Chapter 2

Literature Survey

2.1. Introduction

Over the past decade, governments worldwide have increasingly prioritized energy policy reforms, focusing on what is often referred to as the energy trilemma to address ensuring energy security, maintaining affordability, and promoting environmental sustainability. All developed and developing nations are increasingly striving towards this goal. For example, some nations depend on inexpensive coal to secure energy supply, which compromises environmental goals. On the other hand, some nations look for cleaner energy alternatives that come at a higher economic cost. Achieving a meaningful and sustainable energy transition matrix requires a careful balance between these competing priorities, with policies that support both low-carbon development and overall energy efficiency.

The rapid growth of renewable energy has largely been influenced by global policy initiatives, most importantly the commitments made during the 21st Conference of the Parties (COP21) to the UNFCCC convention on climate change held in Paris. Within this transition, the power sector has attracted the greatest share of investment and deployment, supported by continuous technological improvements and the steady reduction in capital costs. However, the adoption of renewables in other energy-intensive sectors such as industry, buildings, and transportation has progressed more slowly, largely due to insufficient policy support [1]. While renewable energy offers clear benefits in terms of energy security, environmental sustainability, and economic potential, several challenges persist. Chief among these are its competitiveness with conventional fossil fuels and the complexities of integration into existing energy infrastructures. To realize meaningful environmental and economic gains, a fundamental transformation in both energy production and consumption patterns is essential [2].

As fossil fuels become increasingly costly and less favourable due to the global carbon dioxide emissions crisis, the transition toward renewable energy sources gaining momentum. Although conventional fuels like coal remain abundant in many regions, their environmental impact is prompting a growing shift toward cleaner alternatives. Given the choice, many stakeholders prefer to adopt renewable energy solutions, driving a strong demand for sustainable and clean energy sources. In response, the scientific community is actively exploring methods to expand the deployment and efficiency of renewables.

India has been actively progressing toward clean and sustainable energy solutions, with the Government of India launching several flagship missions to reduce dependency on fossil fuels and to support renewable substitutes. One of the most significant initiatives is the National Green Hydrogen Mission, which aims to develop a robust green hydrogen ecosystem in the country. Launched in January 2023, the mission targets the use of green hydrogen as a clean energy substitute in sectors such as refining, fertilisers, steel, heavy transport, and shipping with a financial outlay of ₹19,744 Crore, with the objective to produce 5 million metric tonnes of green hydrogen annually by 2030 and develop at least 125 GW of associated renewable energy capacity [3] [4].

In parallel, the National Solar Mission, a key component of the National Action Plan on Climate Change (NAPCC), was launched in 2010. The initiative is designed to support the sustainable growth of solar energy in India by making power generation more affordable. This is being pursued through long-term policy backing, large-scale installations, continued research and development. The mission has contributed significantly to the rapid growth of solar power capacity in the country, helping India surpass 72 GW of installed solar capacity by 2024, as part of its broader goal to reach 500 GW of non-fossil fuel-based capacity by 2030 [5]. These national efforts underscore India's commitment to global climate goals and its ambition to become a hub for renewable energy production and green hydrogen innovation.

To advance clean energy objectives, the integrated generation and utilization of hydrogen and solar energy, in combination with fuel cell technologies, presents a promising and sustainable solution. This transition strategy to avoid fossil fuel-based energy systems necessitates the widespread growth and deployment of renewable energy technologies to balance energy supply with growing global demand. However, the geographical variability and uneven distribution of renewable resources, such as solar, wind, hydro, and biomass poses significant challenges for the design, integration, and efficiency of modern power distribution networks. At the same time, these renewable sources offer tremendous potential for large-scale, industrial energy generation. A key concept emerging from this transition is the chemical bond as a pivotal link between energy and materials.

Recognizing this, the global chemical industry has increasingly focused on storing renewable energy in various forms of chemical bonds, enabling controlled release and transfer of energy through various storage and conversion technologies. Renewable energy sources, in particular the solar power, can be harnessed not only for direct electricity generation but also for the production of value-added chemicals and fuels, making them vital contributors to sustainable energy systems. Energy stored in the form of chemical carriers (such as hydrogen or synthetic fuels) or as electricity can serve as a clean alternative to fossil fuels, whose continued use remains the dominant contributor to global CO_2 emissions, a primary driver of climate change. To mitigate these environmental impacts, strategies such as carbon capture and utilization (CCU) and the production and storage of carbon-neutral fuels from renewables are being actively pursued. In response, numerous countries including the UK, US, Japan, China, and Germany have significantly increased financial sanctions in renewable energy infrastructure and technologies aimed at reducing dependence on fossil fuels [6].

As one of the largest contributors to global CO_2 emissions, China has taken substantial steps toward reducing its reliance on fossil fuel-based power plants. Among several initiatives, China has developed multiple energy production and storage facilities, including the world’s largest silicon-based solar power plant, installed on a floating sea platform. In a similar effort, Japan has commissioned the world’s largest hydrogen production plant, spanning several kilometres, to support its growing fuel cell infrastructure.

This initiative aims to partially or fully substitute fossil fuels with clean hydrogen energy, further promoting a low-carbon energy future. Considering the projected global energy demand of 22 terawatts (TW) by 2030 and the increasing international momentum toward clean energy, the deployment of renewable energy sources and their efficient storage-either as electricity or chemical fuels, is seen as essential to at least stabilizing current atmospheric CO_2 levels (approximately 400 ppm) [7]. Achieving this goal, however, will require intensified efforts to lower technology costs and develop mature, scalable infrastructure. Accelerating the decoupling of energy systems from fossil fuels within a defined timeframe is critical to ensuring a sustainable and secure energy future.

2.2. Water Electrolysis for Hydrogen Production: Enabling the Future Energy

At present, hydrogen (H_2) plays a critical role in majority of the industrial processes. Industries such as ammonia production, fertilizer manufacturing, oil refining, and petrochemical processing consume more than 25 million tons of hydrogen annually. Interestingly, nature pioneered a sustainable method of hydrogen production over 3.2 billion years ago through photosynthesis, wherein solar energy drives chemical reactions in plants, a process that continues to inspire modern scientific research [8]. Driven by the vision of mimicking this natural, solar-driven chemistry and addressing the intermittency of renewable energy sources like solar and wind, scientists have increasingly focused on hydrogen as a future energy carrier.

Hydrogen stands out as a clean and efficient fuel, boasting the highest gravimetric energy density (120-140 MJ/kg) among known fuels and offering near 100% conversion efficiency, approximately three to four times greater than conventional fossil fuels. Despite its potential, the current hydrogen production landscape is heavily dependent on fossil fuels. More than 90% of global hydrogen is produced through steam reforming of hydrocarbons at high temperatures (700-1100ºC) [9]. This process is energy-intensive and emits significant quantities of carbon dioxide (CO_2) and other pollutants, becoming a major contributor towards global warming and ecological degradation, and posing a growing threat towards environment.

Given these concerns, there is an urgent need of shift towards sustainable hydrogen production methods by connecting renewable sources such as sunlight, water, wind, and biomass. Among these, water emerges as one of the cleanest, most abundant, and accessible sources of hydrogen, offering great promise for the realization of a clean hydrogen economy.

Photo-induced and electrochemical water splitting, the process that generate electrons, protons, and oxygen molecules have drawn significant attention from energy researchers as promising pathways for sustainable hydrogen (H_2) production, offering a strategic route toward a hydrogen-based economy [10]. Several types of water-splitting technologies have been developed, for the production and storage of hydrogen towards the use in applications similar to those currently powered by fossil fuels.

2.3. Why Hydrogen as fuel

Hydrogen is widely regarded as one of the most promising clean energy storage solutions currently under exploration. Electrical energy generated from thermal, solar, wind or nuclear can be utilized to produce hydrogen through water electrolysis. This hydrogen can later be used in fuel cells to regenerate electricity, offering a closed-loop and environmentally friendly energy cycle. Under standard temperature and pressure conditions (273K and 101.325 kPa), hydrogen is a light gas with a density of 0.08988 Kg/m^3 [11]. It possesses the highest energy content per unit mass among all known fuels. However, it’s extremely low density and molecular weight present significant storage challenges, as a large volume of hydrogen is required to store substantial energy. Moreover, hydrogen is highly reactive and can combust explosively in the presence of oxygen, necessitating precise control over its combustion process.

A key environmental advantage of hydrogen is that its oxidation yields only water vapour, producing no carbon dioxide emissions, unlike conventional fossil fuels. Additionally, since water is abundantly available, hydrogen can be generated sustainably and in large quantities, offering a potential long-term solution to the global energy crisis.

Despite these advantages, hydrogen is a hazardous gas that demands strict safety protocols. Due to its lightness and flammability, it requires specialized containment systems with high-integrity sealing and careful handling, especially under pressure. These safety and engineering challenges are essential considerations but lie beyond the central focus of this research.

