Hybrid Hydrogen Energy Stored in Stand-Alone Power System

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Master of Philosophy (Electrical and Computer Engineering)
of
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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ..................................................

Date: ...............................................
ABSTRACT

A stand-alone power system is an autonomous system that supplies electricity to the user load without being connected to the electric grid. This kind of decentralized system is frequently located in remote and inaccessible areas. The purpose of this thesis is the modelling and simulation of a solar hydrogen hybrid power system to supply the typical residential electric customers in stand alone. It couples a photovoltaic (PV) generator, an alkaline water electrolyzer, a storage gas tank, a proton exchange membrane fuel cell (PEMFC), and power conditioning units (PCU) to give different system topologies. The overall mathematical model was obtained by integrating between their various subsystems models derived from literature. The system is intended to be an environmentally friendly solution since it tries maximizing the use of a renewable energy source. The results of the simulations showed that the hydrogen is one of the future energy storage mediums by using both TRNSYS software and HOMER software.

Key words: Electrolyzer, Hydrogen, PEM fuel cell, Photovoltaic, Stand-alone hybrid system.
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Lastly, I would like to thank all the postgraduate students and staff at Department of Electrical Engineering, Curtin University of Technology for sharing knowledge, facilities and providing a comfortable working environment. Without them, it was impossible for me to accomplish this goal.
# NOMENCLATURE

## Substances

<table>
<thead>
<tr>
<th>Substance</th>
<th>Description</th>
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<tbody>
<tr>
<td>a-Si</td>
<td>Amorphous Silicon</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium Telluride</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>GaAs</td>
<td>Gallium Arsenide</td>
</tr>
<tr>
<td>H₂</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>H₂O</td>
<td>Water</td>
</tr>
<tr>
<td>H₃PO₄</td>
<td>Concentrated Phosphoric acid</td>
</tr>
<tr>
<td>KOH</td>
<td>Potassium hydroxide</td>
</tr>
<tr>
<td>Li₂CO₃</td>
<td>Molten carbonate melts</td>
</tr>
<tr>
<td>MgH₂</td>
<td>Magnesium Hydride</td>
</tr>
<tr>
<td>O₂</td>
<td>Oxygen</td>
</tr>
<tr>
<td>Si</td>
<td>Silicon</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>Yttrium-stabilized zirkondi-oxide</td>
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## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AFC</td>
<td>Alkaline Fuel Cell</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>EL</td>
<td>Electrolyzer</td>
</tr>
<tr>
<td>FF</td>
<td>Fill Factor</td>
</tr>
<tr>
<td>FC</td>
<td>Fuel cell</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher Heating Value</td>
</tr>
<tr>
<td>I-V</td>
<td>Current-Voltage</td>
</tr>
<tr>
<td>LED</td>
<td>Light Emitting Diode</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower Heating Value</td>
</tr>
<tr>
<td>MCFC</td>
<td>Molten Carbonate Fuel Cell</td>
</tr>
<tr>
<td>MEA</td>
<td>Membrane Electrode Assembly</td>
</tr>
<tr>
<td>MH</td>
<td>Metal Hydride</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracker</td>
</tr>
<tr>
<td>MW</td>
<td>Megawatt</td>
</tr>
<tr>
<td>NOCT</td>
<td>Normal Operating Cell Temperature</td>
</tr>
<tr>
<td>PAFC</td>
<td>Phosphoric Acid Fuel Cell</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Conditioning Unit</td>
</tr>
<tr>
<td>PEM</td>
<td>Proton Exchange Membrane or Electrolyte Membrane</td>
</tr>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane Fuel Cell</td>
</tr>
<tr>
<td>PR</td>
<td>Performance Ratio of the system</td>
</tr>
<tr>
<td>P-V</td>
<td>Power-Voltage</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic generator</td>
</tr>
<tr>
<td>PV-FC-BAT</td>
<td>Photovoltaic – Fuel Cell - Battery</td>
</tr>
<tr>
<td>PV-Diesel-system</td>
<td>Photovoltaic – Diesel - Battery</td>
</tr>
<tr>
<td>SAPS</td>
<td>Stand-Along Power System</td>
</tr>
<tr>
<td>SOC</td>
<td>State OF Charge for hydrogen storage in the tank</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide Fuel Cell</td>
</tr>
<tr>
<td>STC</td>
<td>Standard Test Conditions</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>Wₚ</td>
<td>Peak watt</td>
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1. INTRODUCTION

1.1 Motivation for study

It is noted and well known these days that the world consumes massive amounts of energy, at a rate that is rising steadily as the world’s population grows, the standards of living improve and the use of energy expands to new arenas. The conventional fossil fuel energy sources such as petroleum, natural gas, and coal constitute 85% of the total energy consumption [Masters 2004, p. 20]. The diminishing of conventional fuel sources and the rising of atmospheric carbon dioxide CO₂ and global warming problems make it more attractive for considering renewable energy as an alternative way for energy sources, such as solar, wind, micro hydro and biomass.

Among the renewable energy sources, the solar photovoltaic (PV) energy has been widely utilized in low power applications. Photovoltaic generators which directly convert solar radiation into electricity have a lot of significant advantages such as being inexhaustible and pollution free, silent, with no rotating parts. At the same time, the advances in hydrogen can be used as a new energy option for supplying power in commercial and residential buildings and in remote off-grid communities.

Renewable systems based on hydrogen can act as an energy carrier. It will be especially useful in areas with access to abundant renewable energy resources and with problems producing sufficient electricity or with insufficient infrastructure [Ulleberg & Pryor, 2002]. The solar energy produced under good conditions can be used to produce hydrogen which can be stored and converted back into electricity when needed. The hydrogen can be used as the energy storage when excess PV power is produced. On one hand, it may serve the load at night time when PV is not

Nowadays, the solar hydrogen power system is a very attractive option to be a future competitor of hybrid PV/diesel/battery systems, especially from an environmental point of view (low noise and zero emission) and operational costs [Oman, 2002]. Furthermore, fuel cell power system is characterized by many attractive features such as efficiency, fast load-response, modular production and fuel flexibility. The practical efficiency of a current low temperature fuel cell is 30-35% but is being improved [Shahid & Elhadidy, 2004]. The combination of using solar-based energy generation and hydrogen as an energy carrier and storage offers a sustainable solution to many aspects of the energy issues, especially in rural electricity generation [Torres, Rodriguez & Sebastian, 1998] for reducing the transmission and distribution investment and the operation and maintenance of the battery storage.

The system under investigation in this study is a hybrid solar hydrogen stand-alone power system which is constituted of a photovoltaic generator, an alkaline water electrolyzer, a proton exchange membrane fuel cell (PEMFC), battery storage, and gas storage tanks [Santarelli & Macagno, 2003]. Hydrogen production in this system is produced by electrolyzing water molecules electrically through the electrolyzer which is used to produce electricity via the PEMFC. Therefore, the hydrogen in this system drastically reduces global pollution emissions of CO2.
1.2 Objectives

The purpose of this project was to design and model a realistic renewable hybrid solar hydrogen stand-alone power system based on technologies that satisfy and abide by the principles of efficient energy conversion and storage of sustainable energy resources. This model can reduce the usage of the fossil fuel and optimise the operation of hydrogen usage with renewable energy resources. Such a hybrid system is intended to be an environmentally friendly solution, and in a near future to decrease the current level of investment and running costs.

The development of appropriate simulation tools assisted in dealing with modelling, simulation, design and energy management of the hybrid solar hydrogen SAPS. The simulation software programs of TRNSYS and Homer were used to simulate the system performance. The system design and performance analysis was achieved through computer modelling and simulation prior to practical realization. The broader goals of the research were to:

1. Explore different strategies and plant design concepts for the optimal design and operation of a solar hydrogen power system.
2. Observe and analyse the system dynamic behaviour using power flow trace over long-term duration
3. Create an accurate system simulation model to predict the real performance of the solar hydrogen power system,
4. Build appropriate component and system model to simulate the solar hydrogen power system and evaluate their performance and efficiency.
5. Investigate cost-effective and technically attractive hydrogen energy storage technologies.
Determine the hydrogen system including the hydrogen production unit, hydrogen storage unit and heat and power generation units.

1.3 Organization of thesis

The thesis presents the modelling and simulation of a hybrid solar hydrogen stand-alone renewable energy system. The introduction is given in Chapter 1 about the concept of solar hydrogen technology in the stand-alone power system and the objectives of study. Chapter 2 covers the literature survey of different practical hybrid hydrogen power systems configurations, explains the background information about all the individual system components used in a hybrid hydrogen system and provides the simulation models that can be used to find optimal operation of a renewable hybrid hydrogen system. Chapter 3 deals with the mathematical models of the all the individual system components used for a solar hydrogen stand-alone power system. Chapter 4 uses the described models to simulate the energy performance of the system. Chapter 5 discusses the balancing cost, operation, modelling of the flexibility, and the future performance of the integrated hybrid hydrogen system. Chapter 6 summarizes and concludes the present study with a summary of findings and proposes recommendations for future work.
2. HYBRID STAND-ALONE POWER SYSTEM

2.1 Introduction

Stand-alone power system (SAPS) systems are small-scale, less than 50 kW, self-contained units, providing electricity independent of the main electricity grid or mini grid network [Marinescu et al., 2006]. A hybrid stand-alone power system can be generally defined as a self-electricity production and distribution system which consists of a combination of two or more types of electricity generating sources in off grid mode, such as solar photovoltaic (PV) panels, wind turbine generators, micro hydro plants and diesel generators. SAPSs range from small diesel generators able to power appliances directly to more complex installations using only renewable energy. A combination of both diesel and solar power also is possible in hybrid SAPS.

Rapid advances in solar photovoltaic technologies have brought good opportunities for the utilization of solar PV power. Moreover, the economic aspects of PV technologies are now sufficiently promising to justify their use in small-scale stand-alone applications for users which are not connected to national electricity grids. In the past decade, solar PV energy has attracted lots of attention and the experts in this field believe that this energy has a promising future. Successful PV hybrid stand-alone systems generally take advantage of a combination of techniques and technologies to generate reliable power, reduce costs, and minimize air emission. Most of the stand-alone hybrid systems models consist of a diesel engine generator to form the hybrid system with photovoltaic cells, battery bank or a wind generation system have been studied and investigated for past 10 years [Hancock et al., 1994, Bopp et al., 1997 & Wichert, et al., 2001].
2.2 Solar hydrogen economy

The emergence of a true hydrogen economy, based upon hydrogen for energy storage, distribution, and utilisation has proven to be a major advantage for the wide spread application of fuel cells. Although there is already an existing manufacturing, distribution, and storage infrastructure of hydrogen, it is still considered limited. The infrastructure costs associated with a large-scale hydrogen distribution is often cited as the major disadvantage for the wide spread use of hydrogen as “a major world fuel and energy vector” [Williams, 2001]. However, with good integration practices for both distributed fuel cell power supplies and stationary power applications, the natural gas can initially be used for hydrogen production during the off peak load in order to remove the initial requirement for the large infrastructure costs associated with a hydrogen distribution system [Wang & Nehrir, 2006].

