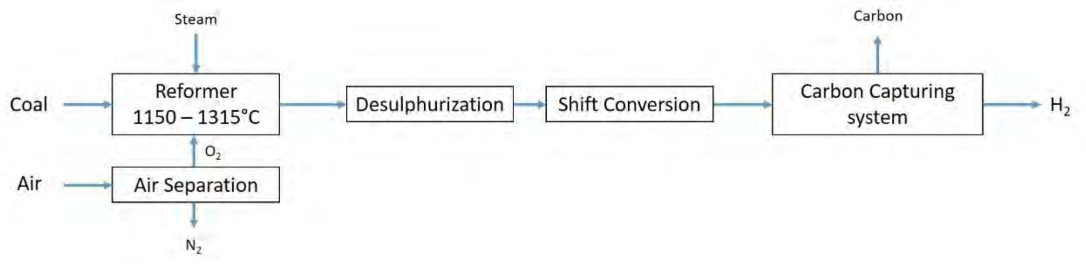

Figure 2.21 Flow diagram of partial oxidation method to produce hydrogen

2.3.4.3 Auto-thermal Reforming

In this process exothermic partial oxidation is used to provide heat and endothermic steam reforming to produce hydrogen. Steam and oxygen is injected to cause reforming and oxidation reaction simultaneously. Thermal efficiency for auto-thermal reforming lies 60–75%. Optimum operating value for inlet temperature ranges 700 – 900°C, ratio for S/C = 1.5, O2/C = 0.45 (Ersöz, 2008). A complete flow diagram for ATR method is represented in figure 2.22.

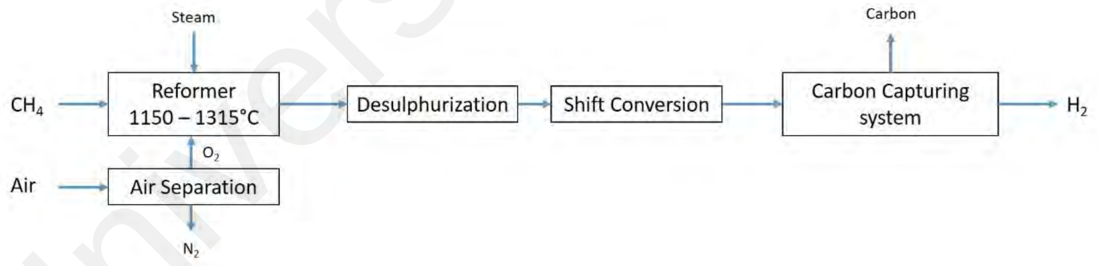

Figure 2.22 Flow diagram of auto-thermal reforming to produce hydrogen

2.3.4.4 Hydrocarbon pyrolysis

It is a well-known process of producing hydrogen, in which only hydrocarbon goes thermal decomposition for producing hydrogen by following equation (2.2):

$$C_n H_m \rightarrow nC + \frac{1}{2} mH_2 \qquad (2.2)$$

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Thermo-catalytic decomposition of light liquid hydrocarbons at temperature of 50 – 200°C is carried out with the production of carbon and hydrogen. Direct de-carbonization of natural gas, is effected in an air and water free environment, at temperature up to 980°C and atmospheric pressure (Nikolaidis & Poullikkas, 2017). This process is illustrated in figure 2.23.

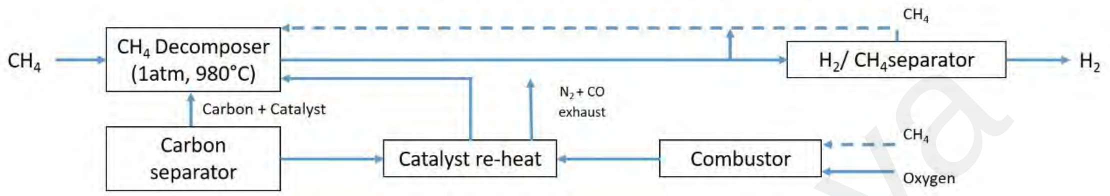

Figure 2.23 Flow diagram of hydrocarbon pyrolysis to produce hydrogen

2.3.4.5 Biological

Most of the biological processes use for production of hydrogen gas are direct or indirect methods of are direct and indirect bio-photolysis, photo and dark fermentations, and multi-stage or sequential dark and photo-fermentation. Biological process gain attention due to its sustainable development and help towards minimization of waste. Normally, this process is done at ambient temperature and pressure making it a less energy intensive method. Feed for bio-hydrogen consists of water and biomass for fermentation process. Water is used photolysis to produce hydrogen from bacteria or algae directly through their hydrogenase or nitrogenase enzyme system, while in the fermentation process of biomass, carbohydrate materials are converted into organic acids to produce hydrogen through bio-processing technologies (Holladay, Hu, King, & Wang, 2009; Kapdan & Kargi, 2006).

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2.3.4.6 Thermochemical

In thermochemical process biomass is converted into hydrogen gas. It is an effected method to produce hydrogen gas with zero emission of GHG (Fremaux, Beheshti, Ghassemi, & Shahsavan-Markadeh, 2015). Thermochemical process is a biomass pyrolysis generating Liquid oils, solid charcoal and gaseous compounds by heating the biomass at temperature of 650–800K at 0.1–0.5 MPa (Demirbaş, 2001). It takes place in the total absence of oxygen. Methane produced from biomass can be steam reformed for hydrogen production. After conversion carbon monoxide into carbon dioxide, hydrogen can be obtained. A general equation for the method is shown in equation 2.3 and figure 2.24.

$$\text{Pyrolysis of biomass} \quad \rightarrow \quad H_2 + CO + CO_2 + \text{hydrocarbon} \qquad (2.3)$$

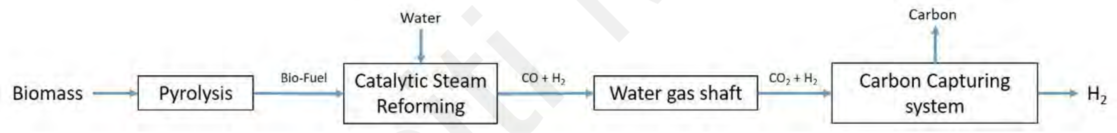

Figure 2.24 Flow diagram of biomass pyrolysis to produce hydrogen

2.3.4.7 Thermolysis

Thermolysis is a thermo-chemical process in which water is decompose into hydrogen and oxygen at high temperature. This temperature need to be above 2500°C. At this high temperature Gibbs function (ΔG) becomes zero and separation of hydrogen and oxygen becomes possible from equilibrium mixture (Funk, 2001). This much amount of heat in not possible to achieve from sustainable heat source, so it can be possible by using several thermochemical cycles (De Falco, Marrelli, & Iaquaniello, 2011; Flamos, Georgallis, Doukas, & Psarras, 2011). Other methods than can be used to achieved such temperature

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is by nuclear or solar heating with large scale of solar collectors (Bamberger & Richardson, 1976). Figure 2.25 illustrate the flow diagram for thermolysis process.

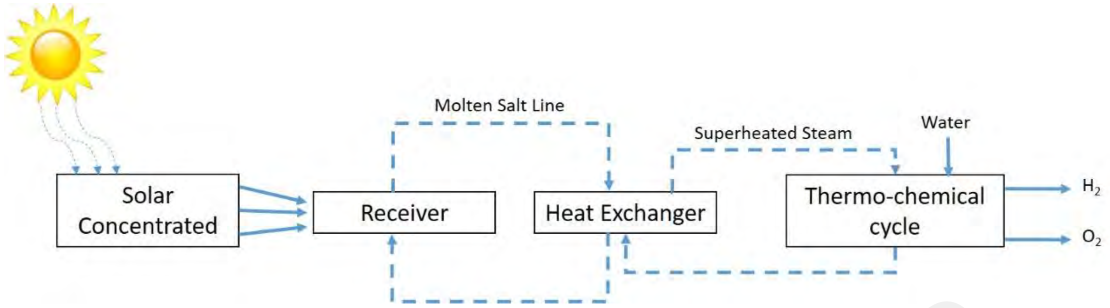

Figure 2.25 Flow diagram of thermolysis to produce hydrogen

2.3.4.8 Photolysis

In this process photo-catalysts helps in absorbing visible light that use its energy in decomposing of water into hydrogen and water in a similar way as in electrolysis. Photolysis or photo-electrolysis use some semi-conductor materials to absorb sunlight (Bak, Nowotny, Rekas, & Sorrell, 2002). When a photon of greater or equal to semi-conductor's band gap energy strikes with the surface of anode, it results in generating an electron-hole pair which is separated by the electric field created between the electrolyte and semiconductor. In this process, generated holes remain at the anode side where they split water molecule into hydrogen ions. These ions than travel through electrolyte towards cathode and oxygen that remains back with water. Whereas, the electrons flow through an external circuit to the cathode where they interact with hydrogen ions to form hydrogen (Nikolaidis & Poullikkas, 2017). This process is summarized in equation 2.4 and illustrated in figure 2.26.

$$H_2O \rightarrow H_2 + 0.5O_2 \tag{2.4}$$

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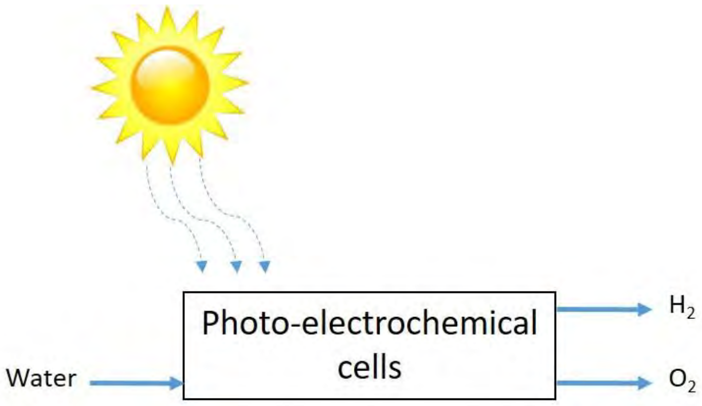

Figure 2.26 Flow diagram of Photolysis to produce hydrogen

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2.3.4.9 Electrolysis

It is a well-known and established technology to produce hydrogen by using electricity. A DC current is used to split water molecules into hydrogen and oxygen. As this is a endothermic reaction so electricity is used as an input energy (Rossmeisl, Logadottir, & Nørskov, 2005). Electrolysis is done by using an electrolyzer which is typically consist of a cathode and anode, immersed into electrolyte. This electrolyte is alkaline in nature. When electric current passes through water, it forms hydrogen at cathode while oxygen is evolved at anode side. Following equation 2.5, is followed during reaction (Rossmeisl et al., 2005).

$$2H_2O \rightarrow 2H_2 + O_2 \tag{2.5}$$

2.3.5 Hydrogen as green fuel technology

There are different technologies to produce hydrogen. These technologies are categorized in four different colors grey, blue, turquoise and green based on the technology of their production of hydrogen (Hermesmann & Müller, 2022) and raw material. A complete illustration based on the characteristics of these technologies is shown in figure 2.27. Hydrogen produced from reforming of fossil fuel is categorized as 'grey hydrogen' (Challiwala, Ghouri, Linke, El-Halwagi, & Elbashir, 2017; Sazali, 2020). Almost 95% of hydrogen produced is grey hydrogen with half of that amount is produced by reforming of natural gas (Sazali, 2020). This method is categorized as 'grey' due to emission of large amount of carbon dioxide along hydrogen production. If these carbon emissions are captured than hydrogen production will be categorized as 'blue' (Hermesmann & Müller, 2022). Obtaining hydrogen by changing the process of reforming to methane pyrolysis is categorized as 'turquoise' (Hermesmann & Müller, 2022). When hydrogen is produced by using some renewable feedstock (water) while energizing process by using renewable resources (like solar, wind etc.) is known as 'green' hydrogen. Normally, water splitting method based on electrolysis method comes under this category. World's largest green hydrogen facility will commence in 2025 with a capacity of 650 ton/day that will be energized by 4 GW of renewable solar energy (Nefedova, Degtyarev, Kiseleva, & Berezkin, 2021).

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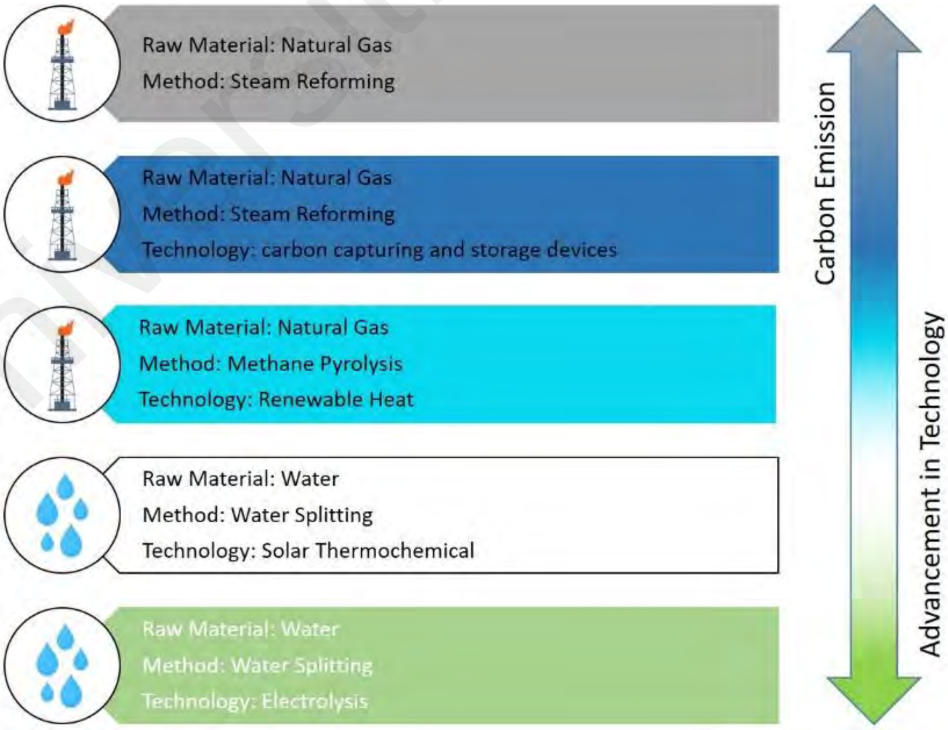

Figure 2.27 Technologies to produce hydrogen based on different categories

Green hydrogen process requires to energized from carbon-low or neutral energy resources like solar or wind. But the feasibility of these either processes depends upon both technical and economic aspects. Dependency of energy either on grid or only renewable source for electrolysis plays a vital role to calculate its feasibility. Cost of electricity from solar or wind is much high than grid. Also cost of electrolyzer itself is much higher than other processes. These indicators are creating hindrances in wide spread of green hydrogen. With the advancement of technologies and materials, it is predicted that in a decade this technology can be lowered to approximately 70% which encourages the wide spread of green hydrogen in near future (Atilhan et al., 2021).

2.4 Electrolysis techniques

Hydrogen production from electrolysis is consider to be free from GHG emission. This is because electrolysis consume water which a non-carbon feedstock. For electrolysis, a cell is used made of two plates known anode and cathode, which is called electrolyzer.

Electrolyzer is essentially an electrochemical conversion device to decompose water into its constituent components by using electrical energy. The electrolysis process is shown in figure 2.28 (Carmo, Fritz, Mergel, & Stolten, 2013; Grube & Stolten, 2010).

$$H_2O_{(l)} + 237.2\ (KJ/mol)_{(electricity)} + 48.6\ (KJ/mol)_{(heat)} \rightarrow H_2 + 0.5\ O_2 \qquad (2.6)$$

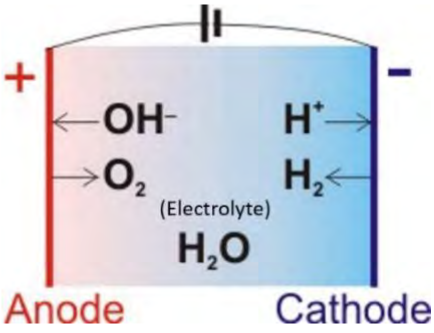

Figure 2.28 Schematic diagram of a water electrolyzer

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Electrolyzer technique can be divided in three subcategories (1) alkaline water electrolyzer, (2) exchange membrane electrolyzer (proton exchange membrane (PEM) and anion exchange membrane (AEM)) and (3) solid oxide electrolyzer cell (SOEC). Among them, alkaline water electrolyzer technique is the only technique that can produce oxyhydrogen gas. In subsequent sections, only alkaline water electrolyzer will be discussed due to our focus on oxyhydrogen.

2.4.1 Alkaline Electrolyzer

Alkaline electrolyzer is considered to be the most common, eco-friendly, mature and cost effective technology (David, Ocampo-Martínez, & Sánchez-Peña, 2019; Ursua, Gandia, & Sanchis, 2011). An aqueous form of 30 wt% KOH or NaOH has been used as electrolyte (Sørensen & Spazzafumo, 2018). Due to the liquid nature of the electrolyte, it can cause a leakage issues. Under part-load, its performance deteriorates due to imbalance production of hydrogen and oxygen at anode/cathode and hydrogen permeability in electrolyte (Mohammadi & Mehrpooya, 2018). Different control techniques for energizing the electrolyzer can help from imbalance production. When electric energy passes through mixture of water and electrolyte in alkaline electrolyzer, following reaction occurs as shown in figure 2.29:

$$\text{Anode:}\quad 4\,OH^- \rightarrow O_2 + 2H_2O + 4e^- \tag{2.7}$$

$$\text{Cathode:}\quad 2H_2O + 2e^- \rightarrow H_2 + 2OH^- \tag{2.8}$$

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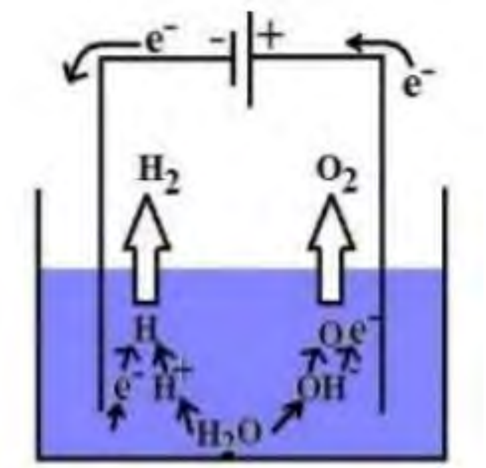

Figure 2.29 Reaction in an electrolyzer for producing oxyhydrogen

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2.4.1.1 Configuration of oxyhydrogen generator

There are two basic configurations of alkaline electrolysis on the basis of stacking of cell: mono-polar and bi-polar.

*(a) **Mono-polar Electrolysis Cell***

In case of mono-polar configuration of electrolysis stack, each electrolysis cell has been connected in parallel as shown in figure 2.30. In this configuration, voltages on each cells are equal to the total applied voltage of electrolysis stack while the total current in the stack is divided in cells. Furthermore, electro-chemical reactions occur on both sides of each electrode. Reaction for hydrogen evolution or oxygen evolution depends upon the polarity of relevant electrodes.

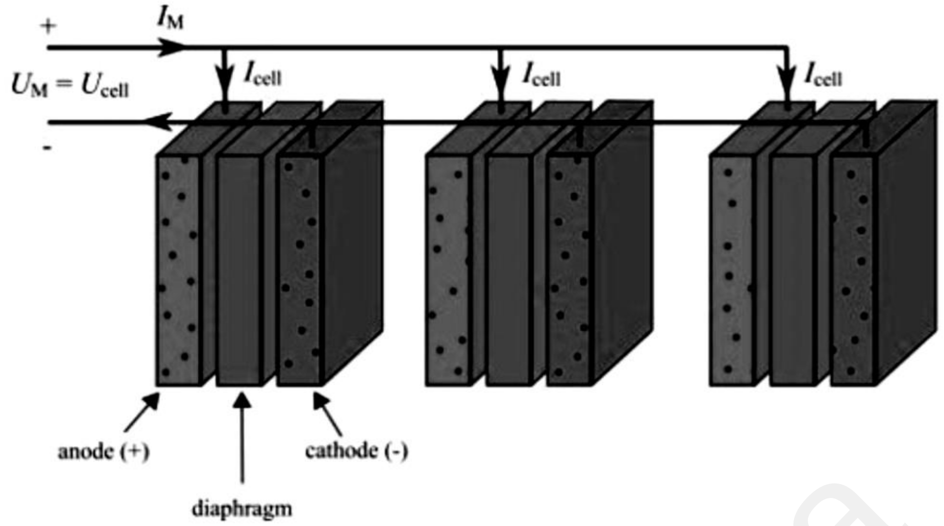

Figure 2.30 Mono-polar configuration of electrolysis stack(Yakdehige, 2017)

(b) Bi-polar Electrolysis Cell

For bi-polar configurations, each electrolysis cell has been connected in series in order to form a stack module of electrolysis as shown in figure 2.31. For bi-polar electrolyzer, total applied voltage on stack is equal to the sum of all voltages between individual cells while total current is equal to the current passed through each individual cell. Unlike mono-polar configuration, in bi-polar stacking different electrochemical reactions occur on both sides of each electrode that is hydrogen evolution on one side while oxygen on the other side. This means that one side of electrode act as a cathode and other as anode at the same time. Gaps between electrode are small defining the distances for ions to travel in electrolyte. As smaller gaps give less resistance for the transportation of ions, so the ohmic loss in bi-polar stacking is less compared to mono-polar configuration. But these smaller gap can cause spark which ultimately turns into an explosion hazard (Zeng & Zhang, 2010). Therefore, maintaining optimal gap is important while considering bi-polar configuration.

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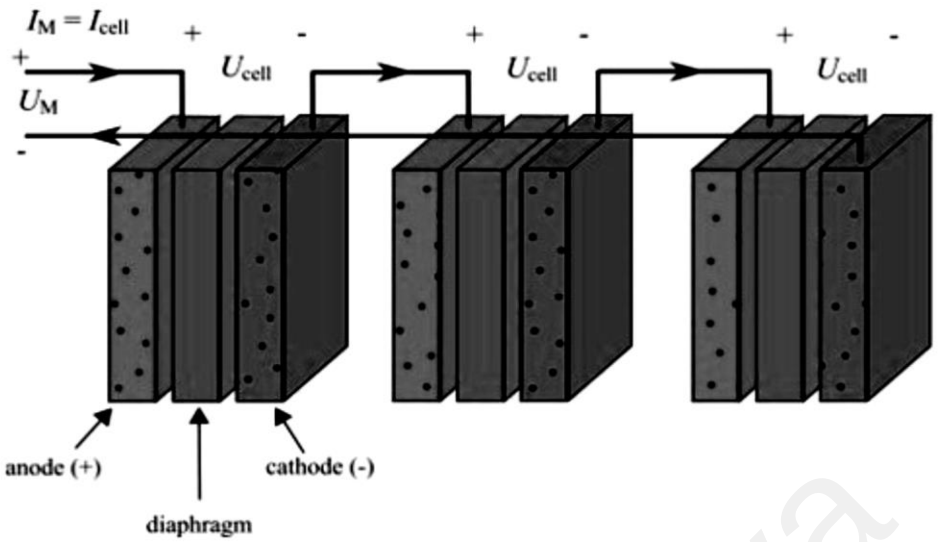

Figure 2.31 Bi-polar configuration of electrolysis stack (Yakdehige, 2017)

2.4.1.2 Types of oxyhydrogen generator

Beside configuration, there are three types of oxyhydrogen generator commonly known as dry cell, wet cell and hybrid cell. In a dry cell electrolyzer, the electrodes are not immersed in electrolytes. The electrolyte only fills the gaps between the electrodes, while in case of wet cell oxyhydrogen generator, all the electrodes are immersed in the electrolyte fluid inside a water vessel. For hybrid oxyhydrogen generator, dry and wet cell are so combined that a dry cell generator is placed in a vessel containing the electrolyte liquid as in the wet cell type. Table 2.5 presents comparative overview of various types of electrolyzer (Sudrajat, Handayani, Tamaldin, & Yamin, 2018).

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Table 2.5 Comparison between different types of oxyhydrogen generator cells

Sr. No.	Dry Cell-Oxyhydrogen generator	Wet Cell-Oxyhydrogen generator	Hybrid Cell-Oxyhydrogen generator
1	Water fills the gap between the cell's plate, the electrodes are not completely water logged	Stable production rate of oxyhydrogen gas	Electrode of the generator cell is submerged in the water of the electrolyte solution
2	Water circulates inside the generator which results in relatively less amount of heat produce during reaction	Design of wet oxyhydrogen generator is easy	Due to the circulation of water, less heat is produced
3	Required less amount of current as less amount power is lost in form of heat	Maintenance is easier	Required less amount of current as less amount power is lost in form of heat. Working temperature is low which does not required any electronic control circuit for temperature control (normally PWM electronic circuits).

2.4.1.3 Efficient production of Oxyhydrogen gas

Oxyhydrogen gas has a special behavior at atmospheric pressure due to high oxidation rate of hydrogen being in stoichiometric ratio and also premixed with oxygen. By using numerical model of combustion, the primary zone of flame of oxyhydrogen burner reveal that temperature values could reach up to 3036°C (Prisecaru et al., 2004). Generally, at 0.1Mpa of pressure and 25°C of temperature, electrolysis requires 1.24 Volts to split. But after adding electrolyte (KOH solution), this voltage can reach between 2 – 2.5 Volts with a current density of 2000A/m2 by rising the temperature of electrolyte up to 80°C (Srinivasan & Salzano, 1977). If a separation of membrane (ion conductive membrane) is not used to separate the hydrogen and oxygen, then hydrogen and oxygen ions blend. This results in evolution of a mixture of H2 and O2 with a volumetric (hydrogen/oxygen)

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ratio of 2:1. It is calculated that 1 kg of water which is consuming an electric power energy level of 22.9 MJ will produce approximately 1860 L of oxyhydrogen gas having 1240L of hydrogen and 620L of oxygen. Ideally, at a pressure level of 0.1MPa and temperature at 0°C, the density of hydrogen and oxygen gas would be 0.09kg/m3 and 0.09kg/m3 respectively. While the density of the mixture (oxyhydrogen) would be 0.54kg/m3. Therefore, 1 liter of oxyhydrogen gas includes 0.666L of hydrogen and 0.333L of oxygen with a mass of 0.06g and 0.48g respectively. An illustration of oxyhydrogen blend is shown in figure 2.32.

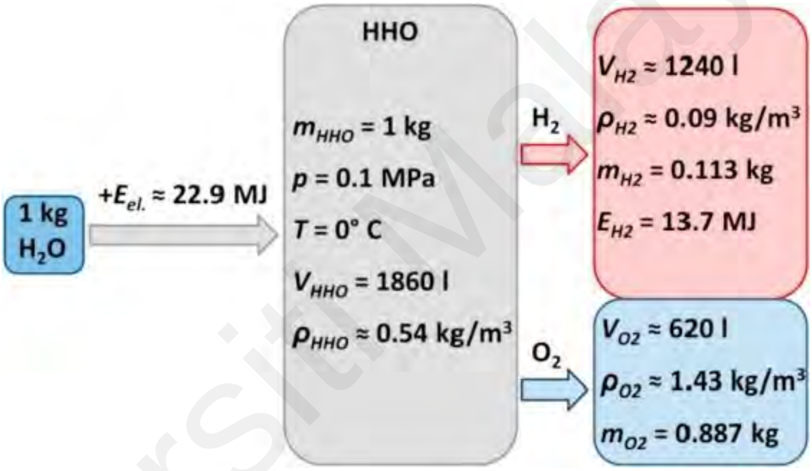

Figure 2.32 Composition and properties of oxyhydrogen gas (Rimkus et al., 2018)

Efficient production of oxyhydrogen gas typically depends upon the configuration of the electrolyzer. This configuration is dependent on factors like voltage applied on cell's plate, number of stacks, surface area of the cell and electrolyte. Faraday's first law of electrolysis states that the rate of gas evaluation during electrolysis is directly proportional to the current flow per unit surface area. Current density is required to meet flow rate of the oxyhydrogen gas. This can be achieved by (1): increasing the concentration of electrolyte (KOH) solution (but it conversely increases in the degradation rate of electrode) (2): increasing the applied potential on electrolyzer or (3): increasing surface

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area of the electrodes (Symes, Al-Duri, Bujalski, & Dhir, 2015). Heat is produced as electrons flow from the plates, which are separated by gasket. Objective of the control of electrolyzer is to minimize the heat loss. Each square inch of a plate surface on one side, efficiently passes 0.54 Amps of electrical current (Current Density). For the production of efficient oxyhydrogen, surface area between the gasket is considered where amperage is going to flow from in order to cross the water. This is the area where electron flow is condensed and plates get hotter. Higher amperage per square inch increases oxyhydrogen production, but also causes even more heat; the more amperage, the more heat (along with more oxyhydrogen). This causes hurdle in long time operations for production of oxyhydrogen. If enough surface area is not available to handle the amperage passing across a plate, the electron flow will pile up at the nearest water crossing and cause more heating at that area. Anything more than the optimal current density causes waste of energy in the form of heat. Therefore, selection of number of plates per cell is significant and surface area is of utmost importance in design stage. For electrolyte NaOH and KOH, minimum voltage required is 1.69 and 1.67 respectively. Therefore, practically 2.0 to 2.3 Volts are required to start the electrolysis. Normally, 12-volt DC supply is used in different applications; therefore, cell needs to be configured by adding series plates as shown in figure 2.33 so that appropriate voltage could drop across each plate.

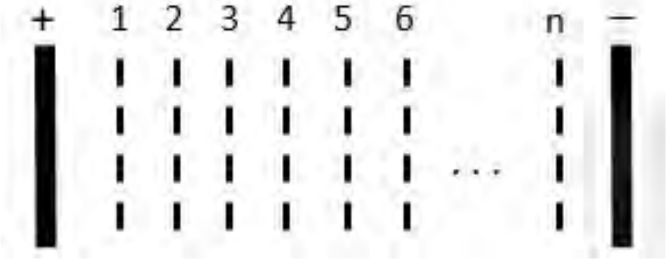

Figure 2.33 Series plate configuration

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According to Faraday (Gupta, 2008), minimum 1.24 Volts are required for electrolysis of water with a production rate of 0.01 LPM per ampere. This is the minimum amount of potential applied between two plates to split water with least amount of loss of energy in form of heat. Higher the potential applied will result in more heat being lost. Operating electrolysis on 1.24 Volts is impractical. Greater potential (than 1.24 Volts) is required to split the water for evolution of hydrogen and oxygen. This difference of voltage is known as over potential or losses (Kroposki, Levene, Harrison, Sen, & Novachek, 2006). This loss is actually the resistances in the cell as seen in figure 2.34. Higher potential is required to overcome this resistance to split water. Table 2.6 shows resistivity of different materials that were studied as electrode of cell. Production is directly proportional to current as given in Equation (2.6):

$$V = [a_0 + a_1 T + b.\ln(T) - (r_0/T)I]N_s \tag{2.9}$$

Here, V is voltage of cell which is normally kept as 2 Volt DC for electrolysis, I represents the current, T represents temperature, $a_0, a_1,$ and b are electrolysis parameters which are determined experimentally depending on the type of electrolysis, r_0 is the initial resistance of the electrolyzer and N_s are number of cells. Also it was seen that in reality electrolyzer work as a non-linear load (resistance) (Şahin, Okumuş, & Aydemir, 2014) and will extract more current from the source during the period it remains turned on. This nonlinear behavior is dependent on the pressure, temperature and chemical structure of the solution which leads to a rise in temperature (El Kady, Farrag, Gad, El Soly, & Hashish, 2020; Sudarmanta et al., 2016). Studies shows that the optimal range of temperature for the electrolyzer is less than 70 °C (Bhardwaj et al., 2014).

There are three main types of resistances in the electrolysis cell: (1) electrical resistance, (2) transport resistance and (3) electrochemical reaction resistance. Electrical resistance is directly responsible for loss of heat energy. Transfer of ions with the

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electrolyte depends on the electrolyte concentration (in case of liquid), membrane (in case of solid) and separation distance between the cathode and the anode (Zeng & Zhang, 2010). Bubbles of hydrogen and oxygen on the surface of electrode create resistance for transfer of ions.

Table 2.6 Electrical resistivity of different materials used as electrode (Symes et al., 2015)

Sr. No.	Material	Electrical Resistivity (at 20°C)
1.	Pt	105nΩm
2.	Gold	22.14nΩm
3.	Iron	96.1nΩm
4.	Silver	15.87nΩm
5.	Nickle	69.3nΩm
6.	Graphite	7800nΩm
7.	Lead	208 nΩm
8.	SS316	100nΩm
9.	Titanium	420nΩm
10.	Copper	16.78nΩm
11.	Aluminum	28.2nΩm
12.	Tin	115nΩm
13.	Zinc	59 nΩm

$$R_{Electrical} = R_1 + R_{\acute{1}}$$

$$R_{Transport\ resistance} = R_{bubble,O_2} + R_{bubble,H_2}$$

$$R_{Electrochemical\ reaction} = R_{membrane} + R_{anode} + R_{cathode} + R_{ions}$$

$$R_{cell\ (total)} = R_1 + R_{\acute{1}} + R_{bubble,O_2} + R_{bubble,H_2} + R_{ions} + R_{membrane} + R_{anode} + R_{cathode}$$

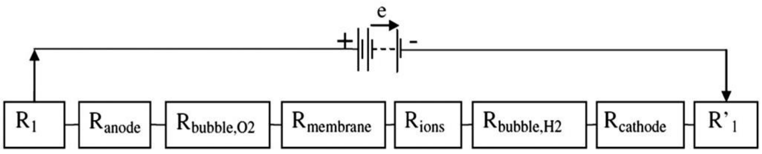

Figure 2.34 Total resistance of an electrolyzer cell(Zeng & Zhang, 2010)

2.4.2 Proton Exchange Membrane Electrolyzer (PEM)

Proton Exchange Membrane (PEM) is an electrolyzer that uses a solid polymeric electrolyzer that addresses leakage issues as in alkaline. This polymeric membrane is of

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acidic nature that allows exchange of protons (H+) (S Shiva Kumar & Himabindu, 2019). Contrary to the alkaline electrolyzer, water is fed at anode and oxidized to O2 which releases proton in result that flows through membrane towards cathode and reduced to form H2 (Carmo et al., 2013) as shown in figure 2.35.

$$Anode: \quad H_2O \rightarrow 2H^+ + 0.5O_2 + 2e^- \tag{2.10}$$

$$\boldsymbol{Cathode}: \quad \boldsymbol{2H^+ + 2e^- \rightarrow H_2} \tag{2.11}$$

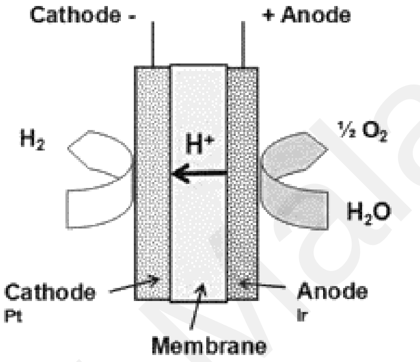

Figure 2.35 Reaction in an proton exchange membrane electrolyzer (Carmo et al., 2013)

2.4.3 Solid Oxide Electrolyzer Cell

Unlike other two option of alkaline and PEM electrolyzer, solid oxide electrolysis (SOE) is known as high temperature electrolyzer working at 900 – 950°C (Carmo et al., 2013). This high temperature phenomena SOEC performs electrolysis process of water vapor at high temperature which results in higher efficiency than alkaline and PEM electrolyzer. Contrarily to other methods of electrolysis, rise in operating temperature of the SOEC will decrease the demand of the electrical energy. So one can reduce the requirement of electrical energy by increasing the temperature of the cell and hence cell requires more thermal energy than electrical (Laguna-Bercero, 2012). Waste heat energy can be used for its working instead of using electricity (An, Zhao, Chai, Tan, & Zeng,

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2014; Vincent & Bessarabov, 2018). Solid electrolyte is used in SOEC which resolve leakage issues. Also compact design of the cell decreases the ohmic value. A complete reaction of electrolysis process in solid oxide electrolyzer cell is shown in figure 2.36. This cell was firstly introduced in 1980 by Donitz and Erdle (Dönitz & Erdle, 1985). In spite of all these qualities, solid oxide electrolyzer cells still are not commonly used for commercial purposes due to it durability issues in severe conditions and high capital cost as increasing temperature of the cell results in the use of costly materials and ceramics.

$$\text{Cathode:} \quad H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{2.12}$$

$$\text{Anode:} \quad O^{2-} \rightarrow 0.5O_2 + 2e^- \tag{2.13}$$

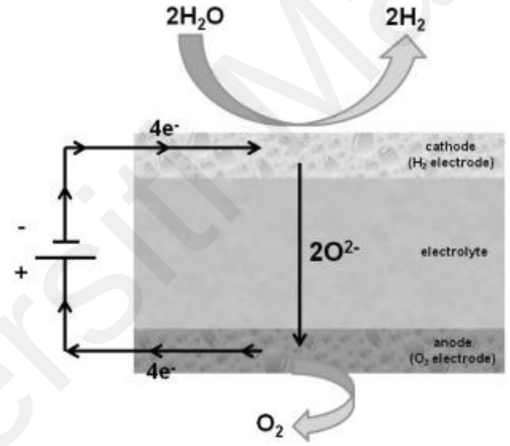

Figure 2.36 Reaction in an solid oxide electrolyzer cell (Nechache, Cassir, & Ringuedé, 2014)

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2.4.4 Comparison between electrolyzer techniques

Due to the maturity of the technology and cost effectiveness, alkaline electrolyzer is the best option for commercial activities. Its efficiency ranges between 52% to 62% (Felgenhauer & Hamacher, 2015). Other electrolyzer such as PEM has advantages like current density, higher purity and greater operating range (Carmo et al., 2013) but at the same time durability and high cost due to titanium based contact elements and high iridium charge electro-catalyst makes it less interesting for commercial purposes (Gago, Bürkle, et al., 2018; Gago, Lettenmeier, et al., 2018). It was calculated that efficiency of PEM ranges from 57% to 64% (Felgenhauer & Hamacher, 2015). In a study of Felgenhauer and Hamacher, they concluded that degradation of PEM type is double than for alkaline electrolyzer i.e. 1.57% and 0.78% respectively (Felgenhauer & Hamacher, 2015). Although efficiency of Solid Oxide Electrolyzer Cell is above 90% but its cost parameter makes him far away from commercial status (Badwal, Giddey, & Munnings, 2018).

Alkaline is also most economical mature option commercially. A study was performed for the economic evaluation of alkaline and PEM including investment, annual maintenance and operation cost per power of hydrogen produced. Study concluded that alkaline electrolyzer are a better option with a capacity of generating over 25 kgH2h-1 (Felgenhauer & Hamacher, 2015). A similar study for the comparison of commercial use of alkaline and PEM were made by Schanlenbacg et al base on economic and technical aspects (Schalenbach, Zeradjanin, Kasian, Cherevko, & Mayrhofer, 2018). In the study it was seen that significant difference in alkaline and PEM electrolyzer was separator that is used to divide cell in to half for the production of hydrogen and oxygen. In case of alkaline this separator is a porous diaphragm which freely allows circulation of the hydroxyls (normally potassium hydroxide) present in solution of alkaline electrolyzer (Divisek, Malinowski, Mergel, & Schmitz, 1985), while in case of PEM this separator is a solid polymeric electrolyte that only allows necessary protons for electrolysis (Carmo et al., 2013).

Porous electrodes are present behind this separator covered with electro-catalyst which allows circulation of water, produced gas, electrons and ions during the reaction (Schalenbach, Lueke, & Stolten, 2016). For PEM cells only platinum group metals for

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electrodes are proved to be tested as stable commercially due to the acidic nature of the cell. This PGM have also acceptability of ionic activity as electro-catalyst in the cell (A. Li, Sun, Yao, & Han, 2018). Normally electrodes of PME are made up of solid polymeric electrolyte coated its base at anode with iridium and cathode with platinum. Contrary to solid polymeric electrolyte, KOH solution provides anions when used in alkaline electrolyzer, where electrodes are normally made up as metallic mesh of Ni (Schalenbach et al., 2016). As stable catalyst made up of Ni, Fe and Co are much cheaper and abundantly available than platinum group metals, so it made alkaline electrolyzer more economical viable for commercial activity than PEM electrolyzer.

There are several issues with the durability (Feng et al., 2017) of the PEM cells as lie during the replacement of the protons with other cations losing conductivity (Sun, Shao, Yu, Li, & Yi, 2014), degradation of cell with the formation of HF (Chandesris et al., 2015), under temperature and pressure dimensional properties of cell suffer (Kusoglu, Karlsson, Santare, Cleghorn, & Johnson, 2007) and oxidation of Ti present in bipolar plates and collector cause ohmic losses (Rakousky et al., 2016). Compare to PEM, alkaline electrolyzer are more stable and durable but most importantly if cell potential falls below 1.23V it required a stand-by power. This is yet a challenge for alkaline electrolyzer when coupled to a direct or isolated interconnection with renewable energy source. A comprehensive difference between alkaline, proton exchange membrane and solid oxide electrolyzer cell is shown in table 2.7.