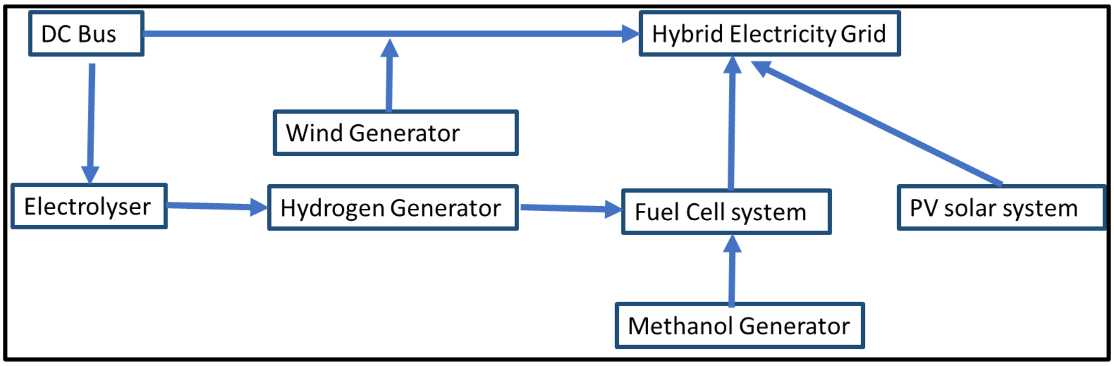

Figure 2.1- Electricity generation scheme [12].

A brief overview of the hybrid electricity grid is shown in **Figure. 2.1**. The system begins with energy generation, specifically from renewable sources, which forms the basis for hydrogen production. This figure illustrates the overall process, highlighting how renewable energy sources are used to generate hydrogen, which can be stored and later converted to electricity through fuel cell technology. Typically, hydrogen is generated using electrolyzers, which split water into hydrogen and oxygen using electrical energy. During off-peak hours, or when renewable generated electricity is not immediately required by the grid, this surplus energy can be directed to electrolyzers to produce hydrogen. Once generated, the hydrogen is stored in specialized tanks, often using advanced materials with nano-porous structures that enable adsorption-based storage. This storage step is one of the most technically challenging aspects of the system, as it requires precise control over pressure, temperature, and material characteristics [13].

Enhancing the adsorption capacity and efficiency of these storage materials is a critical area of ongoing research and system optimization. Subsequently, the stored hydrogen can be converted to electricity using Hydrogen fuel cells, which offer a clean and efficient way to meet varying electrical loads. This process supports grid stability and contributes towards the broader integration of renewable energy into the power system.

2.4. Hydrogen Generation: Concept of OER

Solar energy positions as a promising alternative to conventional energy sources for meeting growing energy demands and achieving zero carbon emissions. Photovoltaic (PV) cells are commonly employed to harness solar radiation and convert it into electricity. However, the effectiveness of this energy supply is inherently limited by factors such as geographic location, seasonal variations, and the diurnal cycle. To overcome these limitations, it is essential to develop efficient and environmentally sustainable methods for harvesting and storing solar energy. One viable approach involves utilizing catalytic processes to directly convert solar energy into chemical fuels. Among these, hydrogen generation emerges as a highly attractive candidate due to its high energy density, carbon-free nature, and ease of transportation.

Solar-driven hydrogen production through water splitting has gained considerable attention as a promising approach to convert solar energy into chemical fuels. **Figure 2.2** illustrate two major strategies for this process. Photovoltaic-electrolysis (PVE) and photo-electrochemical (PEC) water splitting systems. In a PVE system, a photovoltaic module is externally connected to a water electrolyzer, where the electricity generated by the PV module is used to drive the electrolysis of water, as depicted. In contrast, a PEC system integrates light absorption and electrochemical water splitting within a single unit.

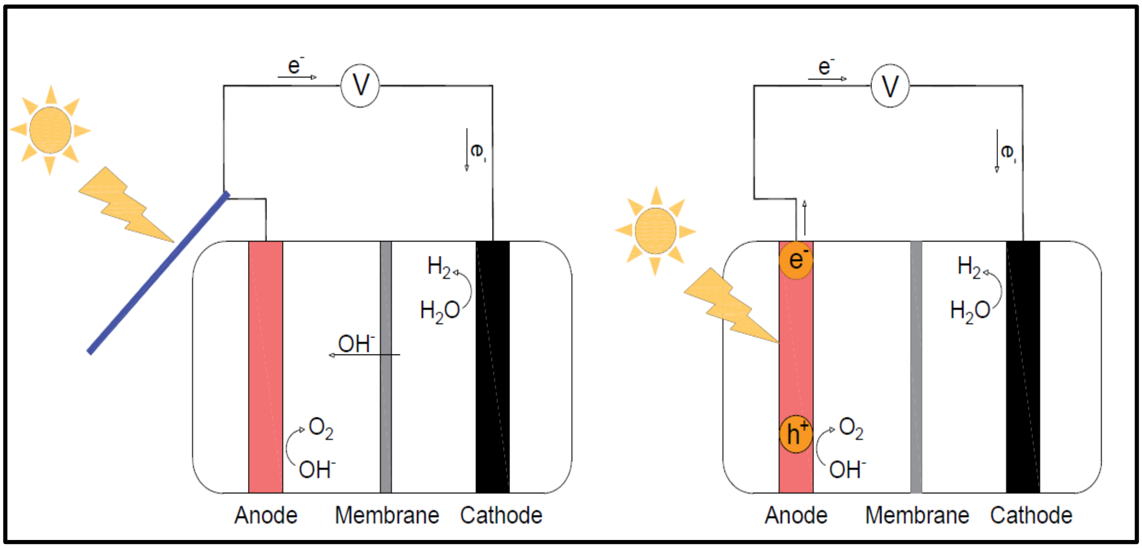

Figure 2.2- Schematic showing water splitting by solar with PV Cell coupled to water electrolyser and Photo-Electrochemical cell coupled to water electrolyser [14].

Conventionally, water electrolysis is carried out using a two-electrode system in which the Oxygen Evolution Reaction (OER) occurs at the anode and the Hydrogen Evolution Reaction (HER) takes place at the cathode. To drive the overall water-splitting process, a minimum thermodynamic potential of 1.23 V vs. RHE (Reversible Hydrogen Electrode) is required [15]. This energy input can be supplied either electrochemically (via electrocatalysis) or photochemically (via photocatalysis).

In photocatalysis, semiconducting materials mimicking the natural photosystem serve as light absorbers and energy converters. Upon irradiation with light, these materials generate electron-hole pairs (excitons) through the excitation of electrons from the valence band to the conduction band. The hydrogen production in such systems is realized through solar-fuel devices that typically integrate photovoltaic materials (PVs), a proton exchange membrane (PEM), and both oxidation and reduction catalysts.

Architecturally, water splitting modules can be classified into two categories namely wireless and wired configurations. In the wireless configuration, semiconducting materials are directly exposed to sunlight. The photo-generated electrons and holes are separated and migrated toward opposite poles, facilitating oxidation and reduction reactions at the catalyst-electrolyte interfaces. Conversely, in the wired configuration, the photoelectrodes are connected via an external circuit, and the anode and cathode are internally separated by a PEM. Upon light absorption, water oxidation occurs at the anode (hole site), and the generated electrons are transported to the cathode through the external circuit, completing the redox cycle. In both configurations, the evolved hydrogen can be collected from the respective electrode while directly utilizing solar energy **(Figure 2.3).**

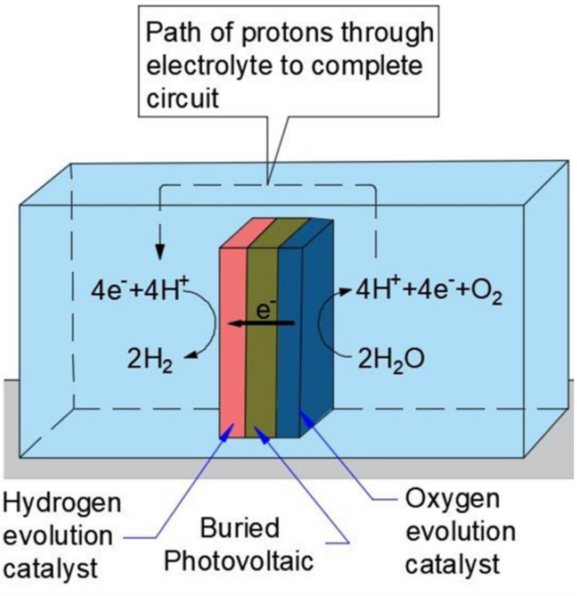

Figure 2.3- Configuration of water splitting module [16].