Solar hydrogen economy is the fuel economy that comes directly or indirectly from the sun, the wind or biomass energies. All of these energy sources are derived from the sun. Either electricity or hydrogen fuel can be used for nearly any energy application. Hydrogen can be made from solar-generated electricity by electrolysis, a process of running electricity through water that separates the H₂O molecules into hydrogen and oxygen gases [Agbossuo, et al. 2000]. Solar hydrogen is a promising long-term global energy option for the post-fossil fuel era. On the first hand, solar hydrogen may have already found an early commercial application in the form of seasonal energy storage for remote stand-alone photovoltaic (PV) applications. In a stand-alone solar hydrogen energy system, the photovoltaic array is coupled with an electrolyzer to produce the hydrogen. At first, the hydrogen will be stored in the hydrogen tank. The fuel cell uses hydrogen as fuel and oxygen (usually from air) as oxidant to produce electricity if necessary.
2.3 Photovoltaic-Diesel-Battery Hybrid Systems

The simplest type of stand-alone PV system is a direct-coupled system where the DC output of the module or array is connected directly to a DC load. The direct-coupled system has no electrical energy storage (batteries) so the load operates only during sunlight hours. However, most systems rely on batteries to store electricity for use at night or during cloudy periods. A photovoltaic system by itself may be uneconomical for stand-alone applications with large energy demands. However, a PV-diesel hybrid system now provides an economically sound solution power supply as the diesel generator is used as the backup source. For the times when the solar system can’t produce the power during the intermittent weather condition, most PV-diesel hybrid systems provide power through a back up diesel generator, incorporating a battery and inverter, can often provide power at a lower cost than a stand alone diesel generator due to the duration of the runtime of the diesel generator. This is because the battery and the inverter can supply the low load periods to prevent the diesel generator operates in low efficiency mode. If the batteries run low, the generator can provide power to recharge the batteries. The addition of photovoltaic can potentially provide fuel savings as well as other benefits such as maintaining a charge into the batteries in times of very low energy consumption [Wichert 2000, p.12].

In addition, diesel generator combined with a battery charger can supply power to the user load when the PV generator fails. If the PV generator is sized for average user load, then during periods of higher user loads, the diesel generator supplies the difference. The diesel set is activated when any of the loads on the subsidiary unit are used or if the battery is discharged below a pre-set level [Shaahid & Elhadidy, 2005]. Hence PV- diesel-battery hybrid systems can play an important role in decentralized based power generation especially in remote locations.


2.4 Photovoltaic-Fuel Cell-Electrolyzer Hybrid System

The new options concerning the impact of integrated renewable energy systems has been proposed by replacing existing diesel and battery with a fuel cell/electrolyzer system. A stand-alone power system coupling a PV, an electrolyzer, and a fuel cell should become an environmentally friendly solution to produce the required energy in remote sites. In this system, excess energy is fed to the electrolyzer producing hydrogen and oxygen at a pressure of maximum 10 bars. Gases are stored without compression for a short or long term period. In case of a renewable energy deficit, the fuel cell is switched on to produce power if the load power exceeds the level of power produced by PV generator.

By using a fuel cell to get back to electricity induces a low efficiency but it allows building a silent energy generator consuming no materials. If the system is sized to cogenerate electricity and heat, these systems (load consumption / renewable production) could reach a high efficiency compared with the PV-batteries systems [Lehman, et al. 1997]. As the by-product of the fuel cell, waste heat can be used in cogeneration power sector to increase the overall system’s efficiency and to reduce the greenhouse gases emissions. Hence, their near-zero emissions and low noise characteristics will allow this hybrid system to be used in populated areas reducing the community’s dependence on overhead electrical T and L systems and leading to improvements in the quality of life. The main drawback of this system is the high capital costs and the lack of system maturity. But it will be one of the best renewable system options to generate energy for SAPS if the prices of the components decrease in future. To conclude the analysis of hybrid stand-alone power system, a comparison of two types of power supplies options is presented in Table 2.1.
Table 2.1: Comparison of hybrid supply options for rural and remote area electrification

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
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</table>
| **Photovoltaic – Diesel - Battery System** | • Reduce the number of diesel generators operating hours.  
• Provide available and easy maintenance, consumables and spare parts.  
• Reach the maturity degree especially in battery and diesel system components.  
• Improve the efficiency of generator operation leads to reduced fuel consumption. | • Batteries must be well loaded to release electricity with a good yield.  
• Produce harmful emission gas from diesel generator.  
• Have short lifetime for the battery bank, thus high replacement cost  
• Provide moderate flexibility to respond to changes in load demand and operating conditions. |
| **Photovoltaic- Fuel Cell - Electrolyzer System** | • Produce the high-energy conversion.  
• Is an environmentally friendly solution - near-zero emissions.  
• Complete the autonomy of hybrid system.  
• Reduce the fuel consumption through the addition percentage of the renewable energy use.  
• Reduce the maintenance requirements.  
• Is economic option where fuel is expensive while renewable fuel is available (for long term investment). | • Has limited experience of customers with the renewable energy systems.  
• Increase the system complexity.  
• Have hydrogen storage/production technical problem.  
• Spend the high capital cost for overall system.  
• Need the additional investment for power electronics converter.  
• Face the immaturity of fuel cell and electrolyzer technologies problem. |
2.5 Hybrid solar hydrogen system components

The utilization of intermittent natural energy resources such as solar and wind energy requires some form of energy storage. A block diagram schematic of solar hydrogen system is shown in Figure 2.1. In the stand-alone renewable energy system, hydrogen is used as the energy storage medium and a proton exchange membrane (PEM) fuel cell as the regeneration technology. When PV electricity is available (during the daylight), the compressor is directly powered by PV voltage. Any excess power produced by the array is supplied to the electrolyzer which produces hydrogen and thus effectively stores solar energy. The rechargeable batteries are included for the safe operation of the fuel cell component and also to supply power during transient load conditions. In addition, a control unit is required to monitor and guide the operation of the components of the system. This chapter presents all types of PV panels, fuel cells, electrolyzers, rechargeable batteries and hydrogen storage methods.

2.6 Solar photovoltaic (PV) generator

2.6.1 Operation of the PV

Around 1839, the French scientist Alexandre Edmond Becquerel discovered that some materials produce a current (electricity) when light shines on them. In 1873, Willoughby Smith first observed the phenomenon in a solid in the element selenium [Smith, 1995]. It was not until the 1950s that the real breakthrough occurred when silicon was found to display light sensitive properties when treated with certain impurities. 'Photovoltaic' literally means electricity from light. A PV cell consists of layers of semiconductor materials in contact with each other and fitted with
metallic contacts to transfer the released electrons to the external load. Most commercial PV cells now available are manufactured from crystalline silicon to provide the required semiconductor qualities.

PV cells work by transforming the photon energy in solar radiation directly into electrical energy without an intermediate mechanical or thermal process. PV cells operate on the principle that electricity will flow between two different semiconductors when they are put in contact with each other and exposed to light. A diode is formed when two layers of semiconductor materials are doped so that one will conduct negative carriers and the other positive carriers.
PV cells produce electricity as long as light shines on them. They require little maintenance, do not pollute, and they operate silently making photovoltaic energy the cleanest and safest method of power generation. It is interesting to note that PV cells actually work best when they are cool. Because of their electrical properties, PV modules produce direct current (DC) rather than alternating current (AC). In the simplest PV systems, DC current is used immediately in applications but where AC is required an inverter is added to the system to convert DC into AC.

### 2.6.2 Types of PV cells

Most PV cells are made from purified silicon, which is doped with other elements to achieve the desired photoelectric properties. Table 2.2 presents the level of efficiency of silicon photovoltaic cells. There are three general types of silicon photovoltaic cells. These are:

**A) Monocrystalline silicon**

Monocrystalline cells are made of polished, wafer thin slices of single crystals of silicon. Originally, all PV cells were made in this way. These tend to be expensive, as the crystals take time to grow, but they have a relatively high efficiency (17%) and a very long lifetime because the crystal structure is very stable. But the manufacturing process required to produce monocrystalline silicon is complicated resulting in slightly higher costs than other technologies.

**B) Polycrystalline silicon**

Polycrystalline ("many crystals") solar cells are made by a casting process in which molten silicon is poured into a mould and allowed to cool, then sliced into wafers.
Table 2.2: Level of efficiency of three general types of silicon photovoltaic cells

<table>
<thead>
<tr>
<th>Material</th>
<th>Level of efficiency in % Lab</th>
<th>Level of efficiency in % Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monocrystalline Silicon</td>
<td>approx. 24</td>
<td>14 - 17</td>
</tr>
<tr>
<td>Polycrystalline Silicon</td>
<td>approx. 18</td>
<td>13 - 15</td>
</tr>
<tr>
<td>Amorphous Silicon</td>
<td>approx. 13</td>
<td>5 - 7</td>
</tr>
</tbody>
</table>

This process results in cells that are significantly cheaper to produce than single crystal cells [Darling, 2000]. However, they tend to be slightly less efficient (~15%). They also have as long a life span as monocrystalline cells with similar performance guarantees.

(C) Amorphous silicon or thin film

Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal. The units absorb the light more effectively than crystalline silicon, so the cells can be thinner. For this reason, amorphous silicon also is known as a "thin film" PV technology. Their overall conversion of light to electricity is low (~7%), but they are easier and therefore cheaper to produce. Their low cost make them ideally suited for many applications where high efficiency is not required but low cost is important. They also have a much shorter life span than others and are usually guaranteed for 6 years from manufacturers.

2.6.3 Solar cell models characteristic

The typical power ratings of solar modules are between 10 to 100 Wmax. The characteristic data refer to the standard test conditions (STC) of 1000 W/m² solar
radiation at a cell temperature of 25° Celsius. The usable voltage from solar cells depends on the semiconductor material used. In silicon it amounts to approximately 0.5 V. The terminal voltage is only weakly dependent on light radiation while the current intensity increases with higher luminosity. A 100cm² silicon cell, for example, reaches a maximum current intensity of approximately 2A when radiated by 1000 W/m². A manufacturer's standard warranty of twenty or more years is quite long and shows the high quality standards and life expectancy of today's products.