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Table 2.7 A comparison between specifications of different electrolyzer (Buttler & Spliethoff, 2018; Dincer & Acar, 2015)

Specification	**Alkaline**	**Proton Exchange Membrane**	**Solid Oxide Electrolyzer**
Technology	Extensive Commercial	Limited Commercial	Research
Pressure (bar)	<30	<30	<30
Temperature (°C)	60 to 80	50 to 80	900 to 1000
Cell voltage (V)	1.8 to 2.4	1.8 to 2.2	0.95 to 1.3
Voltage efficiency (%)	62 to 82	67 to 82	81 to 86
Current density (A cm^{-2})	<0.45	1.0 to 2.0	0.3 to 1.0
Cell area (m^2)	3 to 3.6	<0.13	<0.06
H_2 production per stack (Nm^3H^{-1})	<1400	<400	<10
Stack lifetime (kilo hr)	55 to 120	60 to 100	8 to 20
Hydrogen purity (%)	>99.8	99.999	Under research
System lifetime (yr)	20 to 30	10 to 20	Under research
Cost (Euro kW^{-1})	800 to 1500	1400 to 2100	>2000

2.5 Integration of Electrolyzer with renewable energy (RE)

An electrochemical conversion of water is performed to produce hydrogen in an electrolyzer. Electrolyzer needs to be energize by using electric energy or also with thermal (in case of SOEC). This energy required for the electrolyzer can be harvested from renewable resources (Clarke, Giddey, & Badwal, 2010; Darras et al., 2010). This integration of renewable energy resources with electrolyzer can be advantageous for different applications such as on-demand requirement of hydrogen production on remote sites (Kovač, Marciuš, & Budin, 2019). Electrolysis combined with renewable sources produces less pollution as compared to other conventional ways. There are different renewable energy resources available that have a potential to be coupled with electrolyzer. Two factors were considered while concerning environmental consequences by Bhandehari et al. They analyzed their study on life cycle assessment based on Global Warming Potential (GWP) and Acidification Potential (AP) (Bhandari, Trudewind, & Zapp, 2014). A comparison of these rates are shown in figure 2.37 a & b. for electrolysis for obtaining hydrogen from different renewable resources.

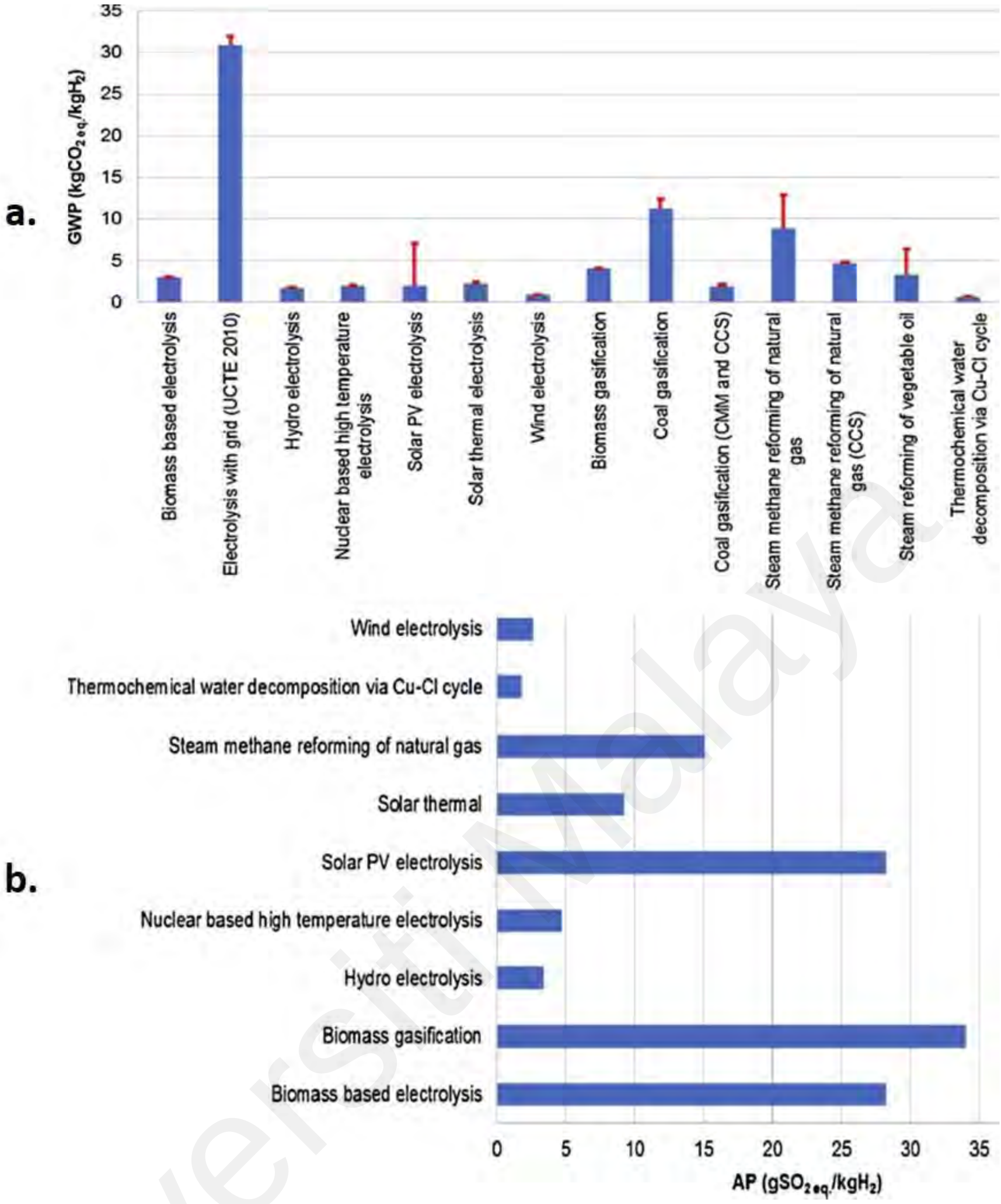

Figure 2.37 various H2 production technologies (a) GWP, (b) AP (Bhandari et al., 2014)

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In 2014, Acar and Dincer (Acar & Dincer, 2014) did a comparative study in Turkey on the performance of different renewable resources including biomass gasification, solar and wind for the production of hydrogen. Six different criteria where set for the study including energy efficiency, exergy efficiency, acidification problem, cost, global warming and social cost of carbon as shown in figure 2.38. Based on efficiency and cost criteria it was resulted that although biomass gasification shows better performance as compare to solar and wind but is poor in terms of social and environmental. On the other side solar and wind electrolysis seems to have better performance in social and environmental aspects. So Acar and Dincer concluded that solar and wind are better options for electrolysis system from which wind is the best due to low cost.

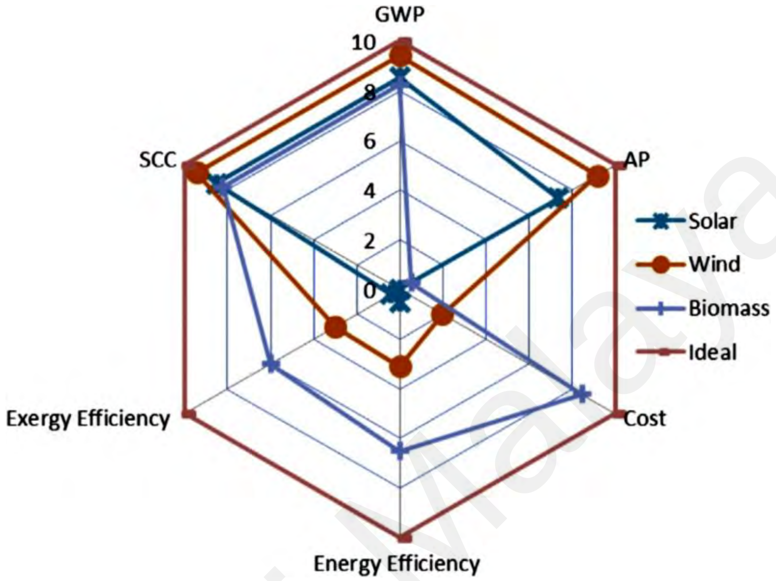

Figure 2.38 Comparison of three different renewable resources couple with hydrogen electrolyzer (Acar & Dincer, 2014)

2.5.1 Solar Energy

Solar energy is the most abundant source of renewable source available that provide both electrical and thermal energy. It gained attention due to its benefits (Ahmadi & Mehrpooya, 2015). Research is underway to use PV for energizing different applications like water pumps (Ba, Aroudam, Chighali, Hamdoun, & Mohamed, 2018; Jegha, Subathra, Kumar, & Ghosh, 2020). Direct coupling of PV with an application is always a challenge due to its intermittent nature. Recently, attempts have been made to directly couple electrolyzer (HHO generators) with solar PV due to the drive towards green energy and to minimize battery-related costs for on-demand HHO generation for various combustion-related applications (Niaz, Lakouraj, & Liu, 2021). Various studies have suggested pulse width modulation (PWM) as a useful technique for this purpose (Arat et

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al., 2016; Baltacioglu et al., 2016; K. P. Kumar et al., 2016; Seerla Sai Kumar & Kumar, 2015; Worawat & AURASOPON, 2015). PWM is a control technique that helps to regulate the input current of electrolyzer by setting its duty cycle and frequency. The duty cycle of a PWM signal is defined as the ratio of "on" times over the full signal period (Butt, Aslam, & Muazzam, 2015). By adjusting the duty cycle of the PWM, the input current can be regulated accordingly so that it can control the current of the electrolyzer. This PWM adjusts the operating voltage on the PV array I-V curve to keep its maximum power point and convert that power into voltage and current according to the requirements of the electrolyzer. A recent study concluded that electronic coupling of a PV by mean of an optimizer can increase the efficiency 5% more than other strategies (Sriramagiri et al., 2019), but the exact efficiency of electronic coupling over direct coupling of PV and electrolyzer is dependent on different parameters such as their I–V behavior, selection of PV, geographic location and scale.

The DC-DC buck convertor has also been used for efficiently connecting electrolyzer with a DC bus bar. Different topologies of DC-DC convertors were considered based on the conversion ratio (Blinov & Andrijanovits, 2013; Özgirgin, Devrim, & Albostan, 2015; Tabanjat et al., 2015). Convertors with high conversion ratio have been deemed beneficial for electrolyzer applications due to their use of very low DC voltages compared to the high DC bus voltage (Damien Guilbert, Collura, & Scipioni, 2017). The conversion ratio is not only an important parameter in designing of the convertor for electrolyzer applications. Some requirements should be taken in consideration which include: (1) the output current ripple that must be as small as possible in order to optimize the electrolyzer lifespan (D Guilbert, N'Diaye, Luberda, & Djerdir, 2017), (2) energy efficiency (Garland, 2010), and (3) cost (Kolli et al., 2015). Based on all these factors, the classic DC-DC buck convertor is the most mature and used topology to couple an electrolyzer with a DC bus bar.

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Abundance of solar energy makes it a potential contender for coupling with electrolyzer system. Some of the review studies are carried out on solar hydrogen productions system (Guo et al., 2010). Studies concluded that solar energy has a potential and still considered as one of the best method to produce hydrogen from renewable resource. There are different types of solar collectors so different configurations for each of them are used to couple with electrolyzer system. Due to these different type of solar collection methods PV considered as one of the most mature technology of renewable energy. PV/Electrolysis technique has gained much attention of researchers as it is cheaper with low maintenance. As PV arrays only generate electricity so it is usually coupled with alkaline and PEM electrolyzer which do not need any thermal energy. But still this technology is needed to improve its efficiencies technically and economically at large scale. An attempt was made in 2019 (Mohammadi & Mehrpooya, 2019) shown in figure 2.39 to couple solar parabolic collectors in order to supply high temperature for solid oxide electrolyzer cell. Optimization studies reveals that an efficiency of the system was achieved to 26.81% while the lowest cost of hydrogen was 4.43$/kg.

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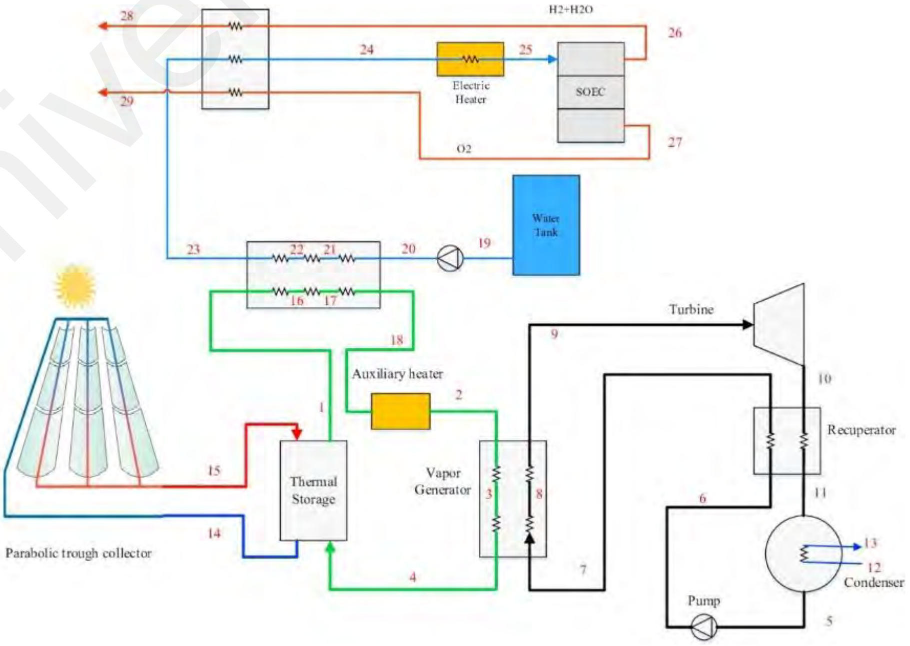

Figure 2.39 Coupling of parabolic collectors with solid oxide electrolyzer cell (Mohammadi & Mehrpooya, 2019)

2.5.2 Wind Energy

Wind energy is one of the important and promising renewable source. One of the biggest disadvantage of wind energy is its intermittent nature so it's not a reliable source of power energy as output power of wind energy is highly variable. To overcome this issue, an energy storage device is needed to integrate with wind turbine for its smooth and constant output power. If electrolyzer cell (especially alkaline electrolyzer) undergoes part load operation or experience over current, it deteriorates the performance of cell significantly. This results in thermal management issues problem which reduces cell efficiency. If electrolysis system coupled with wind turbine, it requires some hybrid system or control strategies. Some studies by De Battista et al. (De Battista, Mantz, & Garelli, 2006), Mantz et al. (Mantz & De Battista, 2008), Muyeen et al. (Muyeen, Takahashi, & Tamura, 2011) suggested different control strategies to couple and match electrolyzer system with wind turbine. With the help of these strategies, electrolyzers can be operate at their full capacity which results in higher rate of production of hydrogen. Study by Kalinci et al. (Kalinci, Hepbasli, & Dincer, 2015) also suggest a hybrid system of PV and wind turbine which has lower net present cost as compared to wind turbine alone. A similar study as shown in figure 2.40 was done by Huang et al. (Huang, Kuo, & Wu, 2016) who proposed a system to produce hydrogen for refueling station for a fuel cell electric vehicle. As wind turbine only generate electricity, so this technology can be coupled with low temperature electrolyzer which include alkaline and PEM electrolyzer.

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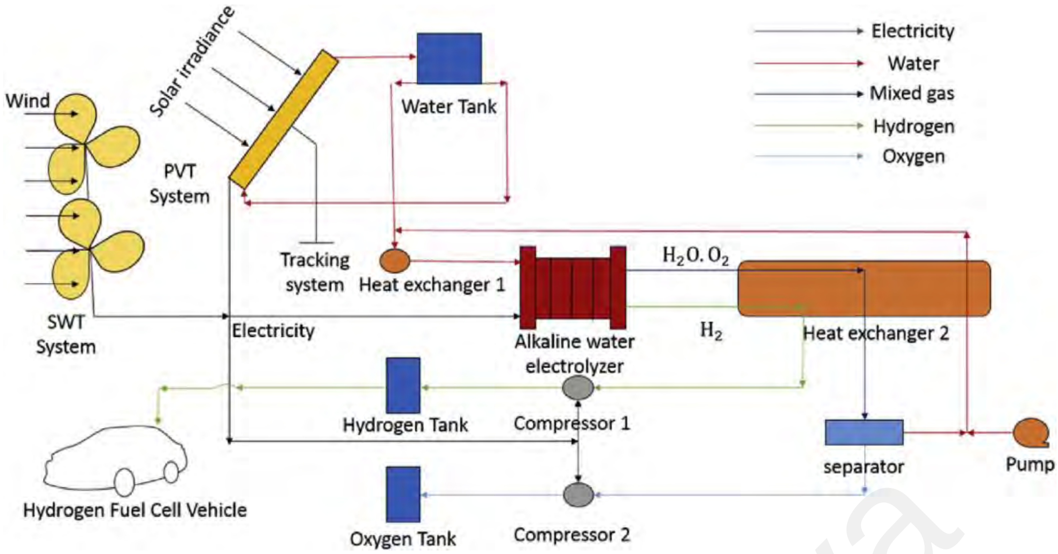

Figure 2.40 Proposed hybrid system of PV panel and wind turbine for hydrogen refueling station (Huang et al., 2016)

2.5.3 Geothermal Energy

Geothermal energy shows a potential to integrate with different methods to produce hydrogen as it can provide both thermal and electoral energy to electrolyzer. Some of the methods are listed by Balta et al. (Balta, Dincer, & Hepbasli, 2010): Water electrolysis by using electricity generated by geothermal power plant, by recovering hydrogen from gas mixture of geothermal steam, high temperature water electrolysis by using electricity and heat energy generated in geothermal power plant, utilizing heat produced in geothermal power plant for thermochemical processes. A similar study was made by Kanoglu et al. in 2010 (Kanoglu, Bolatturk, & Yilmaz, 2010) to make a thermodynamic assessment of four different strategies (shown in figure 2.41) of producing hydrogen by using geothermal energy.

Coupling of high temperature electrolysis process with geothermal energy was first studied by Jonsson et al. (Jónsson, Gunnarsson, Árnason, & Sigfússon, 1992) in which they compared the economic analysis on integrated system in order calculate production cost of hydrogen with other water electrolysis systems. In another study Sigurvinsson et

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al. (Sigurvinsson, Mansilla, Lovera, & Werkoff, 2007) investigated the potential of geothermal hot water thermal energy for solid oxide electrolyzer cell. As SOEC required thermal energy so in this proposed system (as shown in figure 2.42) geothermal energy was used to increase the temperature of water.

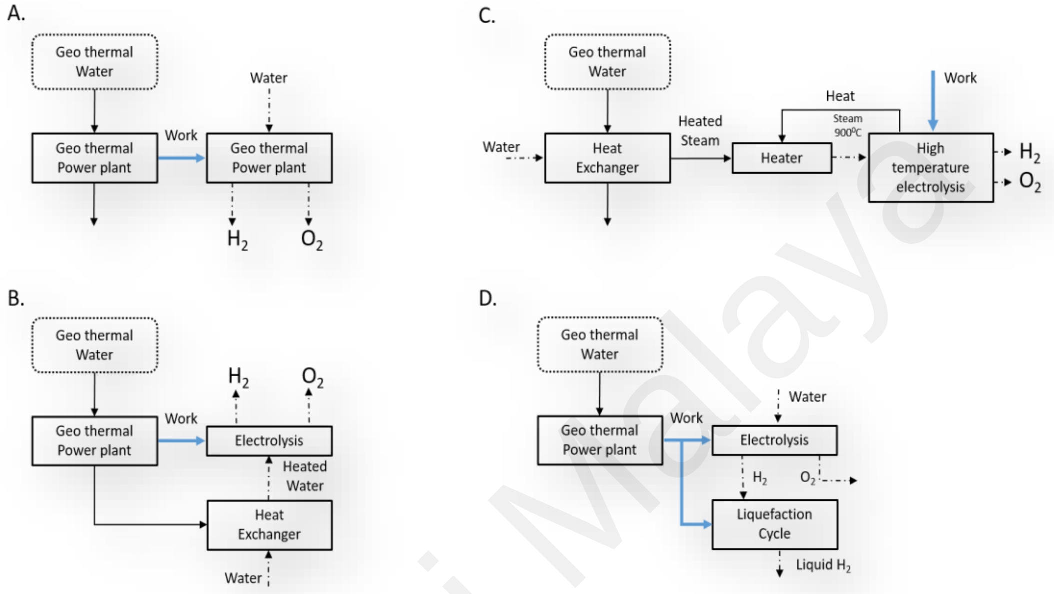

Figure 2.41 Thermodynamic assessment of four different strategies (shown in figure) of producing hydrogen by using geothermal energy (Kanoglu et al., 2010)

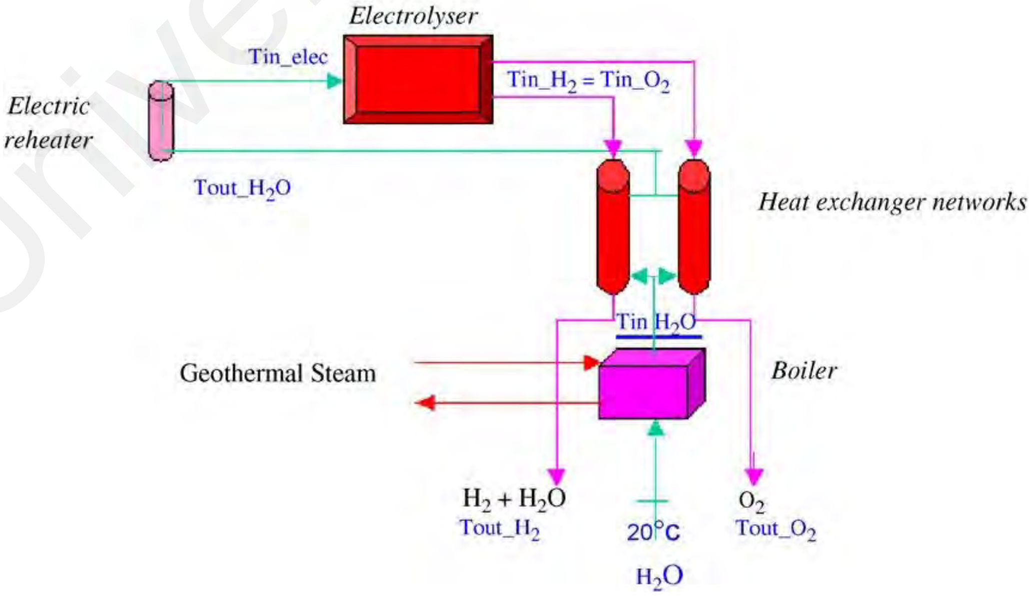

Figure 2.42 Proposed system for coupling SOEC with geothermal energy (Sigurvinsson et al., 2007)

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A feasibility study in Iran (Rahmouni, Settou, Chennouf, Negrou, & Houari, 2014) was made on system of hydro-electrolysis system using electrical energy generated from geothermal energy. Different factors were taken into consideration for this study such as: total number of geothermal fields, distance between main roads and these springs, total energy produce from these springs, total number of stakeholders consuming hydrogen in area, population and available skilled labor, level of air pollution and total area of province under consideration. Study revealed that 1.09 MW of electrical energy was been generated from plant which was used to energize electrolyzer which was producing hydrogen at rate of 22kg/h.

2.5.4 Techno-economic analysis of H_2 production by electrolysis through RE

Moriarty and Honnery (Moriarty & Honnery, 2007) also studies integration of renewable resources with hydrogen electrolyzer. They concluded that hydro, biomass and geothermal has not enough potential to cater need, similarly nuclear energy is also not a good option. They also concluded that wind energy is the most promising option for this purpose. Table 2.8 shows results of different techno-economic studies that were performed on different types of electrolyzer by using different other renewable sources.

Table 2.8 Techno-economic analysis of hydrogen production by different source of renewable energy sources in literatures

System Description	Cost
Solar Energy	
Direct coupled PV-PEM electrolyzer (Sayedin, Maroufmashat, Sattari, Elkamel, & Fowler, 2016)	8.05 \$/kg H_2
Combined PV modules and parabolic trough collectors with SOEC electrolyzer (S Koumi Ngoh, Ohandja, Kemajou, & Monkam, 2014)	5.23 \$/kg H_2
Solar thermal power integrated with alkaline electrolyzer (Simon Koumi Ngoh & Njomo, 2012)	2.92 \$/kg H_2
PV modules with alkaline electrolyzer (Simon Koumi Ngoh & Njomo, 2012)	7.32 \$/kg H_2
Grid assisted PV-PEM electrolyzer (Shaner, Atwater, Lewis, & McFarland, 2016)	6.1 \$/kg H_2

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Gird connected SOEC integrated with parabolic trough collector with phase change material thermal storage for providing thermal energy (Seitz, Von Storch, Nechache, & Bauer, 2017)	4.02 \$/kg H_2
Alkaline electrolyzer with solar Rankine cycle for power production (Boudries, 2018)	6 \$/kg H_2
Wind Energy	
Electrolyzer powered by wind turbine (Genç, Çelik, & Karasu, 2012)	3.1 \$/kg H_2
Wind turbine and alkaline electrolyzer (Simon Koumi Ngoh & Njomo, 2012)	2.60 \$/kg H_2
Wind turbine-electrolyzer-PEM fuel cell (Rahimi, Meratizaman, Monadizadeh, & Amidpour, 2014)	5 \$/kg H_2
Geothermal Energy	
Electrolyzer powered by geothermal energy (C. Yilmaz, Kanoglu, Bolatturk, & Gadalla, 2012)	0.97 \$/kg H_2
SOEC electrolyzer using geothermal energy for water preheating (Sigurvinsson et al., 2007)	1.90 \$/kg H_2
Geothermal plant with CO2 as working fluid and alkaline electrolyzer (Rahmouni et al., 2014)	8.24 \$/kg H_2
Binary geothermal plant and PEM electrolyzer (C. Yilmaz, Kanoglu, & Abusoglu, 2015)	2.36 \$/kg H_2

2.6 Coupling of Electrolyzer with Renewable Energy?

Research trend are focusing on improving gas quality of HHO gas. According to U.S Department of Energy (*Fuel Cell Technologies* 2016) challenges faced by hydrogen production from water electrolysis are: hydrogen cost, electrolyzer efficiency and price of electricity. Therefore, it is important to consider the cost, efficiency and emissions resulting in production of electricity before accessing the advantages and economic feasibility of hydrogen production from water electrolyzer. Different renewable resources are under research for many years as potential alternative of source of energy generation. These include PV, wind, geothermal, biomass etc. For the last decade, oxyhydrogen gains a lot of interest for researchers due to its properties. High burning velocity, wide flammability range, extra oxygen content and carbon-free structure of oxyhydrogen gas made it a clean fuel (Baltacioglu et al., 2019). Oxyhydrogen turns not only clean but with the advancement of technology it has become economical viable too. An estimate energy

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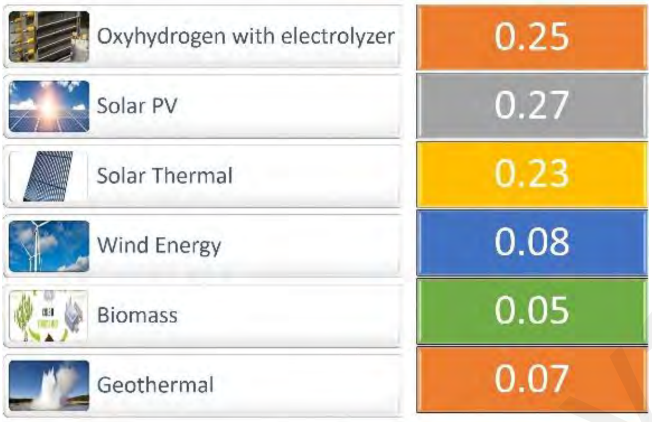
cost of different renewable energy resources was calculated (Al Garni, Kassem, Awasthi, Komljenovic, & Al-Haddad, 2016; Marchenko & Solomin, 2019) is shown in figure 2.43.



Oxyhydrogen with electrolyzer	0.25
Solar PV	0.27
Solar Thermal	0.23
Wind Energy	0.08
Biomass	0.05
Geothermal	0.07

Figure 2.43 Energy cost of different renewable resources in USD/KWh

Advances of integrating hydrogen in power systems have been gradually made in recent years ranging from production and storage to re-electrification and safety issues. Extensive descriptions of the existing progress can be found elsewhere and a number of studies are seeking to characterize the current progress in hydrogen system integration by novel methods. A wide consensus has been reached that producing hydrogen from renewable energy sources (solar, wind, etc.) shows great promise for the world's sustainable development (Yue et al., 2021). Chi et al. have pointed out that changing the hydrogen production by using renewable electricity can enhance the interconversion of electricity and hydrogen and expand the hydrogen application (Chi & Yu, 2018). Numerous researches on renewable hydrogen production technologies were launched and have generated great interest

Researchers are more focused in energizing hydro-electrolysis system be mean of renewable source of energy in order to achieve 'green technology' goal. Different studies have been done on various types of coil, composition and variations in catalyzer. But

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control process of coupling renewable source with the electrolyzer cell is the most promising approach to enhance and improve the quality of gas production. One of the challenge to use electrolyzer for the production of HHO gas by using renewable source is the strategy to integrate renewable source with the electrolyzer system. Different studies have been done in the past decade to optimize the production of HHO gas by controlling renewable resource. Generally coupling techniques are classified in two groups: direct coupling, indirect (convertor) coupling. Most of the studies are focused on photovoltaic generators for hydrogen production. Due to inherent variability of wind as compared to solar energy, less attention has been given to wind turbine for coupling with water electrolyzer for producing hydrogen.

2.6.1 Direct Coupling

Integration of renewable source directly with the electrolyzer is possible but has a limited scope. Normally, it is directly coupled in case of PV systems. Such coupling is done in order to make system simple, minimize electronic interference and would low the cost which in result enhance the economic viability of solar-hydrogen system. A simulation study by Rahim et al. (Rahim, Tijani, Fadhlullah, Hanapi, & Sainan, 2015) was performed for direct coupling of PV panel (60W) and alkaline electrolyzer. Different number of electrolyzer cells were varied to match the available power from PV. This simulation was done on different operating temperatures (40, 60 and 800C). It was observed that there was no significant effect on Faraday’s efficiency of electrolysis process upon different operating temperature. But this efficiency sharply increases to maximum 98% at current density of 90 mA/cm2. In another study a successful attempt of direct coupling of polymer electrolyte membrane was done with matched solar photovoltaic source to produce hydrogen (shown in figure 2.44) (Clarke et al., 2009). An automatic start and shut down control system was design to run the system with a goal of minimum energy loss with maximum safety.

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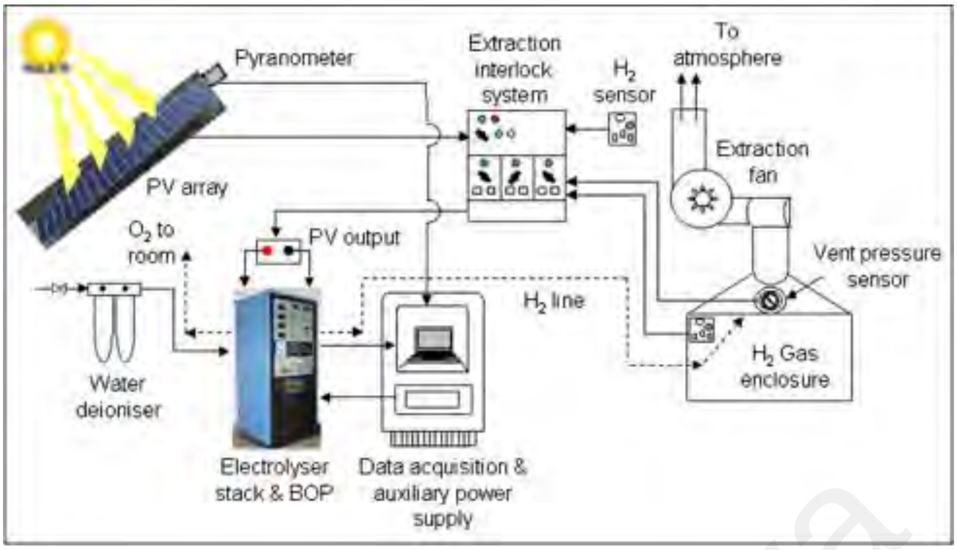

Figure 2.44 Direct coupling of PV array with proton membrane electrolyzer (Clarke et al., 2009)

There are different methods to control the water electrolyzer cells for PV-WE system as a stand-alone and isolated from grid. This control depends upon some weather conditions (Maeda, Ito, Hasegawa, Zhou, & Ishida, 2012). In IV estimation method, IV characteristics of PV module are calculated based on PV temperature and solar insolation, and then this nonlinear equation of current-voltage characteristics of the PV is used to determine the optimum number of electrolyzer cell. For PV temperature method only the temperature and output current of PV module are used to control system. While in PV current method only output current from PV module is used for control. An experimental setup (Maeda et al., 2012) of direct coupling of electrolyzer cell with PV is shown in figure 2.45 was setup to verify these control methods. In this strategy parallel switches are installed which toggle the water-electrolyzer cells on/off to adjust according to the operating conditions. Results shows a high maximum power point tracking efficiency of around 98% was achieved for all these three methods but PV current method is the simplest way of control technique among these three.

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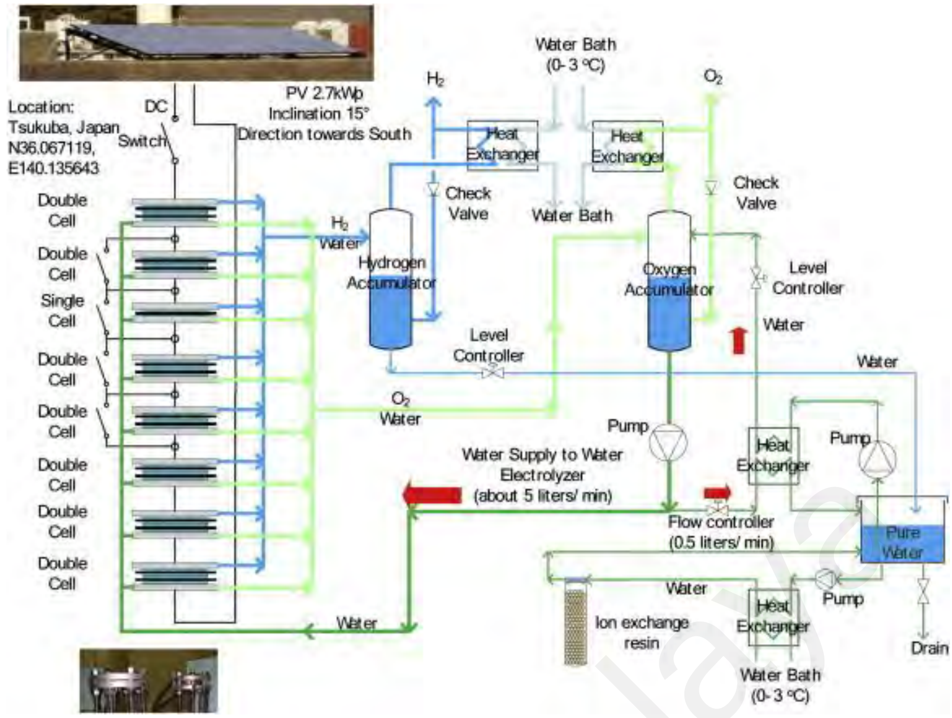

Figure 2.45 Optimization of direct coupling of electrolyzer cell with PV by toggling switch (Maeda et al., 2012)

As there is variation in maximum power point of PV with the fluctuation in irradiance, Duc et al. (Duc, Goshome, Endo, & Maeda, 2019) formed an algorithm shown in figure 2.46 for MPPT that tracks the maximum power point by changing the number of electrolyzer cell. This concluded with an efficiency of PV and electrolysis about 17.2% and 86.5% respectively.

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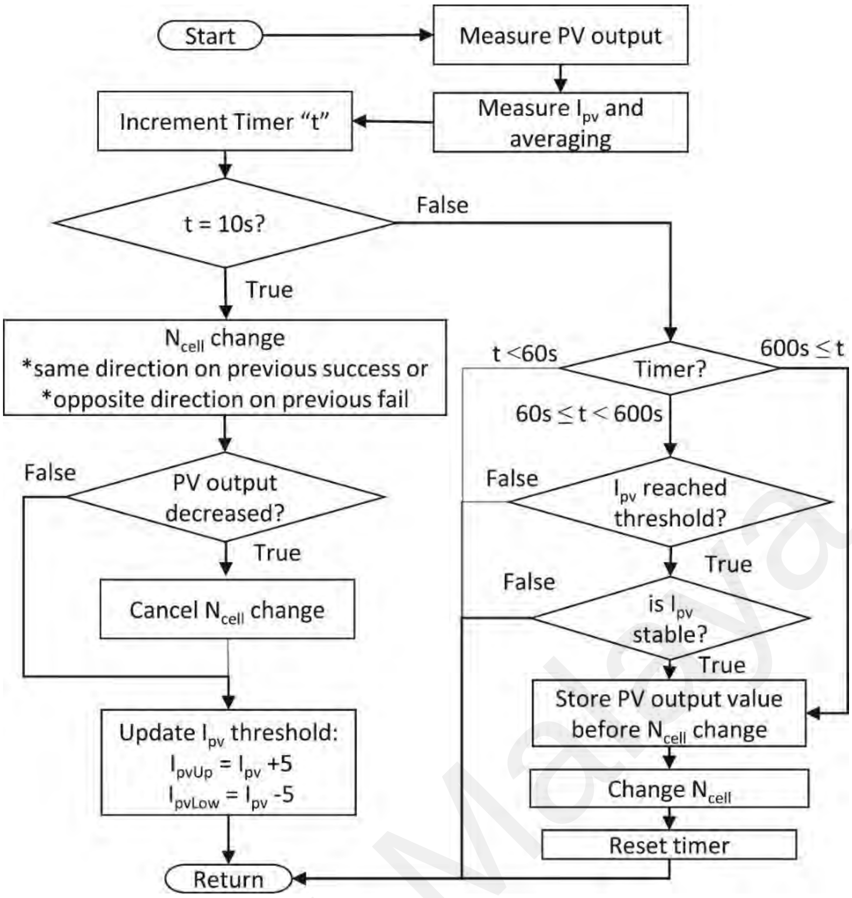

Figure 2.46 Algorithm for MPPT that tracks the maximum power point by changing the number of electrolyzer cell (Duc et al., 2019)

2.6.2 In-Direct Coupling

Interfacing of electrolyzer with renewable sources (especially solar and wind) is always a challenge due to their intermittency. As electrolyzer required a low but constant voltage source so there is need to have an efficient control or coupling technique. Considering the system as an electrical, literature reveals that electrical current is the most principal parameter for controlling electrolyzer with renewable source efficiently (Worawat & AURASOPON, 2015). Pule Width Modulation (PWM) is the suitable solution for to control HHO production (K. P. Kumar et al., 2016). By using this PWM control technique, input current into the HHO gas generate can be regulate by setting the duty cycle and frequency of the current. 'Duty cycle' can be defined as the ratio of "on" state over the full period of signal. Other parameter which is to be kept in mind is the

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temperature of the electrolyzer. Increase in the temperature of the reactor can create vapors which disturb the conductivity of the electrolyte solution which lead to the degradation of the HHO gas. If HHO generator system is directly driven at full load without using control technique, it can raise the temperature up to 90ºC (Sudarmanta et al., 2016). It not only reduces the production of the HHO but also decrease the quality of the gas with more moisture content in it. High temperature in reactor also shorten the lifespan of the system. Pulse Width Modulation (PWM) strategy has a promise to lower the vaporization which can increase the life span of the reactor as well as improve the HHO gas quality. In a study it was reported that upper limit of the temperature for HHO gas generator is 70ºC (Bhardwaj et al., 2014). Therefore, main objective of the PWM technique is to feed current to HHO gas generator by optimizing the temperature below this range.

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Sahin et al. (Şahin et al., 2014), couple the water electrolyzer cell of 2 Volts with a system of solar and batteries of 12 Volts. It was found that practically electrolyzer behave as a non-linear load so ordinary buck convertor cannot be used. So synchronous buck DC-DC convertor was designed and tested at 25 A output current. Jacobs (Jacobs, 2010) also designed a convertor (shown in figure 2.47) for an isolated renewable energy system based on small wind turbine.

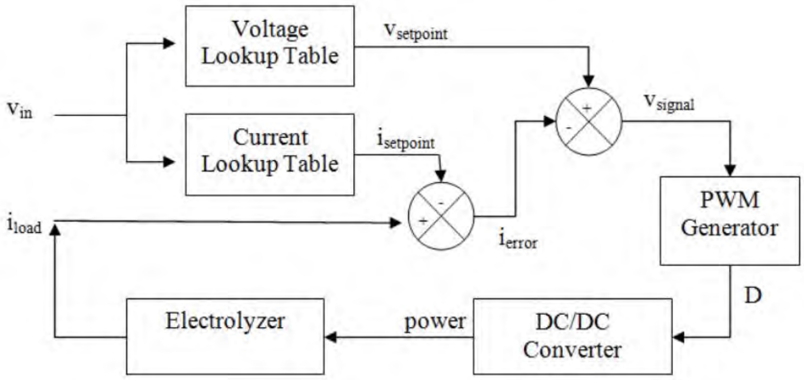

Figure 2.47 Isolated renewable energy system based on small wind turbine (Jacobs, 2010)

In another study (Muyeen et al., 2011) hydrogen generator was connected with a wind farm which is composed of variable speed turbines driving permanent magnet synchronous generators. Rectifier was used for hydrogen generator and each 10 electrolyzer units were controlled by chopper circuit individually as shown in figure 2.48. To smooth the intermittency of the wind farm, a centralized control scheme was developed shown in figure 2.49 to control all 10 units of the electrolyzer. A flow chart is shown in figure 2.50 displaying the complete switching strategy for electrolyzer. This switching strategy based on FIFO algorithm helps to increase the life span of individual working unit at full load.