Table 2.1- Reaction mechanism with potential values.

Reaction	**Half-cell Equation**	**E^0 vs RHE (V)**
OER (Anode)	$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$	+1.23
HER (Cathode)	$4H^+ + 4e^- \rightarrow 2H_2$	0.00
Overall Reaction	$2H_2O \rightarrow 2H_2 + O_2$	1.23

Although these solar-driven water splitting strategies are of considerable scientific and technological interest, they fall outside the scope of the current dissertation. This work will focus primarily on the electrochemical water splitting approach, emphasizing electrode materials, reaction mechanisms, and future perspectives. The fundamental half-reactions for electrochemical water splitting are summarized in **Figure 2.4** and **Table 2.1.**

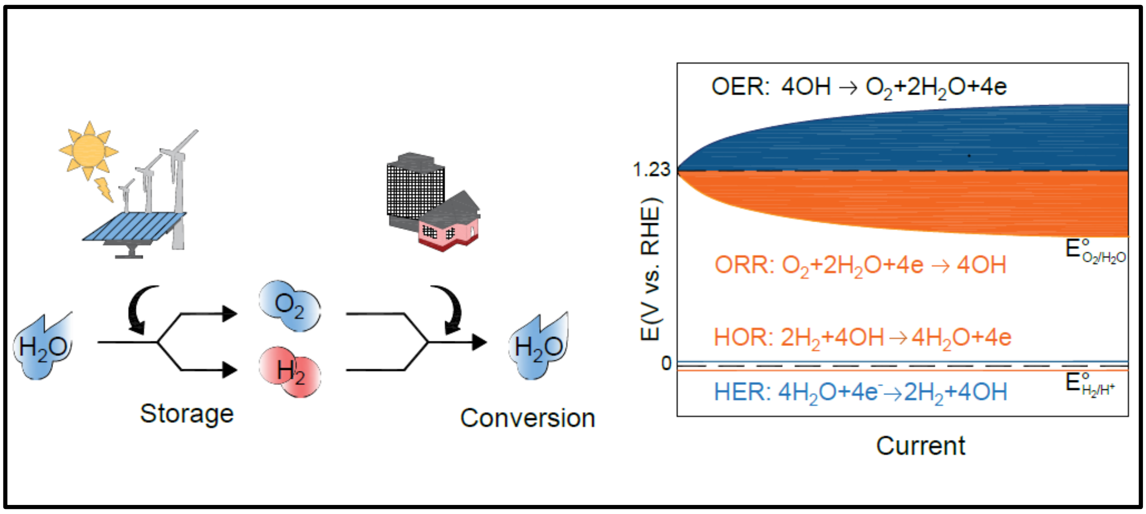

Figure 2.4- Electrochemistry for energy storage and conversion along with reaction formulas for Hydrogen generation and Fuel cell [14].

Both OER and HER are energetically demanding processes that involve multiple electron-transfer steps and exhibit significant kinetic barriers, necessitating the development of efficient and stable electrocatalysts.

2.5. Electrochemical water spitting

Water can be electrochemically split at the electrode-electrolyte interface by applying a potential greater than the thermodynamic requirement of 1.23 V vs. RHE. At the anode, water undergoes oxidation, generating oxygen gas (O_2), protons (H^+), and electrons. The protons migrate through the electrolyte while the electrons travel via the external circuit to the cathode, where they recombine to form molecular hydrogen (H_2), thus completing the redox cycle.

Commercially, two primary types of electrolyzers are widely used namely Alkaline electrolyzers and Proton Exchange Membrane (PEM) electrolyzers. Among these, PEM electrolyzers are known for their high efficiency, capable of achieving current densities in the range of 1000-2000 mA/cm^2. However, this performance comes at the cost of using noble metal-based electrodes, making the system expensive. In contrast, alkaline electrolyzers, which typically employ transition metal based spinel oxides or perovskite-type transition metal catalysts, operate at significantly lower current densities (20-30 mA/cm^2), though they are more cost-effective. Both systems require highly alkaline environments (high pH) for optimal performance.

In addition to these, Solid Oxide Electrolyzer Cells (SOECs) have been developed to function at elevated temperatures, offering improved thermodynamic efficiency. Despite the technological advancements, the high energy input required under ambient conditions and the relatively lower efficiency of conventional water splitting contribute to the elevated cost of hydrogen production-currently 2 to 3 times higher than that from steam methane reforming.

To address this cost barrier, the integration of photovoltaic (PV) cells with electrolyzers presents an advanced and sustainable alternative. In this approach, solar energy harvested by PV cells is directly utilized to power the electrolyzer, as illustrated in **Figure 2.5**. This solar-driven electrochemical water splitting method is increasingly recognized as a promising research direction due to its lower operational cost, modular scalability, and high technology readiness level compared to traditional electrolyzers and standalone photocatalytic systems.

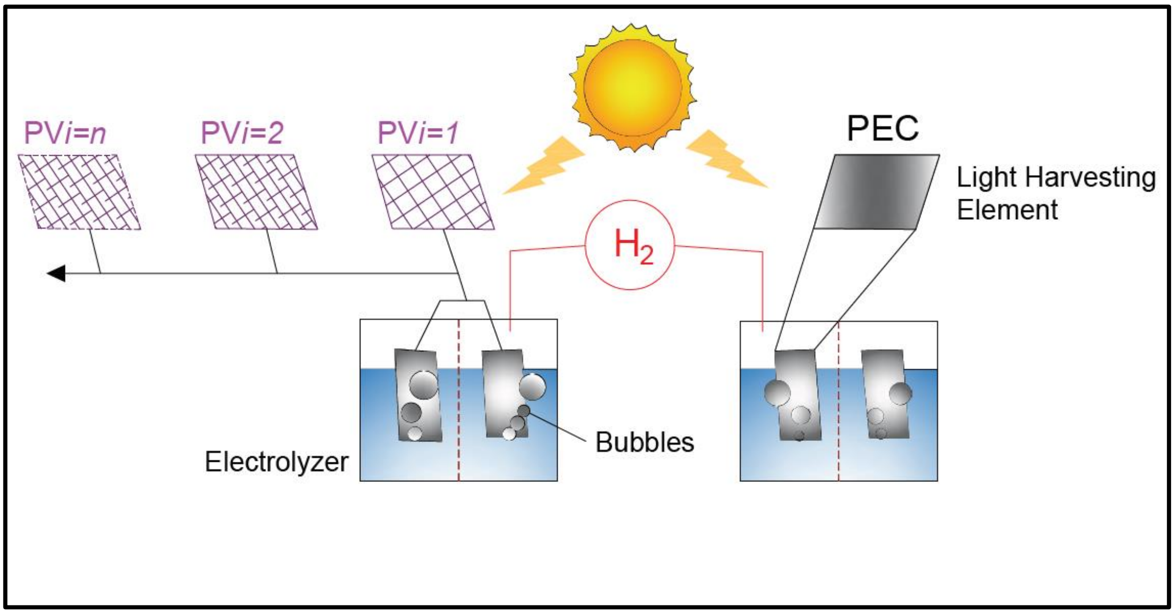

Figure 2.5- Photo-voltaic cell electrolysis and Photo catalytic water splitting [17].

A critical scientific challenge in this context is the development of high-efficiency photovoltaic materials with excellent photon-to-electron conversion efficiency (PEC). These materials must reliably generate and store electrical energy-preferably in integrated battery systems to operate a competent electrolyzer with high overall conversion efficiency. The coupling of these two modules i.e. PV and electrolyzer into a single, compact assembly, along with appropriate hydrogen storage infrastructure, paves the way for a sustainable and independent solar-to-hydrogen energy grid.

However, the broader adoption of this technology also hinges on addressing several non-technical barriers, including technical challenges, societal acceptance, policy frameworks, and research investment. Encouragingly, the growing market penetration of PV cells and the declining cost trajectory signal a positive trend toward realizing the full potential of solar-driven hydrogen production systems.

Improving the catalytic efficiency of electrolyzers is crucial for advancing low-cost and high-efficiency water splitting technologies. This is particularly important for overcoming the energetic barriers associated with the sluggish redox kinetics of the overall process. To address the limitations of conventional electrolyzers and the moderate activity of earth-abundant catalytic materials, several advanced electrochemical models have recently emerged, aimed at enhancing water conversion efficiency. These are categorised as Conventional overall water splitting, Decoupled water splitting, Hybrid electrolysis, and Tandem water splitting as shown in **Figure 2.6.**

Traditionally, the kinetics of the oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) can be enhanced by operating in strongly basic and acidic media, respectively. However, the practical realization of this setup often requires complex electrode compartmentalization, making system design and maintenance more challenging. Consequently, there is a growing interest in developing bifunctional catalysts that can operate efficiently over a wide pH range, preferably under neutral conditions and catalyze both HER and OER effectively. The use of such bifunctional electrocatalysts not only simplifies the electrolyzer architecture but also significantly reduces material and operational costs.