The simplest solar cell model consists of a diode and current source connected in parallel. The current source is directly proportional to the solar radiation. The diode represents pn junction of a solar cell. The equation of an ideal solar cell model is given by the current as follows:

\[ I = I_{ph} - I_S \left( \frac{V_T}{e^{V_T/kT}} - 1 \right) \]  

2.1

where \( I_{ph} \) is the photocurrent (A), \( I_S \) is the reverse saturation current (A) (approximately range \( 10^{-8} \)/m²), \( V \) is the diode voltage (V), \( V_T \) is the thermal voltage (\( V_T = 25.7 \) mV at \( 25^\circ \)C) and \( m \) is the diode idealistic factor = 1, 2, ... \( 5 \times V_T \) (\( m = 1 \) for ideal diode).

The thermal voltage (\( V_T \))/ can be calculated by the following equation:

\[ V_T = \frac{k \cdot T}{q} \]  

2.2

where \( k \) is the Boltzmann constant = \( 1.38 \times 10^{-23} \) J/K, \( T \) is the temperature (K) and \( q \) is the charge of electron = \( 1.6 \times 10^{-19} \) As.
The working point of the PV depends on load and solar insolation. The operating point of the generator is defined by the intersection of its I-V characteristics with the load line of the load connected to it. Figures 2.2 to 2.5 present the typical current-voltage I-V and power-voltage P-V curves of a typical photovoltaic module under influence of solar radiation and cell temperature. The I-V curve is based on the module being under standard conditions of sunlight and module temperature. It assumes there is no shading on the module. Standard sunlight conditions on a clear day are assumed to be 1000 watts of solar energy per square meter (1000 W/m²). This is sometimes called "one sun".

From figure 2.2, the point where the curve intersects the vertical axis is known as the short circuit condition. It defines how the current when a wire is connected between its terminal, shorting it out. This current flow here is known as \( I_{SC} \). Because there is no voltage, the cell delivers no power and \( I_{SC} \) is directly proportional to the available sunlight. The point at which a curve intersects the horizontal axis is known as the open circuit condition. This is where the cell operates if it is unconnected and the voltage produced is denoted \( V_{OC} \). Because the current is zero, no power is delivered. \( V_{OC} \) increases logarithmically with the increased sunlight.

For each point on the I-V curve, the product of the current and voltage represents the power output for that operating condition. A solar cell can also be characterized by its maximum power point (mpp), when the product of \( V_{mpp} \) and \( I_{mpp} \) is at its maximum value. The maximum power output of a cell is graphically given by the largest rectangle (shaded area) that can be filled under the I-V curve. This specific operating point is called \( P_{mpp} \).
From the characteristic curves of the module shown in figure 2.2, it is clear that the increment of the irradiance level causes the current increases proportionally. This is due to fact that when the irradiance level increases, the number of electron-hole pairs separated increases and thus the induced current increases. On the other hand, higher irradiance gives higher output power due to the current shown in figure 2.3. The output current of the PV panel’s is proportional to the power ($I_0 \propto P$). A change in the irradiance will affect the current and thus the power output of the PV module. However, it has a less significant effect on the voltage. Actually, the PV module acts like a constant current source for most parts of its I-V curve [Martins, Weber & Demonti, 2002].

The main effect of increasing temperature is in a reduction of the open circuit voltage and hence the power output shown in figure 2.4 and 2.5. An increase in cell temperature causes the voltage to move leftward while decreasing temperature produces the opposite effect. The power output decreases when the temperature increases. Thus, the I-V curves display how a PV module responds to all possible loads under different solar radiation and cell temperature conditions.

As a measure for solar cell quality, the fill-factor (FF) is defined as the ratio of output power at maximum power point to the power computed by multiplying $V_{OC}$ by $I_{SC}$. It determines the shape of the PV characteristics. The factors which affect the fill factor are the series and shunt resistances of the PV. A good FF is between 0.6-0.8 [Markvert 2000, p.45]. As the photovoltaic generator degrades with age, its series resistance tends to increase resulting in a lower FF. FF can be calculated with the following equation
Figure 2.2: I-V characteristics under influence of solar radiation ($G$) (constant cell temperature $T_{cell} = 25^\circ C$)

Figure 2.3: P-V characteristics under influence of solar radiation ($G$) (constant cell temperature $T_{cell} = 25^\circ C$)
Figure 2.4: I-V characteristics under influence of cell temperature ($T_{cell}$) (constant solar radiation $W = 1\text{kW/m}^2$)

Figure 2.5: P-V characteristics under influence of cell temperature ($T_{cell}$) (constant solar radiation $W = 1\text{kW/m}^2$)
\[ FF = \frac{I_{mpp} \cdot V_{mpp}}{I_{sc} \cdot V_{oc}} \]

where \( I_{mpp} \) is the MPP current (A), \( V_{mpp} \) is the MPP voltage (V), \( I_{sc} \) is the short circuit current (A) and \( V_{oc} \) is the open circuit voltage (V).

In the case of ideal solar cell, FF is a function of open circuit parameters and can be modified from equation 2.4:

\[ FF \approx \frac{V_{oc} - ln(V_{oc} + 0.72)}{V_{oc} + 1} \]

where \( V_{oc} = V_{oc} \cdot \frac{q}{m \cdot k \cdot T} \)

The conversion efficiency of PV is the ratio of the optimal electric power, \( P_{opt} \), delivered by the PV module to the solar insolation, \( E_e \), received at a given cell temperature, \( T \),

\[ \eta = \frac{P_{opt}}{A \cdot E_e} \]

where \( P_{opt} \) is the optimal power (W), \( E_e \) is the insolation (W/m²) and \( A \) is the cell area (m²). Typical values for \( \eta \) are 15% for a monocrystalline silicon cell and 13% for a polycrystalline silicon solar cell.

2.7 Hydrogen

In 1766, the British scientist Henry Cavendish at Royal Society of London first identified the hydrogen. He described the composition of water as a combination of hydrogen and oxygen [History of H₂, 2000]. Hydrogen is the simplest, lightest
element in the universe. It is made up of one proton and one electron. Because of its simplicity, it is believed that hydrogen is the root of all elements. It has no colour, no smell and no taste. Hydrogen is the most abundant element in the universe making up more than 90% of all matter. Most commercial hydrogen is refined from petroleum (natural gas) but can also be produced from water via water electrolysis because of the abundance of water on the earth.

2.8 Fuel cell

In 1839, the first fuel cell was developed in England Sir William Grove developed. His experiments during this time on electrolysis - the use of electricity to split water into hydrogen and oxygen - led to the first mention of a device that would later be termed the "fuel cell." A fuel cell is similar to a battery in that an electro-chemical reaction is used to create electric current [Fuel Cell Energy, 2005]. The charge carriers can be released through an external circuit via wire connections to the anode and cathode plates of the battery or the fuel cell. The major difference between fuel cells and batteries is that batteries carry a limited supply of fuel internally as an electrolytic solution and solid materials (such as the lead acid battery that contains sulphuric acid and lead plates). Fuel cells have similar reaction. However, the reactants are gases (hydrogen and oxygen) which are combined in a catalytic process. Since the gas reactants can be fed into the fuel cell and constantly replenished, the unit will never run down like a battery.
A fuel cell is an electrochemical energy converter. Chemical energy is converted directly into electrical energy by two separated electrochemical reactions. By avoiding the intermediate step of converting fuel energy first into heat, which is then used to create mechanical motion and finally electrical power, fuel cell efficiency is not constrained by the Carnot limit of heat engines. Figure 2.6 shows the difference in conversion between conventional combustion engine and fuel cell.

The fuel cell stack is integrated into a fuel cell system with other components, including a fuel reformer, power electronics, and controls. More details about fuel cell systems and components will be discussed in the following section. The advantage of the fuel cell reaction is its higher overall conversion efficiencies and it produces very little pollution. Much of the hydrogen and oxygen used in generating
electricity ultimately combine to form a harmless bi product, namely water. Figure 2.7 shows the electrochemical reactions of the fuel cell types.

2.8.1 Background on fuel cell types

Fuel cells are a family of technologies that share the principle of electrochemical oxidation of the fuel and spatial separation of oxidation of fuel and reduction of oxidant. Fuel cell types are usually characterized by their electrolyte, temperature of operation, transported ion, and fuel. The situation now is that six classes of fuel cell have emerged as viable systems for the present and near future. A summary of fuel cell types with respective electrolyte materials, transported ions, and operating temperatures are presented in Table 2.3.

(A) Alkaline fuel cells (AFCs)

Alkaline fuel cells were one of the first fuel cell technologies developed. They were the first type widely used in the U.S. space program to produce electrical power and water onboard spacecraft. A solution of potassium hydroxide in water is used in their electrolytes. The catalyst at the anode and cathode can be made using a variety of non-precious metals. AFC designs operate at lower temperatures of below 100°C. They are very efficient, reaching efficiencies of 50% in space applications. However, they are very susceptible to carbon contamination, so require pure hydrogen and oxygen to minimize this chemical process as they are easily poisoned by carbon dioxide (CO₂). Susceptibility to poisoning also affects the lifetime of the cells, further adding to their cost of production.
Table 2.3: Characteristics of major six fuel cell types

<table>
<thead>
<tr>
<th></th>
<th>PEMFC</th>
<th>PAFC</th>
<th>SOFC</th>
<th>MFDC</th>
<th>DMFC</th>
<th>AFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>proton exchange membrane</td>
<td>Liquid phosphoric acid</td>
<td>Solid metal oxide</td>
<td>Molten carbonate salt</td>
<td>proton exchange membrane</td>
<td>Potassium hydroxide</td>
</tr>
<tr>
<td>Reforming</td>
<td>External</td>
<td>External</td>
<td>External / Internal</td>
<td>External / Internal</td>
<td>External</td>
<td>External</td>
</tr>
<tr>
<td>Oxidant</td>
<td>O₂ / Air</td>
<td>O₂ / Air</td>
<td>O₂ / Air</td>
<td>CO₂ O₂ / Air</td>
<td>O₂ / Air</td>
<td>O₂ / Air</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>60-80°C</td>
<td>160-200°C</td>
<td>800 - 1000°C</td>
<td>500-650°C</td>
<td>60-130°C</td>
<td>50-80°C</td>
</tr>
<tr>
<td>Efficiency (without cogeneration)</td>
<td>40-55%</td>
<td>40-50%</td>
<td>55-65%</td>
<td>50-60%</td>
<td>20-30%</td>
<td>35-50%</td>
</tr>
<tr>
<td>Max Power output (size)</td>
<td>250kW</td>
<td>1MW</td>
<td>220kW</td>
<td>2MW</td>
<td>250kW</td>
<td>100kW</td>
</tr>
<tr>
<td>Charge carrier</td>
<td>H⁺</td>
<td>H⁺</td>
<td>O²⁻</td>
<td>CO₃²⁻</td>
<td>H⁺</td>
<td>OH⁻</td>
</tr>
<tr>
<td>Fuel</td>
<td>H₂ (reformed)</td>
<td>H₂ (reformed)</td>
<td>H₂, CO, CH₄</td>
<td>H₂, CO, CH₄</td>
<td>CH₃OH</td>
<td>H₂</td>
</tr>
</tbody>
</table>