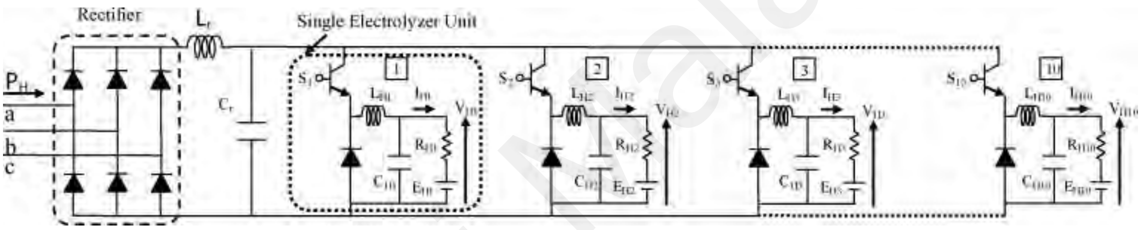

Figure 2.48 Rectifier connected with 10 units of electrolyzer units control by chopper circuit (Muyeen et al., 2011)

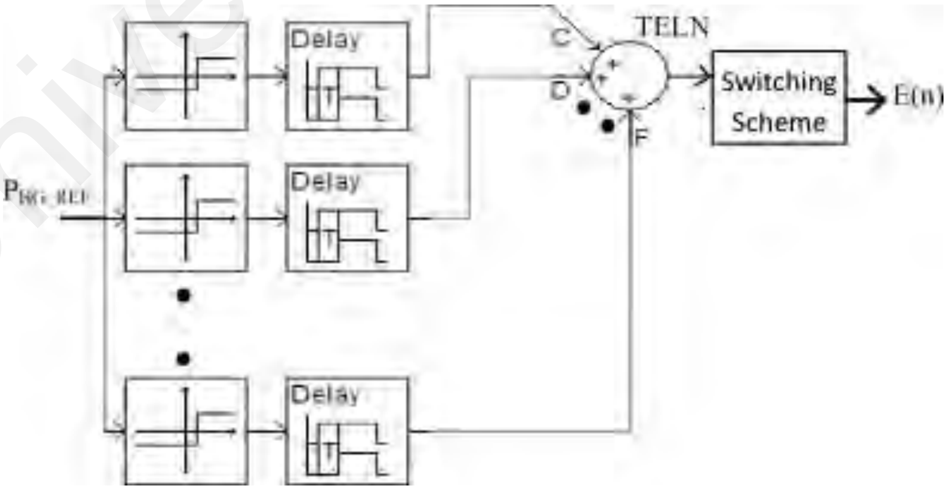

Figure 2.49 A centralized control scheme for connecting electrolyzer with wind farm (Muyeen et al., 2011)

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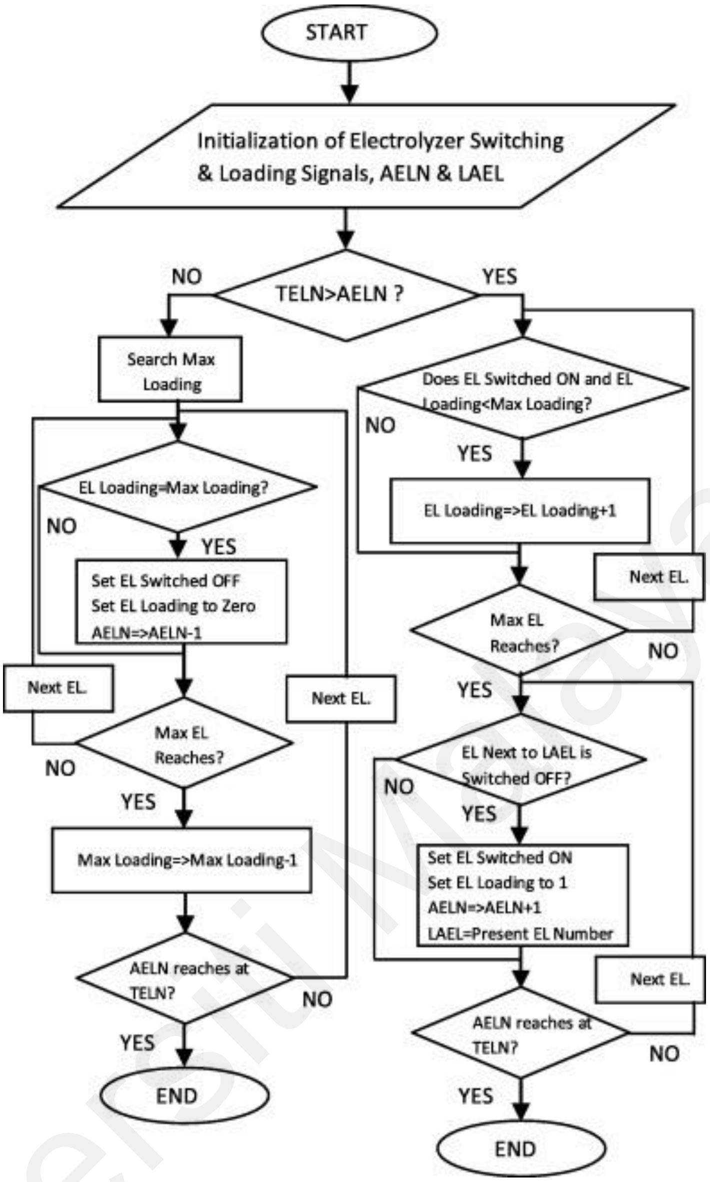

Figure 2.50 Flowchart for complete switching strategy for electrolyzer coupled with wind farm (Muyeen et al., 2011)

In another optimization study by Conker (Ç. Conker, 2019) was made to protect HHO generator from extreme temperature effects by maximizing production of hydrogen. A fuzzy logic controller was designed by aiming two process specific parameters: temperature and HHO flow rate. Study proven that this strategy was an effective way of maximizing production rate of HHO while keeping the temperature to limit by controlling current to certain limits.

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2.7 Safety concern related to hydrogen

Hydrogen with lowest calorific value is 122 KJ/g which is still greater than other hydrocarbons like natural gas with 42 KJ/g and gasoline with 45 KJ/g. So safety concerns must be addressed by maintaining standards and special precautions while handling with hydrogen. In terms of safety factors, hydrogen is equal to 1 as compared to natural gas with 0.8 and gasoline 0.53 (Moreno-Soriano, Soriano-Moranchel, Flores-Herrera, Sandoval-Pineda, & González-Huerta, 2020). Hydrogen is considered as a flammable non-toxic gas, which is odorless, colorless and tasteless. Upon burning it does not create fumes or pollute atmosphere that is a major concern of today. But it’s not easy to work with hydrogen and could be hazardous if not handle properly. Following are some properties that made hydrogen as potential hazards.

It required very low ignition energy. Oxyhydrogen has a major component of hydrogen, so it has a wide range of concentration of combustibility that could be from 4% to 74.2% by volume. On burning it has a nonluminous flame which cannot be visible under bright light. Due to smaller sizes of the molecules of hydrogen present in oxyhydrogen, it can easily pass through porous material.

The most safer way to use hydrogen is ‘on-demand’. In this way oxyhydrogen will be produce to the amount required by the application and no storing or transportation will be involved. This method is mostly observed in different studies of combustion engines when used with oxyhydrogen. This will also reduce of risk factors of leakage of flash over that were major problems for storing hydrogen. Hydrogen produce by renewable sources like PV or wind has a lot of potential for on-demand applications that has a potential to use hydrogen as fuel. Also this on-demand production of hydrogen is much beneficial for fuel cell based vehicles or even for internal combustion engines that required fuel on site/application (Williams, 2010). Usage of on-demand hydrogen

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production will not only prevent for hazard risks but also have a potential for stand-alone applications and systems. A safety control system was suggested for the integration of hydrogen fuel with heating system for on demand production. Control was designed in such a manner that it will determine if ignition is present in a burner assembly prior to generating the oxy-hydrogen fuel and providing it to the burner assembly (Robinson, 2012). Control was also responsible for removing residual hydrogen gas from system lines when heating is no longer needed.

Different safety controls are used while producing and utilizing hydrogen gas. Devices like pressure control device, temperature control device, water level control device and a catalyst level control device are used in a security control system to improve and ensure the security of the hydrogen fuel producing apparatus (S.-Y. Lin, Ko, Lee, Lu, & Lee, 2003). Normally an electronic controller is used to control the current feed to electrolyzer for controlling the production of hydrogen. There is always a chance of back flow of hydrogen gas when pressure is reduced at generation end. This can cause a flash back. To prevent from such incident, bubblers and flash-back arrestors are used in the combustion system. Arrestors keep burning gases from blowing through the tube. These flash-back arrestor are made from special material which are capable of working on low pressure. There are three different forms of arrestors: (1) valve type, (2) filter type and (3) water bubbler. Valve type arrestor (shown in figure 2.51 (a)) uses suddenly increased air pressure in the tube to close a one-way valve. In filter type flash arrestors shown in figure 2.51 (b), bronze wool or permeable stones are used as quenching material when a flash back occurs. Water bubbler is the simplest flash arrestor. It uses water as buffer medium to control the flash backs. Bubbler-type of arrestor is shown in figure 2.51 (c). Furthermore, different materials like calcium carbonate, bauxite, silicon dioxide can be used as suppression material on the explosion of hydrogen gas (Z. Chen, Fan, & Jiang, 2006). Zhihua concluded that calcium carbonate is the best material for suppression

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explosion (Z. Chen et al., 2006). Further with the increase of dust cloud density or the decrease of particle diameter enhance the suppression capability of material.

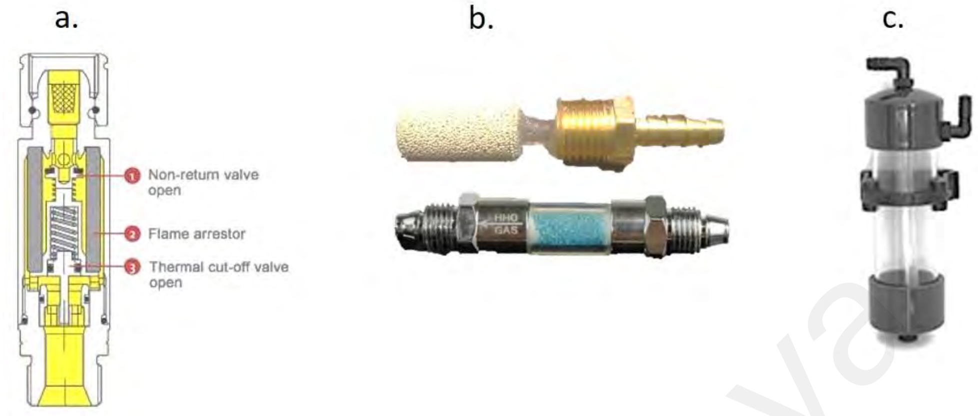

Figure 2.51 (a) Valve- type Flash-back arrestor (b) Filter- type Flash-back arrestor (c) Bubbler- type Flash-back arrestor

2.8 Challenges for waste management

Urbanization has also increase the volume of municipal solid waste (MSW)(Goorhuis & Bartl, 2017). This urbanization is increasing with a rate of 1.5% (Ouda et al., 2016). This urbanization and economic development is escalating MSW (A. Kumar & S. Samadder, 2017).According to a report of World Bank, there will be a tremendous increase in per day generated solid waste from 3.5 million tons to 6.1 million tons by 2025 due urbanization(Hoornweg & Bhada-Tata, 2012).This waste is a big obstacle for the sustainable development of economy and society. Economic and household activities are the main root cause of this waste. Half of the total waste of 4 billion tons generated includes municipal solid waste (ISWA, 2012). Generation of Municipal Solid Waste on economic situation of the countries is shown in figure 2.52.

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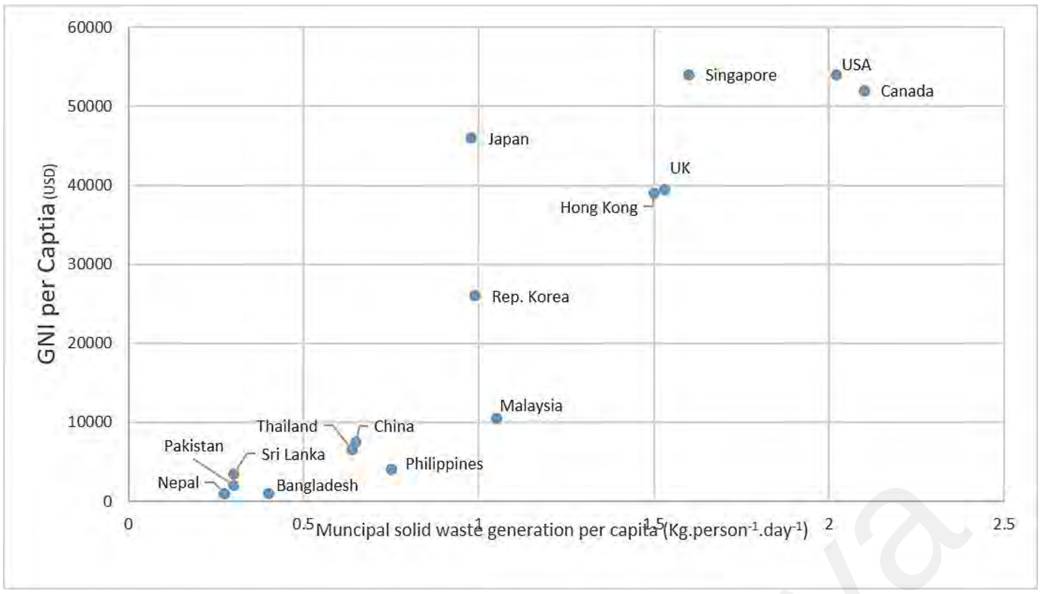

Figure 2.52 Generation of Municipal Solid Waste in different regions of world according to economic situation (Agamuthu & Masaru, 2014; Aleluia & Ferrão, 2016; Siriratpiriya, 2014; Thai, 2014)

Waste management system is one of the options which can not only be a potential source of energy but also address municipal waste problem(Bajić et al., 2015). Different waste to energy technologies like incineration can play a vital role towards sustainable environment. It is considered to be most effective and suitable options for addressing waste relate issues. These are promising technologies to turn waste into useful energy especially for the developing countries. Waste to energy includes all the activities which can turn municipal solid waste into an opportunity of sustainable energy. Waste to energy provides a solution to recover energy in the form of heat, fuel or electricity (by running steam turbines) from waste material(X.-g. Zhao et al., 2016). There is an estimation that municipal solid waste has a potential of 20 billion GJ, which is equivalent to 12.6% of the total energy generated from coal which can be escalated to 21.7% by 2035. It is seen that by incineration of municipal solid waste it can be possible to generate 800 billion kWh of electrical energy which is almost 3.5% of the world’s total generation(Vlaskin, 2018).

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2.9 Types and Characteristics of Municipal Solid Waste

Municipal Solid Waste (MSW) refers to the materials that are discarded and collected by the municipalities to dispose. MSW comprises of majority of household waste and sometimes with little addition of commercial waste. This waste has significant fraction of food waste, wood, leather, paper, and sometimes materials derived from fossil fuel like plastics, rubber and fabrics. Figure 2.53 shows waste composition of waste in different regions of the world.

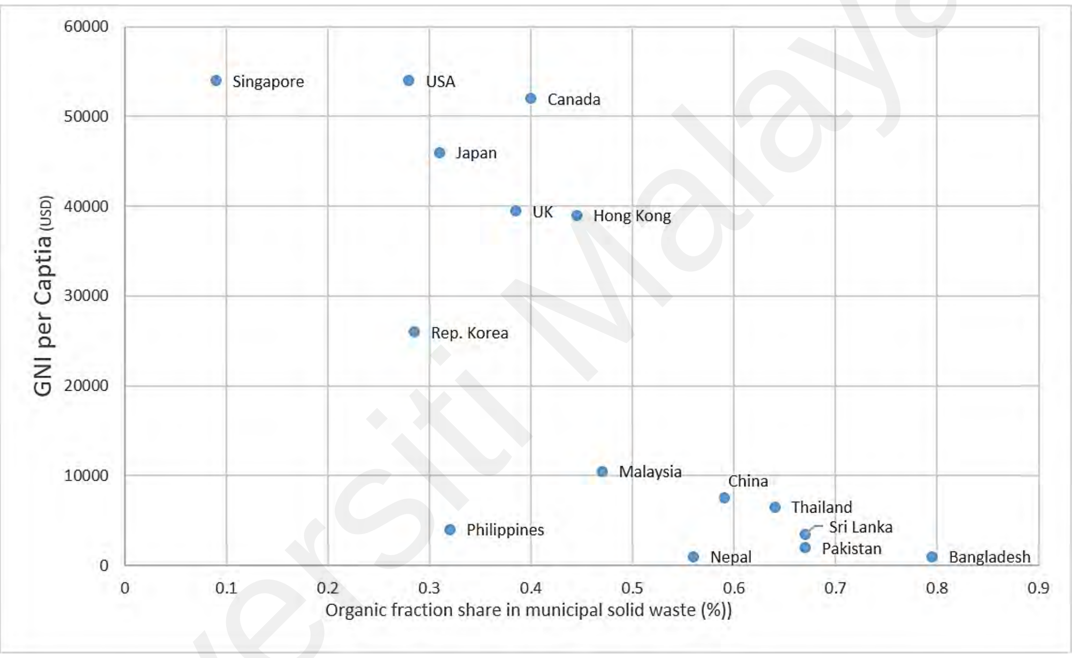

Figure 2.53 Variations in organic composition of Municipal Solid Waste in different regions of world according to economic situation(Agamuthu & Masaru, 2014; Aleluia & Ferrão, 2016; Siriratpiriya, 2014; Thai, 2014)

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Generally, municipal solid waste composes of variety of materials with different characteristics which directly determine combustibility of the waste in the furnace. The composition and volume of the waste is directly linked with the environmental and economic situation of the region. It is also depending upon the living standard, activities of the people, population of the city etc (Beyene et al., 2018). It is seen that under developed countries possess higher share of biodegradable organic waste than the countries with higher economical values as shown in figure 2.53. This study shows that countries in high economic zone are more responsible for paper waste. But in overall picture of waste generation, organic waste shares most of the chunk of the waste generated globally. From figure 2.54, same trend of waste generation can be in Asian region. Countries in lower economic zone like Myanmar, Cambodia are more responsible for generating organic waste than countries like Japan or Singapore. Countries like Malaysia faces several challenges towards treating their waste. These problems are either due to human behavior like sorting of waste at source or lack of technology, high operation cost, expensive than landfilling or emission of pollution. Controlling of hazardous emission and environmental impact with in standards is another big challenge for incineration of waste. In past a public resistance was faced by Malaysian government for Broga incinerator project which cause severe damage to its neighborhood and in result was discarded(Pek & Jamal, 2011). High moisture content is a major barrier for adopting incineration process. It reduces the calorific value of the waste. It was reported that Malaysian waste has range of 6276 to 10878 KJ/Kg as compared to developed countries that is between 8000 to 12000 KJ/Kg(Kokalj & Samec, 2013; Pek & Jamal, 2011).

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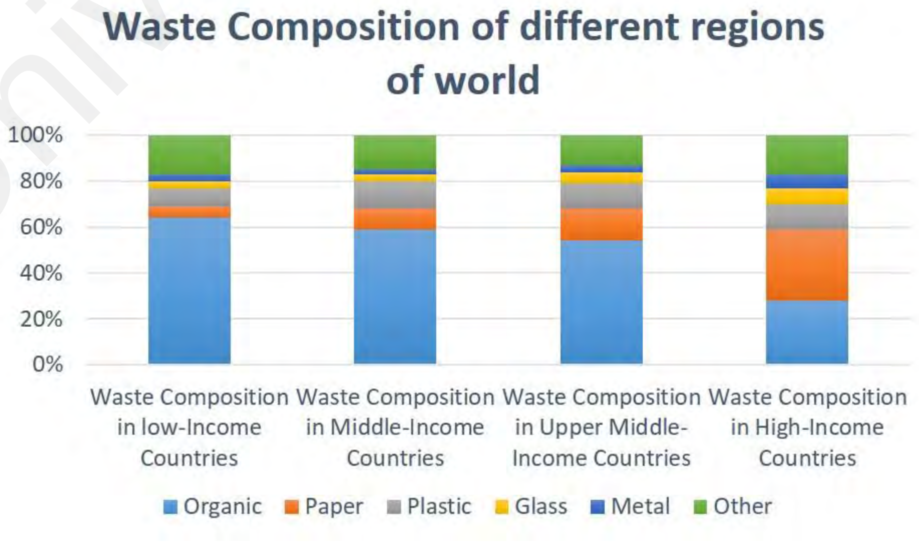

Figure 2.54 Waste composition of different regions of the world on economic situation (Makarichi et al., 2018)

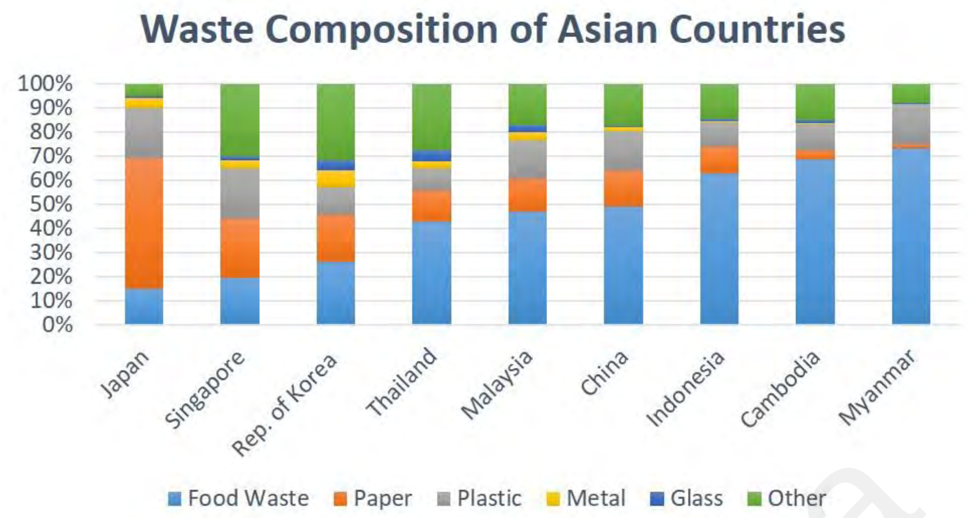

Figure 2.55 Waste composition of different Asian countries (Kamaruddin et al., 2017)

Municipal Solid Waste (MSW) of the region can be effectively managed by using a suitable waste to energy system. This can be done by knowing the characteristics and compositions of the waste generated in that region (Yadav & Samadder, 2017).There are three main contents of the waste determine its efficiency for incineration that is moisture, ash and combustible. For an effective incineration it requires low moisture content in the waste. It is the most crucial parameter as it can increase the weight of the waste without increasing the net yield(Cheng & Hu, 2010; Stoltz, Gourc, & Oxarango, 2010). It can affect the process negatively if the moisture content of the waste is not at the right level, thus result in low yield and make the overall system economically ineffective(Stanley, 2013). Normally, this moisture content is kept below 30%(Stanley, 2013). If the moisture content in the waste is high it will make it more suitable for landfill gas, anaerobic digestion or bio-digester(Zuberi & Ali, 2015). Size and density of the waste are also important as lesser size of organic waste decomposes faster and vice versa. Similarly, higher density in waste indicates its eco-friendly nature and can decompose faster compare to low density materials that are more significant as combustible materials like

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paper, wood, plastics etc. If MSW is not of good characteristics for incineration, it is than co-combust with other fuels to make an economical option. Most Often a tanner triangle is use to determine the proximate values of moisture, ash and combustible fraction is municipal solid waste. As shown in figure 2.56 shaded region represents allowable proximate values of moisture, ash and combustibility that are in range of combustion of MSW without the need of an auxiliary fuel. Figure 2.57 shows a thumb rule for the heat contents for the waste. It also shows the requirement of auxiliary fuel required for incineration according to the waste composition. Above that limit autogenous incineration is possible and requires no auxiliary fuel but below this limit incineration process is un fit for the waste(Sebastian, Kumar, & Alappat, 2019). It can also see from the figure 2.56 that these characteristics differ from region to region, for example MSW produce in United states is more economically favorable for incineration without adding any supplementary fuel as it contains more energy contents, while waste that is produce in China need a co-combustion method by adding some supplementary fuel to make it more economical viable.

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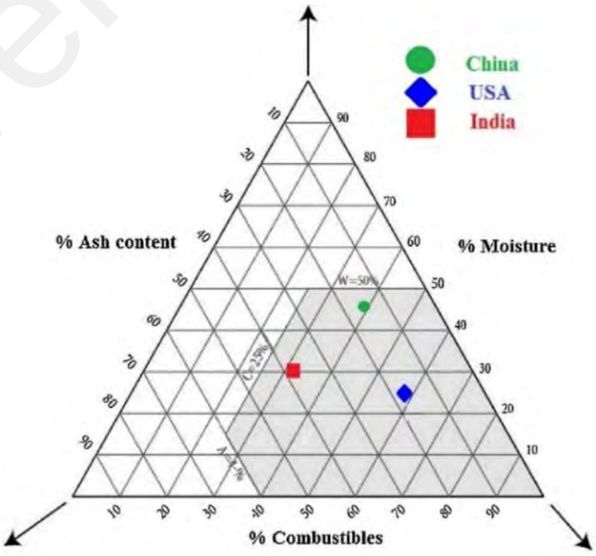

Figure 2.56 Variations in proximate characteristics of MSW in three different regions of world (Lu, Zhang, Hai, & Lei, 2017; Makarichi et al., 2018; Sebastian et al., 2019)

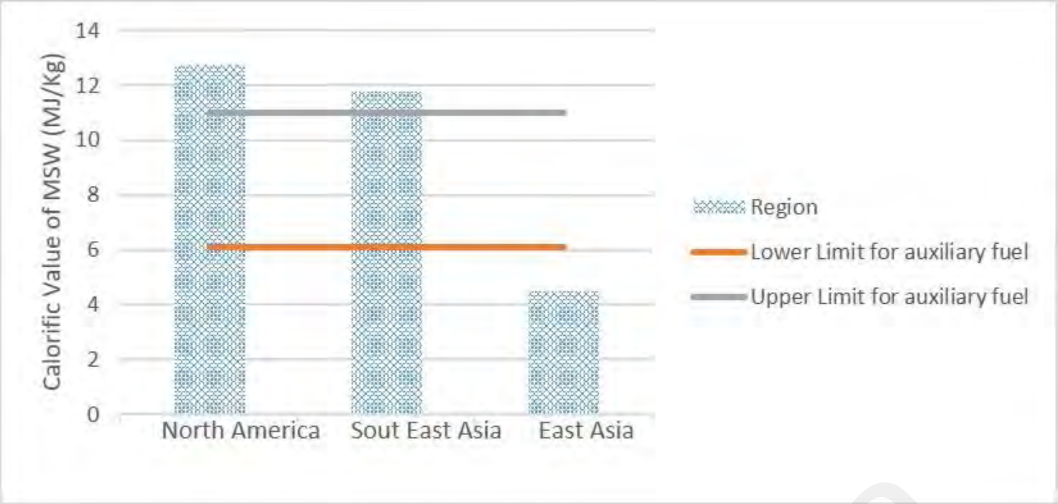

Figure 2.57 Heat content in waste of three different regions of world. Requirement of auxiliary fuel based on this heat content(Lu et al., 2017; Makarichi et al., 2018; Sebastian et al., 2019)

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Calorific value is an important parameter to determine the energy content of municipal solid waste. So for an efficient operation of waste to energy system there is a need to have an accurate and reliable data regarding the characteristics of the MSW(Shi et al., 2016). Normally, this calorific is categorized as higher heating value (HHV) and lower heating value (LHV). HHV is considered as latent of vaporization of waste which is considered as maximum energy content while LHV is not considered as latent heat of vaporization of moisture present in waste stream but the energy content available from complete combustion (Komilis, Evangelou, Giannakis, & Lymperis, 2012). This is measured with the help of bomb calorimeter or with the help of equations.

2.10 Technologies for waste management techniques

There are different types of technologies that are available for waste to energy process. Most common technologies are: (a) thermal conversion, (b) biological conversion, (c) landfill (Kalyani & Pandey, 2014).These technologies are further classified according to their processes and techniques as shown in figure 2.58.

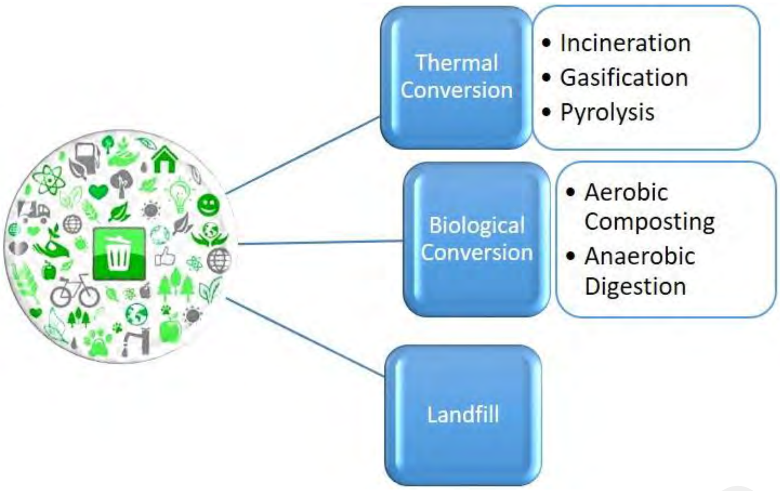

Figure 2.58 Different technologies for treating municipal solid waste (MSW)

2.10.1 Thermal Conversion

In this technology organic material in municipal solid waste under goes a thermal treatment which results in heat energy or some fuel. Thermal conversion technology is more suitable for waste with high percentage of non-biodegradable organic matter with low moisture content. Objectives of treatment have been changed for MSW towards the heat recovery systems with resulting clean flue gases. Incineration is most widely used as a thermal conversion technology for treating municipal solid waste at high temperature (Shi et al., 2016). Other technologies i-e gasification and pyrolysis are not used much for commercial purposes for treating waste and are still under research. May be this is due to unsuitable design of facility, lack in characterization of data or poor quality of MSW (Shi et al., 2016). Different reaction conditions of thermal conversion technologies are shown in table 2.9.

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Table 2.9 Different reaction conditions of thermal conversion technologies(Beyene et al., 2018; Chhabra, Shastri, & Bhattacharya, 2016; A. Kumar & S. R. Samadder, 2017)

Parameters	Incineration	Pyrolysis	Gasification
Temperature (°C)	750 - 1200	300 -1300	800 - 1200
Principal	Full oxidation	Absence of oxygen	Partial oxidation
Pre-treatment	Not required	Required	Required
Raw Municipal Solid Waste	Preferred	Not Preferred	Not Preferred

2.10.1.1 Incineration

For a robust incineration technology, it should have capability of volumetric reduction of municipal solid waste, optimal heat recovery and should able to clean the resulting flue gases up to the certain limits set for environment (Roberts, 2017).Objective of incineration is to destruct and degrade municipal solid waste (MSW) in the presence of oxygen in order to reduce the size and weight of the waste and convert it into energy (figure 2.59). Incineration process is able to reduce mass and volume of the waste depending upon the characteristics up to 70% and 90% respectively (Tozlu, Özahi, & Abuşoğlu, 2016). Initially these technologies were only used to combust and reduce the waste but not as a source of energy (Brunner & Rechberger, 2015). After the advancement of technology in controlling the pollution, it’s now being consider a potential source of clean energy in developing countries (Ouda et al., 2016). In a study it was reported that incarnation is most commonly used technique for waste disposal in US, Japan and EU (Scarlat, Motola, Dallemand, Monforti-Ferrario, & Mofor, 2015). Electricity and district heating in Europe is one of the important applications of the incineration technology (Cucchiella, D’Adamo, & Gastaldi, 2017).It is seen that energy efficiency of incineration technique in terms of heat is 80%, pure electricity 20% while for co-generation (electricity and steam) is 20% to 30% (Beyene et al., 2018). Apart from electricity generation and volume reduction incineration has also advantages in recovery of non-ferrous and ferrous

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materials (Meylan & Spoerri, 2014).Also fly ash is advantageous for production of cement and construction of roads (Allegrini et al., 2014).

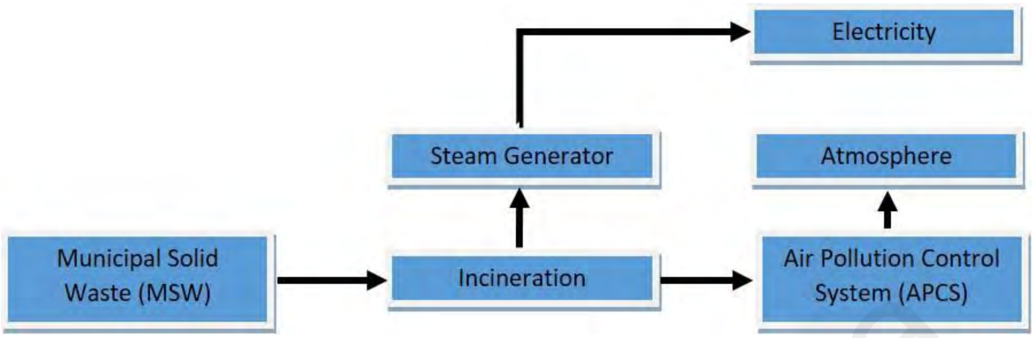

Figure 2.59 Schematic diagram for incineration

2.10.1.2 Pyrolysis

Pyrolysis is an advance thermal technique for the treatment of waste. In pyrolysis process destructive distillation take place in which thermal decomposition take place in the absence of oxygen(Bajpai, 2015).There are three different types of pyrolysis techniques depending upon the temperature ranges shown in table 2.10.

Table 2.10 Different pyrolysis techniques with temperature ranges(Tozlu et al., 2016)

Sr.	Technology	Temperature Range (K)
1.	Conventional	550 – 900
2.	Fast	850 – 1250
3.	Flash	1050 - 1300

The resultant product of the pyrolysis technique is dependent upon temperature range, type of the reactor, heating rate, residence time and most importantly the feedstock used which is reliant on the composition of waste and its particle size(D. Chen, Yin, Wang, & He, 2015; Kalyani & Pandey, 2014; Lombardi, Carnevale, & Corti, 2015).

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This technology is more beneficial for treating specific waste type. Pyrolysis seems more promising for the recovery of oil, carbon black and gas from recycling of waste consists of scrap rubber tires (Lombardi et al., 2015). This technology is not much feasible for energy recovery from municipal solid waste at commercial scale. One successful operating plant was reported in Hamm, Germany using 275 tones/d MSW. Similarly, one working plant is in Toyohashi, Japan with a capacity of 295 tones/d municipal solid waste(Panepinto, Tedesco, Brizio, & Genon, 2015). Another prominent successful plant of using pyrolysis technology is working in Burgau, Germany since 1987 to generate electricity by using 110 tones/d municipal solid waste (MSW) (Panepinto et al., 2015). A brief pyrolysis process is shown in figure 2.60.

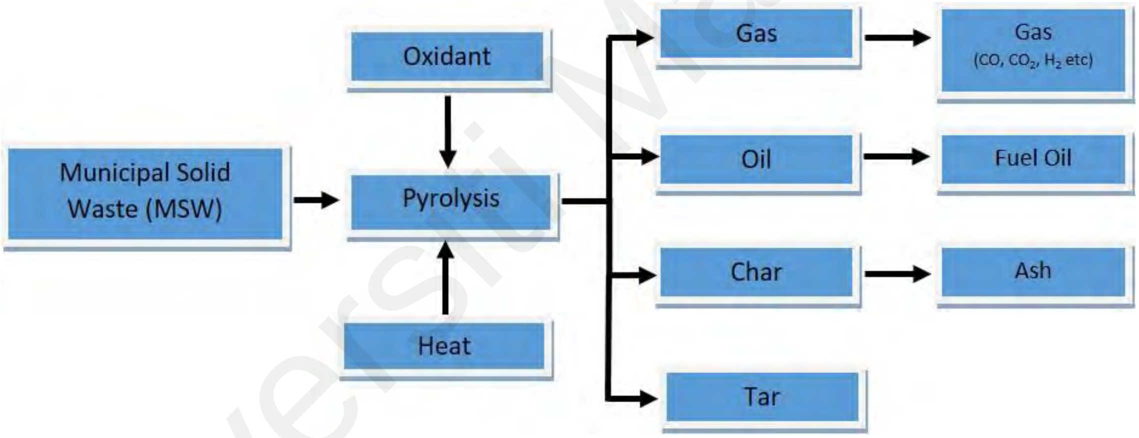

Figure 2.60 Schematic diagram for pyrolysis

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2.10.1.3 Gasification

This type of thermal conversion technology for waste is done in a controlled oxygen atmosphere at high temperature that converts organic compounds into syngas. This syngas is characterized as clean and heat energy which can be further used to produce liquid fuels or feedstock for chemical industry (Yap & Nixon, 2015). Similar to incineration, gasification also produces ash as a result of combustion of MSW which is to be removed from bottom. A complete gasification process in shown in figure 2.61. This technology is mostly used in coal industry. It is expected to use gasification as an alternative source of energy in near future as it may have a potential for recovery of renewable energy from treating municipal solid waste(Beyene et al., 2018).There are only limited gasification plants that are available, making Japan as significant user of gasification technology with 85 plants(Panepinto et al., 2015). Other countries like UK, USA, Germany, and Norway also use gasification for treating MSW on small scale. Both of the thermal conversion techniques of pyrolysis and gasification are more promising technologies and more favorable for environment while treating waste to energy but are not feasible on large scale due to the variable characteristics and composition (particle size, moisture content) of the waste depending up on the region(Luz et al., 2015).

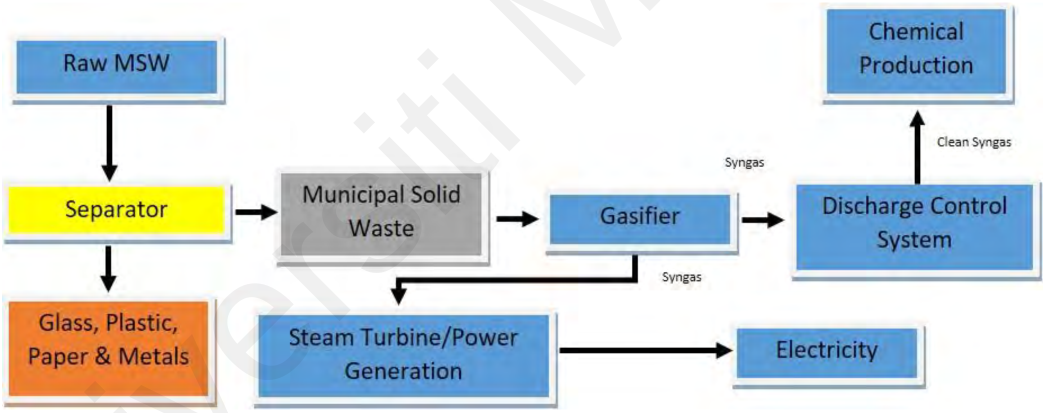

Figure 2.61 Schematic diagram for Gasification

2.10.2 Biological Conversion

In this type of conversion organic content in municipal solid waste is decomposed by the help of microbial. This technology has promise as environmental friendly for energy recovery from waste (Pant, Van Bogaert, Diels, & Vanbroekhoven, 2010). For this technology it is recommended to have a waste with high moisture content and organic

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biodegradable matter. There are two basic types of biological conversion Aerobic and Anaerobic digestion.

2.10.2.1 Aerobic Compositing

Aerobic treatment uses microorganism that converts organic matter into carbon dioxide and bio-mass. This treatment is done in the presence of oxygen so air circulates in the tanks continuously. Aerobic treatment can also be used specifically to remove nitrogen and phosphorus, which is also known as a biological nutrient removal (BNR) system. A pretreatment of the waste could reduce the initial phase of acidogenic and adjustment of aeration rates which results in enhancement of methane generation(Xu, Tian, Kim, & Ko, 2016). Aerobic systems are stand-alone systems and require large amount of energy. This type of treatment produces more sludge as compare to anaerobic systems. Aerobic plays a vital role in the treatment of wastewater. This type of system is more favorable for industrial usage to deal with environmental requirements and discharge the waste water safely.

By product for the aerobic compositing of materials are heat and carbon dioxide. This CO2 is categorizing as greenhouse gas. Heat which is produce in this process is enough to kill harmful bacteria and pathogens. It also supports the growth of bacteria like psychrophilic, mesophilic and thermophilic which are beneficial and can thrive at high temperature.

2.10.2.2 Anaerobic Digestion

It is a microbial degradation process of organic matter in the absence of oxygen which produces biogas composed of carbon dioxide and methane. Process parameters and composition of substrate determine quality of the biogas produce. Typically biogas is compose of 75% methane, 25 – 25% carbon dioxide and 1 – 15% other (NH3, H2S, water vapors etc) (Surendra, Takara, Hashimoto, & Khanal, 2014).Normally, livestock manure,

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wet organic matter and MSW act as feedstock(Beyene et al., 2018). AD method can recover both energy and nutrients from biodegradable waste(Ali, Bashir, Ali, & Bashir, 2016).Anaerobic digestion process works on three steps.

In the first step municipal solid waste is break down by bacteria and organic matter is decomposed into soluble units of monosac-charides, amino acid and fatty acid. In the second step (acidogensis) conversion of disintegrated material into organic acids took place. These are then change into Volatile fatty acid, hydrogen and carbon dioxide. Third and the final phase is methanogens in which organic acid is converted into methane gas. This methane gas can be used as a substitute of energy while other nutrient rich digestants can be used for fertilizer that are formed as a byproduct.