Among the two half-reactions, the OER is inherently slower in kinetics, and often fails to supply the required number of electrons needed for proton reduction at the cathode. To overcome this bottleneck, a decoupled water electrolysis strategy has been proposed, which introduces a redox mediator (RDM) to spatially and temporally separate OER and HER processes. In this setup, the RDM undergoes oxidation instead of water, preventing premature O_2 evolution and avoiding the reverse reaction (H_2/O_2 recombination). The oxidized mediator transfers electrons to the external circuit and is subsequently reduced back at the electrode, enhancing electron availability and minimizing efficiency loss due to OER sluggishness.

Another significant challenge is the high over-potential required for OER, which contributes to increased energy consumption. Furthermore, the oxygen gas generated at the anode is often not considered a value-added product. To address both these concerns, a hybrid water electrolysis approach has been introduced, wherein biomass-derived organic molecules (such as urea, thiourea, or hydroxyl-methyl-furfural (HMF)) are oxidized at the anode. These organic substrates possess more favourable oxidation potentials than water, thereby lowering the required cell voltage and simultaneously producing valuable organic compounds. This strategy not only enhances system energy efficiency but also prevents the mixing of evolved hydrogen and oxygen gases, improving the selectivity of HER at the cathode.

Beyond generation, the cost-effective storage and utilization of hydrogen remain major technical hurdles. To mitigate these, the tandem water splitting approach has been introduced, inspired by natural photosynthetic systems (analogous to photosystem II). In this strategy, the hydrogen generated from water electrolysis is directly utilized at the cathode for the reduction of CO_2, catalyzed by biological or bio-inspired catalysts, to produce value-added chemicals such as methane (CH_4) and ammonia (NH_3).

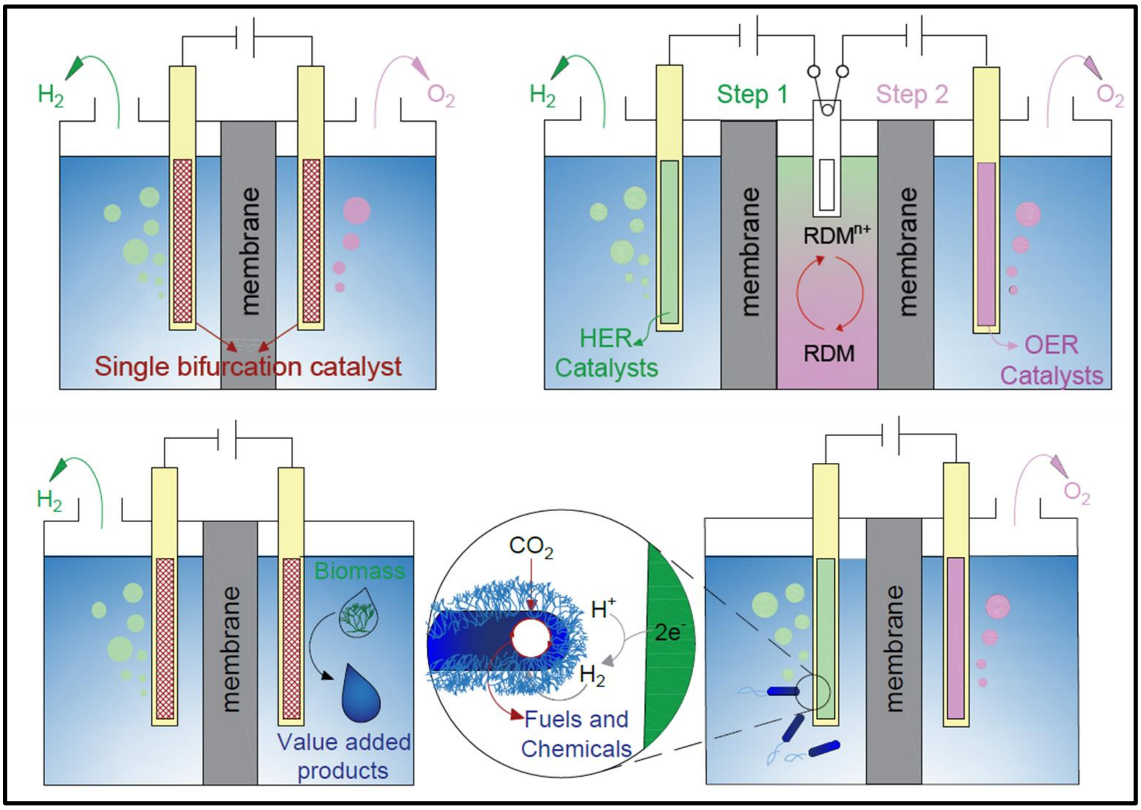

Figure 2.6- Various Electrochemical water splitting modules using bi-functional electrode materials, Decoupled scheme with re-dox mediator, Biomass catalysis and Tandem water splitting [14].

This model holds great promise for large-scale deployment, as it offers an integrated platform for renewable hydrogen utilization, CO_2 sequestration, and green chemical synthesis. Electrochemical water splitting is typically conducted in a well-defined electrochemical cell comprising a standard three-electrode setup: a working electrode, counter electrode, and reference electrode, along with a conductive electrolyte and a potentiostat to control the applied potential. In this configuration, the potential is precisely controlled at the working electrode to facilitate either the oxidation or reduction half-reaction, depending on the thermodynamic requirements of the targeted process.

For overall water splitting, a two-electrode system consisting of an anode and a cathode is used to drive the full redox reaction. However, for evaluating the catalytic activity of individual electrode materials, a half-cell configuration is preferred, wherein only the working electrode is modified with the catalyst of interest (**Figure 2.7**). This setup enables detailed investigation of the electrode's performance under controlled conditions.

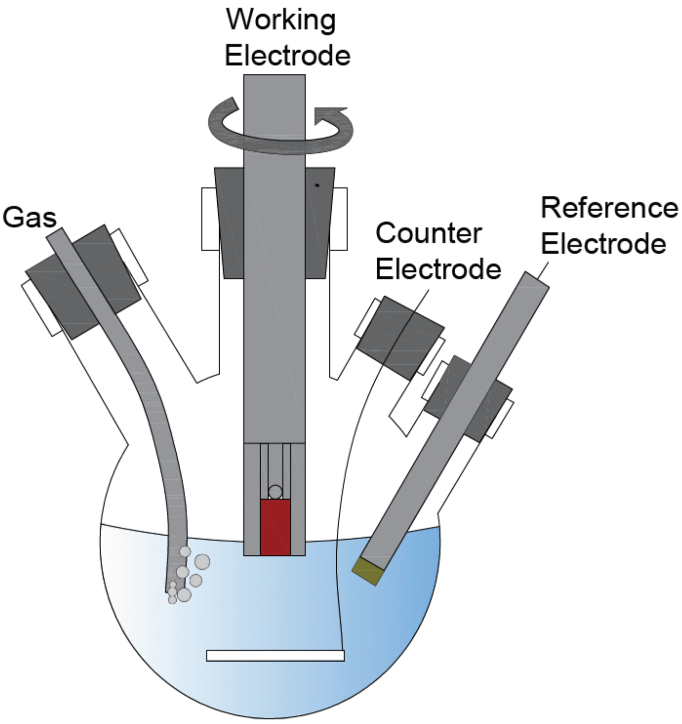

Figure 2.7- Typical three electrode Electro-chemical cell [18].

To comprehensively assess the electrocatalytic efficiency, several key parameters are measured and analysed. These parameters include Over-potential (the additional potential required beyond the thermodynamic value), Tafel slope (indicating reaction kinetics), Electrochemical stability, Turnover frequency (TOF) (a measure of catalytic activity per site), Faradaic efficiency (to quantify the fraction of charge required for the reaction), and Electrochemical active surface area (ECSA) representing the available active sites on the catalytic surface. These metrics collectively provide a detailed understanding of the catalyst’s effectiveness and suitability for water splitting applications.

2.5.1. Over-potential

Over-potential is a key indicator of an electrocatalyst’s effectiveness in driving electrochemical reactions. It represents the additional voltage required beyond the equilibrium potential (EP) to overcome kinetic and resistive losses during a reaction. For water splitting, the EP is 1.23 V vs RHE, which is the minimum theoretical voltage needed under standard conditions. In real systems, this ideal potential is insufficient due to factors such as activation barriers, mass transport limitations, and ohmic resistance, all of which contribute to over-potential. Activation over-potential is linked to the intrinsic catalytic activity and can be minimized by using highly active materials. Concentration over-potential arises from ion depletion near the electrode surface during electrolysis and may be reduced through stirring. Additionally, interface resistance and gas bubble accumulation can further increase over-potential; these effects can be partially corrected through iR compensation.