Figure 2.7: Electrochemical reactions of the Fuel Cell types (Source: Fuel Cells Outlook, 2004)
(B) Polymer Electrolyte Membrane fuel cells (PEMFCs)

Polymer electrolyte membrane fuel cells, also called proton exchange membrane fuel cells, have a solid polymer membrane as an electrolyte. Due to membrane limitations, PEMFCs usually operate at low temperatures (60-80°C) and efficiency is about 40 - 55%. They need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some other fuel cells. This type of fuel cell is sensitive to fuel impurities and typically fuelled with pure hydrogen supplied from storage tanks. The power range of existing PEMFCs is about 50W to 250kW. Due to their fast start-up time, low sensitivity to orientation, and favourable power-to-weight ratio, PEMFCs are particularly suitable for transportation applications (hydrogen buses and scooters) and some small stationary applications in hospitals, nursing homes, hotels and office buildings.

(C) Phosphoric Acid fuel cells (PAFCs)

Phosphoric acid fuel cells use liquid phosphoric acid as an electrolyte with a platinum catalyst. They operate in temperatures around (160-200°C) making them more tolerant to reforming impurities. PAFCs are considered to be the "first generation" of modern fuel cells. It is one of the most mature cell types and the first to be used commercially with over 200 units currently in use around the world. The power range of existing PAFCs is 25-250 kW. PAFCs use hydrocarbon sources such as natural gas, propane, or waste methane. PAFCs are typically used for medium to large-scale stationary power generation, attaining around 45% electrical efficiency and an overall 85% total efficiency with co-generation of electricity and heat. Like PEMFCs, PAFCs require an expensive platinum catalyst which raises the cost of the fuel cell.
(D) Solid Oxide fuel cell (SOFCs)

Solid oxide fuel cells use a hard, non-porous ceramic compound as the electrolyte and electrical efficiencies are around 55-65%. At such high temperatures a reformer is not required to extract hydrogen from the fuel and can reduce cost by recycling the waste heat from internal steam reformation of hydrocarbon fuels. SOFCs are tolerant to CO poisoning, allowing CO derived from coal gas to also be employed as source of fuel. Nevertheless, the ceramic materials that these cells are made from are difficult to handle, so they are expensive to manufacture. The output of the cells is up to 100 kW. SOFCs are well-suited for medium-to-large scale, on-site power generation or CHP. Demonstrated total efficiencies of 80-85% are expected when operating with cogeneration of waste heat.

(E) Molten Carbonate fuel cells (MCFCs)

Molten carbonate fuel cells operate at 600-800°C and use a molten alkali carbonate mixture for an electrolyte. MCFCs typically range between 75-250 kW, but when using combined units, have produced up to 5 MW of power. Electrical efficiencies are around 50-60%, with total efficiencies of 80-85% with cogeneration of waste heat. They require carbon dioxide and oxygen to be delivered to the cathode. The high temperature limits damage from the carbon monoxide "poisoning" of the cell and waste heat can be recycled to make additional electricity. Their nickel electrode-catalysts are inexpensive compared to the platinum used in other cells [Amplett et al. 1995]. But the high temperature also limits the materials and safe use of MCFCs - they would probably be too hot for home use. Also, carbonate ions from the electrolyte are used up in the reactions making it necessary to inject carbon dioxide to compensate.
(F) Direct Methanol fuel cells (DMFCs)

Direct methanol fuel cells are powered by pure methanol, which is mixed with steam and fed directly to the fuel cell anode. Direct methanol fuel cells differ from other fuel cells because they use unreformed liquid methanol fuel rather than hydrogen. DMFCs operate at slightly higher temperatures than PEMFCs (60-130°C) and achieve around 40% efficiency. Since they are refuelable and do not run down, DMFCs are directed toward small mobile power applications such as laptops and cell phones, using replaceable methanol cartridges at power ranges of 1-50 W. Direct methanol fuel cell technology is relatively new compared to that of fuel cells powered by pure hydrogen. Research and development on the cells are approximately 3-4 years behind that of other fuel cell types.

2.8.2 Fuel cell components

The construction of a fuel cell itself is very simple as it consists of only a few parts. The most important components are the electrolyte and the electrodes. In addition, flow-field plates are needed to distribute the reactants homogeneously over the cell area.

(A) Electrolyte

The electrolyte has three main functions in a fuel cell; to conduct ions, act as an electric insulator, and physically separate the anode and cathode reactants. Ions have to pass through the membrane to maintain charge equilibrium between the anode and cathode. The charged species and its direction of flow vary with the type of fuel cell. Any flow of current or reactants through the electrolyte will decrease the performance of the cell so these properties have a very large influence on the fuel cell operation.
(B) Electrodes
The electrochemical reactions take place on the electrode surface. Fuel is oxidised at the anode and oxygen is reduced at the cathode. A combination of membrane and electrodes is called a membrane electrode assembly (MEA). For low-temperature fuel cells, noble metals are needed to increase the reaction rate [Manassen & Cabasso, 1990]. Platinum is the most widely used catalyst sometimes in combination with other metals. At higher temperatures (MCFC and SOFC), this is not necessary and cheaper metals/materials can be used like non-porous ceramic compound for SOFC.

(C) Gas Diffusion Layers (GDLs)
GDLs are only used in low-temperature fuel cells. They are used for the distribution of the reactants to and removal of the products from the electrode surface [Kreutz & Ogden, 2000]. An important issue is water removal from the cathode in a PEMFC. The GDLs are optimised by changing their hydrophobic properties. Since they are placed between the electrodes and the flow-fields (current collectors), they also have to be electrically conductive.

(D) Flow-fields/bipolar plates
The flow-field plates ensure the distribution of fuel and oxidant (air) over the whole cell area. Different channel structures, such as serpentine channel are machined into the plates so that the hydrogen and air can flow through it. The choice of materials varies according to the type of fuel cell. Examples range from graphite, stainless steel, and plastic for low-temperature fuel cells to ceramics for higher temperatures. The flow-fields also act as current collectors.
2.8.3 Fuel cell theory

The heart of the fuel cell is the electrolyte. It is surrounded by two layers: a diffusion and a reaction layer. Under constant supply of hydrogen and oxygen, the hydrogen diffuses through the anode and the diffusion layer up to the platinum catalyst, the reaction layer. The reason for the diffusion current is the tendency of hydrogen oxygen reaction. Two main electrochemical reactions occur in the hydrogen oxygen fuel cell - one at the anode (anodic reaction) and one at the cathode. At the anode, the reaction releases hydrogen ions and electrons because transport is crucial to energy production. This reaction is represented by the equation:

\[ \text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^- \]  \hspace{1cm} 2.6

The hydrogen ion on its way to the cathode passes through the polymer membrane while the only possible way for the electrons is though an outer circuit. The hydrogen ion, together with the electrons of the outer electric circuit and the oxygen which has diffused through the porous cathode reacts to water. This reaction is represented by the equation:

\[ 2\text{H}^+ + \frac{1}{2} \text{O}_2 + 2\text{e}^- \rightarrow \text{H}_2\text{O} \]  \hspace{1cm} 2.7

The water resulting from this reaction is extracted from the system by the excess air flow. The reaction is:

\[ \text{H} + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} \]  \hspace{1cm} 2.8

The chemical energy released in a reaction can be thought of as consisting an entropy-free part, called free energy \( \Delta G \) that can be converted directly into electrical or mechanical work. The “G” in free energy is in honour of Josiah Willard Gibbs (1839 – 1903), who first described its usefulness. The quality is usually referred to as
Gibbs free energy [Mann, et al. 2000]. For the standard potential $E^0$ for the cell reaction, the open circuit voltage of an electrochemical cell can be related to the theoretical free energy change of the overall electrochemical reaction of the cell. The reaction is:

$$E^0 = -\frac{\Delta G^0}{nF}$$

Where $\Delta G$ is the Gibbs’ free energy change of the fuel cell reaction, $F$ is the Faraday constant (96485.3 C mol$^{-1}$), and $n$ is the number of electrons transferred in one reaction.

Fuel cells have attracted interest due to their low degree of pollution and high (theoretical) efficiency. Since the chemical energy of the fuel is directly converted to electricity, fuel cells are not influenced by the Carnot efficiency limit like combustion and heat engines. When chemical energy is converted to electricity via heat (by fuel combustion), the maximum theoretical efficiency is limited by the operating temperatures as shown by the following equation:

$$\eta = \frac{T_{\text{max}} - T_{\text{min}}}{T_{\text{max}}}$$

For fuel cells the theoretical efficiency can be expressed, among many alternatives, as the relationship between chemical energy available (free energy change of the fuel cell reaction, $\Delta G$) and the higher heating value of the fuel cell reaction (enthalpy change of the fuel cell reaction, $\Delta H$). The reaction is given as:

$$\eta_{\text{max}} = \frac{\Delta G}{\Delta H}$$
2.9 Electrolyzer

An electrolyzer converts electricity into chemical energy which produces hydrogen. Hydrogen can be stored for example into pressure tanks or metal hydrides. Hydrogen can be produced from water electrolysis in several ways such as alkaline, acidic, and solar photo production. From an energy systems perspective, electrolyzers are starting to be regarded as a prospective enabling technology for the hydrogen economy. The important key issue is the ability of the electrolyzer to use electrical energy, which cannot be readily or affordably stored in bulk to generate hydrogen and oxygen, both of which can be stored with much greater ease.

(A) Alkaline electrolyzers (AE)

Alkaline electrolyzers (AE) are the earliest known commercial electrolyzers. They have since been manufactured at small, medium and large scale. In terms of gas volume, AE provide the principal route for producing electrolytic hydrogen and oxygen. Typical efficiencies are quoted as 4-6 kWh/Nm$^3$ H$_2$ for steady-state operation. AE tend to be very robust and have operational lifetimes measured in decades rather than years. An alkali solution (usually potassium hydroxide of around 25 - 30% concentration at ~ 80°C) is used in AE as the electrolyte for providing the ion-transfer process.