2.10.3 Landfill

Landfilling is a technique for the disposal of the waste by dumping underground. It is usually used in developing countries for the disposal purpose of MSW. There are two basic ways of landfilling. Sanitary landfill is a scientific way of dumping MSW by using a special manufacturing facility. This facility involves specifications, careful planning and construction in order to reduce the negative impact of biogas recovery from waste on environment(Pressley et al., 2014). Another way of disposal of waste is through unsanitary landfilling. It is a simpler and affordable way to deal with increasing waste for disposal and commonly used in developing countries but It can cause a serious threat to environment (Wang & Geng, 2015). Leachate (a dark intractable material with unusual variable composition) is one of the major pollutants of the resultant of the landfilling that release from dumpsites(Müller et al., 2015) and can pollute nearby groundwater aquifer as well as surface water course.

In some studies, it was reported that in some of the developing countries, waste was disposed at the outskirts of the cities(S. Kumar & Chakrabarti, 2010; Talyan, Dahiya, &

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Sreekrishnan, 2008). Some other similar studies showed that landfilling practice cause more environmental issues than other options of waste to energy management(Cherubini, Bargigli, & Ulgiati, 2009; Emery, Davies, Griffiths, & Williams, 2007; Marchettini, Ridolfi, & Rustici, 2007). However, developed countries are discouraging use of landfilling for waste disposal while more focusing on waste reduction and recycling. Reformed method of landfilling has promise to reduce the weight and volume of the municipal solid waste by 70% and 90% respectively(Bolan et al., 2013). Major products in the result of aerobic and anaerobic process at landfill or dump site are water, carbon dioxide, methane and heat. It is estimated that around 30-70 million tons of methane gas is released from landfills which can be used for electricity generation. In an investigation in 2012 by International Solid Waste Association (ISWA) it was reported that landfilling was still on the top of the available techniques for the treatment of waste (Association, 2013).

2.11 Technologies for waste to energy (WtE)

Waste to energy (WtE) has potential to be as an option for solid waste management and can play a significant role towards future of renewable energy sources, which are economically viable and environmentally sustainable(Bajić et al., 2015). Different technologies are being used by different countries in the world regarding waste to energy technologies according to the waste they produce. Developing countries mostly used insanitary landfilling option as their disposal for the waste. While, developed countries are looking for effective municipal solid waste management as they realized the potential in waste to energy technologies. These technologies depend upon the composition and characteristics of the waste that is available. UAE is more dependent upon recycling and incineration as two of the most urbanized cities, Dubai and Abu Dhabi are located in coastal region, where landfilling is not feasible due to hydrological reasons(Paleologos et al., 2016). Similarly in Hyderabad on of the cities of Pakistan, there is a maximum

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potential available in biochemical and thermo-chemical methods for power generation (Korai et al., 2016). According to Noor et al. in Malaysia landfilling has more potential for recovering methane gas and other types of fuel from waste(Noor, Yusuf, Abba, Hassan, & Din, 2013).In another study done by Jeswani and Azapagic, it was concluded that incineration of the waste in UK has lesser impact on environment than landfill and could easily meet up to 2.3% of UK's total electricity demand which eventually save almost 2 to 2.6 million tons of greenhouse gas emission (Jeswani & Azapagic, 2016). Waste to energy has become an industry in past few years. Different European countries like Sweden, Denmark, Finland and Estonia are global leaders in this industry by incinerating at least 50% of municipal solid waste which in result reduce their landfill to 10% (figure 2.62). Similarly, figure 2.63 shows municipal solid waste treatment options used in different Asian countries. In this study it was observed that except highly developed countries like Singapore and Japan, rest of the Asia countries opted open dumping for managing their waste. This is due to lack of technology and cost that is involved in modern technologies for treatment of waste. Also public behavior and acceptance of these technologies are hurdle to use advance methods of treating waste.

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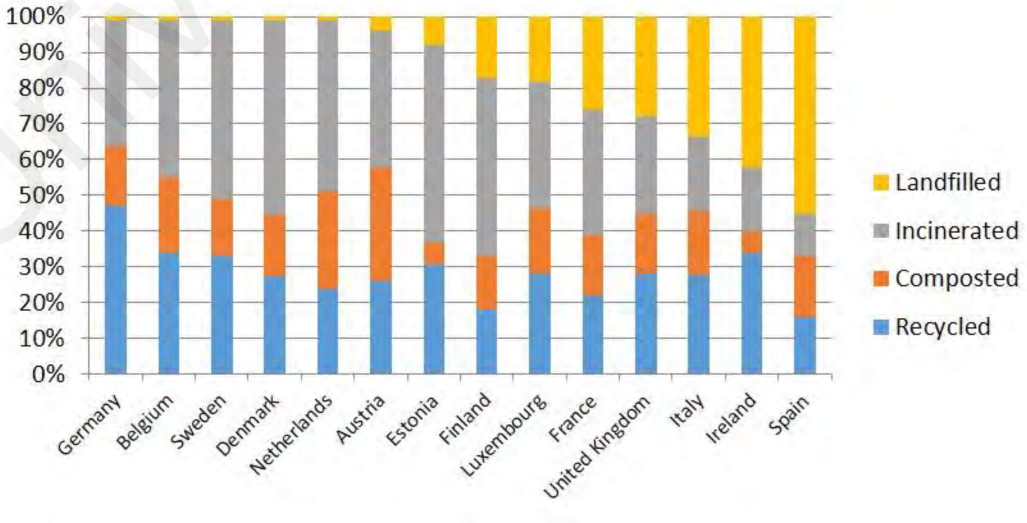

Figure 2.62 Municipal Solid Waste (MSW) disposal and treatment opportunities in EU(Cucchiella et al., 2017)

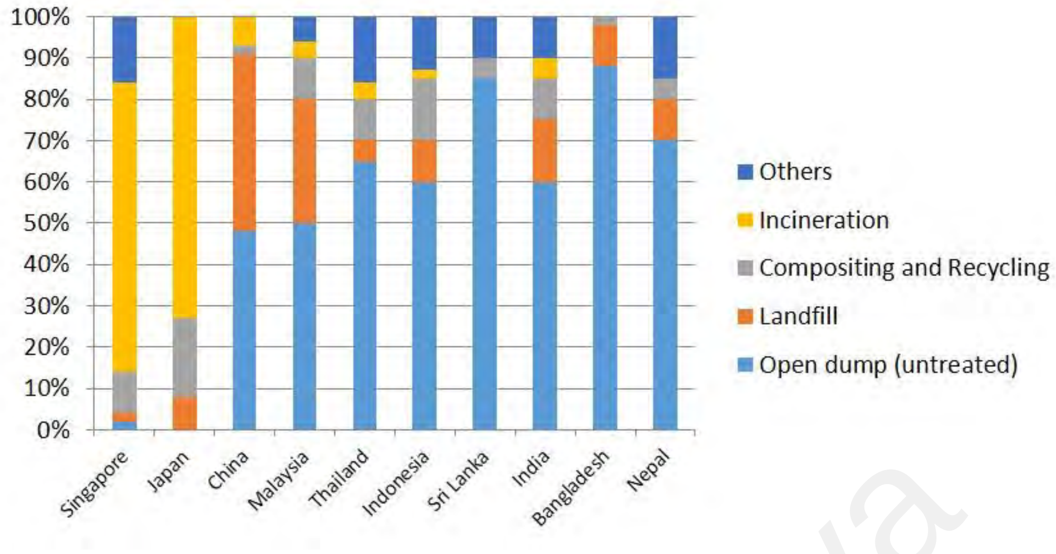

Figure 2.63 Municipal Solid Waste (MSW) disposal and treatment opportunities in Asian Countries (Aleluia & Ferrão, 2016)

Waste to energy technologies is not only beneficial for environment and energy, but they are also economically viable. In a study, it was concluded that net profit margin for waste to energy plants is 25% while return on investment and internal rate of return is up to 18% and 10.94% respectively (Xin-gang, Gui-wu, Ang, & Yun, 2016). Also payback period for these technologies is 12.73 years, so these wastes to energy plants are economically beneficial and can earn a good profit. Now a day with the advancement of technology, waste to energy has become a vibrant industry with an estimated cost of worth USD 24 billion in 2013 (Council, 2013) which is expected to increase up to USD 37.6 billion by 2020 (*Waste To Energy (WTE) Market Share, Size & Trend Analysis Report By Technology (Thermal (Incineration, Gasification, Pyrolysis), Biological) And Segment Forecasts, 2014 - 2024*, 2016).

2.11.1 Incineration as a promising WtE technology

Advantages and disadvantages of waste management strategies are assessed by life-cycle inventory analysis and their impact. These strategies are evaluated on multi-dimensions by keeping in view their environmental performance. These dimensions are

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waste reduction, material and energy recovery, stabilization and greenhouse gases reduction. In a study these dimensions were determined for different waste management strategies. Raw municipal solid waste was used for these studies(Liu et al., 2017). Landfilling results in 34.8% in reduction of waste with a rate of 87.8% stabilization while emitting a significant amount of 116.7 to 192.2 Kg-CO2Eq/t of greenhouse gases. Incineration showed much advantages on these dimensions with a reduction rate of 79.2% by keeping 100% stable rate with controlled emission of greenhouse gases (124.3 Kg-CO2Eq/t). It was also advantageous on recovering 1163.1 MJ/t of electricity at the same time(Liu et al., 2017).

Now-a-days with the advancement of technology, MSW incineration plants are more effective for waste management system by recovering energy in the form steam to produce electricity. Less capital and operational cost, high calorific value and daily throughput (Psomopoulos, Bourka, & Themelis, 2009) making incineration technology as a promising and more attractive than other WtE technologies for developed countries. Incineration of municipal solid waste is extensively done in western part of Europe from 35% to 80% of the waste produce (Reddy, 2011). US use incineration to recover energy from 40% of the total solid waste generated. Feasibility of incineration depends upon cost, characteristics and composition of wastes, technical expertise and cost of land for waste disposal. China expanded its incineration technology in last decades and expected to climb up to 500000 tons/day by 2020 (Y. Li, Zhao, Li, & Li, 2015; Reddy, 2011).

A study was done by Arafatet al. in 2015 (Arafat, Jijakli, & Ahsan, 2015) on the energy (electrical energy) recoverable contents from municipal solid waste by using different waste to energy technologies. This study is reported in the figure 2.64. According to the study three different prominent techniques were investigated i-e anaerobic digestion, gasification and incineration. Anaerobic digestion seems to be best option as waste to

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energy technology for waste compose of food and yard wastes. Gasification showed promise in treating plastic waste. But incineration remain the most attractive option for treating and recovering energy from all streams of wastes (Arafat et al., 2015).

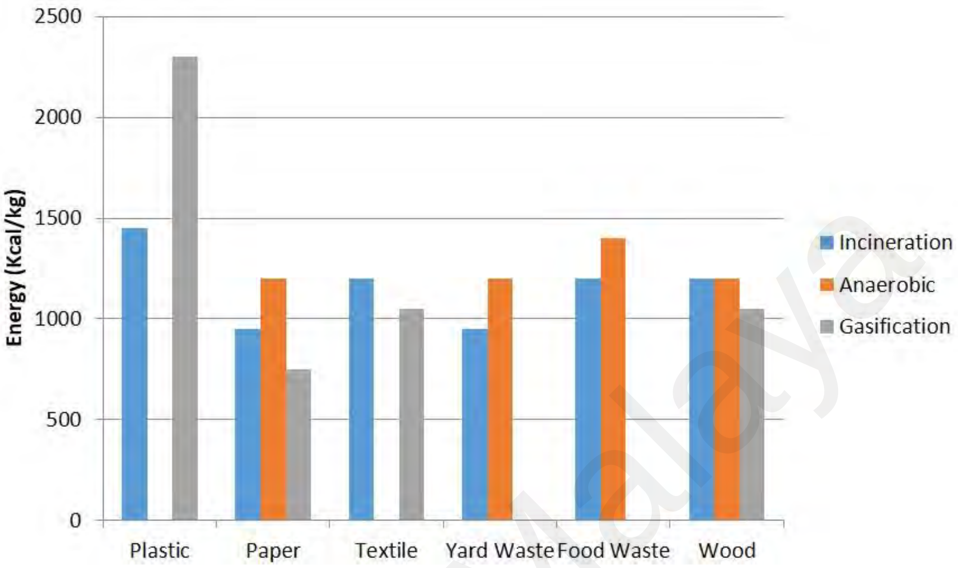

Figure 2.64 Different Municipal Solid Waste (MSW) with their energy recovery potential along different waste to energy (WtE) technologies

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2.12 Fuel technology for incineration

Particularly municipal solid waste is a heterogeneous feedstock for incineration. Its composition, characteristics or sometime whole waste stream can affect combustibility. This make difficult for incineration to maintain the minimum necessary level of temperature. For this reason, auxiliary burners are added which are feed by fossil fuel (natural gas, oil etc) to maintain the temperature of the furnace. These burners set to come on automatically when the temperature drops from the threshold point which is usually 850°C. These burners are used during startup, shutdown and upsets in system(*Waste Incineration and Public Health*, 2000).

Combustion is defined as a rapid exothermic reaction which takes place between a fuel and oxygen. Normally, waste is considered to be primary fuel for the incineration applications although fossil fuels co-fired with this waste in the presence of oxygen from air. In the result of the combustion process, same stable products are produce regardless of the fuel (natural gas, coal, gasoline etc) use for incineration (*Waste Incineration and Public Health*, 2000).

Incineration technology is depended upon combustion mechanism. It is a type of thermal plant that should be operated constantly and evenly on set point of temperature. Most of the reported studies are focused on fuels like gas, oil, coal etc. There are two types of combustion mechanism that are selected according to the waste that is to be incinerated i-e auto-combustion and fuel-assisted. In an auto combustion incinerator, additional fuel such as coal, wood or kerosene is used for the initial ignition. This auxiliary fuel is also then used for pre-heating purpose. At some optimum point, fuel intake is stop and waste it generates and maintains heat to continue combustion for disposal process. This technology is rather cheaper and required special arrangements and composition with secondary fuel (woo, charcoal etc) for disposal of medical or hospital waste(*THE INCINERATOR GUIDEBOOK*, 2010). A fuel-assisted incinerator requires continuous supply of fossil fuel (diesel or gas) and electrical power to operate. Design of the fuel assisted incinerator is important for the control and supply of fuel to maintain a constant temperature for combustion and economize on fuel consumption. This type of incinerator normally has a capacity of destroying about 150Kg of waste in a day by consuming 5 to 8 liters of fuel per hour (4 to 6.5 kilogram of gas) (*THE INCINERATOR GUIDEBOOK*, 2010).

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CHAPTER 3: METHODOLOGY

In this chapter, detailed protocols and procedures have been described for the fabrication of complete PV-ELE Incineration system. All the parts, methods and procedure that are adopted are explained in detail. The chapter has been structured in such a way that the reader could easily get a grasp about materials and methods being used for fabrication, the techniques that are used to validate results and the characterization techniques being employed for the fulfillment of the intended study. Figure 3.1 shows the schematic of the solar powered incinerator system, which consists of two major subsystems, i.e. a solar powered electrolyzer system and a custom-made MSW incinerator. Solar PV has been used to power the electrolyzer by using DC-DC convertor. DC-DC convertor has been employed to control the rated parameters of electrolyzer to produce hydrogen in an efficient way. The generated hydrogen has been supplied as an auxiliary fuel to the incinerator to incinerate MSW.

Current study is divided into two phases based on experimentation. Phase 1 involved the characterizations of the two subsystems. Characterization of each individual system was performed to have a complete understanding of each component. Furthermore, characterization of the municipal solid waste was also performed because it was necessary for analyzing and verifying the operation of incinerator. In Phase 2 of the project, entire system was fabricated and operated together. As seen in Fig. 3.1, this system comprises of solar PV coupled to an electrolyzer through a DC-DC convertor to control the production of hydrogen to the incinerator. Different control strategies were investigated based on different scenarios. A techno-economic analysis was further performed to evaluate the performance of the incinerator system under different operation methods.

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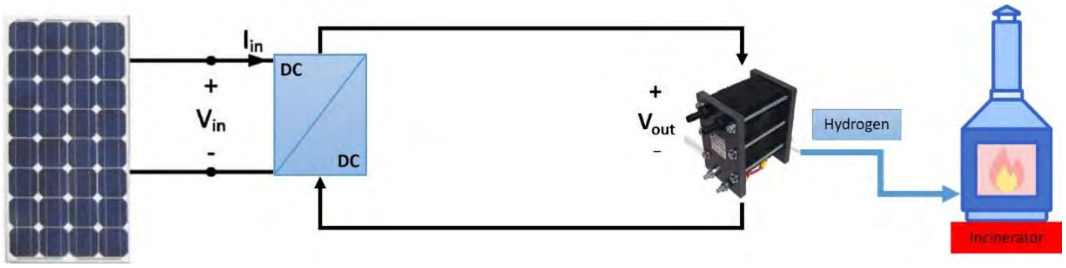

Figure 3.1 schematic diagram for the proposed system

In the following part of this chapter, subsection 3.1 explain an overview of different main components that were used throughout the project. Subsequently, phase 1 of the project starts from section 3.2, where the methodology of the characterization tests performed for different components was explained. Mainly these characterization tests are done for investigating characterization of the waste collected before and after incineration. This investigation involves moisture and residue test of waste. Also operational characterization of electrolyzer was done to study parametric behavior of electrolyzer. These parameters include current, voltage and temperature. Lastly, a series experiments were executed for testing the behavior of convertor designed for coupling electrolyzer with solar PV. Then in Section 3.3, the methodology for Phase 2 of the project is discussed. Experimental setups for two strategies i.e. (i) hybrid mode and (ii) direct mode are explained in detail.

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3.1 Main Components

Following are the items and equipment that are used for fabrication of PV-ELE based incinerator.

3.1.1 Solar Powered Electrolyzer System

3.1.1.1 Solar PV Panel

For this project, a 300 Watt mono-perc solar PV shown in figure 3.2 was used. The panel has an open voltage of V_{oc} = 38.7V and a short circuit current I_{sc} = 9.8A, while voltage and current at P_{max} are 33V and 9.1A, respectively.

Figure 3.2 Itoshi mono-perc solar panel used for research

3.1.1.2 DC-DC Converter

It is known that solar PV have non-linear behavior where the voltage and current characteristics changes with varying irradiance and temperature of the PV panel. On the other hand, an electrolyzer can only operate within a narrow voltage range, where a supply voltage lower than its threshold will not be sufficient to activate the electrolyzer, while a supply voltage that is too high will reduce its efficiency. In order to ensure that the solar PV can continue to deliver the required power to the electrolyzer, a DC-DC

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converter is used in the proposed system. Apart from regulating the varying PV voltage to match the eletrolyzer's operating voltage, convertor is also responsible for tracking the maximum current that can be extracted from the PV. In this way the electrolyzer can utilize the maximum power available from solar energy within its operating region.

In this project, a classic buck convertor with a predictive control technique has been utilized as the DC-DC converter. The electrical characteristics of the buck converter (V_s, I_s Equations (3.1) and (3.2)) are related to those of the PV (V_{PV}, I_{PV}) according to the duty cycle, D_{off} the signal which controls the converter:

$$V_s = DV_{pv} \tag{3.1}$$

$$I_s = \frac{I_{pv}}{D} \tag{3.2}$$

For controlling the buck convertor, Arduino-NANO (shown in figure 3.3) was used. The controller measures the vital parameters such as the voltages, currents and temperature and computes the duty cycle required by the DC-DC converter.

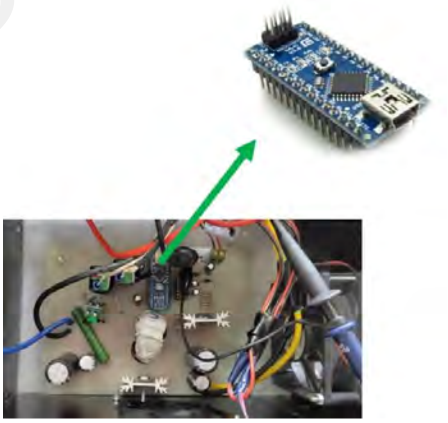

Figure 3.3 Arduino Nano

An Arduino based hall effect linear current sensor module ACS712 was used for current sensor. To allow the current measurement up to 30A range, the sensor module with a 185mV/A sensitivity was selected. For voltage measurement, a simple voltage

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divider circuit with a ratio of 0.41 was utilized. For temperature measurement, K type thermocouple with MAX6675 amplifier module was used. This allows the controller to monitor the temperature of the electrolyzer and control the current in order to maintain the temperature of the electrolyzer to optimize HHO production so that it does not affect the quality of the HHO gas produced.

The pulse-width modulation (PWM) frequency of the controller was set to be 31 kHz. This PWM was then used to control a MOSFET (IRF 4115, International Rectifier IR, El Segundo, CA, USA) through a MOSFET gate driver IC (IR 2110, International Rectifier IR, El Segundo, CA, USA). A schematic diagram of the key components of convertor, as well as the sensors and controller is shown in Figure 3.4.

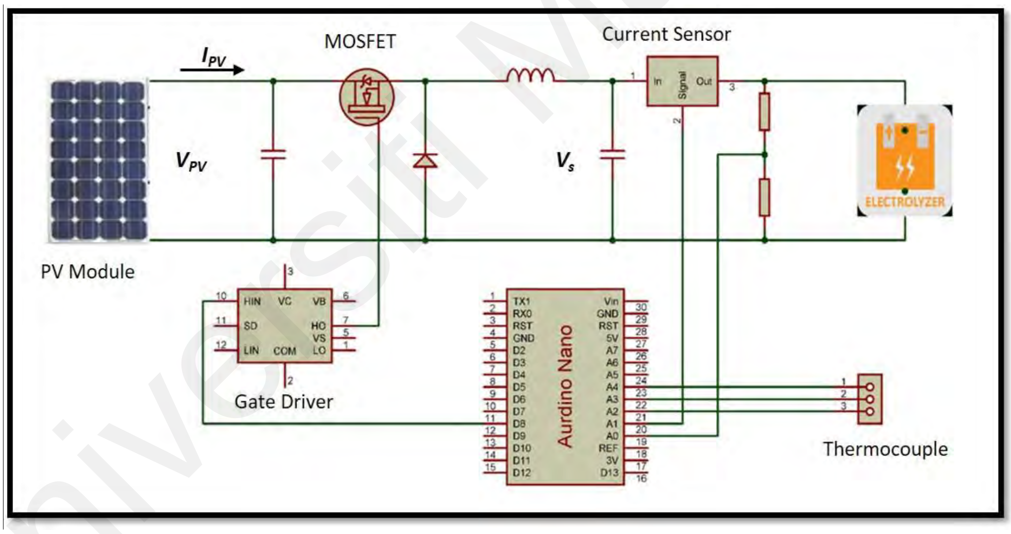

Figure 3.4 Schematic diagram of DC-DC convertor

Normally for MPPT strategies of solar PV, monitoring of the parameters is done for PV in order to track the maximum power. In the proposed system, a modified MPPT control is utilized, where the control is implemented and the electrolyzer is expected to work in its operating region, so this strategy was implemented in the electrolyzer by monitoring its parameters (current and voltage). This was done because the electrolyzer

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is required to run on the maximum available current (if under electrolyzer limitation of current) regulated by the operating voltage. Another reason to implement a control technique on the electrolyzer, because the electrolyzer itself is a non-linear load, so it is important to monitor the electrolyzer parameters in order to run it for maximum production of HHO gas. This control technique is represented in the flowchart shown in Figure 3.5.

A predictive approach was used in the control to track the maximum power available at certain irradiance level. In this control technique, instant temperature and voltage is measured and kept in the operating range. The voltage is to be kept constant for working of the electrolyzer. Therefore, direction of current is noted for tracking the maximum power. Algorithm of the control measures instant operating current of the electrolyzer and compare it with last measured current. If the current is increased by the perturbation, then the current is kept changing by increasing of duty in the same direction. Otherwise the direction of perturbation is changed by decreasing the duty. As an increase or decrease of duty cycle are dependent upon the limitations of the electrolyzer as well as the PV the step size remains constant throughout the algorithm. In this way by applying the algorithm on the load (electrolyzer) side, the maximum available power from PV can be tracked by keeping the electrolyzer in its optimum operating region.

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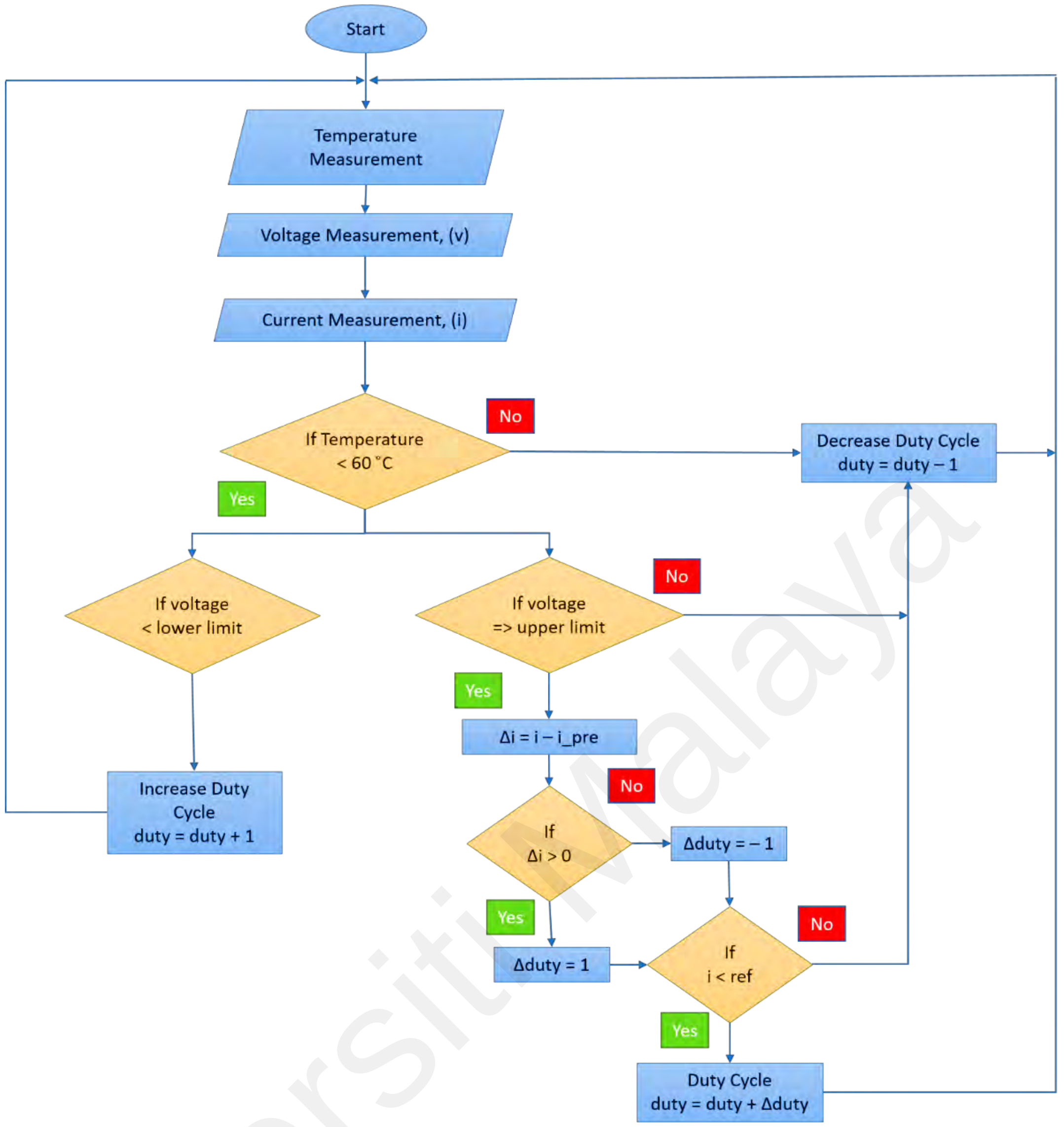

Figure 3.5 Flowchart for the control strategy for the convertor

3.1.1.3 Alkaline Water Electrolyzer

An electrolyzer is a device that utilizes electricity to split water into hydrogen and oxygen via electrolysis process. However, since pure water lacks ions to carry enough charges, alkaline is usually added to assist water splitting. Such electrolyzer is known as alkaline water electrolyzer (AWE). Normally, sodium hydroxide or potassium hydroxide is used for this purpose. Different concentration has different effects in producing gas. For this study, 30% of KOH solution is used as electrolyte for electrolysis process. Also, it is recommended to use distilled water for making electrolyte solution. Three different electrolyzers were used in this study, as shown in Fig. 3.6. These different electrolyzers

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were used due to diverse nature of experiments in the study. Figure 3.6(a) shows a 12V 30 plates electrolyzer (supplied by greenfuelh2o, Orem, UT United States of America, https://www.greenfuelh2o.com/) with a capacity of 0.8 lpm. This electrolyzer was used as the primary electrolyzer for coupling with solar PV and feeding hydrogen to incinerator. Figure 3.6(b) shows a customized electrolyzer that was fabricated as a secondary electrolyzer during study of different strategies of using solar PV to energize electrolyzer to feed hydrogen to incinerator. Secondary electrolyzer has a capacity of 0.4lpm of oxy-hydrogen gas. Its operating voltages are 12V and maximum current 8A. Internal diameter of stainless steel plates was 5inch for each cell in electrolyzer which make area of 19.625inch^2. Total six plates were used to fabricate cells in a series configuration to make a complete electrolyzer. Electrolyzer (Honguang model: H260) in figure 3.6(c) was used to provide HHO fuel to incinerator during characterization of waste. This electrolyzer has a capacity of 1.5 lpm of oxyhydrogen and use DC power supply to energize.

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Figure 3.6 Electrolyzer used in study (a) Primary electrolyzer, (b) Secondary electrolyzer, (c) Testing electrolyzer

Primary electrolyzer from Grennhuelh2o was used for producing HHO gas. It was operated on 12V DC. Electrolyzer was comprises of a total 30 plates of SS316 stainless steel plates. These plates were connected in form of five stacks. Each stack comprises of six cells. These cells are separated with a 2mm thick polymeric rubber gasket as shown in figure 3.7. Active cross sectional area for the plate was 28.2 inch^2. Ideally, electrochemical reaction of the water requires 1.23V. But practically, there exist activation barrier of the reactions shown in figure 2.34. This needs an over potential of more than 1.8 Volts to start of electrochemical reaction (X. Li et al., 2020). Large over potential can create bubbles on the surface of the electrodes. If these bubbles are difficult to break down from active surface area of electrode than it reduces efficiency of system. Therefore, it is difficult to establish potential for water splitting due its dependency on different electrodes and different range in pH level of electrolyte.

For the current experimental setup of the electrolyzer, this potential was kept from 1.8 volt to 2.2 volt per cell for efficient electrolysis process. According to the configuration of the electrolyzer, it includes five stacks so it required between 10.8 Volts to 13.2 Volts for efficient working. Below this voltage level, electrolysis reaction was unable to start to produce oxy-hydrogen. Similarly, above 13.2 Volts electrolyzer starts to produce large amount of bubbles due to increase in temperature. Three parameters were studied in details that effect the working of electrolyzer i.e. current, voltage and temperature. These parameters are responsible for affecting the efficiency of electrolyzer based on the flow rate of HHO gas generated.

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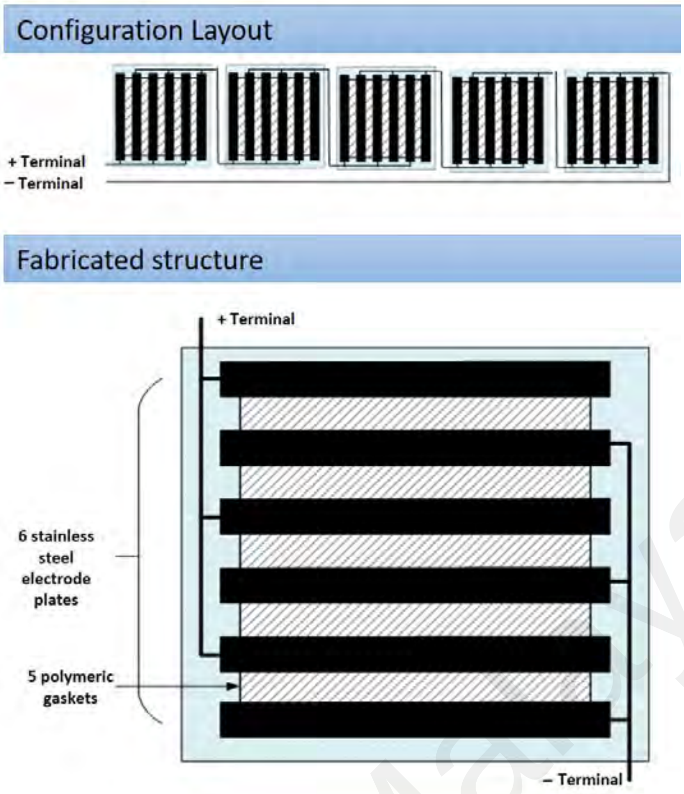

Figure 3.7 Configuration layout of the electrolyzer under test

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During operation, the electrolyzer was fed with a 30% KOH solution and was energized with Sorensen SG Series programmable DC power supply to investigate behavior of electrolyzer under different voltages and current. Gas was allowed to flow from output of the reservoir to a flow meter through a bubbler and flash arrestor. A high precision gas flow meter ALICAT Scientific ST-00024 M-100SLM-D/5V, as shown in figure 3.8, was used for measuring flow rate of the HHO gas during this study.

Figure 3.8 Gas flow meter

Reservoir shown in figure 3.9 is used to supply the electrolyte solution of water to the electrolyzer (dry cell), based on principle of gravity. There are three outlets on the reservoir, which are located at the top left, top right, and bottom position. Electrolyte is supplied to electrolyzer through the bottom outlet, while premixed hydrogen and oxygen gas after splitting is supplied from one top end of the reservoir again to filter water contents from gas. Further gas accumulates on the top of the electrolyze liquid inside reservoir and exit from the other end.

After exiting the reservoir, the HHO gas is passed through a bubbler, which serves as a safety feature to prevent flashback. The bubbler is partially filled with water, which function as a buffer zone between electrolyzer and the flame. This ensures that, in case of low pressure or any other unforeseen circumstances, the flame could not propagate back to HHO gas accumulated within the reservoir or electrolyzer to cause explosion.

Figure 3.9 (left) Water reservoir, (right) Bubbler

As an additional safety feature, a stainless steel flashback arrester has been place after the bubbler. The flashback arrester, as shown in figure 3.10, helps to prevent the mixed gas such as oxygen and hydrogen from lightening by extinguishing the flame. It also prevents the flame from being sprayed outward. During normal operation, the cylinder pressure overcomes the one-way valve spring pressure to open the check valve to supply gas to burners. When tempering occurs, the tempering flame is reversely burned along the gas pipeline, and the tempering flame enters into the Flashback Arrestor chamber.

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Due to the increase in the pressure of the combustion chamber Flashback Arrestor chamber, the pressure of the cylinder is overcome by the interaction of the spring to the check valve, thus closing and stopping the supply of gas. When the tempering is extinguished, the machine resumes normal operation. If there is another tempering, the anti-tempering valve can continuously block and extinguish the temper.

Figure 3.10 Flash arrestor

3.1.2 MSW Incinerator

3.1.2.1 Fabrication of Incinerator

One of the most important part of the project is the incinerator. It needs to be designed in a manner that allows the incinerator to incinerate MSW by using the HHO gas generated from the electrolyzer. The incinerator is fabricated from SS304 stainless steel sheet with thickness of 1mm and a dimension of 10inch x 6inch x 18inch. To provide heat insulation, the inner walls of the incinerator were layered with ceramic wool with a thickness of 1 inch as illustrated in figure 3.11. Subsequently, brick kiln cement was applied onto the surface of the ceramic cool to form a hardened surface in the interior of the incinerator which is able to withstand high temperature during the incineration. After taking into account the ceramic wool and brick kiln cement layer, the completed incinerator has an active incineration compartment with a cross sectional area of 32 square inch (8 inch x 4 inch) and an effective volume of 384 cubic inch (8in x 4 in x 12 in).

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To allow effective incineration to take place, the HHO gas channeled to the incineration compartment needs to be distributed around the compartment and combusted. For this purpose, a specially fabricated burner was made using copper pipe with a diameter of 10mm. Several holes were drilled onto the copper pipe at equal distance of 6cm by using tungsten drill bits to distribute the flame around the cavity in the incinerator. Diameter of holes for burners were determined by dong a series of experiment. A removable steel mesh was placed at the bottom of the incinerator to be used as an ash tray. This facilitate easy removal of the ash from the incinerator after each incineration process. A pulse ignitor was used to devise a self-ignition mechanism for incinerator. Pulse ignitor in figure 3.12(a) is responsible to give pulses when switch on to spark plug shown in figure 3.12(b). It than give spark at the time of plug to ignite the flame.

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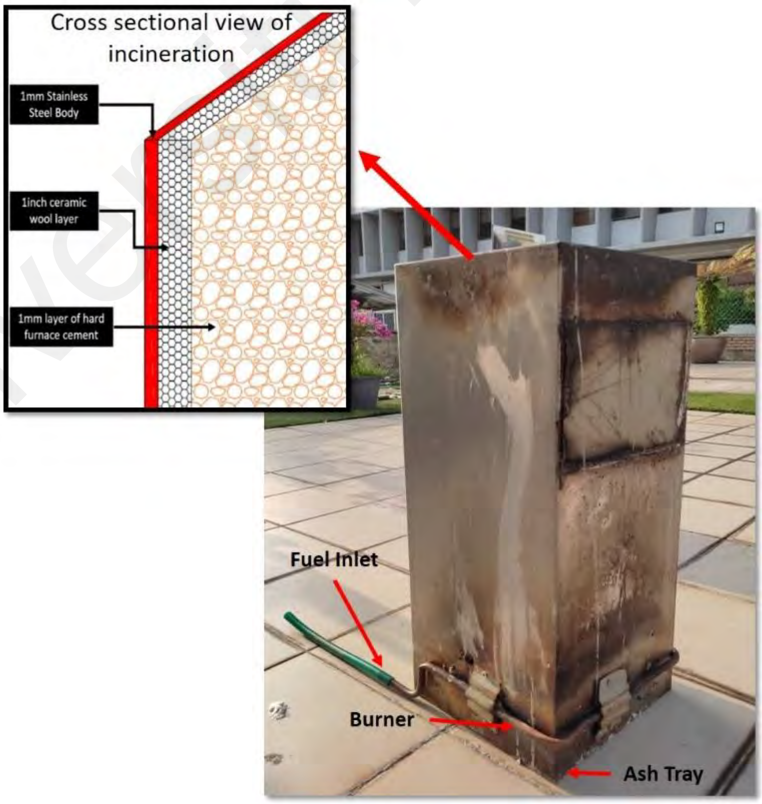

Figure 3.11 Fabricated incinerator for experiment along with its burners

Figure 3.12 (a) Pulse Igniter, (b) Spark Plug

3.1.2.2 Municipal Solid Waste

Figure 3.13 shows the random municipal waste being collected from restaurants and residential houses. Furthermore, simulated waste has also been used individually by intentionally wetting the paper waste and textile waste for comparison. This was done to test the incineration in extreme conditions of moisture content in municipal solid waste. Seven different trial runs of waste were made and their composition was noted in table 3.1. These wastes were further segregated and experimented with into two categories based on their nature (i) homogenous and (ii) heterogeneous. Based on the individual characteristics, paper, textile, and food waste were treated separately. This was done to see the effect of hydrogen incineration effect on each of the individual types of waste. For the heterogeneous nature of waste, all these basic types of domestic municipal household waste (paper, textile, food) were mixed in different ratios. This was done to have the characteristics of real-time waste from a simulated waste.

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Figure 3.13 Variety of Municipal waste used for incineration test (a) Textile waste; (b) Paper waste; (c) Food waste; (d), (e), (f), (g) Mix waste

Table 3.1 Composition of waste collected for the experiment

Batch #	Type of waste	Amount of waste (gram)	Composition of waste
Waste 1	Food	1000	Eggshells, onion peels, potato peels, cabbage, spring beans, long beans
Waste 2	Paper	1000	N/A
Waste 3	Textile	1500	N/A
Waste 4	Mixed Waste Food = 500 Textile = 300 Paper = 300	1100	Eggshells, onion peels, potato peels, cabbage, spring beans, Watermelon rinds, paper, and cloth
Waste 5	Mixed Waste Food = 400 Textile = 300 Paper = 300	1000	Onion peels, eggs, Water Spanish, curry leaves, Methi leaves
Waste 6	Mixed Waste Food = 500 Paper = 500	1000	potato peels, eggshells, onion peels
Waste 7	Mixed Waste Food = 700 Paper = 300	1000	Onion peels, eggs, Water Spanish, curry leaves, Methi leaves, and paper

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3.2 Phase 1: Characterization Tests

3.2.1 Characterization of the Municipal Solid Waste

3.2.1.1 Moisture content test

Before incineration combustion, both homogenous waste and heterogeneous waste were taken for testing moisture content. As high moisture content is a big issue for incineration. So to test the incineration with this new technology at high moisture content scenario, water was additionally added. The composition of each waste is reported for each test batch.

Moisture content was estimated by having five different small samples of 50grams from each of the waste that was taken and chopped into smaller pieces. They are then weighted and noted by using a scale. These samples were then placed into an oven (figure 3.14, model: 30-750) at 105°C for 24hrs. After 24hrs these samples were put in a desiccator to cool down so to avoid any absorption of ambient moisture. Then, again samples were weighed. This time it is the total dry weight of samples. So by using formula moisture content can be calculated for each waste sample.

$$Moisture\ Content = \left(\frac{Wet\ Sample\ weight - Dry\ Sample\ Weight}{Wet\ Sample\ Weight}\right) \text{X } 100 \qquad (3.3)$$

All the five values of moisture content for each waste sample were then averaged to get accurate content.