A lower over-potential suggests a catalyst operates more efficiently, initiating reactions closer to the theoretical limit. A widely used benchmark is the over-potential required to achieve a current density of 10 mA/cm^2, though comparisons are only valid when experimental conditions (e.g., pH, temperature) are consistent.

2.5.2. Tafel slope

In electrochemical systems, voltage and current are key factors controlling energy input and reaction rate. Changing the applied potential alters the driving force between the electrode and the electrolyte. To understand the kinetics and mechanism of multi-step reactions such as the oxygen and hydrogen evolution reactions (OER and HER), the Tafel slope is a widely adopted metric.

The relation between current density (i) and over-potential (η) is described by the Butler–Volmer equation:

$i = i_0 \times \exp(\alpha F\eta / RT)$, i_0 is the exchange current density, α is the charge transfer coefficient, F is the Faraday constant, R is the gas constant, T is temperature in Kelvin, η is the over-potential. Taking the natural logarithm gives: $\ln(i) = \ln(i_0) + (\alpha F\eta / RT)$

And in base-10 logarithmic form: $\log(i) = \log(i_0) + (\alpha F\eta / 2.303RT)$ [19]

Rewriting this gives the Tafel equation: $\eta = a + b \times \log(i)$, Where a is a constant, b is the Tafel slope, defined as $b = 2.303RT/\alpha F$.

The slope (b) indicates how rapidly over-potential increases with current. It is typically derived from a plot of log(i) versus η. A smaller Tafel slope implies a faster electron transfer rate and better electrocatalytic efficiency.

It is essential to analyze this slope near the onset potential, as Tafel values may vary across potential ranges even for the same reaction pathway. Additionally, solution resistance (R_s) and charge transfer resistance (R_{ct}) may distort results, especially when $R_S > 6\ \Omega$ and current density exceeds 100 mA/cm^2. To obtain more reliable kinetic data, Electrochemical Impedance Spectroscopy (EIS) can be used. EIS measurements should be conducted at over-potentials at least 100 mV higher than those identified via CV to reduce error [20]. The inverse of Rct (i.e., 1/Rct) can then approximate the exchange current density, offering a clearer understanding of the electrode kinetics over a broad potential range.

2.5.4. Exchange Current Density(i_0)

Exchange current density is a fundamental kinetic parameter reflecting the intrinsic charge transfer ability between the electrode and electrolyte at equilibrium. A higher i_0 indicates favorable interaction between reaction intermediates and the catalyst surface, suggesting better catalytic efficiency. Although direct measurement is challenging, i_0 can be estimated by extrapolating the Tafel plot to zero over-potential or via charge transfer resistance obtained from impedance studies.

2.5.5. Turnover Frequency

Turnover frequency defines the number of product molecules present per each active site with in unit time. It provides insight into the catalytic activity of surface atoms. A high TOF signifies that the catalyst can efficiently and repeatedly facilitate the target reaction. However, determining TOF accurately is difficult due to uncertainty in the number of accessible surface atoms; it is often estimated from the integrated area of redox peaks corresponding to active species.

2.5.6. Faradaic Efficiency

FE assesses how effectively the input charge contributes to the formation of the desired product. For water splitting, it is determined by quantifying the evolved H_2 and O_2 gases, typically using gas chromatography or water displacement methods. A FE close to 100% indicates high selectivity and minimal side reactions, validating the electrocatalyst’s performance.

2.5.7. Stability Tests (Chronopotentiometry & Chronoamperometry)

Catalyst durability is crucial for practical applications. Chronopotentiometry (constant current, monitor potential) and chronoamperometry (constant potential, monitor current) are commonly used to evaluate long-term stability under operational conditions. These tests reveal structural or compositional changes due to high temperature, pH, or prolonged electrolysis. Ideally, catalysts should remain stable over 24 hours at industrially relevant conditions.

2.5.8. Electrochemical Active Surface Area (ECSA)

ECSA represents the active available surface area participating in the electrochemical process. It is calculated from the double-layer capacitance (Cdl) values measured in the non-faradaic potential window. Plotting capacitive currents against scan rate gives Cdl, which is then normalized by a known specific capacitance (Cs) to yield ECSA. A higher ECSA typically implies more accessible active sites, enhancing overall catalytic performance [21].

2.6. Literature Review: Advancements in Electrocatalysts for Water Splitting

Water is one of the most abundant and hydrogen-rich resources available on Earth. Through electrolysis, it can be split into its elemental components- hydrogen and oxygen- via two distinct half-reactions: the hydrogen evolution reaction (HER) occurs at the cathodic part and the oxygen evolution reaction (OER) at the anodic part. However, the feasibility and energy requirement for such reactions are primarily governed by their thermodynamic parameters, notably the Gibbs free energy change (ΔG). A high ΔG value indicates a less favourable and non-spontaneous reaction, necessitating external energy input.

In the case of water splitting, the ΔG is approximately 237 kJ/mol, implying a minimum thermodynamic potential of 1.23 V under standard conditions for the process to proceed.

Despite its apparent simplicity, water electrolysis involves complex multi-step mechanisms at both electrodes. These include multi-electron transfer reactions and the formation of various reaction intermediates at the electrode–electrolyte interface, making the overall process kinetically sluggish. Moreover, energy losses due to system resistances and intermediate species like OH*, MOOH*, and MO* especially on the anodic side raise the energy barrier further, typically necessitating over-potentials ranging from 500 to 600 mV. This scenario underscores the urgent need for robust, efficient electrocatalysts that can facilitate these reactions at lower over-potentials.

Over the last two decades, both homogeneous and heterogeneous catalytic systems have been explored to enhance the water-splitting efficiency. Homogeneous catalysts, such as transition metal complexes of Fe, Mn, Ru, Ir and Co have demonstrated and proved commendable turnover frequencies (TOFs) and mechanistic flexibility. However, these catalysts pose practical challenges due to difficulties in their recovery, potential side reactions, and limited reusability, which restrict their industrial applicability.

Heterogeneous catalysis, on the other hand, offers more scalable solutions through electrode-immobilized catalysts or catalyst-integrated electrode systems. Among HER catalysts, platinum (Pt) and palladium (Pd) are widely acknowledged as benchmark materials due to their nearly zero over-potential operation and optimal hydrogen intermediate binding. Nevertheless, their high cost, scarcity, and vulnerability to poisoning in wide pH ranges have driven research towards more abundant and stable alternatives.

Conversely, the OER process poses a greater challenge due to its multi-step (4-electron) mechanism, which involves energy-demanding intermediates (e.g., OH*, OOH*, MO*). Ruthenium dioxide (RuO_2) and iridium dioxide (IrO_2) are currently among the most efficient OER catalysts, demonstrating low over-potentials (~220 mV) and high catalytic activity. However, their performance is susceptible to degradation, especially RuO_2 in alkaline media, where it can transform into water-soluble RuO_4, thus limiting its long-term stability.

Transition metal oxides such as NiO, CoO, and CuO have emerged as promising OER catalysts due to their redox flexibility and earth abundance. Additionally, chalcogenides, spinel oxides, and composite structures have been investigated, with some outperforming conventional noble metal catalysts. Despite their activity, issues like unstable intermediate phases and nanoparticle agglomeration continue to hamper their prolonged usability.

In addition, The hydrogen generation through water splitting and electricity generation through direct methanol fuel cell (DMFC) are considered as key sustainable renewable technologies [10,22,23]. At present, RuO_2 and IrO_2 is considered as benchmark electro-catalysts for oxygen evolution reaction (OER) in water-splitting [24,25]. However, the scarce availability and high input cost restricts their usage for wider commercial and industrial adaptation. In this regard, transition metal oxides/hydroxides based electro-catalysts showing good catalytic properties and wider availability offers potential alternative [26,27] .

Among the various transition metals, the Ni based electro-catalysts show good OER and MOR performance in alkaline medium combined with stability and corrosion resistance [4,28]. Generally, the design strategies for the Ni-based electro-catalysts focus on tailoring the surface active sites [29–31], composition [32,33], defects [34,35], doping [36–38], electronic structure [39,40], interface [41,42], catalyst support [43,44] and surface reconstruction [45,46], [47]. A combination or summation of multiple design strategies improves the catalytic performance.

In recent times, the Ni-amorphous alloys based self-supported electro-catalysts have gained attention due to their non-crystalline structure with unique topological and chemical short-range ordering [48,49], compositional flexibility (alloying multiple d-block elements with Ni) [50–52], including high electrical conductivity leading to low charge transfer resistance [18], and variable oxidation state, (e.g., 0, +2 and +3 for Ni in elemental form, ($Ni(OH)_2$ and (NiOOH)) during catalysis [53,54]. Moreover, the addition of heteroatoms, like Fe, Mn, and Co, modifies the electronic distribution of the primary catalytic site and influences the adsorption energy of the intermediates [55,56].