Typical current densities are 0.2-0.4 A/cm$^2$ in AE which are designed for either atmospheric or operation at up to 30 bar. Without purification, gas qualities of around 99.8% for hydrogen and 99.2% for oxygen are typically achievable. One key factor favouring the alkali-based electrochemistry is that it obviates the need for precious-metal catalysts. Although Platinum/Ruthenium catalysts are essential for
efficient acid-based PEM electrolyzers, the alkali-based variant can operate with cheaper catalysts such as Nickel. This could prove to be an important economic consideration if the future electrolyzer industry operates on greater scales than today especially given the tendency of material cost to dominate all other factors in high volume manufacture.

(B) Proton-Exchange Membrane Electrolyzers (PEME)

Proton-Exchange Membrane Electrolyzers emerged from the development of thin polymeric films that form ion-conducting media. In contrast to systems based on liquid alkali electrolytes, their key distinction is that the electrolyte is a solid material (an ionomer) which conventionally operates acidic electrochemistry conveying H⁺ ions (protons). The film also behaves as a virtually gas-impermeable membrane maintaining gas separation at the respective electrodes.

Normal operating pressures are around 15 bars with efficiencies of 5-6 kWh/Nm³ at current densities of greater than 1 A/cm². The purity of the hydrogen evolved from a PEM electrolyzer stack is typically 99.999%, with some systems being designed to provide 99.9999% [Zhong & Hou, 2006]. The need for gas purification steps beyond the electrolyzer output is less with PEME than AE due to the absence of the mixing effects of recirculating lye. PEME technology tends to be operated at relatively high current densities when compared with AE. This permits PEME units of smaller footprint per unit of gas produced. In high current density applications, the electrolyzer efficiency is low, operational electricity costs are high and the need to remove heat is increased.
(C) Solid-Oxide Electrolyzers (SOE)

The Solid Oxide Electrolyzer is the subject of limited research and development; it is not yet available commercially [Newborough, 2004]. As with PEME, it employs a solid electrolyte but its operation is based on ceramic ion conductors which either transfer oxygen ions (O²⁻) at 750-1000°C or hydrogen ions (H⁺) at 450-750°C. Energetically, the thermodynamic advantage of a high temperature steam electrolysis process is exploited in the SOE. Less electricity is required at elevated temperatures to convert water to hydrogen and oxygen.

This use of thermal energy means that requiring a source of high-temperature process heat to drive in steady-state operation. Although having the advantages of a solid electrolyte and lower electricity consumption, the SOE (like the AE) is effectively a process plant and it lacks the applications flexibility of the PEME. In contrast to AE and PEME, the long-term stability of SOE is as yet unproven and thermal cycling to high temperature remains a major materials challenge to operate and control in the hydrogen power system.

2.10 Hydrogen storage

Hydrogen is the lightest and most abundant element in the universe. It forms the basis of all organic compounds and living things and is present in the essence of life - water. Hydrogen is not a primary energy source but it is utilized as an energy carrier between power generation and the power utilization. Power is generated from hydrogen by conversion in a fuel cell. Hydrogen is characterized by a low density under normal conditions so that its storage is difficult compared with liquid fuels. It can be stored in many basic configurations such as gaseous, liquid, as a solid
combined with a metal hybrid, ammonia form, or in carbon nanotubes [Banerjee, Murad & Puri, 2006]. The various storage types have different characteristics. The most suitable storage method is dependant upon safety aspects, environmental issues, economic criteria, and the end-use of hydrogen.

(A) Compressed Hydrogen Gas

The most commonly used and simplest method of the hydrogen is to store it in its natural form as a gas. Storage of gaseous hydrogen is primarily limited by volume considerations as a result of hydrogen's low density. At high-pressure, very large volumes are required resulting in high material costs. Hydrogen gas can be compressed and stored in storage tanks that can hold it at the required pressure. The tanks can either be made with steel, aluminium, or copper alloys that may be encased in fibreglass. The steel tanks are most often used for static applications where weight is not a hindrance as the steel tanks tend to be heavy. Today, gaseous hydrogen is stored in steel cylinders at a pressure of 150-200 bars and at an ambient temperature of approximately 298K. The most common conventional steel gaseous cylinders contain a volume of 40 litres and a pressure of 150 bar and in the last decade significant progress has been made in a move towards lightweight cylinders using chrome-molybdenum steel.

(B) Liquid Hydrogen

Hydrogen can be stored as a liquid (LH₂) at 21.2 K at ambient pressure in cryogenic tanks. Liquid hydrogen has long being the fuel of choice for rocket applications. Once liquefied, it can be maintained as a liquid in cooled and pressurised containers which have to be quite large since (LH₂) has a very low density. The cooling and
compressing process requires energy, resulting in a net loss of about 30% of the energy stored in the liquid hydrogen [John, 1978].

Primarily, the liquidification requires a large expenditure of energy and secondly, through the use of insulation, liquid hydrogen must be continually kept at a low temperature (<20K). There are risks associated with this constant low temperature due to the high expansion ratio of liquid hydrogen to gaseous hydrogen. If there was a warming of liquid hydrogen, extremely high pressures could accumulate and result in damage or an explosion.

(C) Metal Hydrides

Another means of hydrogen storage is that of metal hydride storage. This method is a relatively new method. The advantages of the system are that hydrogen is stored as a metal at low pressure and it stores more volume than compressed gaseous or liquid hydrogen. At high temperatures and under the right pressure, hydrogen reacts with many transition metals and their alloys to form hydrides. A hydride is a compound that contains hydrogen and one or more other elements. It is stable compared to native hydrogen and can be stored, transported, or used in applications. A second reaction to release the hydrogen is required when the fuel is used in, for example, a fuel cell. The metal hydride storage system for hydrogen is considered safe in catastrophic events, like a collision, because a loss of pressure in the storage tank cools down the metal hydride and stops the release of hydrogen.

The hydrating alloy is stored in stainless steel tubes and according to the Vann’s Hoff equation hydrogen reacts with the metal alloy granules in the tank at a specific
temperature and pressure. The steel tubes are surrounded by a water jacket that facilitates heat exchange during absorption and desorption of hydrogen gas. The need for a compressor is eliminated in the hydride system as the hydriding and dehydriding reactions occur at specified temperature and pressure depending on the electrolyzer specifications.

(D) Ammonia Form

Ammonia (NH₃) is the second most commonly produced chemical in the world used in the production of fertilizers and sports a comprehensive infrastructure for making, transporting, and distributing the substance. It also can be used to store the hydrogen with the ability to release it in a catalytic reformer. Ammonia also provides very high hydrogen storage densities and can be stored either as a liquid or in solid form.

(E) Carbon Nanotubes

Carbon nanotubes are (microscopic) cylindrical carbon molecules that can be used in a wide range of applications. One such application is the ability to store hydrogen within the microscopic tube structures. The US Department of Energy has established a standard whereby carbon materials need to have a storage capacity of 6.5% of their own body weight if they are to be used for transportation use. Research continues on the use of carbon nanotubes for hydrogen storage. One of the drawbacks of nanotubes is their extremely high cost. Two pounds of the material can sell for approximately US$50,000.
2.11 Rechargeable battery

A battery is a collection of cells which store electrical energy in chemical reactions. They have evolved into different types to meet different needs. The characteristic of a battery depends on the selection of component materials, the configuration of the individual cells, and on the overall design of the battery. Nowadays, rechargeable batteries used in hybrid power system include Sealed Lead Acid (Pb Acid), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium ion (Li-ion), and Lithium Polymer (Li-Poly). The following explains the characteristic of each of the battery chemistries listed.

(A) Nickel Metal Hydride (NiMH)

The rechargeable sealed NiMH cell absorbs hydrogen in the metal alloy makeup of its negative electrode during charge. As the cell is discharged, the metal alloy releases hydrogen to form water. NiMH batteries have a long cycle life (minimum of 500 cycles) and good storage characteristics [Vosen & Keller, 1999]. Furthermore, the battery can be recharged at any time without experiencing voltage depression (or memory effect). Most importantly, the NiMH battery is an environmentally friendly product.

(B) Nickel Cadmium (NiCd)

The Nickel Cadmium (NiCd) cell chemistry is different from NiMH cell chemistry in that the NiCd cell absorbs cadmium where the NiMH cell stores hydrogen. Cadmium is much larger and heavier than hydrogen which leads to lower volumetric and gravimetric energy densities of the NiCd cell. The NiCd’s cycle life and discharge voltage profile are equivalent to NiMH. Also, NiCds can be placed into storage at any state of charge (SOC). Nevertheless, the NiCd battery needs to be completely
discharged before it is charged to avoid the occurrence of voltage depression (or memory effect). Furthermore, the primary disadvantage to the use of the NiCd chemistry is the environmental concerns and health risks associated with the use of cadmium.

(C) Lithium ion (Li-ion)
Rechargeable Lithium Ion (Li-ion) cells have a negative electrode (anode) made from lithium compounds. Lithium is a highly reactive material and is much lighter than the hydrogen-absorbing metal alloy of the NiMH negative electrode. This leads to higher gravimetric energy densities for the Li-ion cell. One of the advantages of Li-ion cells is that they have a self-discharge rate much lower than NiMH cells. As a result, Li-ion cells can stay in storage for 12 months without requiring maintenance. The expected cycle life of a Li-ion cell in an application is about 500+ cycles. Storing the Li-ion batteries fully charged at high temperature significantly degrade their capacity. This is encountered, for example, when using a laptop at full charge while plugged into an electricity source.

(D) Lithium-polymer (Li-Poly)
Lithium Polymer Ion batteries provide the performance of the Li-ion in a thin or modular package. They do not use a volatile liquid electrolyte and can sustain significant abuse without explosion or fire. As with all batteries, they should still be handled with care as there is significant energy stored in the cell. The lithium-polymer uses a polymer soaked with gelled electrolyte to replace the traditional porous separator [Shaahid & Elhadidy, 2005]. Lithium-polymer is not a mature technology and low manufacturing costs have not yet been realized. Lithium-
polymer has its market niche in wafer-thin geometries, such as batteries for credit cards and other such applications. The expected cycle life of Li-Poly batteries is about 500 cycles.