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Figure 3.14 Oven for drying samples

3.2.1.2 Loss on Ignition (LOI)

The incineration residue has been tested for combustion efficiency. The residual weight was measured using a precision weighing balance (A&D HK-250AZ) and loss on ignition (LOI) has been measured according to ASTM D7348 standard. In brief, samples of the ash residue left of incinerated waste were collected in a crucible and weighted. In the first step samples in the crucible were heated at 110°C for 1 hour in a preheated oven. Then the sample was removed from the oven and left in a desiccator for 60mins to cool down before being reweighted. The weight loss observed in this step was the moisture content of fly ash. For the second time, this dried fly ash was then placed in a muffle furnace (Berkeley 'Thermolyne 30400 furnace muffle oven') shown in figure 3.15 and heated in a stepped schedule of 2 hours to attain 950°C for 2hrs. The samples have been furnace cooled and weighted to calculate Loss on Ignition (LOI).

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Figure 3.15 Berkeley Thermolyne 30400 furnace muffle oven

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3.2.1.3 Reduction in weight test

Waste samples were weighted as a whole before incineration process. After incineration process completed, waste ashes and residue was taken out and weighted again. By using weight of waste before incineration and weight of residue after incineration was divided to calculate weight in reduction of the waste due to incineration.

3.2.2 Experimental setup to study operational characteristics of Electrolyzer

To study operational characteristics of electrolyzer a setup was made as shown in figure 3.16. These characteristics were studied based on three important parameters of the electrolyzer i-e. voltage, current and temperature. Electrolyzer under test was allowed to feed with a 30% solution of electrolyte and was energized with a variable power supply to investigate behavior of electrolyzer of different voltages and current. Gas was allowed to flow from output of the reservoir to a flow meter through a bubbler and flash arrestor. Flow meter was used to measure the flow of HHO gas at different parameters.

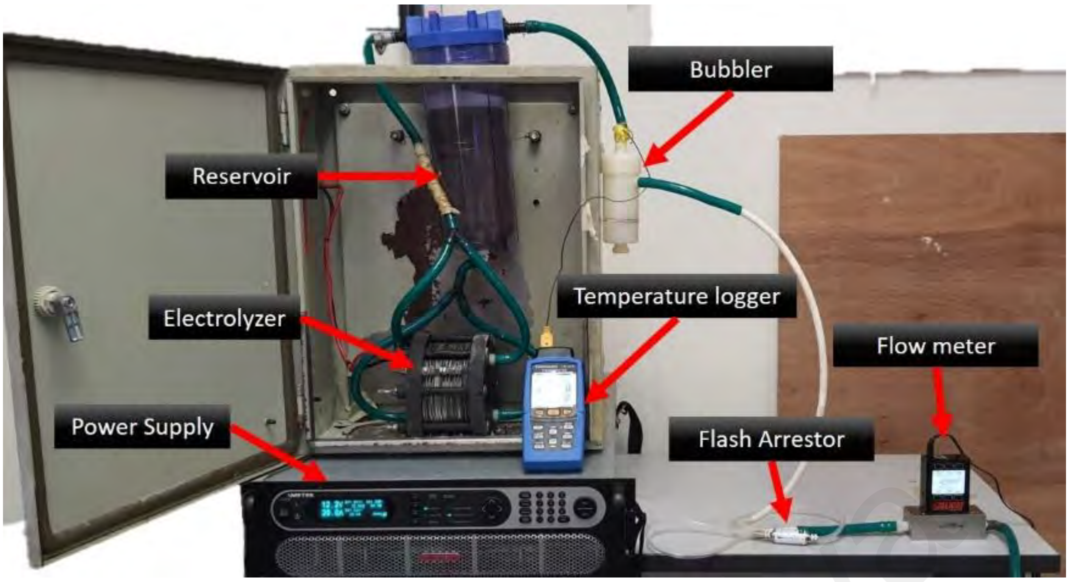

Figure 3.16 Setup for characterization of electrolyzer

3.2.3 Characterization of the Solar Powered Electrolyzer

3.2.3.1 Experimental Setup for testing DC-DC convertor

In this study a prefabricated electrolyzer has been used. This electrolyzer was coupled with solar PV by using an electronic convertor. A complete schematic diagram of the system is shown in Figure 3.17. A 30% KOH solution has been used as an electrolyte which is fed to the electrolyzer from a container by means of gravity.

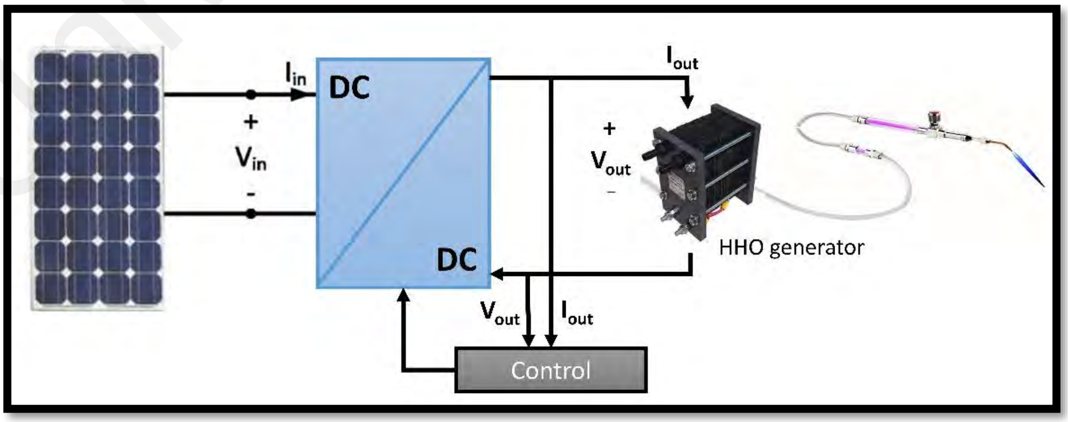

Figure 3.17 Schematic diagram of coupling of solar PV with electrolyzer

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From the literature it was established that the cells required from 1.8–2.2 Volts which depends upon the reversible thermodynamic decomposition voltage, anode over-potential, cathode over-potential and the inter-electrode Ohmic drop. The characteristic size itself is dependent on the cell configuration (such as cell and electrode geometry) and operational parameters (such as current density, electrolyte flow conditions, temperature and pressure). As the electrolyzer under investigation is comprised of six cells in each stack so it required between 11 Volts to 13.2 Volts for efficient working. A simulated laboratory environment was used as shown in Figure 3.18. As the irradiance was decreased the power output was lowered, which eventually lowered the power of electrolyzer and as a result decreased the production of HHO. For the overall efficiency, that is solar to hydrogen (STH) for this system, the total hydrogen production in moles and the size and design of the electrolyzer are required. As in this case the HHO production is dependent on the current and voltage of electrolyzer which is dependent on its design (internal resistance, electrolyte, over potential), the equation for STH can be written as equation 3.4:

$$STH = \frac{I_{Ele} \times V_{Ele}}{A_{pv} \times \rho_{sol}} \eta_{sys} \tag{3.4}$$

Here, I_{Ele} and V_{Ele} are the current and voltage of the electrolyzer that are required to split water, A_{pv} is the area of the solar PV system and ρ_{sol} is the irradiance in W/m^2, while η_{sys} includes the efficiency of the panel, efficiency of the convertor and efficiency of the electrolyzer. For this instant values of the current and voltage of the electrolyzer were recorded as the outcome of all these efficiencies.

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Figure 3.18 Test rig for testing the PV-ELE system, coupled with a DC-DC convertor

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For illuminance on the solar PV system, 160 DECOSTAR halogen lAmps (with UV filter, colour temperature 2950 K, Osram, Munich, Germany) of 50 Watts each were used. Measurement of solar irradiance was one of the most important parameter that was to measured and monitor for this study. A HT SOLAR02 Remote Unit (shown in figure 3.19(a) along with a HT HT304N (figure 3.19(b)) reference cell (HT Italia srl, Via della Boaria, Italy) was used to monitor the irradiance level on the PV. It instantly measures the irradiance due to its reference cell and display its results in W/m^2 on the remote unit. For this study it was also needed to log this irradiance for the whole experimental run. So an improvised logger was made to measure as well as log the data for irradiance. For this matter a reference solar PV of 20Watt, I_{sc} = 1A and V_{oc} = 21.6V was used that gives current to a PZEM 017 energy meter that analyze and records the irradiance for every second of interval into a memory card through a data logger shield of Arduino. Different irradiance levels were set by changing the light intensity of the bulbs.

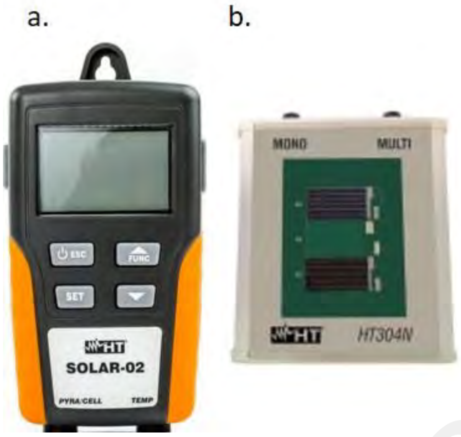

Figure 3.19 (a) HT SOLAR02 Remote Unit, (b) HT HT304N reference cell

To test the system in a real environment, the whole setup was tested and investigated for four hours under Sun irradiance, as shown in Figure 3.20. The PV panel was exposed to the Sun and the working of the convertor and electrolyzer was continuously monitored to examine the real time performance of the converter.

Figure 3.20 Outdoor setup for real time testing of PV-ELE system

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3.3 Phase 2: System Tests

During phase 2 of the project, the two subsystems were combined to operate together. The solar PVs are used to energize the alkaline water electrolyzer for splitting of water to produce hydrogen. This hydrogen is than fed to incinerator through the burners for municipal waste incineration. This research comprises of two different strategies that were under study to run hydrogen fueled incinerator by using PVs. (i) By using a hybrid (PV + battery) system (figure 3.21(a)) to keep the incinerator active even during intermittency; (ii). By using direct coupling of PVs with the hydrogen (figure 3.21(b)).

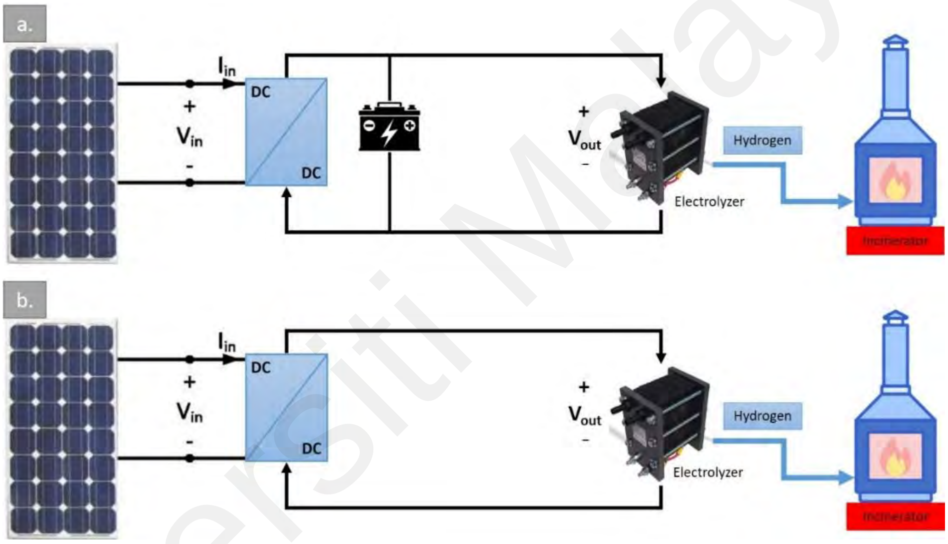

Figure 3.21 Schematic diagram of solar base PV electrolyzer incineration system (a) by using PV + Bat-Electrolyzer (b) by using direct coupling of PV-Electrolyzer

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3.3.1 PV-ELE coupling strategies for incinerator

Three strategies were formulated to run the PV Electrolyzer incinerator as a stand-alone system. i) PV + Battery (Hybrid mode); (ii) auto-ignition (Direct coupling); and (iii) PV + Secondary-Electrolyzer (Direct coupling assisted with secondary electrolyzer) have been envisioned shown in figure 3.22.

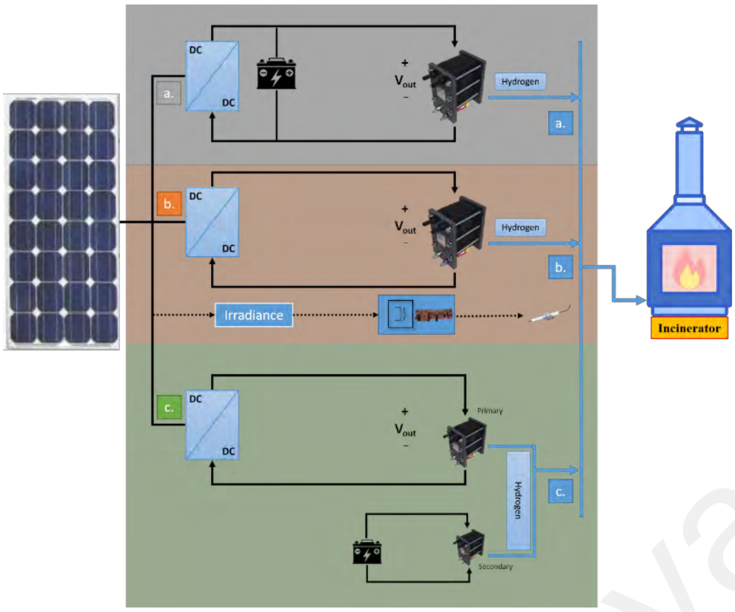

Figure 3.22 Schematic diagram of solar base PV electrolyzer incineration system (a) by using PV + Bat-Electrolyzer (b) by using direct coupling of PV-Electrolyzer

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Two 12 Volts lead acid batteries, with a capacity of 60Ah and 20Ah respectively, were used for energizing electrolyzer during study. First battery was used when system was running on hybrid configuration mode, while second low capacity battery was used to energize secondary electrolyzer when system was running with secondary electrolyzer configuration.

A series of indoor experiments were performed to see the working behavior of incinerator while using first strategy of direct coupling of electrolyzer with the PV. This behavior was tested in a simulated environment (shown in figure 3.23) by changing different irradiance level.

For the second strategy, two different direct coupling approaches were introduced to make a system that controls electrolyzer with in its operation region while catering the intermittency issue. This will energize the electrolyzer to provide hydrogen fuel to the incinerator while addressing the intermittency of the sun light.

For this experiment a small incinerator is made of a stainless steel sheet with 1 mm thickness with a dimension of 4-inch x 4-inch x 18 inch. Furthermore, this incinerator is layered with ceramic wool of 1inch thickness. A 10 mm copper pipe was used for the burner wrapped around the incinerator at the bottom of the incinerator. These burners were fabricated by using a mini hand drill with micro tungsten carbide drill bits. The selection of burners was done on basis of rigorous experimental testing with different diameters of orifices. Figure 3.24 shows that four burners of 0.4 mm diameter orifice can effectively cover the incinerator thermally for incineration waste when electrolyzer working in operating region at 0.9 lpm of production of fuel.

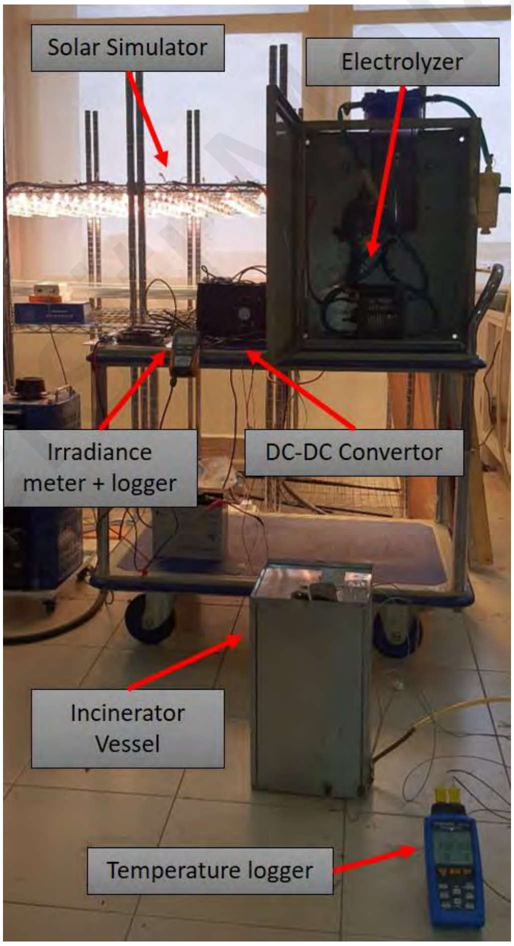

Figure 3.23 Solar simulated environment for testing thermal behavior of incinerator

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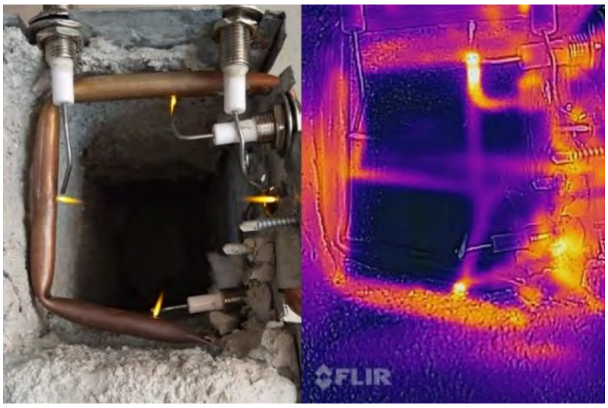

Figure 3.24 Inside view incinerator with flamed burners (left) actual image; (right) thermal FLIR image

From a study of incineration that was using hydrogen as a fuel, it was observed that 40 litters of hydrogen were required to incinerate the 1kg of waste with 60% of moisture content (Osama Majeed Butt, 2022). For testing this PV-ELE based incineration, 500gm of mix waste of 60% moisture content was used to incinerate. It was important to measure and log temperature during study of operation characteristics of electrolyzer and to study the thermal behavior of the incinerator. During the experiment a model: TENMARS TM-747D along with thermocouples (K-type) shown in figure 3.25 were used for monitoring and logging temperature at each interval of second.

Figure 3.25 Temperature logger

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This was used to monitor changes in temperature because temperature starts to fall rapidly as the waste incineration reached close to completion of incineration process (Osama Majeed Butt, 2022). From equation (3.5), total energy produces in electrical terms from hydrogen was calculated:

$$Energy\ Produce = 1\ kg\ of\ H_2 \text{ x } 33.3\ kWh \tag{3.5}$$

Continuous logging of parameters i-e. voltage, current and irradiance are crucial for analysis of this study. Therefore, an Arduino-based data logger was fabricated to measure voltage and current for electrolyzer and solar PV at each interval of second. This measured data was also logged by using logger shield attached with Arduino. Beside voltage and current, irradiance was also logged by using same setup.

This data logger shown in figure 3.26 consists of an Arduino MEGA development board with data logger shield and three separate PZEM 017 energy meter with individual shunts. A program was written to sample the voltage and current parameters from each of the PZEM 017 meters at an interval of 1sec and store them onto the SD memory card on the data logger shield.

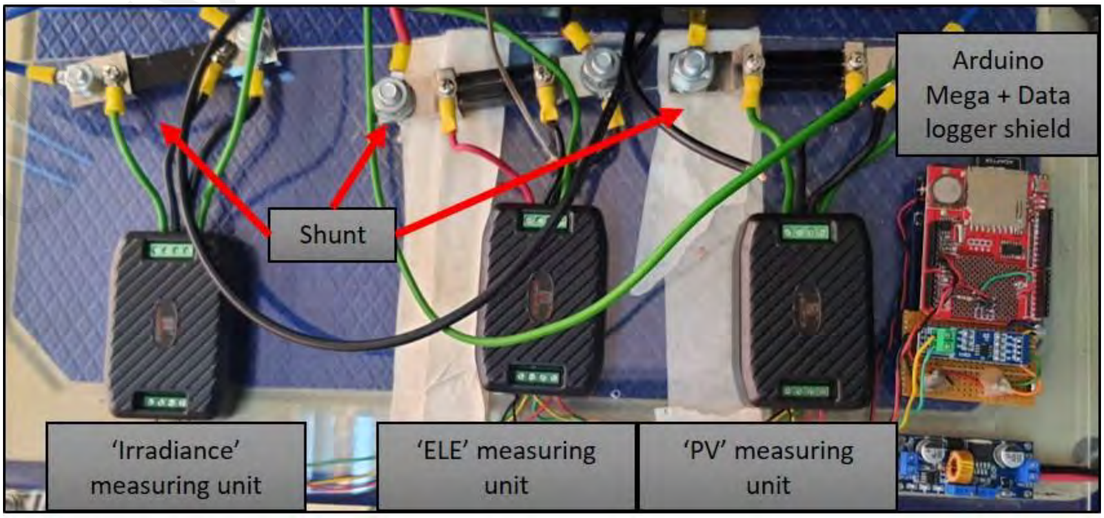

Figure 3.26 Arduino-based Data logger Used in the Experiment.

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Total production of hydrogen was calculated by logging current utilized by electrolyzer at each second. That current was then used to see flow rate of gas (HHO) based on the operational characteristics of electrolyzer. Gas flow (HHO) is comprised of 67% of hydrogen. Therefore, by using equation (3.6) total energy produce from gas generated from electrolyzer can be calculated as:

$$Total\ Energy\ Produce = \left(\sum HHO_{\ (litters\ per\ sec)}\right) \text{ x } 0.67 \text{ x } 33.3\ kWh \qquad (3.6)$$

For verification of incineration process, weight reduction method and loss on ignition test was performed. The residual weight was measured using a precision weighing balance (A&D HK-250AZ) and loss on ignition (LOI) has been measured according to ASTM D7348 standard.

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3.3.1.1 Hybrid Mode Coupling

In this strategy, electrolyzer is connected with the PV by using a DC-DC convertor through a battery. This PV-BAT energizes the electrolyzer to split water to feed hydrogen gas to incinerator for incineration purpose of municipal solid waste. A Battery (12Volt, 60Ah) used in this strategy, that stabilize the energy provided to incinerator during intermittent energy from PV. Size of the battery is design to withstand 1-2 complete hours of intermittency and electrolyzer continues to work during that course of period. DC-DC convertor act as a solar charger for battery to recharge the drain energy. Another part of the convertor was responsible for maintaining the voltages and current at rated values of electrolyzer (12Volts, 15Amps) by using pulse width modulation (PWM).

3.3.1.2 Direct Mode Coupling

In this setup, electrolyzer was allowed to couple with the solar PV by a DC-DC convertor (Butt, Saeed, et al., 2021). Solar PV was the only source to energize the electrolyzer to produce hydrogen that was feed to incinerator. To verify the inside working temperature of incinerator, a setup was made shown in figure 3.27. This setup was used to see the temperature behavior inside the incinerator affected by fluctuation of energy from solar PV due to intermittency of sun light. It was physically observed that flame was quench number of times due to intermittency of sun light.

Figure 3.27 Outdoor setup for PV-ELE incineration

This quenching of flame was happened due to fluctuation in production rate of hydrogen during intermittency. Flame inside the incinerator was not able to sustain during fluctuation at low production rate of hydrogen.

So, a simulative environment shown in figure 3.23 was setup where burners were allowed to ignite in the same manner to see the thresh hold of the flow rate which could sustain the burner flames and irradiance level at that power. Test were performed on different irradiance level using HT SOLAR02 Remote Unit along with a HT HT304N reference cell (HT Italia srl, Via della Boaria, Italy), while burner was observed

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physically. Also continuous monitoring of temperature inside the incinerator was done by using temperature logger (model: TENMARS TM-747D), and thermocouples (K-type).

Two solutions were proposed in this study under direct coupling strategy to resolve problem of quenching of flame due to this intermittency. Either to have (i) an auto ignition system or have minimum (ii) threshold flow of hydrogen to sustain the flame during intermittency.

In ‘auto ignition’ approach of direct coupling a mechanism of auto ignition is added as shown in figure 3.28. Irradiance is being recorded for every second. An auto pulse ignitor starts to re-ignite burners as irradiance level crosses threshold of irradiance level. A signal is sent from irradiance logger to the ‘pulse ignitor’ that will generate spark in the ‘ignitor’ assembled with burner inside the incinerator.

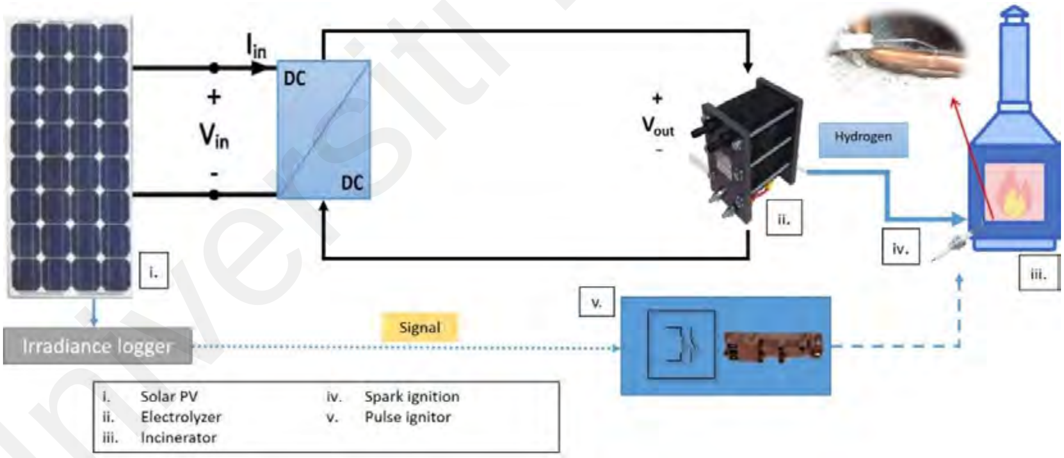

Figure 3.28 ‘Auto-ignition’ approach proposed for direct coupling strategy for PV-ELE incineration system

Another approach in figure 3.29 was proposed to cater the intermittency issue of sun light that effect the flow rate of gas. According to this approach an independent secondary electrolyzer is been connected with the system. Secondary electrolyzer powered by battery of 12V 20Ah was only responsible to give a stable flow rate of the gas at the

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minimum amount that is required to keep the flame. This methodology helps to kept the flame sustain even under extreme low irradiance and not required to lit up again. Also it only required a significant small battery to energize this small secondary electrolyzer.

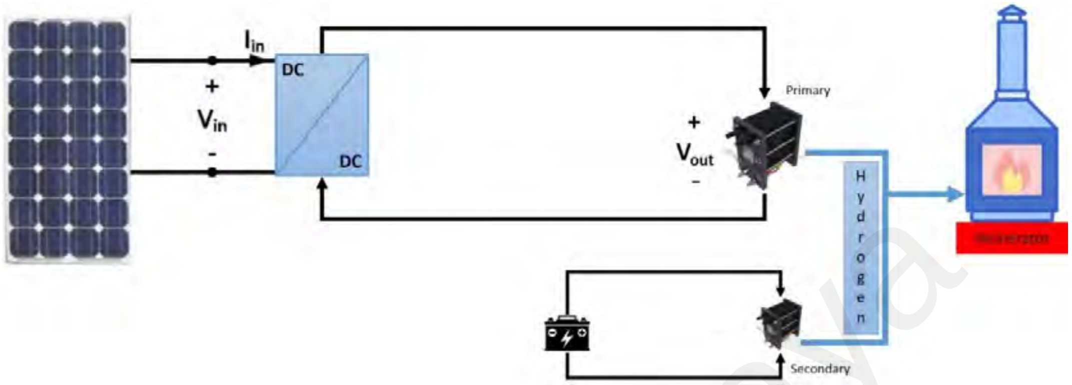

Figure 3.29 'PV + Sec-ELE' approach proposed for direct coupling strategy for PV-ELE incineration system

3.3.2 Techno-Economical Analysis

Three different methods for PV-ELE incinerator were studied based on their mechanism to cater intermittency of solar energy: 1) PV + Battery, 2) Auto Ignition (without battery), 3) PV + Secondary electrolyzer. A complete cost break-up is given in table 3.2 while costing of electrolyzer for capacity of 0.4lpm (used in PV + Secondary ELE approach) is given in table 3.3. This cost was used to analyze along with other parameters of these systems including time required to incinerate, hydrogen produced, total energy consumed by system and its efficiency.

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Table 3.2 Cost break-up for equipment used in experiment

Item	Cost ($)
PV + Bat (Hybrid)	
Electrolyzer (complete kit as purchased)	360
PV	300
Battery (12volt, 60Ah)	75
PWM convertor	45
Wires + Breaker	10
Charge Controller	10
Total	800
Auto-Ignition	
Electrolyzer (complete kit as purchased)	360
PV	300
DC-DC convertor	50
Wires + Breaker	10
Irradiance logger + Ignitor Driver	42
Ref PV Cell for Irradiance Measurement	10
Ignitor Pulser + Spark Plugs	3
Total	775
PV + Sec ELE	
Electrolyzer (complete kit as purchased)	360
PV	300
DC-DC convertor	50
Wires + Breaker	10
Secondary Electrolyzer (0.4lpm, self-fabricated)	95
Battery for Sec Elec (12volt, 20Ah)	25
PWM convertor	45
Wires + Breaker	10
Total	895

Table 3.3 Cost break-up for electrolyzer with capacity of 0.4lpm

Items	Cost ($)
Acrylic end plates	3
Stainless steel plates	10
Rubber gaskets	4
Stainless steel bolts and screws	2
Hoses and pipes	2
Bubbler and water reservoir tank (2.5 L)	4
wires and circuit breaker	10
PWM controller	45
Total	95

Incineration of MSW is determined by three main content of waste that is moisture, ash and combustible. Above all, moisture is the most crucial content as it can increase the

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weight of the waste without increasing the net yield. MSW with higher moisture content than 50% are unfit for autogenous incineration and requires auxiliary fuel (Sebastian et al., 2019). This auxiliary fuel is used to dry up high moisture content from waste so MSW can help in self-combustion process for incineration based on calorific value of waste. In the current study, reduction in energy is calculated that is required for a particular waste based on its moisture content. For Malaysia average calorific value of municipal solid waste is 1.74 kWh/Kg (6276 kJ/kg) (Pek & Jamal, 2011), while moisture content ranges from 52 – 66% (Aja & Al-Kayiem, 2014) (60% was taken for current study). As energy required for evaporating 1 kg of water is 626 kWh/kg. Reduction in energy for a particular waste equivalent to required amount based on its moisture content was calculated by using equation (3.7):

$$\% \; of \; Energy \; reduction = \frac{(Energy \; required \; to \; evaporate \; moisture \; content - Energy \; supplied \; in \; form \; of \; H_2)}{Energy \; required \; to \; evaporate \; moisture \; content} \tag{3.7}$$

For further cost and life span analysis, capital cost of solar PV and batteries were taken as $1/watt and $104/kwh respectively (Christensen, 2020). Life span of lead-acid battery is 4 years (Kebede et al., 2021) while for electrolyzer it can be up to 30 years (Christensen, 2020). By neglecting the maintenance cost for each setup, a forecasting for capital cost analysis based on life span of electrolyzer and batteries was analyzed on the current scenario and experimental setup placed in Kuala Lumpur, Malaysia.

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CHAPTER 4: RESULTS AND DISCUSSION

The objective of current study was to fabricate a hydrogen based incinerator for MSW management. Hydrogen was produced from electrolysis process. Moreover, this electrolysis process was energized by solar PV to establish it as a green technology. These incineration experimentations were conducted for MSW based in Kuala Lumpur, Malaysia. Therefore, all the parameters related to waste moisture, characteristics and irradiance were considered for this region.

First section of the chapter describes the burner design for the incinerator that are fed by pre-mixed hydrogen and oxygen in stoichiometric ratio. Second section is based on the characterization of municipal solid waste after incineration by using hydrogen as fuel. A complete analysis of incinerated waste based on moisture, weight reduction and loss on ignition was done. Third section investigates the operational characteristics of electrolyzer. These parameters involve voltage, current and temperature of the electrolyzer. Furthermore, in this section, a predictive approach was design to directly couple electrolyzer with the solar PV to energize it to produce hydrogen by splitting of water by DC current. This approach of coupling electrolyzer with solar PV was based on characteristics of the electrolyzer. In last section of this chapter, a detailed comparison of different strategies for PV-Electrolyzer hydrogen fueling incinerator system was studied. These strategies were investigated from both technical and economical perspectives.

4.1 Design of Burners

The selection of burners was done on basis of rigorous experimental testing with different diameters of orifices. As different engineering factors are used to determine the compatibility of gases (fuel) with appliances. Wobbe index is the most common and simple to determine this compatibility (Dodds et al., 2015). As for hydrogen, the Wobbe index is around 48MJ/m^3. This makes hydrogen gas compatible as it is within range of

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natural gas safety regulations for burners (Zachariah-Wolff, Egyedi, & Hemmes, 2007). Although the wobbe index is within natural gas safety, burners used for natural gas cannot be directly used with hydrogen. This is because of combustion characteristics i.e., flame speed. The burner orifice size needs to be reduced compared to natural gas (Dodds et al., 2015). Therefore, dedicated burners were fabricated and were fed with premixed hydrogen and oxygen in a stoichiometric ratio.

Choosing of appropriate orifice of the burner was based on the number of orifice and available flow rate of gas from electrolyzer. This design of burner was decided on the affected area of inside of the incinerator that flame have to cover.

Burners with different diameters of orifices were tested on different constant flow rate of HHO. A series of experiments were performed at each flow rate of gas from 0.5 lpm to 3 lpm of oxyhydrogen. At first instant, orifices of diameters i.e., 0.2 mm, 0.3 mm, 0.4 mm, 0.5 mm, 0.6 mm, 0.7 mm and 0.8 mm have been tried keeping the mass flow constant at 0.5lpm (hydrogen and oxygen stoichiometric mixture). Imagery results for these experiments are presented in figure 4.1. For orifice sizes 0.2 mm, no stable flame was observed. This is because of high gas velocities due to small orifice sizes which caused flame blow-off. A stable flame was achieved for 0.3 mm burner orifice size for 0. 5lpm gas flow. At diameter of 0.3mm orifice, 0.5 lpm was able to produce 1.9inches of the flame. This can be seen from FLIR image in figure 4.1(a), while visible image shows that flame is only 0.5inch. Increasing diameter of orifice to 0.4mm also increase the length of the flame to 2.1 inches with a visible flame to 0.625 inches (figure 4.1(b)). Moreover, increasing in orifice to 0.5mm, 0.6mm and 0.7mm diameter results in increase of the flame length with 2.4inch, 2.75inch and 3inch with visible flame length of 0.71inch, 0.812inch and 0.9inch respectively. As orifice diameter increase to 0.8mm its flame length decrease to 2.8inches that can be seen in FLIR image of figure 4.1(f) but visible

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flame increases a little bit up to 0.93inches. By increasing diameter of orifice further to 0.9mm, flame could not sustain and a flash back occurs. This results the limit of orifice diameter for 0.5lpm of HHO.

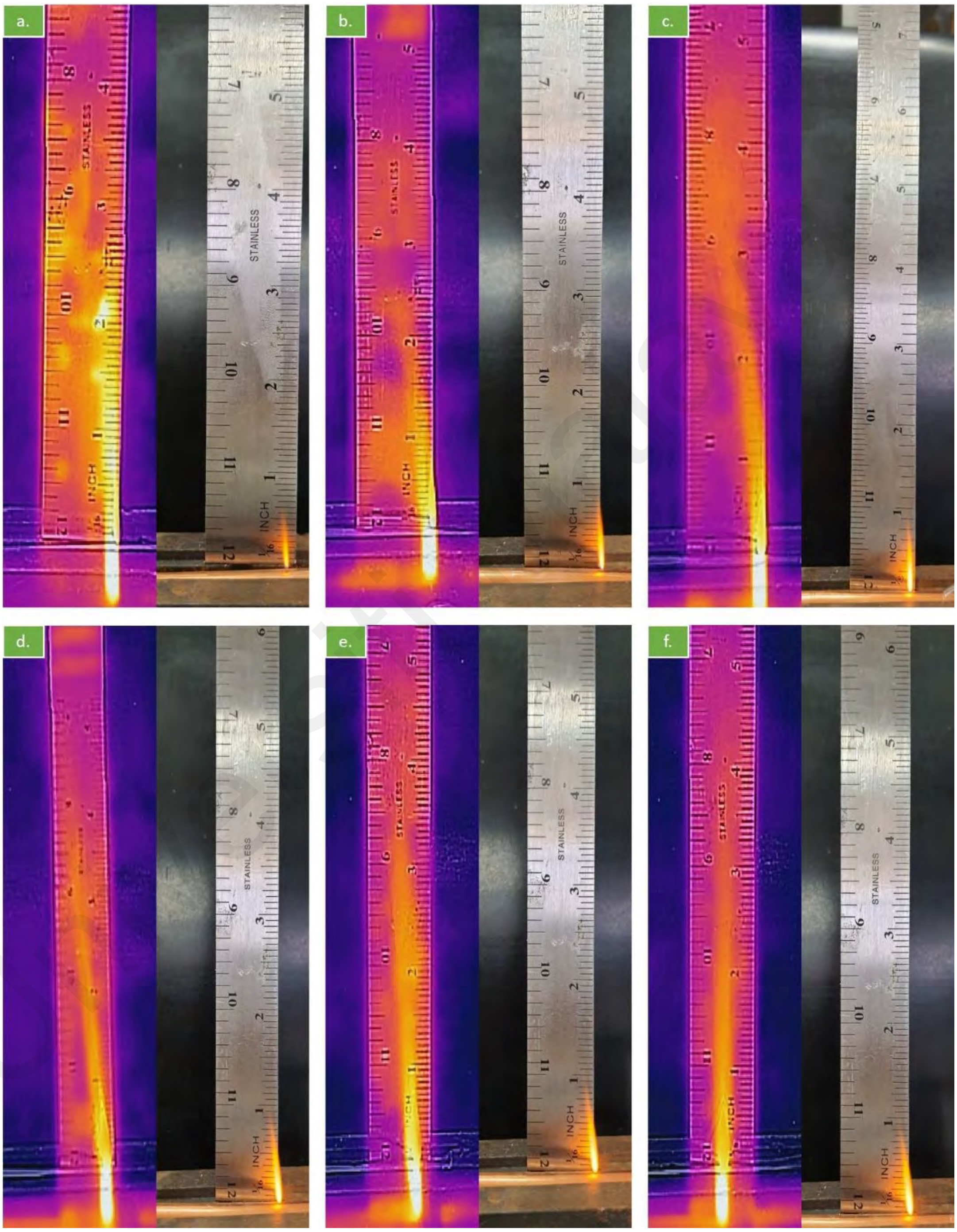

Figure 4.1 Flame length of working burner on 0.5LPM of oxyhydrogen (left) FLIR image (Right) visible image: (a) 0.3mm orifice, (b) 0.4mm orifice, (c) 0.5mm orifice, (d) 0.6mm orifice, (e) 0.7mm orifice, (f) 0.8mm orifice

A similar series of experiments were repeated for 1.0 lpm with different diameters of the orifice. Imagery results of flame length for different orifices are presented in figure 4.2. With 1.0 lpm of HHO gas, flame length for orifice diameter 0.3mm was reported to be 3 inches with a visible length of 1.18 inches. Upon 0.4 mm effective flame length increased to 3.2 inches with a visible flame length of 1.86 inches. With increase in diameter of orifice more to 0.5mm, it increased visible length flame up to 2.5 inches. But FLIR image in figure 4.2 (c) shows that effective length of the flame was increased to 4.5inches. Similarly, this effective flame length increases to 5 and 5.1 inches with the increase in diameter of orifice of burner by 0.6 mm and 0.7 mm respectively. This increase was not much seen in visible flame length (figure 4.2(d) & (e)) only up to 2.8inches but intensify the flame. As diameter of the orifice increased to 0.8 mm, it decreased the visible length to 2.35 inches as well as effective flame length to 4.5 inches (figure 4.2(f)). Further increase in the diameter of orifice to 0.9 mm, 1.0 mm and 1.1 mm decrease the flame length to 4.3 inches, 4 inches and 3.7 inches. Also insignificant decrease in the visible flam length was noted with intense flame. When the diameter of orifice was further increased to 1.2 mm, it suddenly quenches the flame as burner was allowed to lit up. In result a flash back occurred. This resulted limit of the orifice diameter to 1.1mm, for HHO gas with a flow rate of 1.0 liter per minute.