Considering this, a number of Ni-amorphous alloys namely NiFeP, NiFeMo, NiCoFeMoMn, NiFeBSiP, NiZrMo, NiTiZrAg, etc., in the form of melt-spun ribbon were studied for HER and OER performance [57,58] . The attempts were made to improve mass transfer kinetics and development of more active phases in Ni-amorphous alloys with multiple surface-reconstruction techniques, like, nanoporous structure through selective de-alloying, cathodic corrosion, sputtering, nanocrystallization, etc. [59,60]. For example, Jiang et al, adopted combination of annealing and cyclic voltammetry of NiFBSiP amorphous ribbon resulting a lower over-potential of 269 mV (10 mA cm^{-2}) and smaller Tafel slope of 40.5 mV dec^{-1} [61].

Qian et al, fabricated a nanoporous NiFeMoP alloy ribbon through chemical etching acts as a bifunctional catalyst for OER and HER reaction in 1M KOH and achieved 10 mA cm^{-2} current density at potential of 1.41 V (vs RHE) in overall water-splitting [62]. Chen et al. reported a de-alloyed FeCoNiMoPB ribbon with superior OER performance, depicting a lower over-potential of 281 mV (10 mA cm^{-2}) and a smaller Tafel slope of

36.4 mV dec^{-1} [63]. Xiao et al, synthesised free standing surface-modified FeNiNbPC ribbons a lower over-potential of 248 mV (10 mA cm^{-2}) in 6 M KOH with excellent long-term stability [64]. Also, it is reported a simple potentiostatic cathodic corrosion of FeSiB amorphous ribbon surface offers an alternate way of creating favourable catalytic (hydroxyl) sites by optimally controlling the etching time [65,66].

Layered double hydroxides (LDHs) represent another compelling class of OER catalysts. Structurally, LDHs consist of brucite-like layers composed of divalent and trivalent metal cations, intercalated with anions or water molecules. Their 2D layered architecture enables high exposure of active sites and tunable interlayer spacing, which can be optimized by varying metal compositions and synthesis conditions. Ni-Fe, Ni-Co, Co-Fe, and Cu-Fe. LDHs have demonstrated excellent OER activity, primarily due to their inherent electronic conductivity, rich redox chemistry, and favourable interaction with water molecules. Post-synthesis exfoliation and hybridization with conductive supports (example. GO, CNTs, g-C_3N_4, or porous MOFs) [13] can further enhance their performance and stability.

The development of efficient electrocatalysts for the oxygen evolution reaction (OER) and methanol oxidation reaction (MOR) is crucial for advancing clean energy technologies, such as water electrolysis and direct methanol fuel cells. These vital reactions are challenged by high over-potentials and sluggish kinetics, necessitating efficient, noble-metal-free electrocatalysts. Nickel-based hydroxides and oxyhydroxides are promising electrocatalysts, with their performance greatly enhanced by strategies such as heteroatom doping, nanostructuring, surface de-alloying, and self-supported designs [67].

These approaches respectively tailor electronic structures to lower activation barriers, increase surface area and active site density, enrich surfaces with active species, and improve mechanical stability by eliminating external substrates [68]. However, these strategies are often explored in isolation, limiting their collective potential to address the multifaceted demands of OER and MOR electrocatalysis. Flexible Ni-based amorphous alloy self-supported catalysts offer a unified platform that integrates multiple design strategies to enhance electrocatalytic performance [61]. The multicomponent alloy enables heteroatom doping to tune electronic structures and improve charge transfer, while surface treatments like de-alloying introduce nano-porosity, increasing surface area and exposing more active sites [50,62]. The self-supported architecture ensures strong adhesion and durability under harsh electrochemical conditions. Although each strategy shows individual promise, their combined effects remain underexplored.

Recent research has also delved into the atomic-level design of catalysts, particularly single-atom catalysts (SACs), which offer the ultimate atom economy and maximized utilization of active sites. These SACs are typically anchored on conductive and porous matrices, ensuring high dispersion and reactivity. However, the agglomeration of single atoms under electrochemical stress and declining activity over time remain open challenges. The above studies highlight the importance of the chemical composition of Ni-amorphous alloy and surface re-construction techniques to improve the catalytic performance.

In summary, despite extensive advancements in catalyst design for water splitting, the development of cost-effective, stable, and highly efficient materials remains essential. Future innovations must balance catalytic performance, material availability, and structural integrity especially when integrated into solar-driven electrolyser systems for sustainable hydrogen production.

By looking into the above literature and to address the gap areas, we carried out this present thesis work. In this work, a novel $(Ni_{87}Fe_4Cr_9)_{78}Si_8B_{14}$ amorphous alloy ribbon is considered and different proportions of α-$Ni(OH)_2$ are synthesized in-situ on the ribbon surface through potentiostatic cathodic corrosion, applied for varied times (30, 45, 60, 90 and 120 minutes). Corroded ribbon samples are investigated as electro-catalysts in presence of 1 M KOH and 1 M KOH + 1 M MeOH respectively, for OER and MOR studies. This work highlights the application of amorphous ribbons and their surface-corroded counterparts as self-supported up-scalable electrocatalyst for OER and MOR. While previous studies have explored Ni-based amorphous alloys for OER applications, to the best of our knowledge, this is the first report demonstrating the potential of such materials for MOR. The findings underscore the versatility of amorphous alloys in electro-catalysis and introduce a new class of materials for direct methanol fuel cell (DMFC) applications.

2.7. Direct Methanol Fuel Cell (DMFC)

Direct Methanol Fuel Cells (DMFCs) are a subset of Proton Exchange Membrane Fuel Cells (PEMFCs) that utilize methanol (CH_3OH) as a liquid fuel. In a DMFC, methanol is introduced at the anode, while oxygen from ambient air is supplied at the cathode. At the anode, methanol undergoes electrochemical oxidation in the presence of a platinum-ruthenium (PtRu) catalyst:

Anode reaction (Methanol Oxidation Reaction, MOR) is as below:

$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^{-}$ ……………… (1)

The resulting protons (H^+) migrate through the proton exchange membrane (PEM) to the cathode, where they react with oxygen in the presence of a platinum (Pt) catalyst to form water. Cathode reaction (Oxygen reduction reaction, ORR) is given by (3/2). $O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$, over all reaction comes to be $CH_3OH + (3/2)\ O_2 \rightarrow CO_2 + 2H_2O$. (**Figure 2.8**) [69]**.** As protons move through the PEM, electrons flow through an external circuit, generating electrical power that can be used to operate electronic devices (**Figure 2.9**).

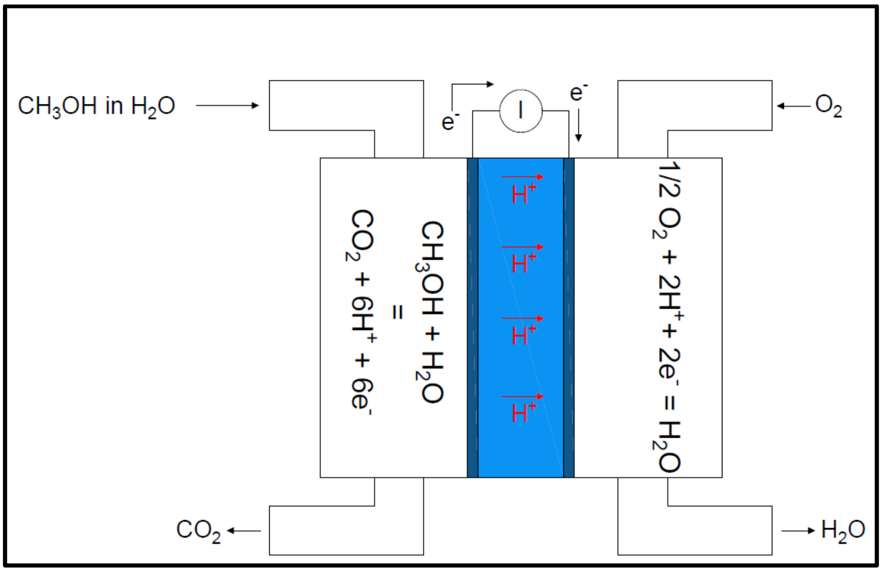

Figure 2.8- PEMFC working schematic [70].