(E) Sealed Lead Acid (Pb Acid or SLA)

The main attraction for Sealed Lead Acid (Pb Acid) cells is the low cost of lead. This makes the Pb Acid cell very inexpensive to be manufactured. Lead is a relatively heavy metal and when used in a Pb Acid cell results in low volumetric and gravimetric energy densities. The life cycle of a Pb Acid battery is directly proportional to the amount of energy removed from the battery during discharge. To obtain an equivalent cycle life of a NiMH system, only 30% of the Pb Acids capacity can be used. Another disadvantage to the Pb Acid chemistry is that these cells need to be charged before being placed into storage or they will lose cycle life. Furthermore, there are some environmental concerns regarding the use of lead acid batteries due to the improper disposal of old batteries and of lead smelting operations.

2.12 Power conditioning units (PCUs)

Photovoltaic or fuel cell power systems, which generate power as a direct current (DC), require power conversion units to convert the power from DC to alternating current (AC). This power can be connected to the transmission and distribution network of a utility grid. There are other applications where it is necessary to be able to control power flow in both directions between the AC and DC sides. For all these cases, power conditioning units are used. Power conditioning units (PCUs) are defined generally as electronic units that transform DC power to AC power.
(inverters), AC power to DC power (rectifiers), both (bi-directional power electronic converters), or convert DC power at one voltage level to DC power at another voltage level. The lifetime of existing power conditioning units is limited to about 5 - 10 years, which does not compare well with the guaranteed 25-year lifetime of the photovoltaic modules. Depending on the system size, the PCU can constitute between 30% and 50% of the overall cost in both systems. The development of a power integrated circuit will reduce the component count, increase reliability and reduce costs in future.

2.13 Summary
This chapter reviews all components of the hybrid solar hydrogen power system. From the characteristics of the main components of the system, PV energy should be generated with highest efficiency before converting and storing it in the form of hydrogen. The compressed hydrogen storage process is the best alternative relative to other storage processes where energy densities are not critical. The usefulness of compressed hydrogen might rise if its container is made from some composite materials which allow increased pressured hydrogen gravimetric energy density and thus decreasing the storage costs.

PCUs are important for a solar hydrogen stand-alone power system as they are used with a PV generator to track the MPP which give the highest possible power output. Moreover, PCUs are operated with the expensive electrochemical units (fuel cell and electrolyzer) for preventing the damages of these units, especially for large scale systems. Lastly, PCUs are used with all components of the system to invert, to regulate, and to wave-shape the output characteristics.
Further, the next chapter will illustrate the mathematical modelling for all the main components of the hybrid solar hydrogen power system. It is crucial to design an optimum system to improve the system efficiency and balancing cost. In Chapter 3, different modes of operation were used to compare their simulation output based on the system design in the previous chapter. A typical hybrid solar hydrogen power system will be analysed in two different site locations to evaluate the performance and operation of the system.
3. Modelling of PV solar hydrogen System

3.1 Introduction

The price of oil continues to increase and there is no end in sight. Therefore it is important to increase production of alternative, sustainable energy and to be able to store the energy. This chapter will develop the mathematical modelling for the design of the solar cells and hydrogen components. By using the computer simulation, it will help to develop and optimize the system in order to make the supply reliable and keep the technological expenses at a minimum cost. The computer-modelled simulation of renewable electricity networks is a method for the research and optimization of electricity / energy systems with a high share of renewable energy suppliers.

Momoh, Wang & Eddy-Posey [2004] used the optimal power dispatch of photovoltaic system with random load to model the components. This chapter describes the models required to simulate the components of a solar hydrogen stand-alone power system. Each physical component is modelled as a separate component subroutine for a modular system simulation program and provided a detailed description of the different component models. All models described here focus on the study of long-term energy performance of a solar hydrogen stand-alone power system over one year duration time. All the mathematical modelling of the system’ components were based on the model in the simulation program called TRNSYS 16.0 version and will operate in a steady state mode. The schematic layouts of the solar hydrogen stand-alone power system are shown in Figure 3.1. The main components of these models included PV cells, a Polymer Electrolyte Membrane Fuel Cell (PEMFC), an electrolyzer, power conditioning units, hydrogen storage tanks and rechargeable battery.
For the operation of the solar hydrogen stand-alone power system, the solar panel converts sunlight into electrical energy by the excitation of silicon. The Proton Exchange Membrane (PEM) fuel cell is the "engine" that will take the hydrogen and combine it with oxygen from the air. The PEM and the bipolar plates provide a current path for the electrons (50-60% of them) that are given off by the hydrogen atom when it combines with oxygen to form water.

The electrolyser splits water into hydrogen and oxygen. Pure water is an insulator, so an electrolytic solution (25% KOH) is needed to make the water conductive. The KOH is constantly split by the electrical flow, reacts with the water, and produces free H2 and O2. The hydrogen tank is used for hydrogen storage, most tanks are made of composite material because of hydrogen embrittlement. The inverter is the power electronic device which converts direct current (DC) to alternating current (AC). The solar batteries store power generated from the sun and discharge the power as needed through the inverter.
3.2 Photovoltaic cell model

A detailed approach to PV cell module or array modelling based on a mathematical description of the equivalent electrical circuit of a PV cell is given in [Fahmy, 1997]. Three models are used to describe the equivalent electrical circuit of a PV cell module or array: the one-diode, the two-diode, and the thermal model. The most commonly used configuration is the one-diode model that represents the electrical behaviour of the pn junction. The two-diode model allows for a more detailed description of the recombination process of charge carriers both on the surface and in the bulk material. The thermal model is a good fit for the measured current-voltage (I-V) curve and has a less number of parameters than in the other two models.

3.2.1 One-Diode model

A model of a photovoltaic device must be based on the electrical characteristic like the I-V relationship of the cells under various levels of radiation and at various cell temperatures. Siegel [1980] and Eckstein [1990] had presented a relatively simple idealized one-diode model for the simplicity for the computer simulation. The photovoltaic cell is represented as an equivalent circuit containing a current generator (modelling the conversion of solar radiation to electric energy), a diode (accounting for the physical properties of the semiconductor cells), and two resistances (shunt and series). The equivalent circuit of one diode model is shown in Figure 3.2. The one-diode model configuration will be used to represent the electrical behaviour of the pn-junction of PV array in the TRNSYS simulation model.

Duffie & William [1991] emerged that the I-V characteristics of a PV highly depended on both the insolation and temperature. The I-V equation for the equivalent circuit of the one-model model is given as:
\[ I = I_L - I_D - I_{sh} = I_L - I_0 \left[ \exp \left( \frac{q}{nkT_C} (V + IR_S) \right) - 1 \right] - \frac{V + IR_S}{R_{sh}} \]

3.1

where \( I \) is the PV operation current (A), \( I_L \) is the light current (A), \( I_D \) is the diode current (A), \( I_{sh} \) is the shunt current (A), \( I_0 \) is the diode reverse saturation current (A), \( q \) is the electron charge constant, \( \gamma \) is the empirical PV curve-fitting parameter, \( k \) is the Boltzmann constant (J/K), \( T_C \) is the module temperature (K), \( R_S \) is the series resistance (\( \Omega \)), \( R_{sh} \) is the shunt resistance (\( \Omega \)) and \( V \) is the PV operation voltage (V).

The power \( P \) produced by the PV generator is simply given as:

\[ P = VI \]

3.2

At short circuit conditions, all of the generated light current \( I_L \) passes through the diode. Thus, at reference conditions:

\[ I_{sc,ref} = I_{L,ref} \frac{G_T}{G_{T,ref}} \]

3.3
At open circuit conditions, the current is zero and the 1 in equation 3.1 is too small compared to the exponential term. Thus the equation of the open-circuit current can be stated as:

\[ I_{OC,ref} = I_{L,ref} \exp\left(\frac{-V_{OC,ref}}{\gamma_{ref}}\right) \] 3.4

where \( I_{L,ref} \) is the module photocurrent at reference conditions (A), \( G_T \) is the total radiation incident on PV array (W/m\(^2\)), \( G_{T,ref} \) is the incident radiation at reference conditions (W/m\(^2\)), and \( \gamma_{ref} \) is the empirical PV curve-fitting parameter at reference conditions. The reference insolation solar radiation and temperature used in this thesis is \( G_{T,ref} = 1000\text{W/m}^2 \) and \( T_{C,ref} = 25 \text{°C} \) for the Standard Test Condition (STC).

Fry [1999] had shown that the negative reciprocal of the short-circuit I-V slope closely approximates the shunt resistance. So the equation is expressed as:

\[ R_{SIL} \approx \frac{-1}{\left(\frac{dI}{dV}\right)_{V=0}} \] 3.5

This expression reduces the number of unknown variables to four: \( I_{L,ref}, I_{o,ref}, \gamma, R_s \). Rearranging Equation 3.1 (and neglecting the “-1”) at open-circuit, short-circuit, and maximum power conditions yields the following expressions for \( I_{L,ref}, I_{o,ref}, \gamma \). Thus, the expressions for the variables are given as:

\[ I_{L,ref} = I_{SC,ref} \left(1 + \frac{R_s}{R_{SIL}}\right) \] 3.6

\[ I_{o,ref} = \frac{I_{L,ref} - V_{OC,ref}}{R_{SIL}} \exp\left(\frac{-q}{\gamma k T_{C,ref}} \cdot V_{OC,ref}\right) \] 3.7
\[
\gamma = \frac{[q(V_{mp,ref} - V_{OC,ref} + I_{mp,ref} \cdot R_s)]}{kT_{c,ref} \ln \left( \frac{I_{k,ref} - I_{mp,ref} - \frac{V_{mp,ref} + I_{mp,ref} \cdot R_s}{R_{SH}}}{I_{SC,ref} \cdot \frac{V_{OC,ref}}{R_{SH}}} \right)}
\]

At this point only \( R_s \) is needed to solve the system. An iterative search routine is used to find the correct values for \( R_s \) and \( \gamma \) by matching the analytical value for \( \mu_{voc} \).