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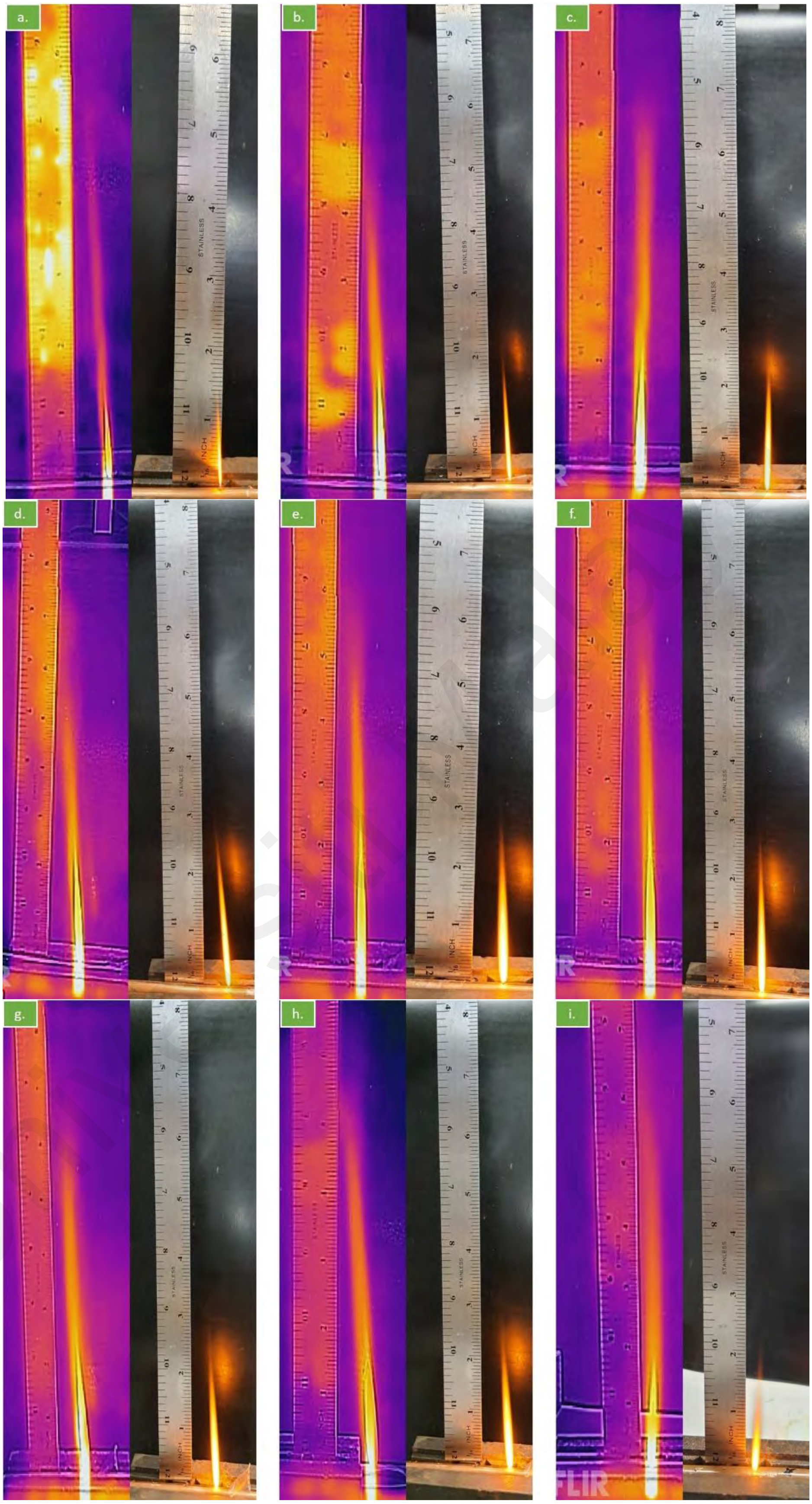

Figure 4.2 Flame length of working burner on 1.0LPM of oxyhydrogen (left) FLIR image (Right) visible image: (a) 0.3mm orifice, (b) 0.4mm orifice, (c) 0.5mm orifice, (d) 0.6mm orifice, (e) 0.7mm orifice, (f) 0.8mm orifice, (g) 0.9mm orifice, (h) 1.0mm orifice, (i) 1.1mm orifice

It was seen that with increasing the diameter of orifice there is increase in the length of flame. As increasing in size of the orifice hits the limit for respective flow rate, flash back occurs. Now flow rate of the gas was set to be 2 liters per minute and same series of experiments were repeated. This time a flash back occurs at 0.3mm of diameter which shows that orifice size was quite small for such a flow gas. Flame was sustained at 0.4mm so it was considered to be lower limit for 2 lpm of gas. Same trend was followed by 2 liters per minute flow rate of gas as previously seen in case of 0.5 lpm and 1.0 lpm. As shown in figure 4.3(a), using FLIR imaging length of flame was increased up to 12 inches for orifice diameter of 1.1mm with a visible length of 3.7 inches. Further increasing in orifice diameter to 1.2 mm decrease the effective flame length to 10 inches with a visible length of 4 inches. This decrease of length was noted to be 7.3 inches and 6.5 inches for 1.3 mm and 1.4 mm of diameter of orifices respectively. For 1.3 mm diameter visible length was seen to be 4.17inches while for 1.4 mm it decreased to 3.5 inches but the flame was observed to be intense for 1.4 mm orifice. As orifice was increased to 1.5 mm, a flash back occurs which was evident to be limit of the diameter for orifice.

A 3.0 liters per minute of HHO was given for the same diameter of orifice i-e 1.5 mm which was flash backed in the last series of experiments for 2.0 lpm. From figure 4.4(a) it can be seen that it gives a 7.5 inches of effective flame with a visible flame length of 4.5 inches. Again same experiment was repeated with 1.6 mm of diameter of orifice. This time FLIR image in figure 4.4(b) shows an increase in flame length of 9 inches. But visible flame length was not significantly increase. Now 1.7 mm diameter of orifice was used for 3.0 lpm of HHO gas. It gives a decrease in flame the and showed 8.5 inches of length while there was no any significant change in length of visible flame except it intensifies the flame. As the orifice diameter was increased to 1.8 mm, a sudden flash

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backed occurred, which verified the limit for diameter of orifice to be 1.7 mm. Same 1.8 mm diameter of orifice which was flash backed was used for higher flow rate of 4.0 lpm and 5.0 lpm. But it again results in flash back. So it was testified that diameter of orifice size cannot be increase any further.

It was established to be an incremental trend with the increase in diameter of orifice to the flame length up to certain extent for a specific flow rate. After that limit, flash back occurs and flame can no longer sustain at that particular flow rate. Also from experiments, it was resulted that maximum diameter that can be used for HHO was 1.7 mm. Beyond that size of diameter of orifice flame cannot be sustain even at high flow rates.

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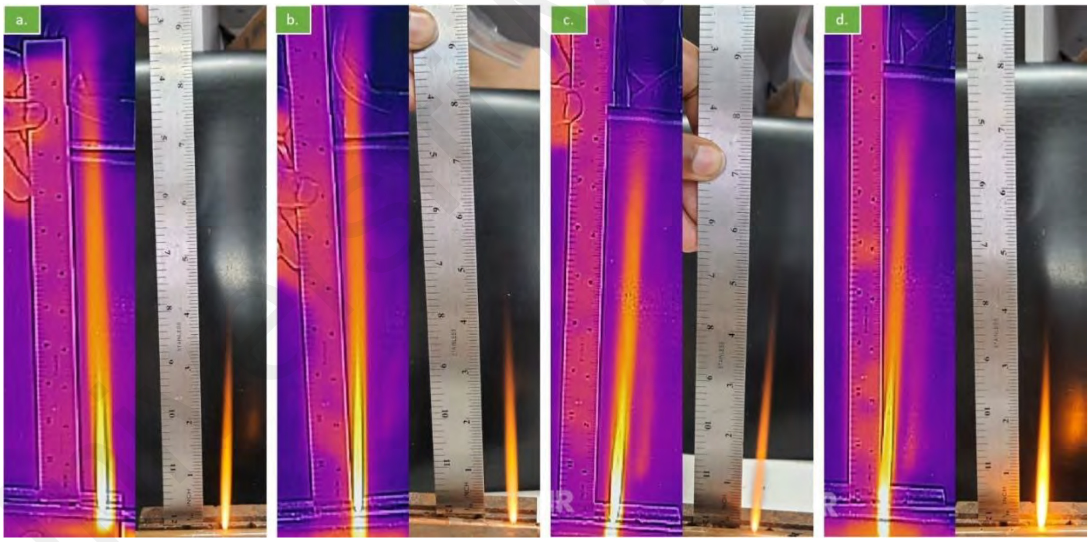

Figure 4.3 Flame length of working burner on 2.0LPM of oxyhydrogen (left) FLIR image (Right) visible image: (a) 1.1mm orifice, (b) 1.2mm orifice, (c) 1.3mm orifice, (d) 1.4mm orifice

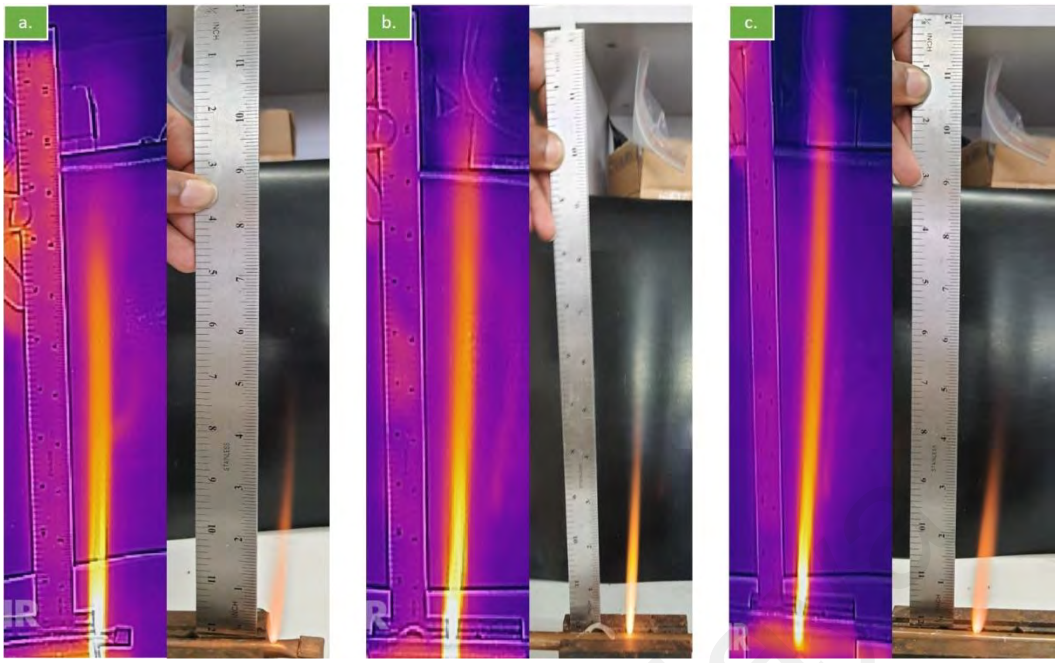

Figure 4.4 Flame length of working burner on 3.0LPM of oxyhydrogen (left) FLIR image (Right) visible image: (a) 1.5mm orifice, (b) 1.6mm orifice, (c) 1.7mm orifice

4.2 Waste Incineration through Hydrogen

Based on the experiments and for homogenous heat distribution within the combustion chamber (chamber cross-section area: 6x6inches), the orifice diameter of 0.6mm was selected for our further experiments. One by one orifice was increased as shown in figure 4.5 to see the effective length. The optimum number of orifices and diameter have been adjusted to ‘5’ (figure 4.5(e)) for 3 lpm fuel flow and cross-sectional area of the combustion chamber. Further increase in the number of burners leads to a reduction in flame length and possible flashbacks.

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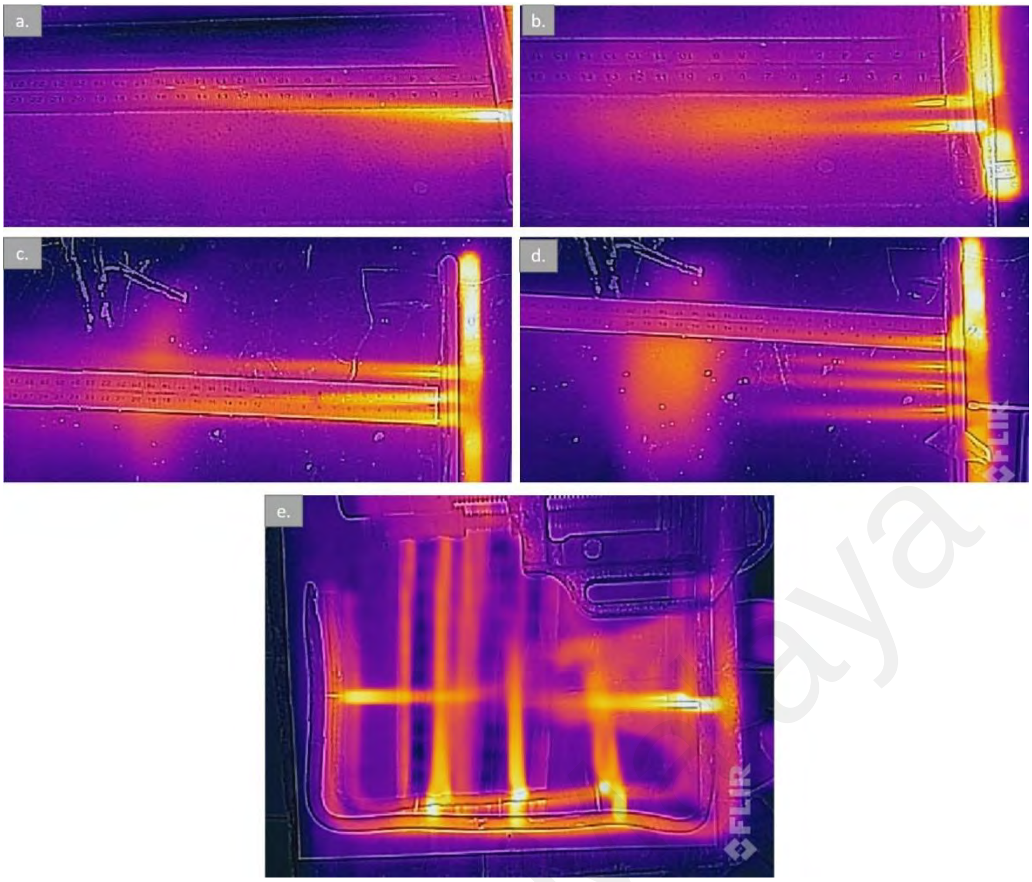

Figure 4.5 Testing of quantity of burner orifices for experimental setup for 0.6mm orifice (a) 1- orifice, (b) 2 – orifices, (c) 3 – orifices, (d) 4 – orifices, (e) burner used with 5 – orifices

The incinerator was allowed to run on premixed hydrogen and oxygen in stoichiometric ratio for incineration. Figure 4.6 shows the relationship between temperature and time for the incineration chamber at various heights when run without garbage. The temperature close to the flame (the thermocouple was placed just 1-2 inches above the flames at the center) in empty condition reached approximately ~400ºC in 200 seconds. The temperature reached ~600ºC after 3500 seconds and maintained 600ºC. In the middle section of the incinerator, the temperature was attained ~200ºC in 500 seconds which was maintained at ~300ºC after 2700 seconds of running the experiment. The temperature at the top of the incinerator reached ~150ºC in 600 seconds and was maintained to ~200ºC after 3500 seconds.

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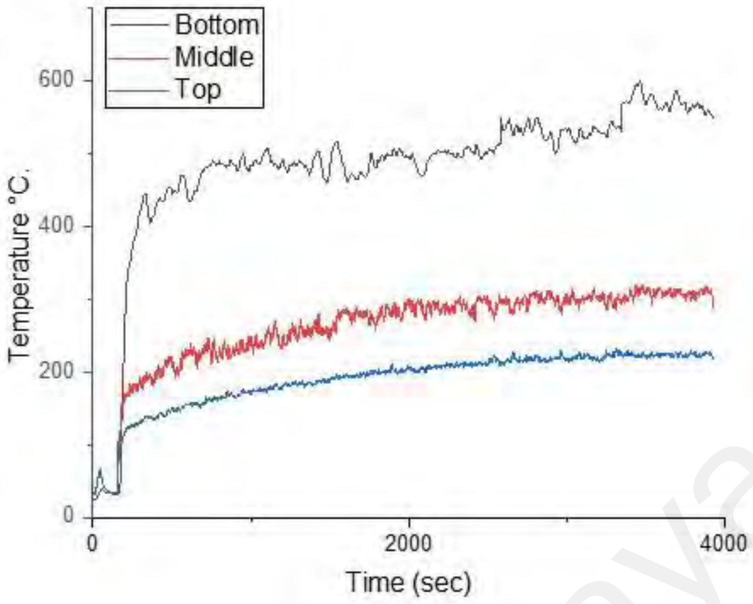

Figure 4.6 Temperature data at three different positions of empty incinerator using hydrogen as combustion fuel

It has been observed that hydrogen as fuel can easily maintain a temperature of up to 600°C where the combustion of the waste is to be done. Overall hydrogen keeps the temperature of the incinerator good enough for an efficient incineration process of MSW. Note that the characteristic flame temperature of hydrogen is 2800ºC.

4.2.1 Incineration of Homogenous Waste

The incineration experiments have been first conducted using individual waste i.e., paper waste, textile waste, and food waste. Figure 4.7a, b shows the time & temperature relationship for incineration and schematic diagram of working of incinerator with MSW respectively. The detailed parameters have been presented in table 4.1. The hydrogen supply has been cut-off after reaching the temperature plateau and leaving the incinerator running (keeping the blower on) for complete combustion. As it can be observed in figure 4.7a, the temperature for food waste of 1000g with 87% moisture content reached 580°C in 3200 seconds. The amount of hydrogen being consumed was calculated to be 107.2 liters which translates to 353.76 watt-hr of energy being supplied for the food waste. For

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the textile waste of 1.5 kg with a moisture content of 90%, the temperature reached ~800°C in 2200 seconds. Almost 73.7 liters of hydrogen equivalent to 243 Wh of energy was supplied for textile waste. In the case of paper waste, only 36 liters of hydrogen was required to raise 780°C of temperature in 1100 seconds for its complete incineration. Paper required much less time than others due to its highly combustible nature.

Further analysis on the energy required and energy from the waste was presented in table 4.1. As it was seen that calorific value of food waste, paper waste and textile waste is 4650 kJ/kg, 16600 kJ/kg, 17450 kJ/kg (Hermesmann & Müller, 2022) which are equivalent to 1.3 kWh/kg, 4.61 kWh/kg and 4.84 kWh/kg respectively. Based on the calorific values and moisture content in waste in it was calculated that food waste can give 220 Wh, paper 1840 Wh and textile 243 Wh of energy.

In principle, the burners consumed hydrogen to burn and/or dry the highly moist MSW whereas, the blower provide the required oxygen for complete combustion of dried waste. The vertical shaft type design allows hot gasses to rise up and partially dry off the incoming feed as can be seen in figure 4.7(b).

The food waste raised the lesser higher temperature to incinerate than the paper and textile waste. This is because of the calorific value of paper and textile waste than food waste. Furthermore, the moisture content is a key factor affecting the time to rise in temperature. the initially provided energy was consumed to evaporate the water content. That was 545.19 Wh for food waste, 375.9 watt-hr for paper waste and 845.9 Wh for textile waste. The combustion of waste started after the removal of moisture content.

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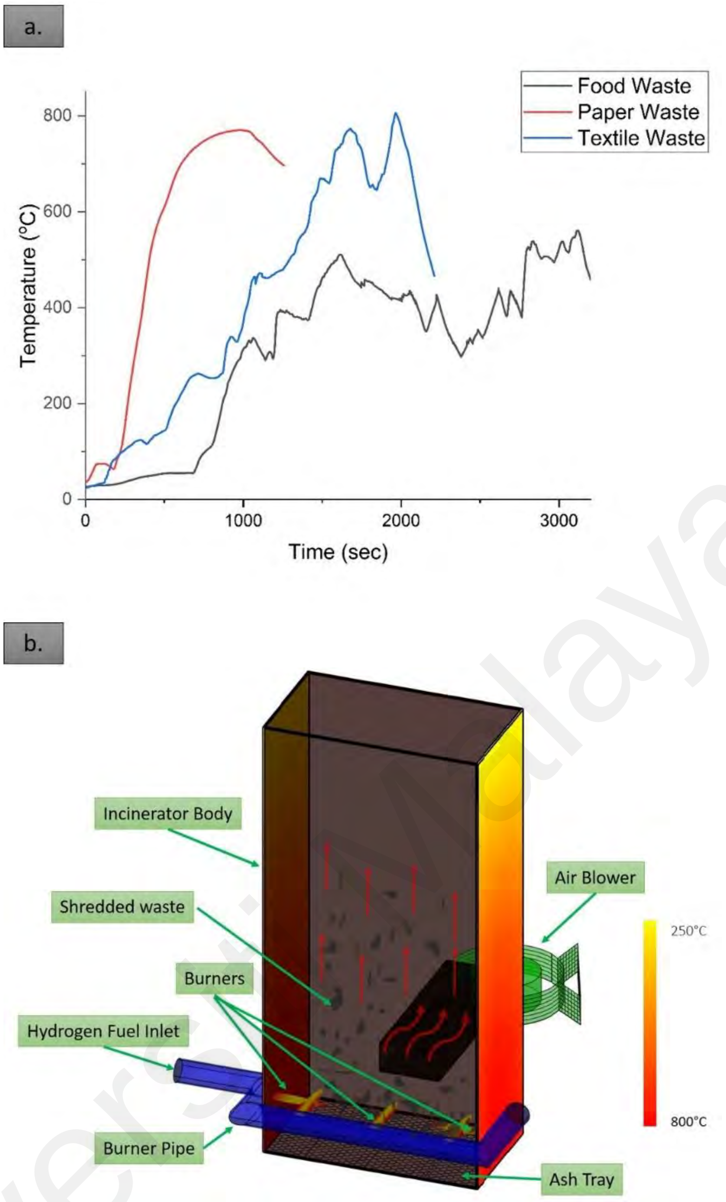

Figure 4.7 (a) Temperature graphs for the homogenous respective wastes; (b) Inside working of incinerator

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Table 4.1 Data of the respective homogenous waste during incineration

Batch	Moisture Content %	Energy Required (Wh)	Temp °C	Time (Sec)	H_2 given (liters)	Energy from H_2 (Wh)	Energy from waste (Wh)	Percent energy provided by H_2
Waste 1 (Food)	87	545.19	580	3200	107.2	353.76	221	64.88%
Waste 2 (Paper)	60	375.9	780	1100	36	118	1840	31.39%
Waste 3 (Textile)	90	845.9	800	2200	73.7	243	720	28.73%

*Additional 50% of moisture by weight is added using water in paper & textile used as waste

4.2.2 Incineration of Heterogeneous Waste

To test the hydrogen incinerator for real-time waste, different types of waste (food, textile, and paper) were mixed in a known ratio as presented in table 3.1. Figure 4.8 (a & b) shows the temperature vs time pattern and performance parameters (i.e., power consumed and time) respectively. Detailed parameters of the waste batches have been presented in table 4.2. It has been observed that the waste with more moisture content required more time and energy for complete incineration. This is due to the higher moisture contents which require extra energy to evaporate. During the combustion, temperature rises as premixed hydrogen and oxygen are fed as fuel. Also, the waste itself acts as fuel as moisture content reduces due to high temperature. It has been observed that, as the waste incineration reached close to completion, the temperature starts to fall rapidly. This is because of no waste left for combustion in the incinerator chamber. It has been inferred that no more hydrogen fuel has been required from that time when the temperature falls significantly.

Waste batches 4, 5 and 7 have been incinerated in approximately 2100, 2000, and 2200 seconds respectively whereas waste 6 has been incinerated within 1200 seconds. Furthermore, it has been observed that the waste 6 rapidly reached ~800°C and maintain that peak temperature for a longer period, while other batches i.e., waste 4, waste 5, and waste 7 raised their temperature gradually and maintain peak temperature (i-e ~800°C) for a shorter period. This was happened due to the low moisture content in waste 6 compared to other wastes. Waste 4, waste 5, and waste 7 are required to dry-off high moisture content of the waste before waste could catch fire, while waste 6 has a low moisture content, therefore, the waste abruptly catches fire which in turn leads to a rapid rise in temperature. The amount of energy required for complete combustion of each type of waste along with the maximum temperature reached has been presented in table 4.2.

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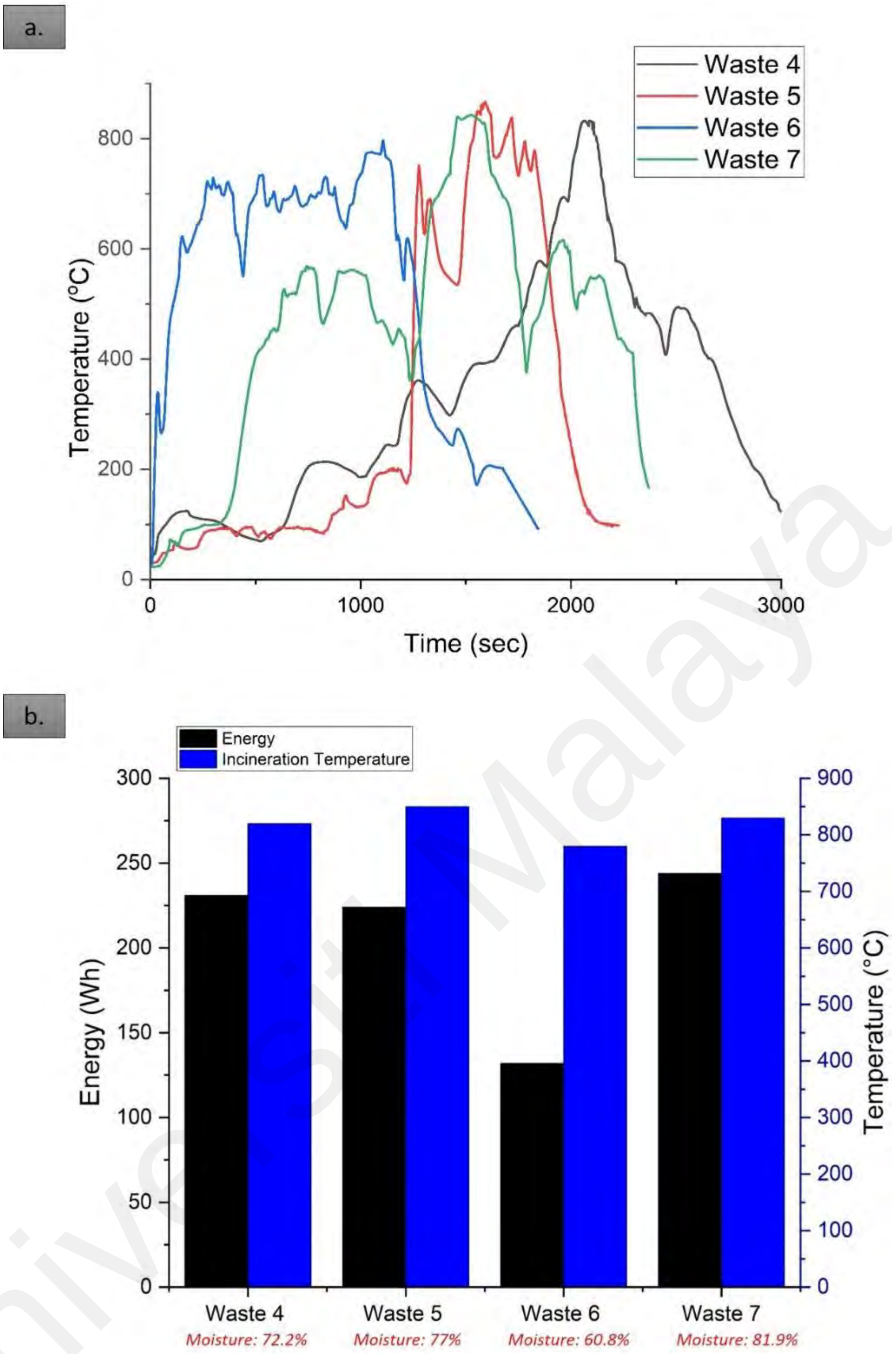

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Figure 4.8 (a) Temperature graphs for the heterogeneous respective wastes (b) Energy required for incineration of respective waste

Based on the mixing ratio of the experimental waste and calorific values, it was calculated that 'waste 4', 'waste 5', 'waste 6' and 'waste 7' can evolve 975.5 Wh, 805 Wh, 1234.8 Wh and 465.17 Wh of energy up on incineration. As 'waste 4' has 72.2% of moisture content so it required 497.69 Wh of energy to fully dried up for combustion.

Similarly, ‘waste 5’, ‘waste 6’ and ‘waste 7’ has moisture content 77%, 60.8% and 81.9% which required 482.52 Wh, 381 Wh and 513.23 Wh of energy. But for ‘waste 4’ on 70 liters of hydrogen is given as a fuel assisted incineration process which is equal to 231 Wh of energy. This means that 53.58% less energy is given to ‘waste 4’ to initiate incineration process based on its moisture content. On similar grounds ‘waste 5’ of moisture content 77% was given 53.57% less energy with 68 liters of hydrogen, ‘waste 6’ of moisture content 60.8% was given 65.3% less energy with 132 liters of hydrogen and waste 7 with 81.9% moisture content was given 52.45% less energy with 244 liters of hydrogen.

Table 4.2 Data of the respective heterogeneous waste during incineration

Batch	**Moisture Content %**	**Energy Required (Wh)**	**Temp °C**	**Time (Sec)**	**H_2 given (liters)**	**Energy from H_2 (Wh)**	**Energy from waste (Wh)**	**Percent energy provided by H_2**
Waste 4	72.2	497.69	820	2100	70	231	975.50	46.42%
Waste 5	77	482.52	850	2000	68	224	805	46.43%
Waste 6	60.8	381.00	780	1200	40	132	1234.8	34.7%
Waste 7	81.9	513.23	830	2200	74	244	465.17	47.55%

4.2.3 Residue analysis

The residue after incineration has been collected and tested for its LOI. Figure 4.9 shows the residues left for all the homogeneous and heterogeneous waste batches. The detailed parameters have been presented in table 4.3. The weight reduction has been calculated to be 88.88%, 97.14%, 96.50%, 91.80%, 86.41%, 91.80% and 94.52% for the batches waste 1 to 7 respectively which is in high agreement with the standard reduction values for incineration i.e., between 75%–90% (S. Kumar & Ankaram, 2019; Ouda et al.,

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2016). Further, it has been observed that wastes with more moisture content were reduced less in weight as compared to low moisture content waste

The LOI values have been calculated for all the waste batches using a high-temperature furnace as explained in the above section (chapter 3). The calculated values for batches of waste 1-7 were 1.74%, 2.80%, 6.41%, 6.12%, 5.38%, 2.97%, and 3.72% respectively which lies within the standard LOI values i.e., between 2 – 6% (S. Kumar & Ankaram, 2019). The residue of paper waste (waste 1) showed a minimum LOI value which is due to the high combustibility of paper waste. The residue of food waste (waste 2) showed the second lowest value of LOI whereas, textile waste (waste 3) shows the highest value of LOI (6.41%). This can be due to unusual moisture content in waste (90%).

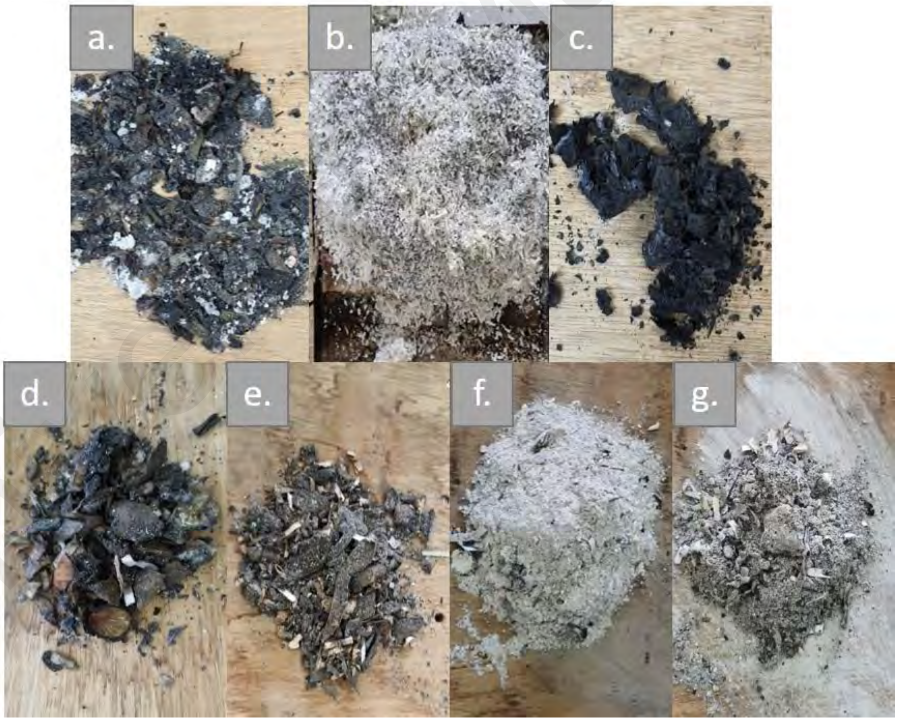

Figure 4.9 Bottom ash for incinerated waste (a) waste 1, (b) waste 2, (c) waste 3, (d) waste 4, (e) waste 5, (f) waste 6, (g) waste 7

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Table 4.3 Reduction in weight of waste and LOI after incineration

Batch Number	Initial Moisture Content %	Amount of waste (gram)	Residue Left (gram)	Reduction in weight %	Loss on ignition %
Waste 1	87	1000	111.2	88.88	1.74
Waste 2	60	1000	28.6	97.14	2.80
Waste 3	90	1500	52	96.50	6.41
Waste 4	72.2	1100	90.2	91.80	6.12
Waste 5	77	1000	136	86.41	5.38
Waste 6	60.8	1000	87.6	91.24	2.97
Waste 7	81.9	1000	54.8	94.52	3.72

The LOI for waste 4 (containing 500g food waste, 300g textile waste, and 300g paper waste) with 72.2% moisture content showed a 6.12% LOI value which is due to the high percentage of hard to incinerate food waste (especially watermelon rind, etc.). Waste 5 (containing 400g food waste, 300g textile waste, and 300g paper waste) showed a bit less 5.38% LOI value than waste 4. This was due to the absence of hard crust food waste. However, waste 6 & waste 7 showed lower LOI values of 2.97% and 3.72% with the moisture content of 60.8% and 81.9% respectively. This is due to the type of food waste present and less moisture content. It can be inferred from the results that the type of waste may affect the incineration performance. Furthermore, the moisture content of around 80% can be handled by the presented design. However, waste with a moisture content of more than 90% reduces the incineration performance.

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4.3 Strategies for coupling PV-ELE for incinerator

One of the objective of this study was coupling of the solar PV with the electrolyzer. Based on coupling technique, PV-ELE incinerator system was further classified into two strategies (i) Hybrid mode and (ii) Direct mode. For designing the coupling of electrolyzer with the solar PV, it was necessary to find out operational parameters of the electrolyzer.

4.3.1 Operational parametric study of electrolyzer

4.3.1.1 Influence of current on Electrolyzer in HHO production

Behavior of current on production of HHO gas was tested. By using Sorensen SG Series power supply applied current was varied with a range from 6 to 24 Amps at rated constant voltage of 12 Volts. The resultant graph in figure 4.10 showed that HHO gas production rate gradually increased with the applied current increase. The deviation from straight line trend of HHO flow rates with increased of the applied current happened because of the current leakage increase. This also led to the decrease the efficiency of electrolyzer. Increase of applied current from 6 to 24 Amps increases flow rate from 0.3 liters per minute of HHO to 1.31 liters per minute. The faster bubbles formation occurred on the electrode surface were produced from the higher applied current. This was happened as the applied current on oxyhydrogen generator increased from 16 Amps. These bubbles on the surface of electrode created an instability for electrode which effects the flow of electric current. The increase of the applied current led to the increase of the exchange between the positively charged hydrogen ions and electrons. The current increase led to the electrodes conductance increase and effective ion collisions. The increase of current led to the increase rate of electron transfer between the electrodes which have an effect on the rate of water dissociation. The ions presence reduced the electrical resistance and increased the electrical conductivity under the current increase effect. The overcurrent increase led to the plate heating, water evaporation and less efficiency. This is the reason that efficiency of electrolyzer remains between 66 – 65%

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until 14 Amps, but as the current increased more this efficiency start decreasing and led to electrolyzer to work on 58.3% on 24 Amps. Results shows that flow rate was continuously increasing with current that showed 1.31 lpm at 24 Amps of current. But due to bubbles and evaporation of water at high current, there was a small fraction of water vapors that were mixed with HHO gas which decrease the quality of the gas.

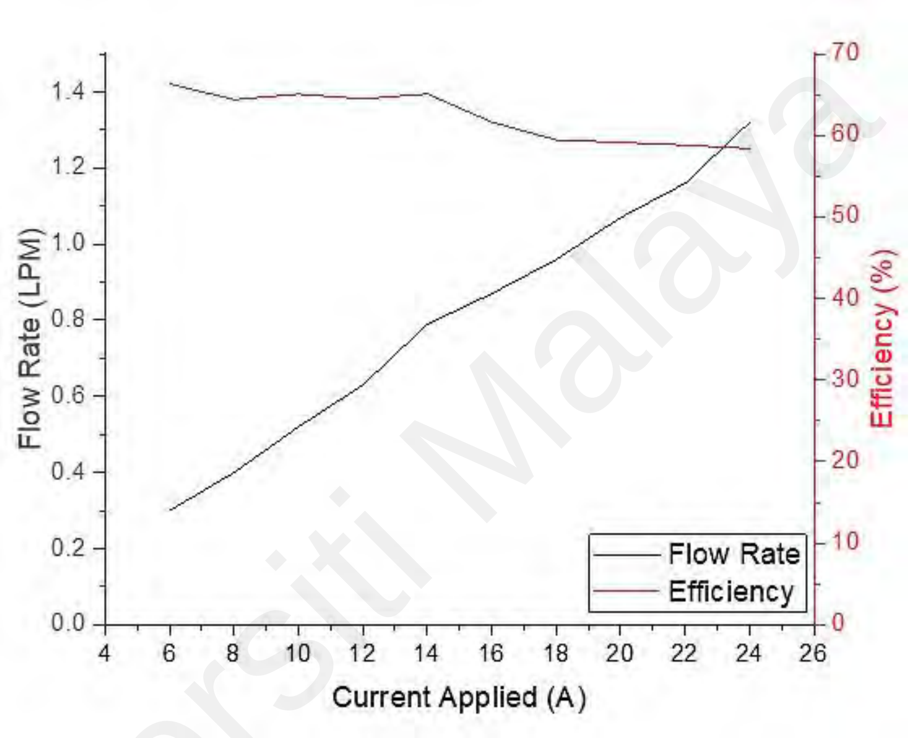

Figure 4.10 Effect of constant voltage with applied current on electrolyzer for production of HHO gas

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4.3.1.2 Influence of voltage on Electrolyzer in HHO production

Production of HHO gas from electrolyzer is influenced by current as well as voltage applied. Ideally, 1.23 Volts of potential is required for electrolysis process for splitting water into hydrogen and oxygen. Higher voltages than this amount is known as 'over-potential' which is due to several reasons including surface of electrode, concentration of electrolyte, gap between electrode, gasket size of electrolyzer. Practically, it was seen that effective electrolysis occurs between 1.8 volt to 2.2 volt for a single cell. For current scenario, HHO production was studied over stainless steel electrodes used in electrolyzer at room temperature of 25 °C and 30% KOH concentrated solution of electrolyte. From previous section it was resulted that 14 Amps of current was most ideal value for current electrolyzer. Therefore, to study influence of voltage over HHO production, a series of six experiments were performed by keeping current constant at six different levels from 14 Amps to 24 Amps. For each current level, voltage was varied from 9 Volts to 13 Volts (according to six cells per stacks). Results for each experiment is presented in figure 4.11. It was seen that HHO gas production rate gradually increased with the applied voltage increase due to the uniform charge density increase, ions exchange on the electrode surface and the reaction kinetics acceleration. For constant current 14 Amps in figure 4.11(a), flow rate kept increasing gradually for voltage 9 to 13. This also increase the efficiency of electrolyzer up to 65%. Increasing voltage beyond 12 Volts was meaningless because limit of constant current was already achieved. So, the constant current was set to 16 Amps. This time it was seen that flow rate was increasing with increase of the voltage but efficiency start decreasing which end up in resulting 61.6% for 12 Volts. Now current was set to be constant at 18 Amps. This time similar behavior was seen (figure 4.11(c)) of significant decrease in efficiency of 58.9% at 12 Volts but flow rate was achieved to be 0.96 liter per minute. Voltage above 12 Volts could not be achieved because electrolyzer was having current limits for above voltages. Now the current was set at 20 Amps and voltage was varied from 9 Volts to 14 Volts. Similar trend of decline was notices in figure 4.11(d). Efficiency was dropped to 58.17% at 13 Volts but flow rate was increased to 1.07 liter per minute. For the fifth time current level was set to be constant at 22 Amps with varying voltages from 9 – 13 Volts. From figure 4.11(e), It can be observed that although flow rate was increased to 1.16 liters per minute of HHO but with efficiency to 56.86%. For the last time current limits were set at 24 Amps and experiment was run by varying voltage level from 9 – 13 Volts. This time efficiency was

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further decrease to 57.48% but from figure 4.11(f) it can be seen that flow rate was increased to 1.3 liters per minute at 13 Volts.

The increase of voltage from 9 to 12 V_{DC} led the electrolyzer efficiency and actual flow rate increases to but from further increasing voltage at different current levels led the efficiency to decrease. This is due to the higher losses and current leakage led electrolyzer to decrease with increase in voltage at high currents. The cell overvoltage also resultant in temperature to increase, which effects flow and quality of gas production. This is because, water vapors were start mixing with the gas as output. Therefore, results show that cell overvoltage effects the efficiency of electrolyzer to decrease.