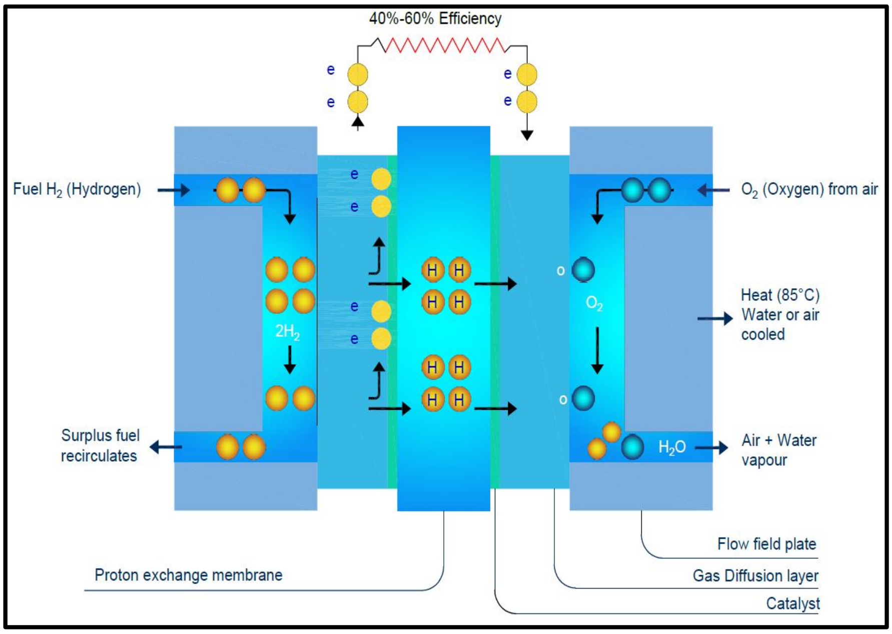

Figure 2.9- Hydrogen Fuel cell working schematic [70].

2.7.1. Advantages of DMFCs

DMFCs offer several benefits, particularly for portable and transport applications. Methanol, being a liquid fuel, is easy to store and transport under ambient conditions, unlike gaseous hydrogen which requires high-pressure storage. Although DMFCs emit CO_2, methanol can be sourced from renewable biomass, classifying it as a cleaner alternative fuel.

Methanol has a high theoretical gravimetric energy density of approximately 6,100 Wh kg^{-1}. While the actual operational efficiency of DMFCs is around 20%, yielding a practical energy density of about 1220 Wh kg^{-1}, this still surpasses that of lithium-ion batteries (~250 Wh kg^{-1}). Additionally, methanol's volumetric energy density (~4,400 Wh L^{-1}) is notably higher than that of compressed hydrogen at 700 bar (~1555 Wh L^{-1}). These properties make DMFCs attractive for mobile power systems and light-duty vehicles.

Hydrogen, while a promising long-term fuel, currently faces limitations related to production, storage, and infrastructure. Furthermore, its high flammability poses safety challenges. Methanol, by contrast, can be safely handled in liquid form at room temperature and pressure, offering logistical and safety advantages.

2.7.2. Challenges of DMFCs

Despite their benefits, DMFCs have notable drawbacks. Methanol is toxic and burns with an invisible flame, necessitating careful handling. Two major technical challenges hinder the DMFC performance. The MOR at the anode exhibits sluggish kinetics, requiring high catalyst loading to achieve acceptable performance levels.

Unreacted methanol can diffuse through the PEM and reach the cathode, where it reacts with oxygen directly. This creates a mixed potential, reducing the cell's voltage and efficiency. To mitigate MCO, diluted methanol concentrations (typically 0.25- 5 mol L^{-1}) are used. However, this compromises the energy density, diminishing one of the main advantages of DMFCs over batteries and hydrogen fuel cells. Moreover, due to slow MOR kinetics, DMFCs require significantly higher catalyst mass at the anode up to 22.5 times more than in hydrogen fuel cells (HFCs). Since these catalysts contain rare and expensive metals like Pt and Ru, this adds substantial cost.

2.8. Catalyst materials for Direct Methanol Fuel cells

In recent years, significant progress has been made in the field of direct alcohol fuel cells (DAFCs), attracting considerable attention from researchers and industry alike. This interest stems from the quest for alternative energy sources that are not only sustainable but also offer advantages such as environmental friendliness, cost-effectiveness, ease of transport, and the inherently high energy density of alcohols like methanol and ethanol. Among DAFCs, Direct Methanol Fuel Cells (DMFCs) have emerged as promising candidates due to their ability to operate at low temperatures, rapid and convenient refuelling capabilities, and the elimination of the need for external electrical recharging. These features make them particularly attractive for portable power applications.

Despite these advantages, DMFCs still face several critical challenges that hinder their broader commercialization. Key issues include the high cost of platinum-based catalysts, methanol crossover through the proton exchange membrane (PEM), and the complexities involved in thermal and water management, which impact the long-term operational stability and durability of the system.

Additional technical obstacles involve the optimization of membrane-electrode assemblies, controlling membrane thickness, improving diffusion layer properties, and enhancing power density. Moreover, the sluggish kinetics associated with the methanol oxidation reaction (MOR) at the anode and the oxygen reduction reaction (ORR) at the cathode significantly limit overall performance. In micro DMFC systems, increasing the catalyst loading, typically platinum-based has been a common strategy to improve methanol conversion. However, this often results in exacerbated methanol crossover and increased material costs due to the reliance on precious metals. To mitigate these issues, extensive research has focused on developing alternative catalysts that offer improved electrochemical activity, enhanced durability, and reduced cost. These innovations are crucial for advancing the practical viability and commercialization of DMFCs as reliable and sustainable power sources.

The performance and reliability of Direct Methanol Fuel Cells (DMFCs) largely depend on the electrocatalysts used, particularly at the anode for methanol oxidation. Currently, there is a strong research focus on developing cost-effective alternatives to traditional noble metal catalysts like platinum. The goal is to identify materials that offer high catalytic activity, durability, and resistance to CO poisoning, while reducing cost and complexity. Efforts have been directed toward catalysts with lower Pt content, or those incorporating non-noble metals such as nickel, cobalt, and copper, either in pure, alloyed, oxide, or supported forms. Noble metal-based variants such as platinum, rhodium, and palladium in pure, alloyed, or supported forms continue to be studied as benchmarks.

Catalyst performance is typically assessed by parameters like peak current density (from cyclic voltammetry), long-term stability (via chronoamperometry), and mass-specific activity. Other factors, including morphology, composition, surface area, and tolerance to intermediate poisoning (CO), also influence catalytic behaviour and are considered in comparative studies. Platinum (Pt)-based catalysts are commonly employed in micro-DMFCs for methanol oxidation, but higher loadings while improving conversion, can increase methanol crossover and cost. To address Pt's high cost and CO poisoning, alloying with metals like ruthenium (Ru) or using transition metal alternatives is explored. Materials effective in the water-gas shift reaction are particularly beneficial for CO removal.

Advanced nanostructures such as Pt nanowires, nanosheets, nanospheres, and dendrites (including Rh-based) enhance surface area, mass transfer, and durability. Hybrid catalysts like Pt on graphene oxide (GO), poly-vinyl-pyrrolidone (PVP), or Rh on reduced graphene oxide (RGO) show improved activity and conductivity. N and S-doped graphene supports for palladium (Pd) also offer high stability and current density.

Support materials play a key role in catalyst performance. Conductive polymers (e.g., polyaniline), carbon-based supports (e.g., carbon black, carbon nanofibers, nanotubes, graphene), and mesoporous silica are widely used. Hybrid supports, such as g-C_3N_4 combined with carbon black, have shown enhanced MOR activity. Partial sulfonation of polyaniline further improves thermal stability and interaction with active sites.

Ni-based catalysts have emerged as promising candidates, especially in alkaline media. When combined with noble metals, the active sites are typically the precious metal components. In contrast, noble-metal-free Ni catalysts rely on Ni^{3+} species for activity but require higher over-potentials, making them more suitable for methanol-assisted water splitting rather than fuel cells.

Pure Ni catalysts often suffer from low activity and poor CO tolerance. To overcome this, research focuses on Ni-based composites or hybrids that improve performance through enhanced active site exposure and better mass transport. Strategies such as hetero-structure design, electronic tuning, defect engineering, and surface modification have significantly boosted catalytic efficiency. However, understanding the individual role of each component in hybrid systems remains a key challenge for optimizing catalyst performance.