Differentiating equation 3.1 with respect to temperature at the open-circuit condition:

\[
dV_{OC} = \frac{dV_{OC}}{dT_c} = \mu_{voc} = \frac{\mu_{isc} \cdot \frac{I_{o,ref}}{T_c} \cdot \left( 3 + \frac{q \cdot \varepsilon}{A \cdot k \cdot T} \right) \exp \left( \frac{q}{k \cdot \gamma \cdot T_{c,ref}} \right)}{\frac{q}{k \cdot \gamma \cdot T_{c,ref}} \cdot \frac{I_{o,ref}}{T_c} \exp \left( \frac{q}{k \cdot \gamma \cdot T_{c,ref}} \cdot V_{OC,ref} \right) + \frac{1}{R_{SH}}} \]

where \( A = \frac{\gamma}{N_s} \), \( N_s \) is the number of individual cells in module, \( \mu_{voc} \) is the temperature coefficient of open-circuit voltage (V/K), \( \mu_{isc} \) is the temperature coefficient of short-circuit current (A/K), \( I_{o,ref} \) is the diode reverse saturation current at reference conditions (A), \( \varepsilon \) is the semiconductor bandgap (eV), \( T_{c,ref} \) is the module temperature at reference conditions (K), \( I_{mp,ref} \) is the current at maximum power point along I-V curve for reference conditions (A), \( V_{mp,ref} \) is the voltage at maximum power point along I-V curve for reference conditions (V), \( V_{oc,ref} \) is the open-circuit voltage at reference conditions (V), and \( I_{sc,ref} \) is the short-circuit current at reference conditions (A).
### 3.2.2 Two-Diode model

The two-diode model is derived from the same equivalent circuit of the one-diode model. The only main difference is the addition of one more diode which is in parallel with first diode. Recombination of minority carriers, both on the surface and in the bulk material, is the major determinant of the open-circuit voltage occurring readily at trapping levels of the depletion zone. When modelling the recombination phenomena, the first diode is associated with neutral (base and emitter) regions, whereas the second diode simulates the space-charge recombination effect by incorporating a separate current component $I_{D2}$ with its own exponential voltage dependence [Bzura, 1995]. The advantage of this model is its accuracy while the disadvantage is to require more parameters than the one-diode model.

Thus, the model is only suitable when detailed PV cell and module experiments can be performed in advance [Ulleberg, 1998, p.100]. The relationship between the voltage and the current is given by the two-diode model as:

$$I = I_L - I_{D1} \left[ \exp \left( \frac{q(V + IR_s)}{\gamma_1 k_B T_C} \right) - 1 \right] - I_{D2} \left[ \exp \left( \frac{q(V + IR_s)}{\gamma_2 k_B T_C} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

3.10

where $I_{D1}$ and $I_{D2}$ are the two dark currents expressed by:

$$I_L = k_0 G_T \left[ 1 + \beta_0 (T_C - 273.15) \right]$$

3.11

$$I_{D1} = k_1 T_C^3 \exp \left( \frac{-e_{gap}}{\gamma_1 k_B T_C} \right)$$

3.12

$$I_{D2} = k_2 T_C^{2.5} \exp \left( \frac{-e_{gap}}{\gamma_2 k_B T_C} \right)$$

3.13
Figure 3.3: The equivalent circuit for the two-diode PV generator model

where $\gamma_1$, $\gamma_2$ are the parameters for diode 1 and diode 2 respectively. $k_0$ is the parameter for light current ($\text{Am}^2/\text{W}$), $k_1$, $k_2$ are the diode parameters that are dependent on $\gamma$ for diode 1 and 2, $\beta_0$ is the temperature coefficient ($^\circ\text{C}^{-1}$), and $E_{\text{gap}}$ is the band gap of material (eV).

### 3.2.3 Module operating temperature (thermal model)

The temperature $T_{\text{cell}}$ of the PV cell(s) depends mainly on the ambient conditions but also on the operation of the PV module. In principle, the solar energy that is absorbed by the module is converted partly into thermal energy and partly into electrical energy which is removed through the external circuit [Rahman & Chowdhury, 1988]. The thermal energy is dissipated by a combination of convection, conduction, and radiation. The rate at which these heat transfer processes occur depends largely on the design of the PV system.

For instance, the cells may be cooled artificially by passing air or water on the backside of the module. If a PV module is mounted directly onto the top of a roof,
less natural cooling on the backside occurs compared to when it is mounted on a structure at some distance away from the roof. The developed thermal model for the PV generator based on the energy balance was proposed by Duffie & Beckman [1991]. The advantage of this model, as opposed to more detailed models is that it only needs relatively little information about the design of the PV system. This is because all of the heat losses to the surroundings are lumped together into an overall heat loss coefficient $U_L$. A heat balance of a PV cell can be determined using simple or complex thermal models, depending on the need for accuracy. Assuming a lumped thermal capacitance model is used, the overall thermal energy balance can be expressed as a linear, first order, non-homogeneous differential equation.

This model uses temperature data from the standard Nominal Operating Cell Temperature (NOCT) measurements to compute the module temperature $T_C$ at each time step. The NOCT temperature ($T_{C,NOCT}$) is the operating temperature of the module with a wind speed of 1 m/s, no electrical load, and a certain specified insolation and ambient temperature [Duffie & Beckman, 1991]. The values for insolation $G_{T,NOCT}$ and ambient temperature $T_{a,NOCT}$ are usually 800 W/m$^2$ and 20° C. The NOCT, as well as the number of elementary series cells $N_s$, is given in the PV cell module manufacturer’s data sheet.

This model can operate in 3 modes for the PV cell temperature:

(A) MODE 1: The temperature of the PV-array is given as an input.
(B) MODE 2: The cell temperature is calculated using an overall heat loss coefficient ($U_L$).
(C) MODE 3: The cell temperature is calculated based on an overall heat loss coefficient ($U_L$) and a lumped thermal capacitance ($C_T$).
(A) Mode 1

The energy balance on a unit area of a PV module, which is cooled by losses to the surroundings, can be written as

$$C_i \left( \frac{dT_C}{dt} \right) = \tau \alpha \cdot G_f - \eta_c \cdot G_f - U_L \left( T_C - T_a \right)$$

3.14

where $C_i$ is the thermal capacitance of PV module (J/Km²), $\tau \alpha$ is the transmittance-absorptance product of PV cells, $T_C$ is the cell temperature (K), $T_a$ is the ambient temperature (K), $\eta_c$ is the efficiency of PV cells, and $U_L$ is the overall heat loss coefficient (J/m²).

(B) Mode 2

No thermal capacitance is included in the energy balance on the PV module. Substituting $C_i = 0$ into equation 4.9, it gives the following expression for PV cell temperature as:

$$T_C = T_a + \left( \frac{\tau \alpha \cdot G_f}{U_L} \right) \left( \frac{1 - \eta_c}{\tau \alpha} \right)$$

3.15

Normally, measurements of the cell temperature, ambient temperature, and solar radiations are needed to determine the overall heat loss coefficient ($U_L$). NOCT measurements are needed to compute the module temperature $T_C$ at each time step.

When the NOCT is available, then the overall heat loss coefficient ($U_L$) can calculated by:

$$U_L = \left( \frac{\tau \alpha \cdot G_{T,NOCT}}{T_{C,NOCT} - T_{a,NOCT}} \right)$$

3.16
U_L uses the NOCT data to determine the ratio of the module transmittance-reflectance product to the module loss coefficient and normally it is estimated around 0.8 to 0.9.

(C) Mode 3

In this mode, the thermal capacitance and overall heat loss coefficient is included in the energy balance on the PV module. A linear, first order, and non-homogenous differential equation is expressed as

\[
\frac{dT_c}{dt} + xT_c - y = 0 \Rightarrow T_c(t) = \left(T_{C,\text{ini}} - \frac{y}{x}\right)\exp(-xt) + \frac{y}{x}
\]

3.17

with the constants

\[
x = \frac{U_L}{C_t} = \frac{1}{\tau_t}
\]

3.18

\[
y = \frac{(\tau \alpha - \eta_C) \cdot G_T + U_L \cdot T_a}{C_t}
\]

3.19

where t is the time (s), T_{C,\text{ini}} is the cell temperature at the initial conditions (K), and \tau_t is the thermal time constant for the PV module (s).

Equation 3.17 shows that this is a convenient method to describe the thermal dynamic behaviour of a PV module. The value of the thermal capacitance and heat loss coefficient can be estimated based on the measurements of PV operation.
3.3 Fuel cell model

The fuel cell model here depends on physical and theoretical analysis, so-called, analytical model. The first step to model this unit is defined by its ideal performance. Once the ideal performance is determined, the losses can be calculated and then deducted from the ideal performance to give the actual operation. Also, to simplify the analysis of the model, water management analysis has to be excluded.

A fuel cell is an electrochemical device that converts the chemical energy of a fuel and an oxidant to electrical current (DC). The oxidant can be pure oxygen or a gas containing oxygen, such as air. In the case of a hydrogen-air fuel cell (OXMODE = 1), hydrogen (H₂) is the fuel and air (O₂) is the oxidant. In the case of a hydrogen-oxygen fuel cell (OXMODE = 2), hydrogen (H₂) is the fuel and oxygen (O₂) is the oxidant [Jarvis, Atwater & Cygan, 1997]. Equation 3.20 and 3.21 show the anodic and cathodic reactions taking place in a PEM fuel cell where it is fed with hydrogen containing anode gas and an oxygen-containing cathode gas.

Anode: \[ \text{H}_2(g) \rightarrow 2 \text{H}^+(aq) + 2 \text{e}^- \]  
Cathode: \[ 2 \text{H}^+(aq) + 2 \text{e}^- + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) \]

The product is the pure water (H₂O) and the total fuel cell reaction is

\[ \text{H}_2(g) + \frac{1}{2} \text{O}_2(g) \rightarrow \text{H}_2\text{O}(l) + \text{electrical energy} \]

The electrolytes used in low-temperature H₂/O₂ fuel cells are acidic solid polymer in the proton exchange membrane fuel cell (PEMFC).
3.3.1 Electrochemical model

The performance of a fuel cell (output voltage) is defined as the electrical energy obtained from a fuel cell only when a current is drawn. The actual cell potential \( V_{\text{cell}} \) is decreased from its equilibrium thermodynamic potential (E) because of irreversible losses. When current flows, a deviation from the thermodynamic potential occurs corresponding to the electrical work performed by the cell. The deviation from the equilibrium value is called the overpotential and has been given the symbol \( V \). The overpotentials originate primarily from activation overpotential \( V_{\text{act}} \), ohmic overpotential \( V_{\text{ohmic}} \) and concentration overpotential \( V_{\text{con}} \).

The equivalent circuit of the fuel cell system is shown in Figure 3.4. There is a first order delay in the activation and the concentration voltage components (represented by the resistances \( R_{\text{act}} \) and \( R_{\text{con}} \), respectively). This delay is caused by the charge double layer effect [Kim, Hyun & Goo, 2000]. Such phenomenon normally exist, on every contact between two different materials, due to a charge accumulation on the opposite surfaces or a load transfer from one to the other. The charge layer on both electrode/electrolyte interfaces (or close to the interface) is storage of electrical charges and energy; in this way, it behaves as an electrical capacitor. This effect causes retardation in the dissipation of the electrical charges near the electrolyte/electrode interface. Then, when there is an increase or decrease in the FC current, there is a delay until the FC voltage decreases or increases. The ohmic overpotential is not affected by the charge double layer as it is directly related to the current (represented by the resistance \( R_\Omega \)).
Furthermore, the capacitor is positioned in parallel with the activation and concentration voltages (represented by their equivalent resistor) which shown in Figure 3.4 to take into account the dynamic effect of these voltage drops. This resulting loop is then connected in a series with the Nernst potential (thermodynamic potential) and with the ohmic voltage drop (represented by its equivalent resistance).