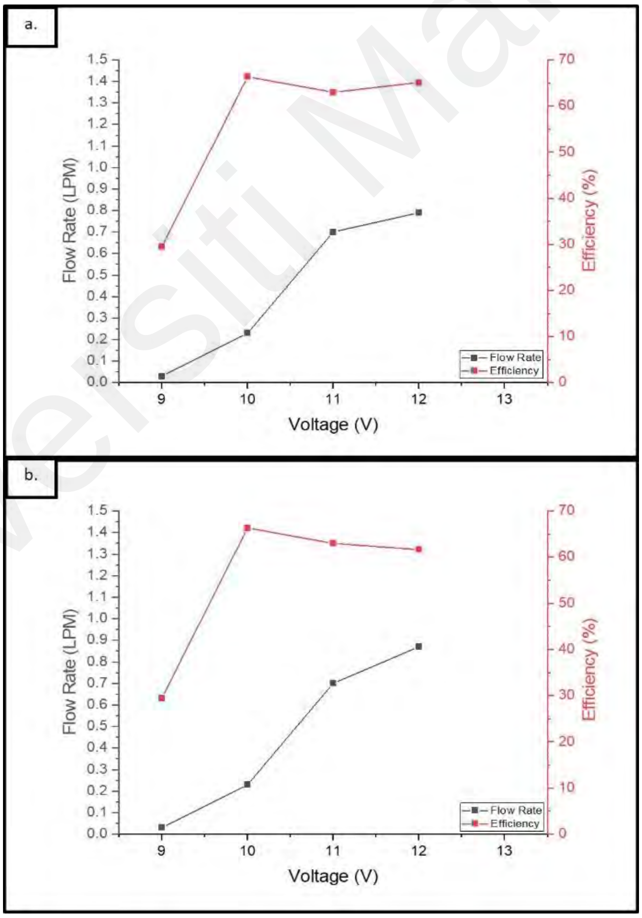

Figure 4.11 Effect of constant current with applied voltage on electrolyzer for production of HHO gas (a) 14 Amps, (b) 16 Amps, (c) 18 Amps, (d) 20 Amps, (e) 22 Amps, (f) 24 Amps

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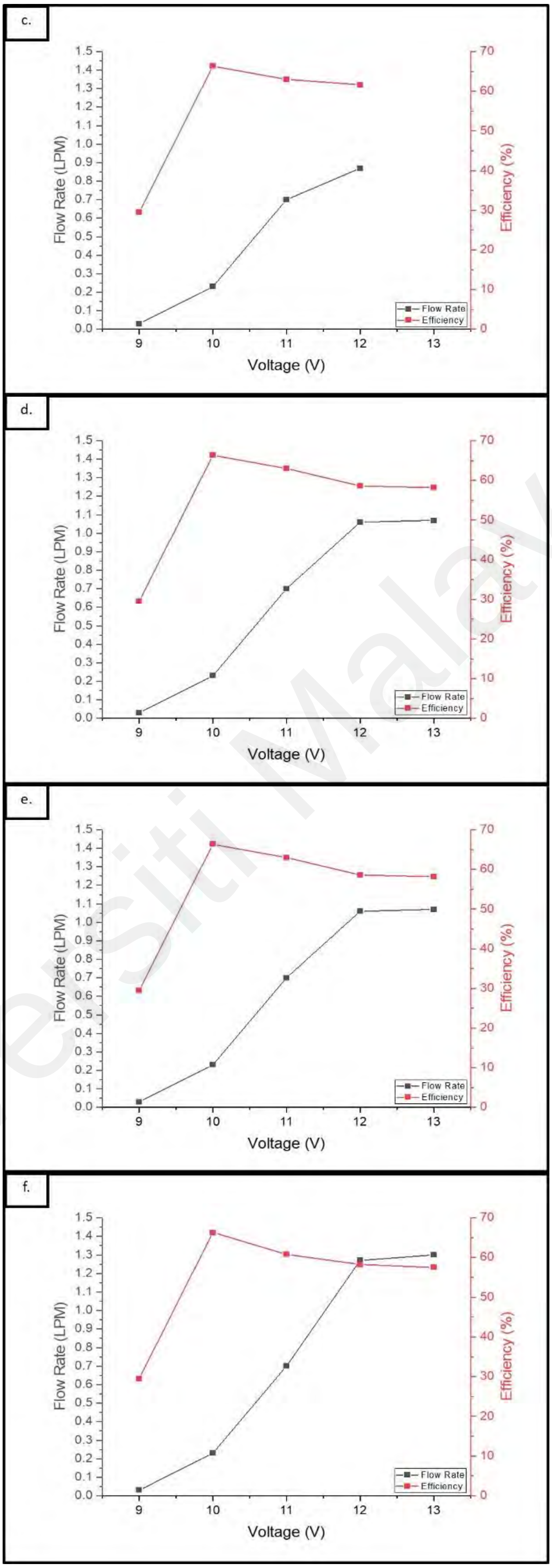

Figure 4.11 (contd.) Effect of constant current with applied voltage on electrolyzer for production of HHO gas (a) 14 Amps, (b) 16 Amps, (c) 18 Amps, (d) 20 Amps, (e) 22 Amps, (f) 24 Amps

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4.3.1.3 Influence of temperature on Electrolyzer in HHO production

Electrolyzer was allowed to run on different current levels for 30 minutes to see the behavior of flow rate of HHO and temperature due to current. At the start of electrolysis process, the rate of HHO gas production was gradually increased but after some time rate of gas production reached to stable position. The fouling and destruction of electrodes was started as the current applied and increased as the time passed. Production rate of HHO gas was stabilized as the operating pressure and temperature were in steady state. As the time passes with the current applied on electrodes, it gradually increased in the molecules movement and the molecular collisions between the hydrogen and oxygen gases. This results in increase of average kinetic energy of molecules and yield in higher production of gas.

Temperature is directly related to the potential applied on HHO electrolyzer. Over-potential on electrolyzer can cause to generate extra heat. With the increase in production time of gas results in the increase of generating HHO temperature. It was observed that with electrolysis process increased, it increased the temperature as well as rate of HHO gas production at given fixed operating time of 30 min set for experiment. This increase of temperature due to increase in operating time was due to mobility of electrons and the heat transfer rate increase on the plates. Also fouling and destruction of electrodes were increased with time. The effect of electrolyte (30% of KOH solution) temperature at different currents at 12 Volts is given in figure 4.12.

Firstly, experiment was performed with 20 Amps of current for 30 minutes. Initial temperature was noted to be 34.2°C. and flow rate of gas was 1.06 liters per minute. As the time passed the temperature rises rapidly and reached 68.5°C after 30 minutes (figure 4.12(a)). Although flow meter recorded HHO yield to be increased to 1.1 liters per minutes but water vapors at outlet can easily be seen which was due to such high

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temperature. These vapors were responsible for low quality of gas beside such high flow rate. Further, literature suggests that temperature should not be reach to 70°C (Bhardwaj et al., 2014). Therefore, it was resulted that such high amperes are not suitable for this electrolyzer. Now the experiment was repeated with 15 Amps of current and presented its results in figure 4.12(b). Flow rate was started from 0.8 liters per minute and reached to 0.83 liters per minute after 30 minutes. But this time temperature was observed well under limit and low at 45.2°C. Now again the experiment was repeated for third time with 10 amperes of current in figure 4.12(c). This time flow rate of HHO gas production was started at 0.51 liter per minute but didn’t increased significantly after 30 minutes (0.52 lpm). Also temperature was only raised with 4°C from beginning and reached 40.8°C. There was no significant flow rate and also change in temperature.

Higher the resistance of electrolyte and electrode will produce more heating for electrolyzer. With the increase in temperature, increases molecular collisions between ions. According to Faraday’s law, this will result in higher yield of HHO gas. But over increase of temperature led to increase the concertation of electrolyte which results in water evaporation. At this point, even yield of gas is shown high but the quality of gas will be low due to mixture of water vapors. Therefore, it was resulted that 15 Amps of the current was the most optimum value of the current for the existing electrolyzer under test as it gives significant amount of flow rate of HHO gas production without increasing much temperature for electrolyzer system.

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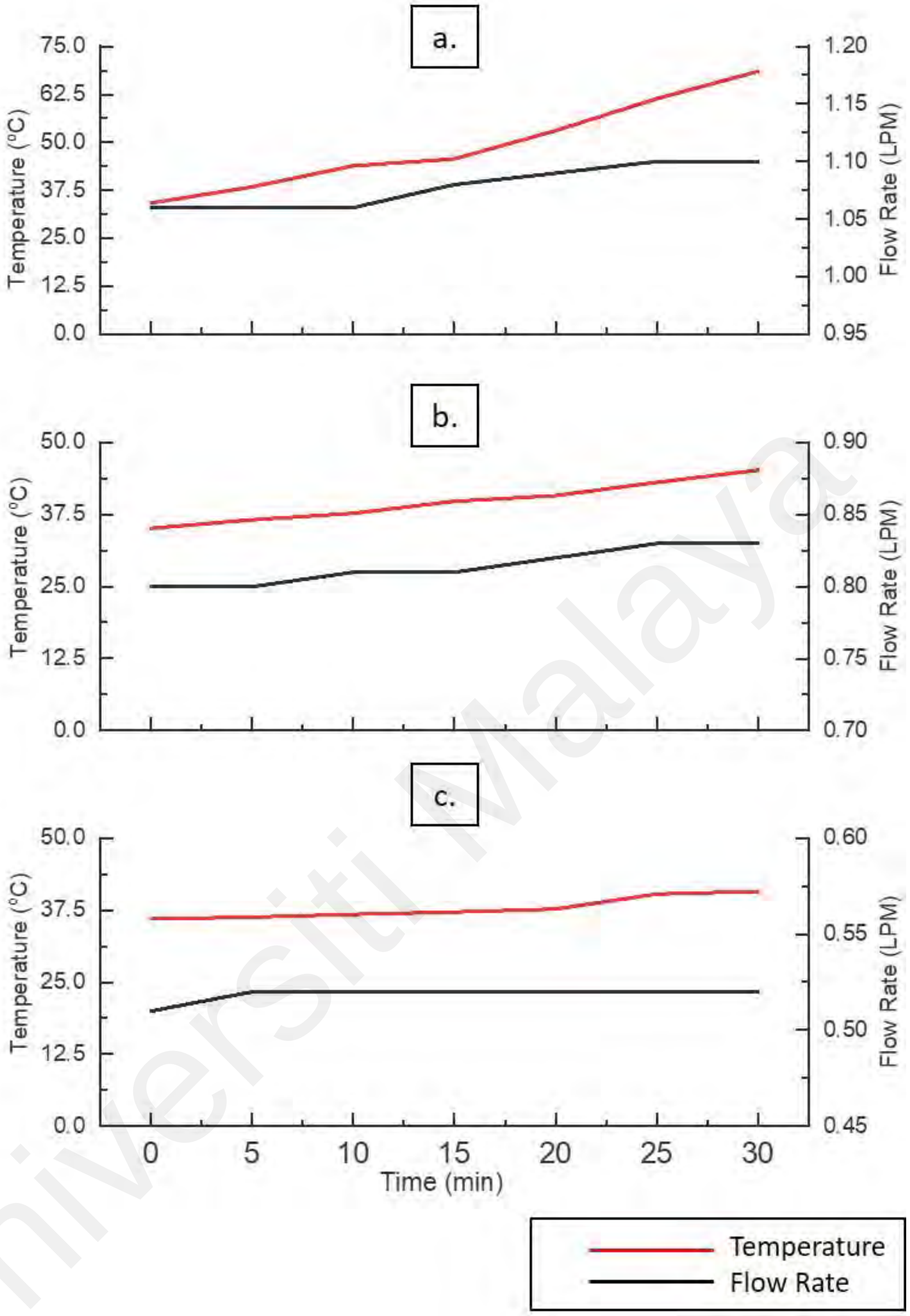

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Figure 4.12 Effect of temperature on electrolyzer at different current (a) 20 Amps, (b) 15 Amps, (c) 10 Amps

A brief summary of the parameters of the electrolyzer in its operating region is shown in Table 4.4.

Table 4.4 Operating parameters of electrolyzer

Parameter	**Value**
Voltage	10.8–13.2 Volts
Current	15 Amps
Optimum temperature	60 °C

4.3.2 Coupling of Electrolyzer with solar PV

For coupling of electrolyzer with PV, the characteristics of the electrolyzer as well as PV were determined. IV testing was performed to see the working behavior of the PV and electrolyzer. The IV curves of the solar PV and electrolyzer based on the tests, are shown in Figures 4.13(a) & (b) respectively. From Figure 4.13(b) we can easily analyze the operating parameters of the electrolyzer i-e 12 Volts and 15 Amps.

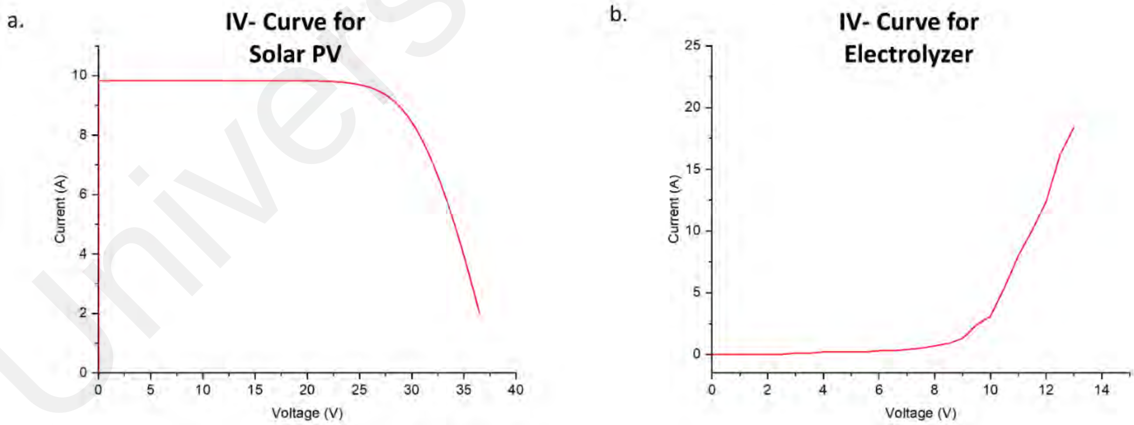

Figure 4.13 (a) IV curve for the solar PV under test, (b) IV curve for the electrolyzer under test

To see the working of the electrolyzer coupled with the solar PV, the test rig was allowed to run under different irradiance levels. Data of voltage, current and power for the PV and electrolyzer were recorded as seen in in figure 4.14 by using an oscilloscope.

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Voltages and current for both PV and electrolyzer at different irradiances can be seen in (i) part of all figures in figure 4.14. In the (ii) part of all figures of figure 4.14, it can be seen that electrolyzer power is following the power that is delivered from PV due to DC-DC convertor. The system was allowed to run for 30-minute time interval for each irradiance until steady state was reached. Further data was analyzed and is summarized in Table 4.5.

Power for the PV and electrolyzer was analyzed for the steady state by using a weighted moving average. This was used to calculate the efficiency of the convertor and its working for tracking maximum power point. At 1200 W/m^2, although more power was available than utilized by the electrolyzer but it was due to working of DC-DC convertor. This convertor was responsible to keep the electrolyzer within limits of its operating voltage and current as determined earlier. So even more current could be drawn by electrolyzer but convertor was not allowing to exceed current from 15 Amps. Similar behavior was seen for 1000 W/m^2 of irradiance. Table 4.5 shows that efficiency is increased for lower irradiance. This is because electrolyzer was running at its peak values of voltage and current while available power for 1200 W/m^2 was more than in case 1000 W/m^2 that was un-utilized due to electrolyzer characteristics. In case of 800 W/m^2 irradiance efficiency was more increased to 96.2% because un-utilized available power was less available. After 800 W/m^2 of irradiance available power was reduce and hence less current was supplied to electrolyzer which reduces the flow rate of HHO production. Although at 200 W/m^2 of irradiance, mathematically the convertor was working at 89% but the system was actually not working, hence resulting in 0% yield of the HHO. This is because at this low level of irradiance the electrolyzer was not working in its operating region, so no significant HHO was producing.

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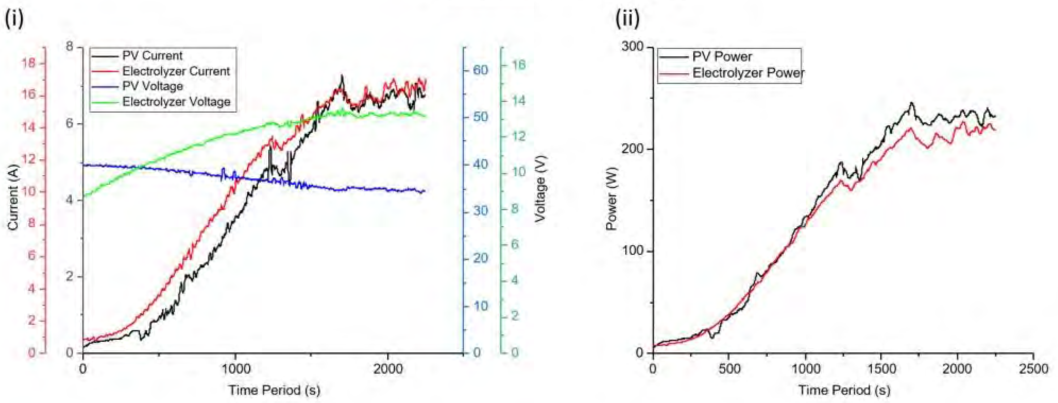
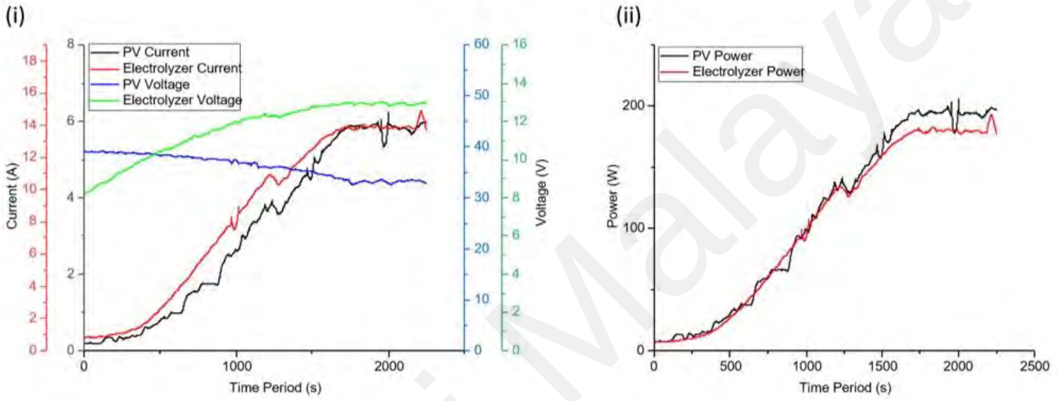
a. Irradiance at 1200 W/m^2



b. Irradiance at 1000 W/m^2



c. Irradiance at 800 W/m^2

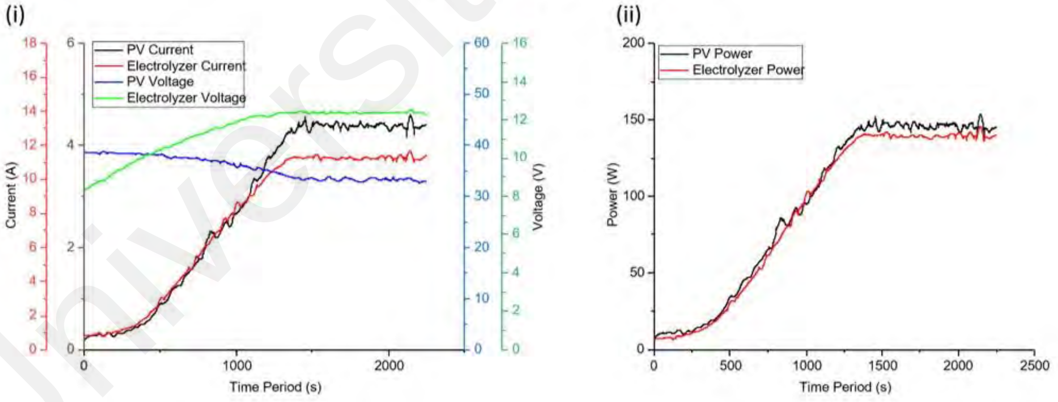


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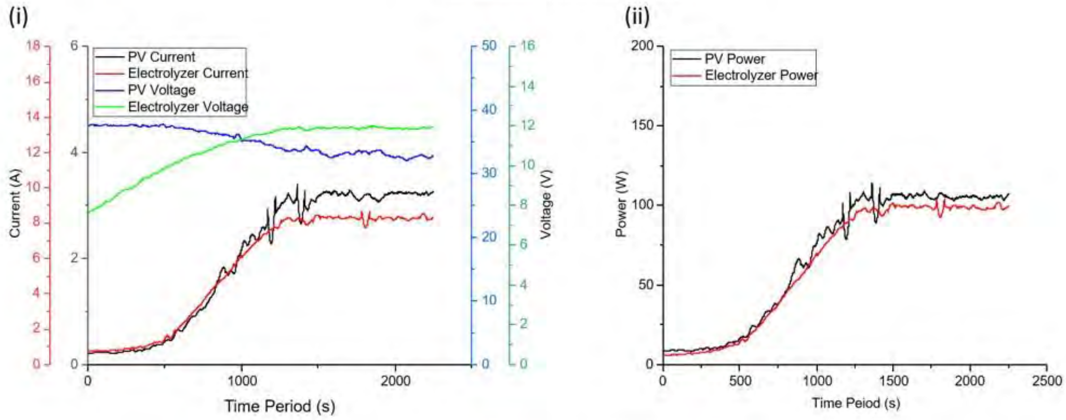
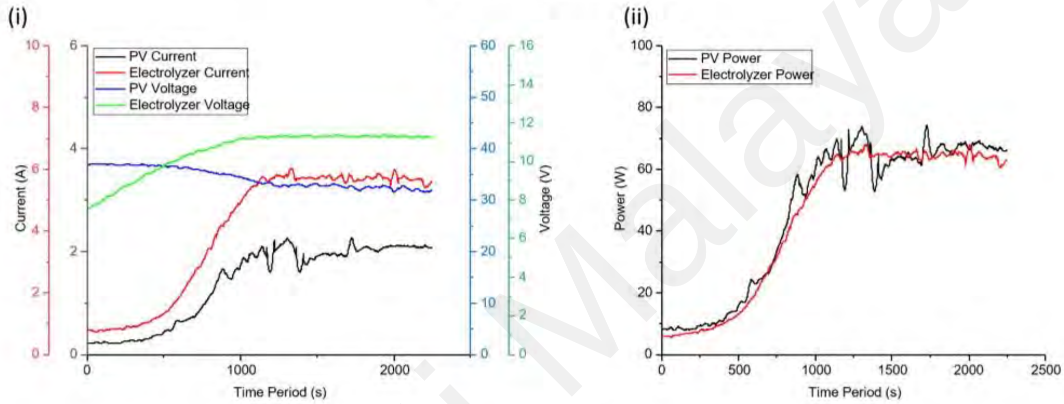
Figure 4.14 Voltage and current of the PV and electrolyzer monitored on oscilloscope and power was being calculated for each at different irradiance level: (a) 1200 W/m^2; (b) 1000 W/m^2; (c) 800 W/m^2; (d) 600 W/m^2; (e) 400 W/m^2; (f) 200 W/m^2

d. Irradiance at 600 W/m^2



e. Irradiance at 400 W/m^2



f. Irradiance at 200 W/m^2

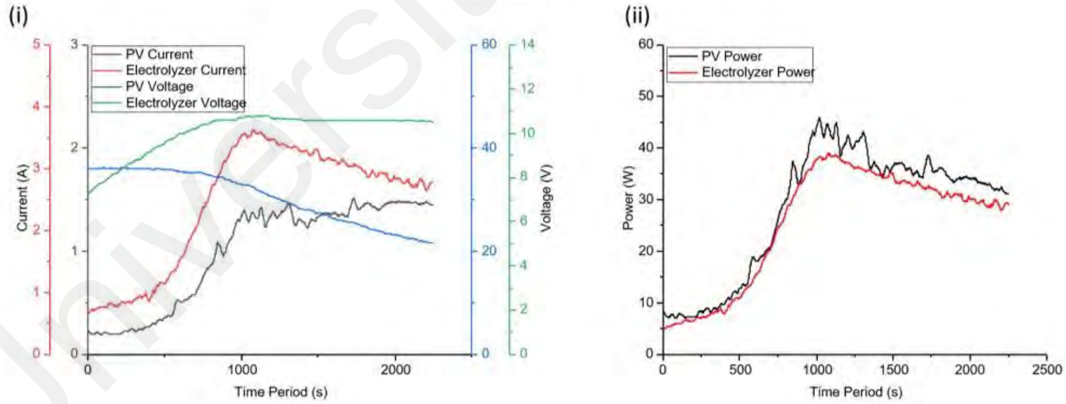


Figure 4.14 (contd.) Voltage and current of the PV and electrolyzer monitored on oscilloscope and power was being calculated for each at different irradiance level: (a) 1200 W/m^2; (b) 1000 W/m^2; (c) 800 W/m^2; (d) 600 W/m^2; (e) 400 W/m^2; (f) 200 W/m^2

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Table 4.5 Summary of the analysis of the convertor and PV-ELE based on different irradiance levels

Irradiance (W/m^2)	PV Power (W)	Electrolyzer Power (W)	Efficiency of Convertor (η_c)	HHO Production (LPM)	STH Efficiency (η_{STH})
1200	235.5	222	94.4%	0.885	12.60%
1000	195.5	185.6	94.9%	0.800	11.47%
800	146.1	140.6	96.2%	0.620	10.88%
600	105.7	101.2	95.7%	0.440	10.59%
400	67.57	64.23	95.0%	0.300	10.10%
200	32.88	29.37	89.3%	0.000	00.00%

From Figure 4.15, it was observed that the convertor was tracking the maximum power available from the PV to electrolyzer by keeping the electrolyzer in its operating region.

It is also seen from Table 4.4 that the maximum efficiency of the convertor is available when the solar PV is working in the electrolyzer operating range. Furthermore, IV-curves and power curves were analyzed to see the behavior of the working of the electrolyzer with the solar PV. Power curves and IV-curves were drawn in Figure 4.15 by keeping in view the actual data of the PV and the duty of the convertor at the respective irradiance in order to correlate the analysis with the electrolyzer curves. From Figure 4.15 it is more evident that the convertor kept the electrolyzer into its operating region while tracking the maximum power of the PV. In all (i) parts of figure 4.15, maximum point of power is tracked for a particular irradiance while keeping the electrolyzer in operating mode. On the other (ii) part of all figures in figure 4.15, IV curve is drawn while displaying maximum operating point for electrolyzer. It has also determined from figure 4.15, that control strategy for the convertor is not analyzing maximum power point of PV (in figure 4.15, tracked power point is not on the tip of curve for this system as happens in case for traditional MPPTs) as it is dependent on operating region of electrolyzer. So it is determining the maximum operating point of electrolyzer from available PV power.

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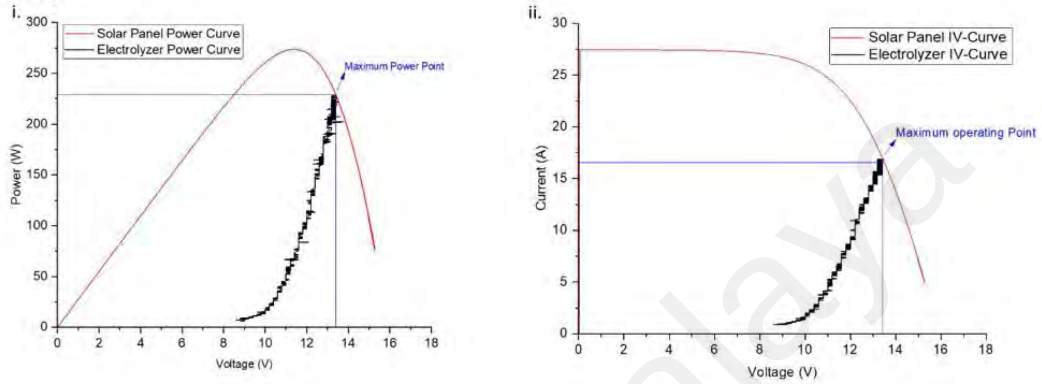
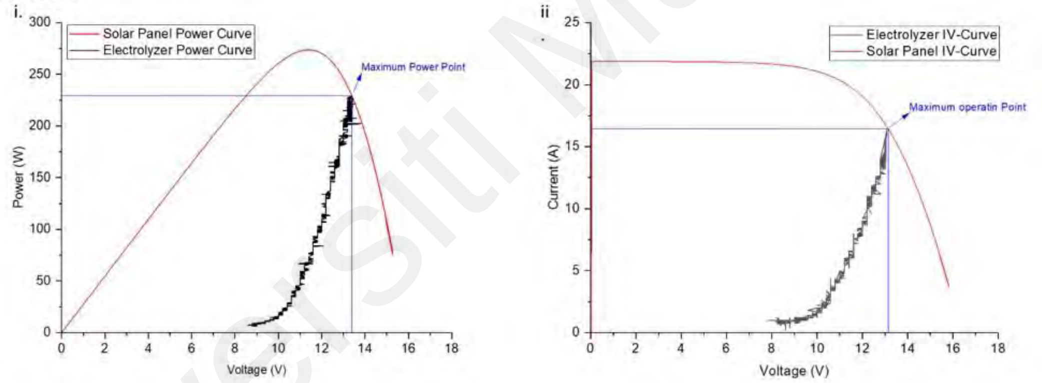
After 200 W/m^2 of irradiance, the PV system was unable to provide enough power for keep the electrolyzer working in its operating region. Although at this level of irradiance, the DC-DC convertor tries to keep the electrolyzer operating, the electrolyzer does not operate (Figure 4.15f(i)) shows that less than 10.7 Volts are available for electrolyzer).

(a) 1200 W/m^2



(b) 1000 W/m^2



(c) 800 W/m^2

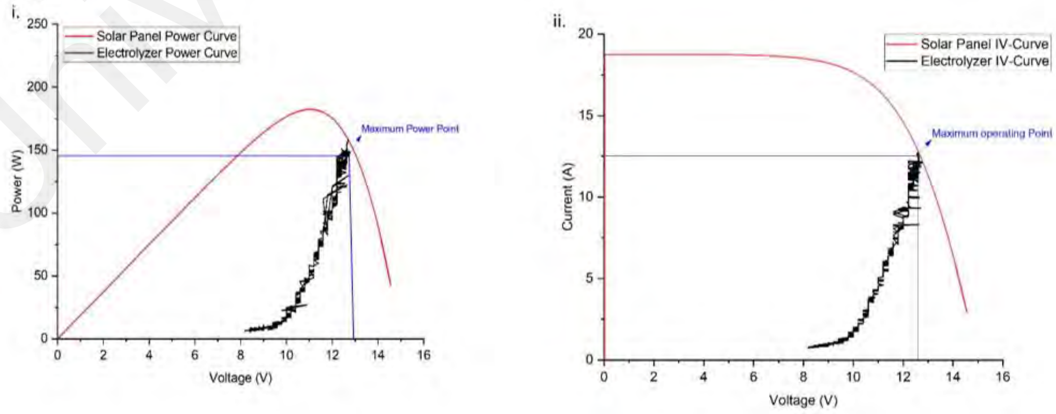


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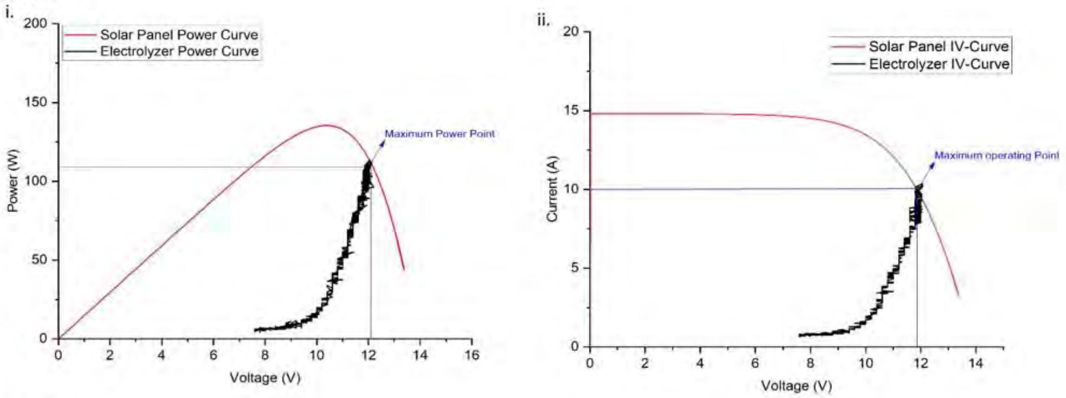
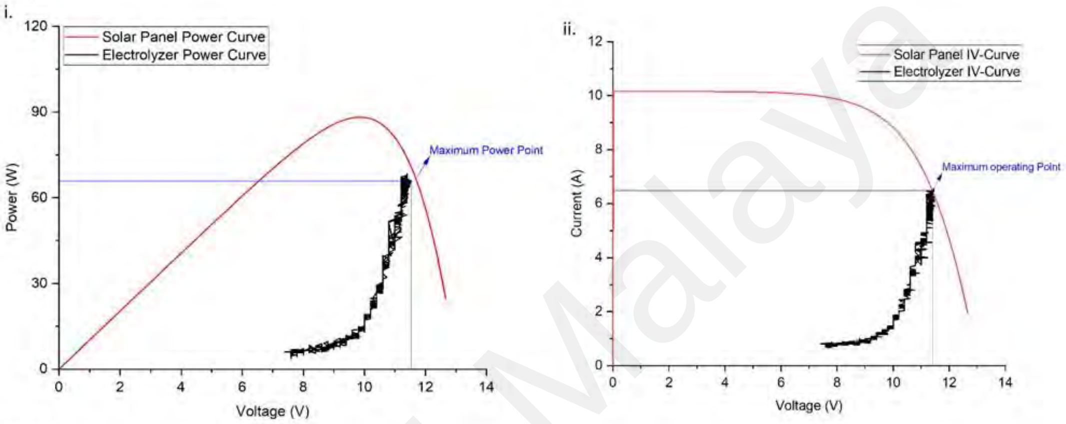
Figure 4.15 VI and Power curves of Solar PV and Electrolyzer under test: (a) 1200 W/m^2; (b) 1000 W/m^2; (c) 800 W/m^2; (d) 600 W/m^2; (e) 400 W/m^2; (f) 200 W/m^2

(d) 600 W/m²



(e) 400 W/m²



(f) 200 W/m²

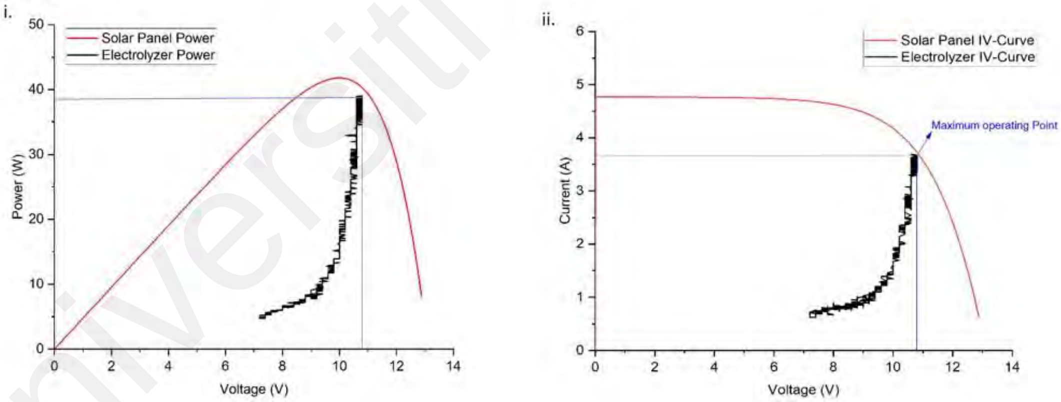


Figure 4.15 (contd.) VI and Power curves of Solar PV and Electrolyzer under test: (a) 1200 W/m^2; (b) 1000 W/m^2; (c) 800 W/m^2; (d) 600 W/m^2; (e) 400 W/m^2; (f) 200 W/m^2

To see the effect of changing irradiance on runtime and tracking of maximum power, the test rig was allowed to run for 20 min while the irradiance was changed by changing the intensity of the bulbs. The intensity was thus gradually changed from 1200 W/m^2 to 200 W/m^2. This tracking of power can be analyzed from Figure 4.16.

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From Figure 16 it can be seen that after a certain irradiance (in the experiment it was below 200 W/m^2) the PV panel is not able to provide enough power for the electrolyzer to be in the operating region (the non-operating region is shown by shading). The same can be seen for higher irradiance, even though at 1200 W/m^2 more power was available for the electrolyzer and the convertor was keeping the electrolyzer in its region of operation (i-e 10.8–13.2 Volts and 15 Amps).

It was investigated that at lower irradiance, the convertor was working at high duty regardless of the power of the PV in order to maintain the operating range of the voltages for the electrolyzer to work. At low irradiance, Vpv becomes so low that even at high duty, V_{ELE} does not remain in the operating range. This can be mathematically seen by using equation (15). In this non-operating region, the duty of the convertor was fully increased up to 90%. This situation makes it difficult and very slow for the convertor to reduce the duty when the irradiance is again high after a low irradiance period. This is because of the slow response nature of the alkaline electrolyzer. This means that lower duty is more beneficial for the efficiency of the PV-ELE system.

Finally, a test of four hours under Sun irradiance was performed to see the behavior of the convertor and electrolyzer due to intermittency. The power of the PV system was recorded for each interval of time depending upon the intermittent nature of solar irradiance along with the power delivered to the electrolyzer due to convertor keeping the electrolyzer in its operating region. From Figure 4.17, it can be seen that the convertor is tracking and delivering the maximum power available in the PV system by keeping itself in the operating region of the electrolyzer. It was also concluded that at some instants not enough power is available from the PV system to energize the electrolyzer so in that instance the electrolyzer is not in its operating region and hence no HHO is produced.

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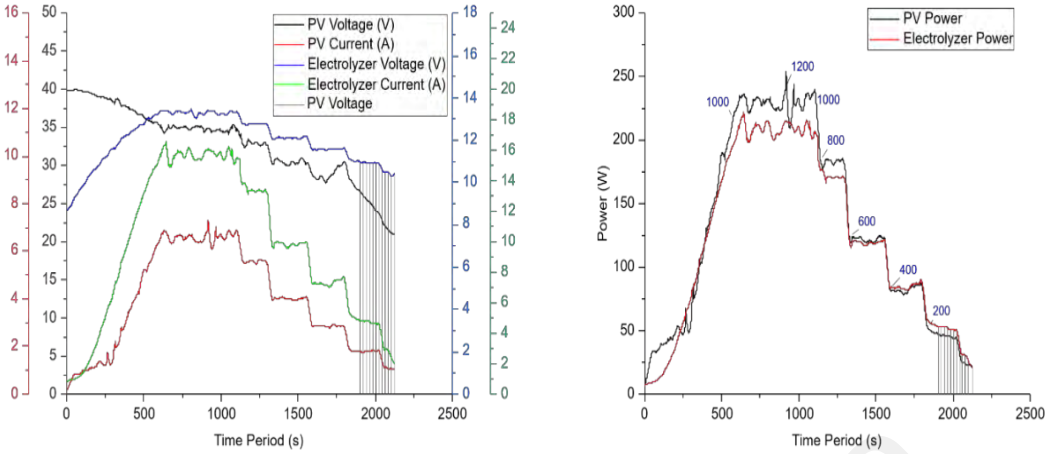

Figure 4.16 (left) Voltage and current (right) power; measured for PV and Electrolyzer in a 30mins continuous test (results from the indoor test rig). The shaded region shows the non-operating region of the electrolyzer.

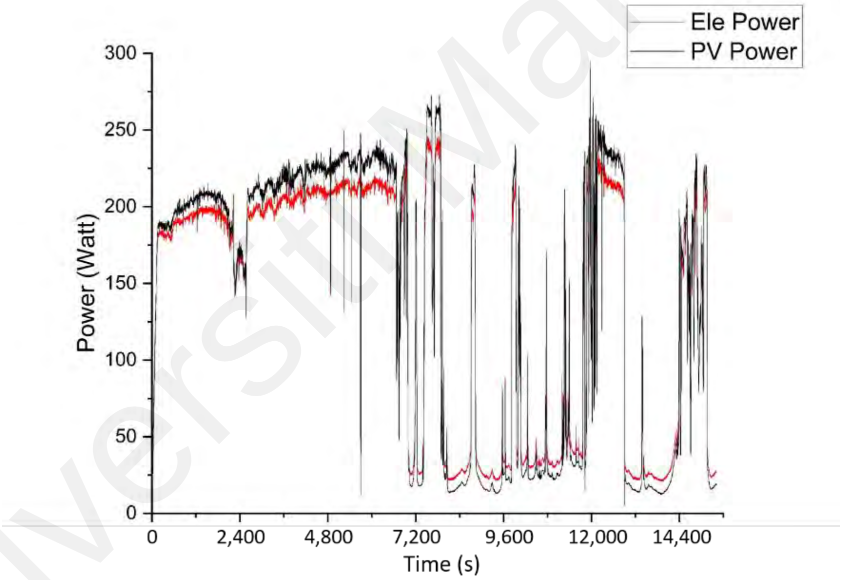

Figure 4.17 Delivery of the maximum available power from PV to the electrolyzer by tracking the power while keeping the electrolyzer in its operating region (4 hrs under actual Sun irradiance).

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4.3.3 Hybrid mode of PV-ELE incinerator

To test the working of this PV-ELE incineration strategy, a half kilogram of mixed municipal solid waste was taken for incineration. From the figure 4.18 it is evident that electrolyzer is running on its rated parameters irrespective of the intermittency of sun light while temperature for incineration rises to a peak of 720°C. This continuous supply of energy was supplied to electrolyzer due to battery which act as a source during solar PV experiences low irradiance. By using this strategy incinerator was supplied with continuous feed of hydrogen splitting from water due to electrolysis and hence an efficient incineration process occurred. Further all the parameters of incineration were monitor which are briefed in table 4.6. During experiment, 10.98 liters of hydrogen was being produce and fed to burners to incinerate. The incineration process took 20 minutes which completely incinerates the waste. To verify the completion process of incineration, weight in reduction and loss on ignition test was performed on left over residue. Results showed a significant reduction in weight of 96.1% in waste and a loss on the ignition of 1.73% for residue after incineration. These results testify completeness of incineration process through this strategy.