2.9. Photo Voltaic Plant

Global energy consumption index of a country symbolizes the overall progress of the nation. Growth in energy demand of the nation indicates the growth rate of the economy in particular and plays a pivotal role in inclusive growth. India is the fastest developing nation and to build a sustainable format of growth in the era of industrialization, maintaining energy security is a big challenge. With the increase in energy demand from all sectors, India is meeting the requirement with a total connected capacity of 425.40647 GW [71] wherein the major share is catering from thermal power plants, amounting to 239.29291 GW. Renewable energy sources are amounting to 131.78339 GW of which solar installations contribute with an installed capacity of 70.10 GW. Globally, India ranks 3rd among power generating nations [3] with a drawback that more than 70% generation is from coal-fired thermal power plants. With the fast depleting reserves of coal and unavailability of quality reserves, India is at potential risk of future’s energy security and addressing this situation is the major issue at hand. To bring energy security by avoiding the dependency on foreign nations for quality coal import, the country is looking for economical and feasible solutions. Renewable energy is envisaged to meet the immediate basic needs of the huge amount of population present in the remote corners of the country and is expected to become a viable option financially without adding pollution to the environment. Peninsular India by virtue of its geographical location and with the vast coastal area has a futuristic opportunity in the field of the renewable energy sector. For harnessing the geographical advantage, wind and solar energy generation seem to be future potential opportunities. Having a moderate to high insolation all over India, is a boon while aiming prosperity in solar power generation sector [72].

For capitalising this opportunity in India, a road map has been prepared by MNRE (Ministry of New and Renewable Energy) partnering with Central Electronics Limited and Solar Energy Corporation of India Limited under GOI and inviting tender to add 50GW solar power annually, targeting 500 GW solar power creation by the end of 2030. India presently has 168.96 GW of total renewable energy capacity (as of 28th February 2023) with about 82 GW in various stages of implementation and about 41 GW in the tendering stage. This includes 42.02 GW of wind power, 64.38 GW of solar power, 51.79 GW of hydropower, and 10.77 GW of bio power [73].

Regulations and tariffs are also set by MNRE for state grids to encourage on-grid/off-grid rooftop solar plant setup [74]. Different reforms in project financing are brought by introducing new business models and redefining the role of grid power suppliers for effective implementation of solar projects. As an initiation, a comprehensive program covering project activities, research and development, demonstration, commercialisation dedicated to solar water pumping in the irrigation sector has been introduced on a pilot basis in India [75,76]. It is widely acknowledged that to become a feasible alternative, these technologies must optimise the available resources [77]. Apart from irrigation and solar pumps, emphasis has been on the development of novel technologies to integrate solar energy into agricultural sector and related fields [78], [79], [80]. There are efforts to reduce dependency of agriculture sector on conventional power grids renewable based hybrid energy systems are developed [81], [82].

With the sprawling share of PV generation across the world, research and development work for novel, efficient materials for solar cells and corresponding manufacturing process has gained immense attention worldwide. Silicon-based solar cells considered to be first generation materials, currently constitute 80% of market share in solar installations. With the advancement in manufacturing technologies leading to enhanced commercial viability, solar cells with thin layer made up of CdTe, CIGS (copper indium gallium selenide) are emerging as a feasible option. These are recognised as second-generation solar materials with lower efficiency levels compared to silicon-based materials.

High-end research is in progress for improvement in the third-generation organic solar cells having future prospects for low costs and higher efficiencies. High efficiencies are also targeted with multi-junction cells by reducing the costs of manufacturability [83] [84]. In addition to research and development towards novel solar materials and their manufacturability, it is equally important to decide the mode of power production. Wide varieties of solutions are available for PV module application, which caters to a range of requirements from a solar water heater to supplying peak loads to industrial establishments [85,86]. This classification also varies from the capacity of the plant's energy output to type of application targeted. Based on the operation philosophy, solar power plants are classified as on-grid PV (photovoltaic) system, off-grid PV system, central grid-connected systems, and hybrid systems [87], [88].

As PV powered generating systems are increasingly getting integrated into the Power Grid ways to assess and improve its reliability are also getting momentum[89], [90].

Solar utility application will also differ from the mode of PV panel mounting. In slant roof mountings, the angle is constrained by the existing roof and suitable only for limited power generation. In flat roofs, design philosophy along with variable tilt angle can be explored with some amount of flexibility. In ground mounting systems, designers have flexibility in terms of the orientation of panels, variable tilt angle, etc. so that power generation can be maximised. In order to ensure the maximum power generation, sizing the inverter with the best possible technical features is also an important consideration. Maximum power point tracking (MPPT) is the methodology for maximising power availability from the PV array for converting to AC output [91], [92].

New topologies for MPPT controllers are also proposed in research for increasing efficiency [93], [94]. High-performance power electronic control schemes are developed for improving solar plant performance by reducing inherent power losses and overshoots, thus improving system dynamics [95], [96]. In addition to basic research in the development of solar PV materials and inverters, it is therefore equally important to establish the standard and optimised engineering protocols to maximise the power generation from solar installations, which benefits large sector of the solar industry along with potential users.

The present work discusses the optimal designing and engineering issues related to supply, installation, testing, and commissioning of 500 kWp OGRTS system installed in the industrial city of Jamshedpur. Critical aspects of project feasibility analysis for defining the electricity utility scenario, shadow analysis, solar radiation analysis, electrical SLD for power distribution along with power evacuation strategies are discussed by correlating the data obtained from the plant site. In addition, an attempt is made in the form of engineering drawings, flow charts along with techno-economic analysis for a broader insight into the utility and solar sector. Performance parameters of the designed plant, simulated through PVSYST© V6.63 is compared with the actual generation data to get the idea of energy output, performance ration and capacity factors.

2.10. Hybrid Energy system

The term hybrid typically refers to a combination of two or more distinct elements. In the context of energy systems, Hybrid Energy Systems (HES) refer to the integration of multiple power generation technologies commonly including renewable sources like solar photovoltaic (PV) panels or Hydrogen Fuel cells, Methanol Fuel cells, wind turbines, paired with backup generators (e.g., diesel engines) or energy storage systems such as lithium-ion batteries. These systems are especially valuable in off-grid locations or micro-grids, where consistent and reliable electricity supply is essential.

When discussing Hybrid Renewable Energy Systems (HRES) specifically, the term denotes the combination of two or more renewable energy sources that are jointly connected to the same grid infrastructure. The main purpose is to inject electricity into the grid while utilizing shared transmission capacity. A key challenge in this setup arises when the combined output of the renewable sources occasionally exceeds the available grid connection capacity, potentially leading to curtailment or energy loss. These systems may include energy storage, but it is not a mandatory component. Another strategy to optimize grid usage is known as overpowering. This involves installing more generation capacity than the rated capacity of the grid connection. It is commonly practiced in solar PV plants, where the solar field's peak power exceeds the inverter or grid connection rating. The inverter typically acts as the limiting factor to regulate output. Similarly, wind farms undergoing repowering where older turbines are replaced with higher-capacity ones can reuse the existing grid connection, effectively overpowering the grid.

However, unlike hybrid systems, overpowered setups lack generation profile diversity, as the entire capacity often produces at the same time. This increases the likelihood of output surpassing the grid limit, leading to greater curtailment losses compared to hybridized systems where temporal distribution of power output can be optimized. The core advantage of hybridizing renewable energy systems lies in the shared use of grid infrastructure. By integrating multiple generation sources into a common transmission pathway, projects can reduce capital costs, enhance grid utilization efficiency, and improve the economic feasibility of new renewable developments.

The concept of the Smart Grid marks a transformative shift from the conventional 20th century electric power systems to an advanced, digitally integrated network. Unlike traditional grids that operate on centralized control and limited interactivity, the Smart Grid blends electricity infrastructure with real-time data processing, communication technologies, and computational intelligence, enabling dynamic monitoring and management across the entire power supply chain from generation and transmission to distribution and end-use consumption.

Fundamentally, the Smart Grid is designed to enhance system reliability, operational efficiency, and environmental sustainability, while minimizing costs. By leveraging digital technologies, it enables the integration and coordination of distributed renewable energy generators (DREGs) such as solar panels, wind turbines, and fuel cells. These generators are often deployed closer to consumption points, thereby reducing transmission losses and increasing system resilience. However, the introduction of such decentralized and intermittent sources also adds layers of complexity to grid operation and control.

To summarise, an effort has been made to address the issues related to electrode materials which are key components of Hydrogen generation and Fuel cells. An effort has been made for development of transition and earth rich abundant metal based electrode materials as an alternative to precious metals thus reducing the cost of generation. These cathode materials are used in anodic side OER reactions so that the hydrogen generation at cathode side is possible at reduced potentials.

In similar lines, engineering and installation aspects of 500kWp solar PV plant is addressed as a research direction towards use of renewable energy systems for meeting the energy needs. Hybrid energy systems, essentially a conglomeration of various renewable energy sources to feed the different kinds of loads is developing as a major research field to Electrical Engineers. Combination of Hydrogen generation to use as fuel for Hydrogen fuel cell, Generation aspects from Methanol fuel cell and installation and performance aspects of PV plant will pave as a path way in research direction towards hybrid electrical system.