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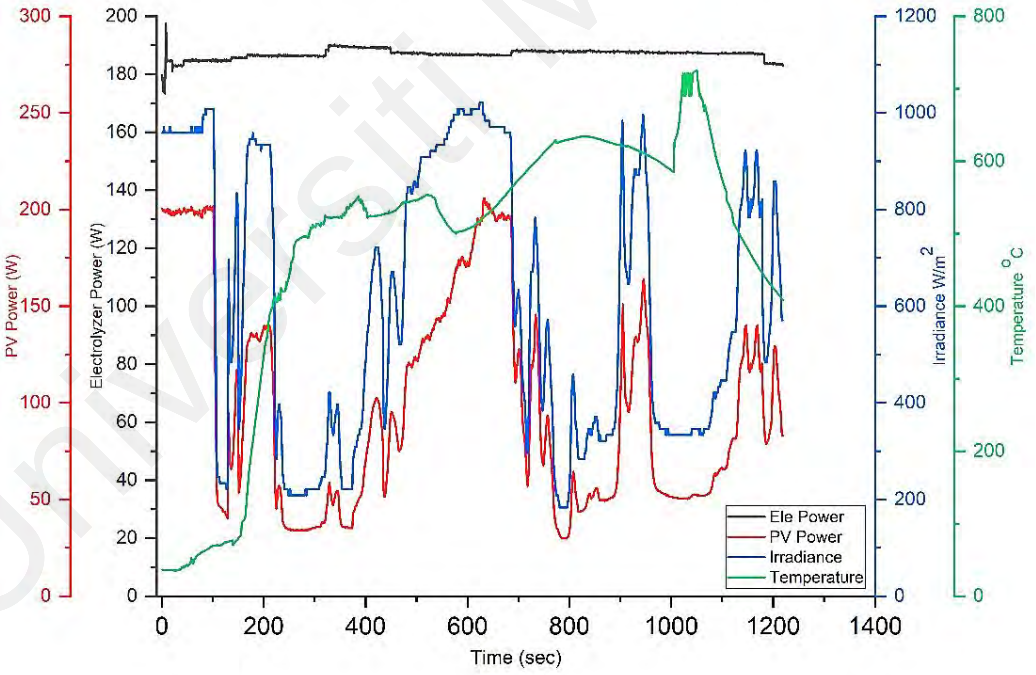

Figure 4.18 Characterization of ‘PV + Bat’ approach for PV-ELE incineration during incineration process

Table 4.6 Data after incineration using 'PV + Bat' approach

Quantity	Value
Moisture Content of waste %	60
Hydrogen Produced (liters)	10.98
Total Energy Produced from Hydrogen (Wh)	36.26
Energy Consumed by Electrolyzer (Wh)	59.94
Peak Temperature (°C)	720°C
Time required for incineration (min)	20
Residue left/Reduction weight (%)	96.1
Loss on Ignition LOI (%)	1.73

4.3.4 Direct coupling of PV-ELE incinerator

To test thresh hold of the flow rate which could sustain the burner flames, burners were allowed to ignite for 30 minutes for different irradiances. This was done to have a stable thermal profile inside incinerator and temperature variations on these irradiances. This was recorded in figure 4.19. Results show that at 1000 W/m^2 of irradiance, electrolyzer was running at its peak operating region. A physically larger flame was observed at the burners. This flame rises a significant temperature inside the incineration chamber which was recorded approximately ~300°C. This temperature was kept maintained as long as system was energized. At 800 W/m^2 level of irradiance temperature of the chamber was dropped but still flame sustained at burners by maintaining inside temperature of incinerator at ~250°C. As the irradiance level dropped to 600 W/m^2 flame at burner was observed with low intensity. Also rise in temperature required more time of 500 secs than earlier high irradiance experiments to rise to a maximum stable temperature of ~150°C. Temperature was recorded to maintain at ~150°C. For 400 W/m^2 a significant drop in temperature was witnessed along with a very low intensify but stable flame at burner. This time temperature was recorded to maintain only ~100°C inside the chamber of incinerator.

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Below 400 W/m^2 of irradiance, burners fabricated for the incinerator could not support the flame, and a flashback occurred. However, the electrolyzer produced hydrogen below 400 W/m^2 of irradiance, to less power and a low flow rate of hydrogen production. Therefore, in table 4.7, it was resulted that for the current scenario, burners would quench the flame below 0.42 LPM of the flow rate of production of gas from the electrolyzer that, corresponds to 400 W/m^2 of irradiance.

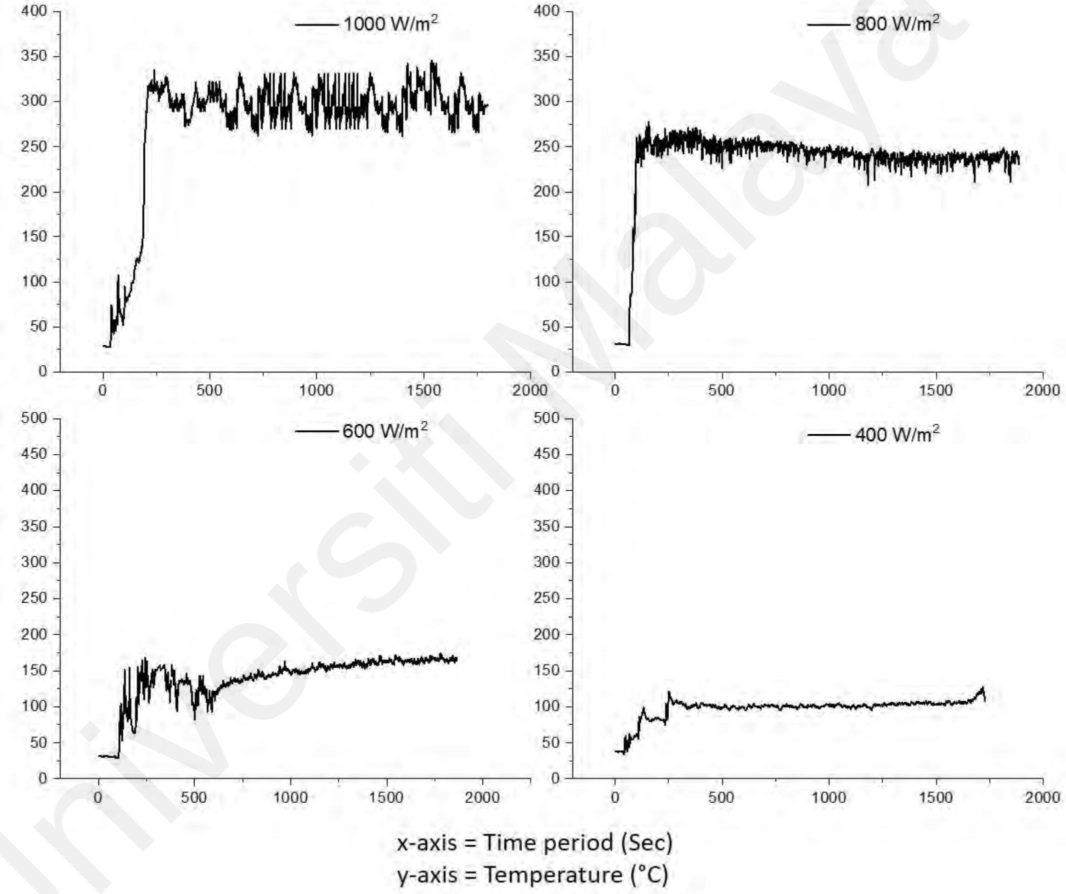

Figure 4.19 Thermal behavior of incinerator at different irradiance during direct coupling strategy

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Table 4.7 Measured parameters of electrolyzer at different irradiance level

Irradiance (W/m^2)	Electrolyzer Parameters			Flow Rate HHO (LPM)
	Voltage (V)	Current (A)	Power (W)	
1000	12	15.75	190	0.84
800	11.73	13.95	163.6	0.75
600	11.10	11.61	128.8	0.57
400	10.8	8.46	91.3	0.42
200	9.81	3.4	33.32	0.23

4.3.4.1 Auto ignition system

In this approach of direct coupling a mechanism an auto pulse ignitor starts to re-ignite burners as irradiance level crosses threshold of irradiance level which was 400 W/m^2 as per resulted in section 4.3.4.

Incinerator was allowed to run empty to see temperature behavior by using this approach for 5 hours. This thermal behavior was recorded in figure 4.20. As per proposed approach, a signal was continuously sent to pulse ignitor to spark ignition again as irradiance crosses threshold level. It was further observed from figure 4.20 that below the threshold level of irradiance, temperature of incinerator immediately starts dropping and remains below 80°C of temperature. But as irradiance level stabilize and let back from threshold level (400 W/m^2), ignitors ignites flame again. As irradiance increase more and more, temperature rises more. Maximum average temperature that can maintain during maximum irradiance was 170°C.

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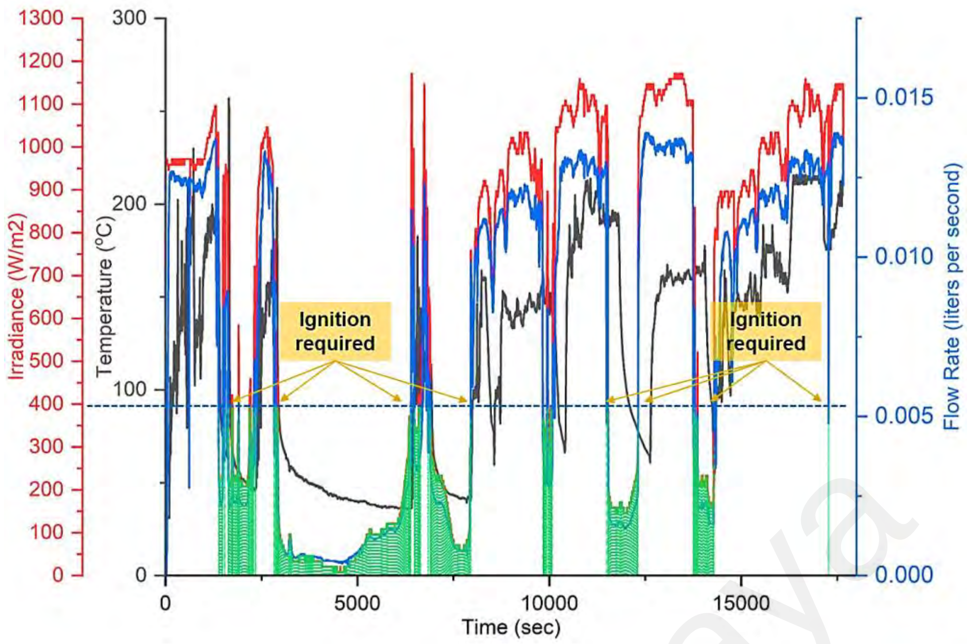

Figure 4.20 Thermal behavior of incinerator for 'Auto-ignition' method along its working behavior due to change in irradiance. Shaded region shows non-utilization of electrolyzer due to low irradiance/flow rate

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A brief summary of testing temperature behavior with irradiance by having an arching mechanism for a direct coupling approach is presented in table 4.8. During testing of temperature behavior with irradiance for this said approach, a total of 91 liters of hydrogen was produced. But it was already observed that due to low flow rate at low irradiance burners could not withstand the flame. So hydrogen producing at that low flow rate wasted as unutilized hydrogen for an amount of 6.9 liters and was not used by burners as a flame. Therefore, from a total of 300 Wh of energy only 277.23 Wh of energy from hydrogen was utilized by the burners for combustion while electrolyzer consumed a total of 535 Wh of energy.

Table 4.8 Measured parameters during thermal behavior characterization of incinerator for 'Auto-ignition' method

Quantity	Hydrogen Produced (liters)	Un-utilized Hydrogen (liters)	Total Energy Produced from H_2 (Wh)	Energy wasted due to un-utilized hydrogen (Wh)	Energy Consumed by Electrolyzer (Wh)	Efficiency (%)	Mean Temp (°C)
Value	91	6.9	300	22.77	535	51.81	134.6

An incineration test was performed to investigate this 'auto ignition' approach to incinerate waste. A half kilogram of mix municipal solid waste with 60% of moisture content was taken for the test. Continuous monitoring and logging for temperature and irradiance was done and reported in figure 4.21. During the incineration process, irradiance was lowered than 400 W/m^2. It was observed physically that auto ignition mechanism successfully detected this threshold and ignite the spark again as irradiance crosses this onset point. Figure 4.21 shows that auto ignition was occurred two time during the course of experiment at point 'A' and 'B'. Further it was seen that a total of 30 minutes were required to totally incinerate the said waste. To verify incineration effectiveness, reduction in waste and loss on ignition test were performed. Results of these tests were presented in Table 4.9. Reduction in weight and Loss on ignition was reported to be 94.6% and 2.13% respectively which is within their range to satisfy completion of incineration process (S. Kumar & Ankaram, 2019). It was also seen that total 18.1 liters of hydrogen was generated from which 1.4 liters was un-utilize.

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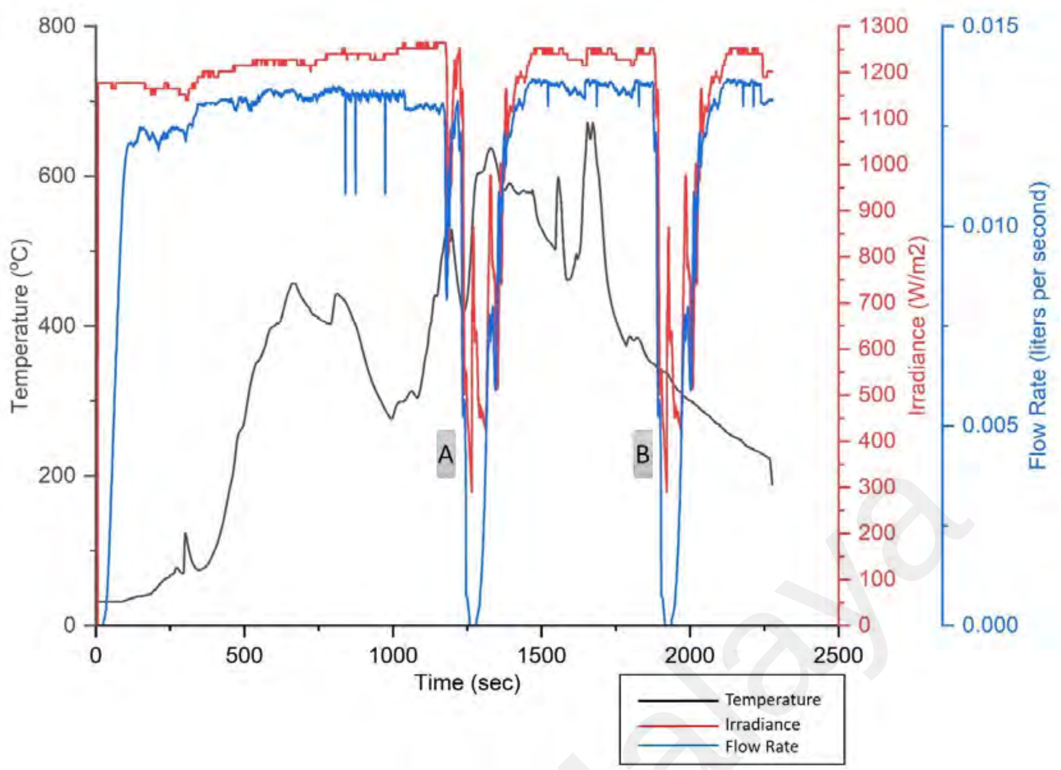

Figure 4.21 Characterization of 'auto-ignition' approach for PV-ELE incineration during incineration process. Auto-ignition system ignite spark at point 'A' & 'B'

Table 4.9 Data after incineration using 'auto-ignition' approach

Quantity	**Value**
Moisture Content of waste %	60
Hydrogen Produced (liters)	18.1
Unutilized Hydrogen (liters)	1.4
Total Energy Produced from Hydrogen (Wh)	55.11
Energy Consumed by Electrolyzer (Wh)	104.11
Peak Temperature (°C)	620
Time required for incineration (min)	30
Reduction weight (%)	94.6
Loss on Ignition LOI (%)	2.13

4.3.4.2 Threshold flow of hydrogen

Base of the results of threshold level of flow rate of gas, a secondary electrolyzer has been used for a capacity of production rate at 0.4 lpm with operating parameters of 12Volts, 8 Amps and powered by 12 Volt, 20 Ah battery. This kept the flame sustain when primary electrolyzer was not producing enough oxyhydrogen during intermittency of sunlight.

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Thermal behavior shown in figure 4.22 for this approach was tested by running the setup with empty incinerator without waste. Burners were allowed to flame up using premixed hydrogen and oxygen in stoichiometric ratio. Gas was being fueled from two sides, one was from primary electrolyzer coupled with PV by mean of DC-DC convertor and the second was from secondary electrolyzer that was energized by battery and producing a minimum amount of gas required by burners to withstand flame. From the figure 4.22 it was observed that maximum temperature of 200°C was achieved and minimum temperature that was maintained during the experiment was 120°C. Even at the lowest irradiance this temperature was maintained as flames were not quenched due to secondary electrolyzer. Previously this temperature was dropped to 60°C when irradiance was low (flame was quench due to insufficient flow of hydrogen).

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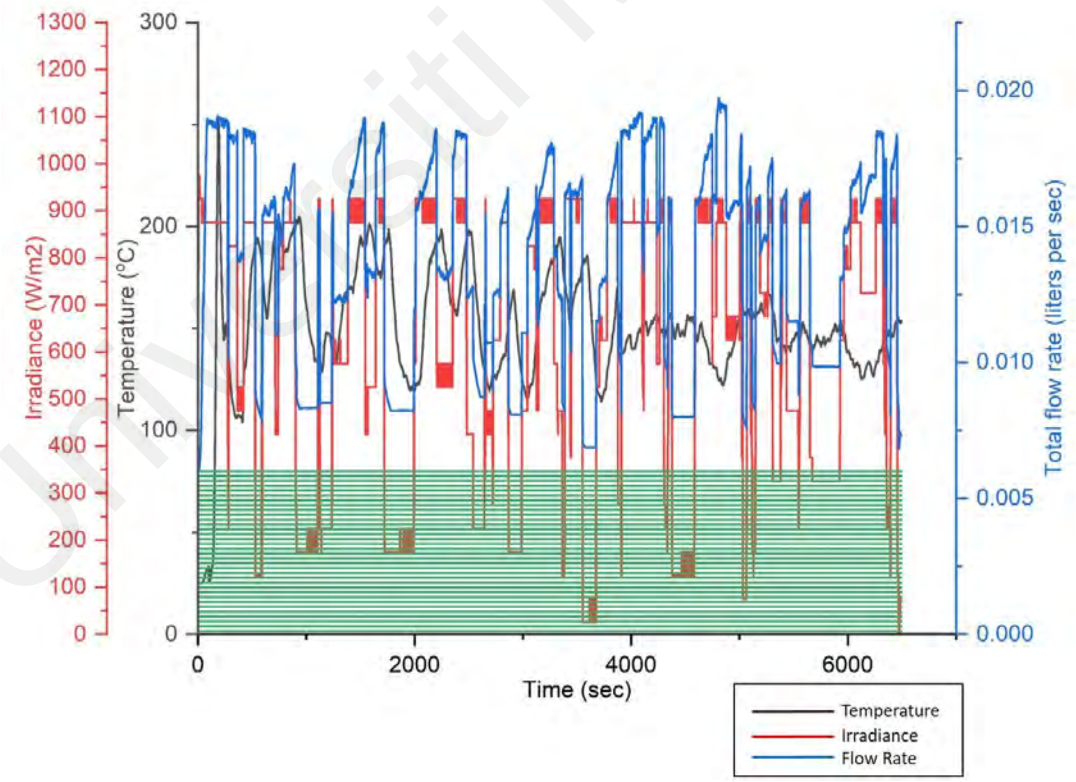

Figure 4.22 Thermal behavior of incinerator for 'PV + Sec-ELE' method along its working behavior due to change in irradiance. Shaded region shows the minimum flow rate that is constantly added from secondary electrolyzer

Summary of this thermal behavior is presented in table 4.10. It was resulted that due to two electrolyzers (primary & secondary) total hydrogen feed to burners was 69.64 liters which produces a total energy of 229.812Wh, while total individual energy consumed by primary and secondary electrolyzer was 208.45 and 192Wh respectively. On contrary to previous approach where temperature was spasmodic, this approach resulted in less variation in temperature and maintained at a mean temperature of 172.2°C.

Table 4.10 Measured parameters during thermal behavior characterization of incinerator for keeping minimum 'Thresh-hold flow of H_2' method

Quantity	**Hydrogen Produced (liters)** *Primary + Secondary*	**Total Energy Produced from Hydrogen (Wh)**	**Energy Consumed by Electrolyzers (Wh)** *Primary + Secondary*	**Efficiency (%)**	**Mean Temp (°C)**
Value	37.48 + 32.16 = 69.64	229.812	208.45 + 192 = 400.45	57.45	173.3

A real time testing for this approach was done for incineration with a half kilogram of mix municipal solid waste having a moisture content of 62%. Data in figure 4.23 shows that irradiance was fall down from threshold value three times (figure 4.23 at point 'A', 'B', & 'C') but during the incineration it was physically observed that flame was not quench. This is because secondary electrolyzer was providing minimum amount of gas required by the burners to sustain the flame. All the parameters of incineration process are summarized in table 4.11 which shows that this mechanism required less time (18 min) to incinerate MSW of same amount & characteristics than by using 'auto ignition' mechanism (30 min). This is due to two reasons: (i) flames were not quench during the whole period of experiment (ii) temperature was not dropped and continuous combustion process happened. This even consumed less total energy of 70.56 Wh while able to achieve temperature ~650°C. Also reduction in weight and Loss on ignition test were

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performed and reported to be 96.8% and 1.02% respectively which satisfy incineration process.

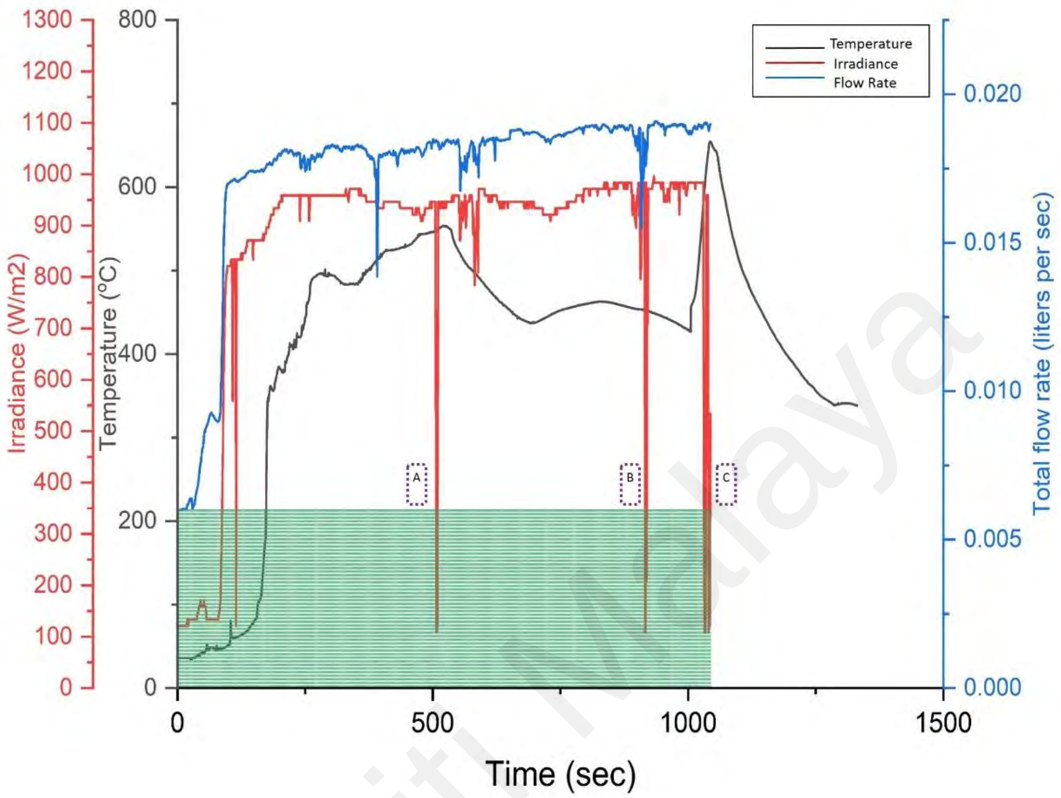

Figure 4.23 Characterization of 'PV + Sec-ELE' approach for PV-ELE incineration during incineration process. Shaded region shows the minimum flow rate that is constantly added from secondary electrolyzer. Primary electrolyzer was ineffective at point 'A', 'B' & 'C'

Table 4.11 Data after incineration using 'PV + Sec-ELE' approach

Quantity	Value
Moisture Content of waste %	63
Hydrogen Produced (liters) Primary Electrolyzer	7.95
Hydrogen Produced (liters) Secondary Electrolyzer	4.8
Total Energy Produced from Hydrogen (Wh)	42.075
Energy Consumed by Primary Electrolyzer (Wh)	45.6
Energy Consumed by Secondary Electrolyzer (Wh)	24.96
Total Energy Consumed by Electrolyzers (Wh)	70.56
Peak Temperature (°C)	652
Time required for incineration (min)	18
Reduction weight (%)	96.8
Loss on Ignition LOI (%)	1.02

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4.3.5 Techno-economic analysis

A comparison of these three methods under current scenario based on five different attributes including cost, time required to incinerate, hydrogen produced, total energy consumed by system and efficiency was presented in figure 4.24. Economic analysis is based on actual cost given in table 4.12, while technical attributes were taken from table 4.6, 4.9 & 4.11. Figure 4.24 shows that PV + Bat system consumes 42.42% and 15.07% less energy than auto-ignition and PV + Sec-ELE method respectively. Although PV + Sec-ELE showed similar efficiency with PV + Bat and less time required for incineration, but this approach cost 15.4% and 11.8% more than auto-ignition and PV + Bat method respectively. It was seen that PV + Sec-ELE required less time to incinerate than PV + Bat method. This is due to additional secondary electrolyzer which produces 16.1% more hydrogen to keep flames sustain during intermittency. This continuous supply of 0.4 lpm of gas from secondary electrolyzer feed burners with more gas and helps to incinerate more quickly. Contrary auto-ignition method produces more hydrogen than PV + Sec-ELE method. But still it requires more time. This is due to quenching of flame again and again due to insufficient flow of gas during intermittency. Although auto-ignition produces more hydrogen than all two methods but in result it requires more time and hence reduces its efficiency in terms of energy.

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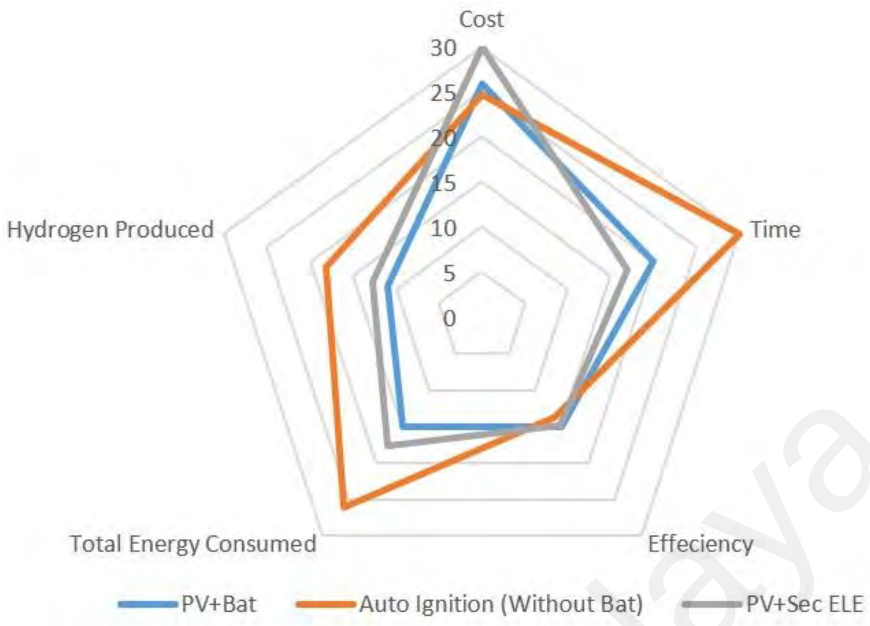

Figure 4.24 Comparison of three different approaches based on their technical and economical attributes. *Scaling factor: 'Cost' by 30; 'Total energy consumed' by 4; 'Efficiency' by 4; 'Time' by 1; 'Hydrogen produced' by 1

By using experimental results and characteristics of wastes, an energy analysis was made in figure 4.25. Therefore, by using equation (3.7), it was resulted that PV + Bat method gives 80% less in terms of required energy equivalent to waste moisture content while auto-ignition and PV + Sec-ELE showed 70.5% and 77.5% of reduction in energy respectively. Also from figure it was further analyzed the expected amount of heat energy that can be available for recovery for using in other thermal applications during incineration process. It was perceived from the data that waste with more moisture content gives less amount heat recovery energy.

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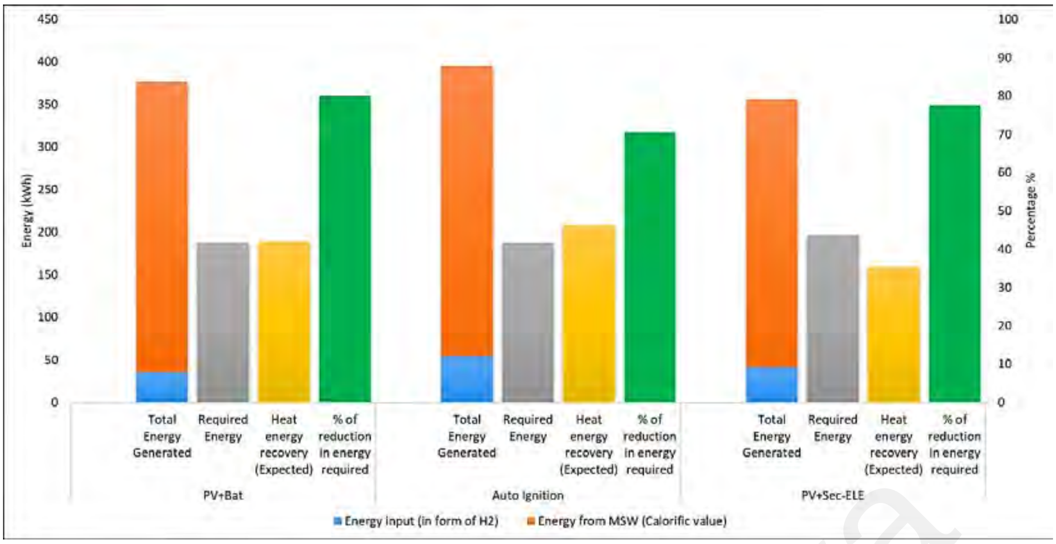

Figure 4.25 Energy analysis based on experimental results for PV + Bat, Auto-ignition, PV + Sec-ELE approach

A cost and life span analysis, is presented in figure 4.26. It shows that about 23.3% of increase in the cost of PV + Bat setup than PV + Sec-ELE, while 73.3% of increase than auto-ignition method at end of 30 years of life span of electrolyzer. This difference of cost can be increase when using large scale of incineration setups.

Although electrolyzer system based on combination of PV + battery gives a stable output but battery used in system has much less life span than the additional electrolyzer in PV + Sec-ELE which is reported to be 30 years. Also maintenance cost for electrolyzer is negligible. These two characteristics shows that replacing of battery operated PV-ELE system to some other mechanism which can sustain flame and temperature for large scale incineration application can be more economically feasible. Use of either method is likely to be depends upon the application, its scale of usage and climatic conditions.

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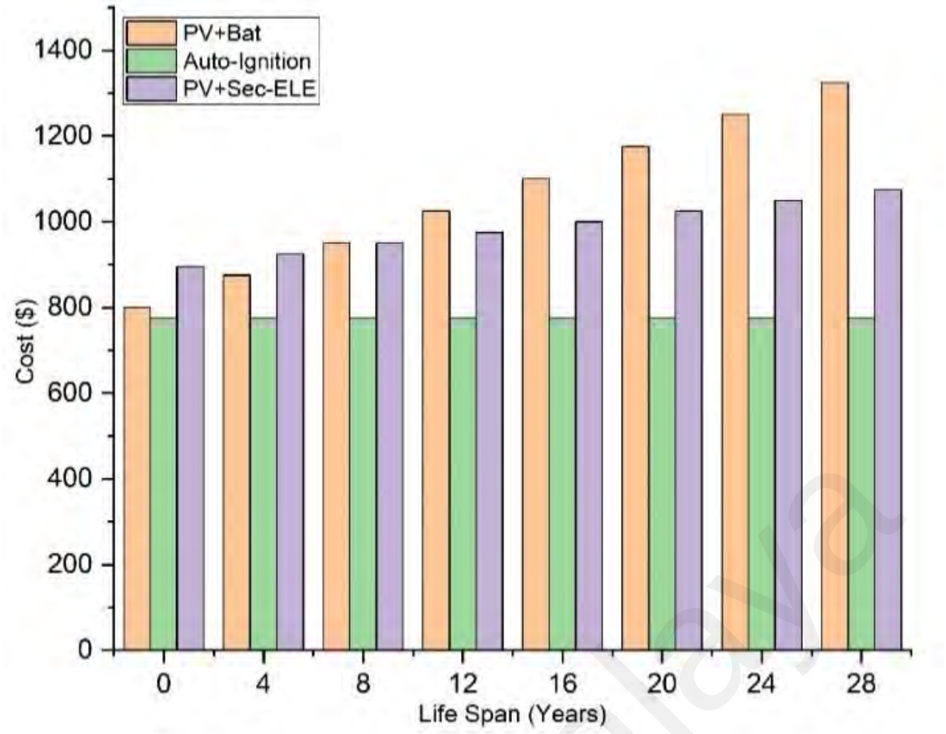

Figure 4.26 Cost forecasting of PV + Bat, Auto-ignition, PV + Sec-ELE approach based on 30 years of life span

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CHAPTER 5: CONCLUSION & RECOMENDATIONS

5.1 Conclusion

The extensive and inefficient utilization of fossil fuels lead to high environmental concerns and energy security. Scientists are merely emphasizing on renewable energy sources and their appropriate utilization. The grave environmental situation and ongoing CO2 emissions would jeopardize the ecosystem on the planet earth. At this pace, the human race would be at the edge of eminent catastrophic failure within 30-40 years. In this regards, short and long-term solutions based on clean and green energy are the need of the day to sustain life on earth. Hydrogen as fuel is an attraction for researchers as a green step. This is due to non-pollutant and sustainable properties of hydrogen. Hydrogen can be term as ‘grey’, ‘blue’, ‘turquoise’ or ‘green’ hydrogen depending upon ways of their production. Production of hydrogen by splitting of water through an electro-chemical process is consider as ‘green’ hydrogen. This method can be step towards green and environmental friendly if the electricity is sourced renewably, such as hydro, wind or solar.

The requirement of fossil-based fuels for incineration has been a biggest challenge for sustainable future. Sustainable waste management warrants sustainable and green fuels. In this regard, hydrogen as sustainable fuel attracted huge interest due to its versatility and ability to decarbonize hard-to-abate energy sectors. Following conclusion were made on the basis of the experiments and analysis mad during this study.

- For efficient and effective electrolysis, it is necessary to operate the electrolyzer into its operating region of voltage, current and temperature. Over-current and over-voltage results in rising the temperature of electrolyzer which deteriorate the electrodes of electrolyzer. Also high temperature creates bubbling which not only destructive for electrolyzer but also lower the quality

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of production of hydrogen gas by mixing water vapors. So it was seen that maximum temperature that can be operative for effective hydrogen is 70°C.

- It was seen that pulse-width modulation (PWM) technique is the most effective and efficient way to control the production of oxyhydrogen gas. This technique not only promise oxyhydrogen based system as a green and clean system but also made it a sustainable system. The concept of on-demand production and utilization is a safer and green way to use hydrogen. The study helped determine an approach to use solar energy independently to power an electrolyzer with PV. It was seen that it is important to operate the electrolyzer in its operating region. The strategy of the convertor that was used in this study was successfully established with 94% efficiency by considering two objectives: (i) working of the electrolyzer in its operating region, (ii) delivering the maximum available power of the PV system to the electrolyzer directly by tracking the maximum power of the PV. It was seen that this strategy works in achieving these objectives. It was further explored that due to the slow response nature of alkaline electrolyzer it makes the convertor slow while the tracking power is in a high intermittency situation as it increases the duty to a high level. It was established that duty of the DC-DC convertor plays a crucial role for the system. It was further recommended that increasing in number of PV panels can help in lowering the optimized duty necessary for tracking the maximum power during high intermittency periods by keeping the electrolyzer in its operating region. Another solution is to use a hybrid system which include a battery to account for this intermittency effect.
- In this study, a systematic investigation has been presented to examine the feasibility of hydrogen as the primary fuel for waste management. A shaft-type waste incineration chamber has been used which was fitted with specially

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designed burners. A pre-mixture of hydrogen and oxygen in a stoichiometric ratio has been fed to the burners and burners have been properly arranged for homogenous heat distribution. Various combinations of diverse waste materials i.e., food, textile, & paper with varying moisture contents have been employed. Furthermore, the reduction in weight and LOI have been calculated to estimate incineration performance. A maximum temperature of 850°C for MSW (containing food, textile, and paper waste) with 77% moisture content has been recorded. A total of 68liters of hydrogen has been consumed for 1kg MSW which translates to 224Wh of energy being consumed. The reduction in weight and LOI have been calculated to be within 86-94% and 1.74%-6.41% respectively. The system worked efficiently for diverse MSW with a maximum moisture content of approximately 80%. The optimum performance at high moisture content can be correlated with the characteristic high-temperature (i.e., 2800°C) and a focused flame of hydrogen. However, an increase in moisture content to 90% leads to a reduction in performance.

- Three different approaches were studied for energizing electrolyzer based on direct and hybrid mode of coupling with PV. Further techno-economical study of these three approaches with focus of waste incineration was done by incinerating half kilogram of waste with 60% of moisture content. It was concluded that all approaches successfully satisfied incineration process by reducing weight 94.6 – 96.8% and LOI 1.02 – 2.13%. 'PV + Bat' gives a stable incineration and consumes 42.42% and 15.07% less energy than 'auto-ignition' and 'PV + sec-ELE' method respectively. In 'auto-ignition' flames quench at low irradiance due to low flow rate that could not sustain flame by burners. For this approach burners can also be design according to specific application and usage so that they can sustain flame at the lowest flow rate during low

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irradiance. 'PV + sec-ELE' required less time for incineration than other two methods because of extra feed of gas from a secondary electrolyzer with minimum required flow rate to avoid quenching of lame at low irradiance/flow rate. That's why 'PV + sec-ELE' produces 16.1% more hydrogen than 'PV + Bat'. Above all, a 30-year life span analysis forecasted that 'PV + Bat' method get more expensive than other two approaches due to additional cost of battery after every 4 years. This study could be beneficial in selecting of any strategy according to the use of application, its scale of usage and climatic conditions where its being used.

5.2 Recommendations

Incineration of municipal waste management by using hydrogen as a fuel from electrolyzer is a new technique towards waste management. It has a potential not only to solve problems related to an alternative for depleting fossil fuel but also towards effective waste management. Due to a new integrated system, many aspects still need attention and collaborative work. In this regard, our recommendations are as follows.

- Incineration with hydrogen gas being produced using RE-integrated alkaline electrolyzer can be a revolutionary step towards green technology. This will help in developing an environmental friendly standalone technology for waste management system, which can work in both urban as well as rural areas.
- Oxyhydrogen has a potential to replace fossil fuel for combustion applications. As it has high calorific value and due to presence of oxygen in oxyhydrogen gas, it is supportive during combustion which make more fuel molecules to take part in the combustion process results in emission of less un-burnt hydrocarbon.

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- Appropriate burner design for hydrogen is an essential for more effective incineration as it will combust the municipal solid waste homogenously. Also due to high velocity of hydrogen orifice size should be consider importantly.
- Furnace operations claim approximately 80% energy share in related industries. In addition, it produces high amount of greenhouse gasses due to high consumption of fuel. hydrogen gas can be a potential alternative fuel for furnaces as primary or secondary (blend with other fuels) fuel for this industry. This approach would reduce fuel utilization, cut cost of thermal energy and reduce carbon footprint of furnaces.
- As different renewable resources are used for producing pure hydrogen by using alkaline, PEM and SOEC. So there is a lot of potential in PV-integrated oxyhydrogen production systems that can produce oxyhydrogen gas as on-demand energy source for safe and efficient utilization.
- These systems have ability to install on the source site of waste generation and can be scales accordingly. So it can be economically beneficial for waste management as they have a potential to reduce transportation cost. Also these systems have life span of 20 years with minimum maintenance cost but a bit high capital cost. Therefore, it can be forecasted that these systems are suitable as a long term investment.

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5.3 Future work

Hydrogen based municipal waste incineration system can be a source of energy for future. Heat energy from incineration process can further be used by appropriate heat-exchangers for thermal applications like water heating and steam generation. Hydrogen can be used for re-electrification through combustion process. Increase in renewable energy into current energy system raises the need of large energy storage devices.

Hydrogen-based energy storage system can be a cost-effective and viable solution for this requirement. Current system under this study can be a potential hydrogen-based

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