Therefore, the dynamical equation of the model presented in Figure 4.4 is

\[
\frac{dv_d}{dt} = \frac{1}{C} \cdot i_{FC} - \frac{1}{\tau_{FC}} \cdot v_d
\]

where \(v_d\) represents the dynamical voltage across the equivalent capacitor (associated with \(V_{\text{act}}\) and \(V_{\text{con}}\)), \(C\) is the equivalent electrical capacitance, and \(\tau_{FC}\) is the FC electrical time constant. The time constant is defined as:

\[
\tau = C \cdot R_a = C \cdot (R_{\text{act}} + R_{\text{con}}) = C \cdot \frac{V_{\text{act}} + V_{\text{con}}}{i_{FC}}
\]

where \(R_a\) is an equivalent resistance.
Including the dynamic behaviour represented by Naso, Lucentini & Aresti [2000], and the basic expression of the voltage of a single cell is defined by:

\[ V_{FC} = E_{Nernst} - V_{act} - V_{ohmic} - V_{con} \] 3.25

where \( V_{FC} \) is the fuel cell voltage (V), \( E_{Nernst} \) is the reversible thermodynamic potential (reversible voltage) of each unit cell (V), \( V_{act} \) is the voltage drop associated with the activation of the anode and the cathode (V), \( V_{ohmic} \) is the ohmic voltage drop → a measure of the voltage drop associated with the conduction of protons and electrons (V), and \( V_{con} \) is the voltage drop resulting from the decrease in the concentration of oxygen and hydrogen (V).

The first term of the equation 3.21 represents the FC open circuit voltage, while the last three terms represent reduction in this voltage. The resulting voltage \( V_{FC} \) is the FC useful voltage for a certain operating condition. In addition to the three terms representing voltage drops, there is another term involving the PEMFC operation. This additional voltage drop results from the circulation of electronic currents through the electrolyte or, similarly, from the fuel crossover through the electrolyte. This voltage drop is modelled considering a permanent FC current density (\( J_a \)) that is added to the main FC current density even when the FC is operated without any load.

(A) Cell reversible voltage

The reversible voltage of the cell (\( E_{Nernst} \)) is the potential of the cell obtained in an open circuit thermodynamic balance (without load). The equation is shown as:

\[ E_{Nernst} = 1.229 - 0.85 \times 10^{-3} \cdot (T - 298.15) + 4.31 \times 10^{-5} \cdot T \cdot \left[ \ln(P_{H_2}) + \frac{1}{2} \ln(P_{O_2}) \right] \] 3.26
where \( P_{H_2}, P_{O_2} \) are the partial pressures (atm) of hydrogen and oxygen, respectively, T is the cell absolute temperature (K).

(B) Activation voltage drop

The activation overpotential, including anode and cathode, can be calculated by:

\[
V_{act} = -\left[ \xi_1 + \xi_2 \cdot T + \xi_3 \cdot T \cdot \text{In}(c_{O_2}) + \xi_4 \cdot T \cdot \text{In}(i_{FC}) \right]
\]

where \( i_{FC} \) is the cell operating current (A), \( c_{O_2} \) is the concentration of oxygen in the catalytic interface of the cathode (mol/cm\(^3\)). The \( \xi_i \) \( (i = 1...4) \) represent the parametric coefficients for each cell model.

(C) Ohmic voltage drop

The ohmic voltage drop results from the resistance to the electrons transfer through the collecting plates and carbon electrodes and the resistance to the protons transfer through the solid membrane. In this model, a general expression for resistance is defined to include all the important parameters of the membrane. The ohmic voltage equation is represented by:

\[
V_{ohmic} = i_{FC} \cdot (R_M + R_C)
\]

where \( R_M \) is the equivalent membrane resistance to proton conduction (\( \Omega \)), \( R_C \) is the equivalent contact resistance to electron conduction (\( \Omega \)).

The equivalent membrane resistance \( (R_M) \) can be calculated by:

\[
R_M = \frac{\rho_M \cdot \ell}{A}
\]

where \( \rho_M \) is the membrane specific resistivity (\( \Omega \cdot \text{cm} \)) obtained by:

60
where the term $181.6/(\Psi - 0.634)$ is the specific resistivity ($\Omega \cdot cm$) at no current ($i_{FC} = 0$) and at temperature of 30°C ($T = 303$ K). The exponential term in the denominator is the temperature factor correction if the cell is not at 30°C. The parametric coefficient $\Psi$ is considered an adjustable parameter with a possible value of $14 < \psi < 23$.

(D) Concentration or mass transport voltage drop

Mass transport affects the concentrations of hydrogen and oxygen. This, by its turn, causes a decrease of the partial pressures of these gases. Reduction in the pressures of oxygen and hydrogen depend on the electrical current and on the physical characteristics of the system [Wingelaar, Duarte & Hendrix, 2005]. To determine an equation for this mass transport voltage drop, it is defined as a maximum current density ($J_{\text{max}}$), under which the fuel is being used at the same rate of the maximum supply speed. The current density cannot surpass this limit because the fuel cannot be supplied at a larger rate. Typical values for $J_{\text{max}}$ are in the range of 500 to 1500 mA/cm$^2$

$$V_{\text{con}} = -B \cdot \ln \left(1 - \frac{J}{J_{\text{max}}}\right)$$  
$$c_{\text{O}_2} = \frac{P_{\text{O}_2}}{5.08 \times 10^{-6} \cdot e^{\left(\frac{498}{T}\right)}}$$
And, for $n$ cells connected in series and forming a stack, the voltage $V_S$ can be calculated by:

$$V_S = n \cdot V_{FC}$$

where $J_{max}$ is the maximum current density (mA/cm$^2$), $J$ is the actual cell current density (A/cm$^2$) including the permanent current density ($J_p$) (mA/cm$^2$), and B is a constant dependent on the cell type and its operation state.

### 3.3.2 Thermodynamic model

Thermodynamics provides a framework for describing reaction equilibrium and thermal effects in electrochemical reactors. It also gives a basis for the definition of the driving forces for transport phenomena in electrolytes and leads to the description of the properties of the electrolyte solutions [Zhong & Hou, 2006]. In this section, the description of the thermodynamics of the low-temperature hydrogen-air or hydrogen-oxygen electrochemical reactions used in the fuel cell model will be illustrated.

The following assumptions can be made about the water splitting reaction: (a) Hydrogen and air (or oxygen) are ideal gases, (b) water is an incompressible fluid, and (c) the gas and liquid phases are separate. Based on these assumptions the change in enthalpy $\Delta H$ of the water splitting reaction can be calculated with reference to pure hydrogen ($H_2$), oxygen ($O_2$), and water ($H_2O$) at a standard temperature and pressure (25°C and 1 atm). The total change in enthalpy for splitting water is the enthalpy difference between the products ($H_2$ and $O_2$) and the reactants ($H_2O$). The same applies for the total change in entropy. The total amount of energy released in the fuel cell reaction (Equation 3.20) is equivalent to the change in
enthalpy $\Delta H$. The standard enthalpy for splitting water is $\Delta H_0 = 286$ kJ mol$^{-1}$. The total energy demand $\Delta H$ is related to the thermo-neutral cell voltage by the expression:

$$V_{th} = \frac{\Delta H}{n \cdot F}$$  \hspace{1cm} 3.34

where $N$ is the number of moles of electrons transferred per mole of water ($n=2$), and $F$ is the Faraday constant (96,485 C/mol).

(A) **Thermo neutral voltage (per cell)**

At standard conditions $V_{th} = 1.482$ V, but it will change with temperature and pressure. In the applicable temperature and pressure range, $V_{th}$ is almost constant with negligible change [Pepe & Selkainaho, 2007]. The energy efficiency can be calculated from the thermoneutral voltage (Equation 3.34) and the cell voltage (Equation 3.20) by the expression:

$$\eta_v = \frac{V_{cell}}{V_{th}}$$  \hspace{1cm} 3.35

where $V_{cell}$ is the voltage across a single cell (V) and $V_{th}$ is the thermoneutral voltage(V).

(B) **Energy efficiency**

Equation 3.35 shows that a high operating voltage $V_{cell}$ is required for high efficiency at a fixed fuel flow rate. However, utilization declines with increasing operating voltage. The power also decreases as operating voltage is raised from the maximum power voltage which in common experience is slightly less than half the open circuit voltage. The greatest efficiency at any given fuel flow is obtained at the operating voltage which results in the highest power output.
(C) Hydrogen and oxygen (Air) flow rates

According to Faraday’s law, the consumption rates of hydrogen and oxygen (air) in a fuel cell is directly proportional to the transfer rate of electrons to the electrodes which in turn is equivalent to the electrical current in the external circuit. Hence, the total consumption rate of hydrogen and oxygen (air) in a fuel cell, which consists of several cells connected in series, can be expressed as:

\[ n_{H_2,\text{cons}} = \frac{N_{\text{cells}} \cdot I_{\text{FC}}}{n \cdot F} \]

3.36

\[ n_{O_2,\text{cons}} = \frac{1}{2} n_{H_2,\text{cons}} \]

3.37

\[ n_{\text{air,cons}} = 4.76 \cdot n_{O_2,\text{cons}} \quad \text{(if OXMODE = 1)} \]

3.38

where \( n_{H_2,\text{cons}} \), \( n_{O_2,\text{cons}} \), \( n_{\text{air,cons}} \) are the hydrogen, oxygen and air consumption flow rates (mol/s) respectively, \( N_{\text{cells}} \) is the number of cells in series, \( I_{\text{FC}} \) is the fuel cell operating current, \( N \) is the number of moles of electrons transferred per mole of water (n=2), and \( F \) is the Faraday constant (96,485 C/mol).

The inlet rates of hydrogen, oxygen and air are sized by empirical stoichiometric factors of the consumption rates. Hydrogen, oxygen and air inlet rates are given as:

\[ n_{H_2,\text{in}} = S_{H_2} \cdot n_{H_2,\text{cons}} \]

3.39

\[ n_{O_2,\text{in}} = S_{O_2} \cdot n_{O_2,\text{cons}} \]

3.40

\[ n_{\text{air,in}} = S_{O_2} \cdot n_{\text{air,cons}} \quad \text{(if OXMODE = 1)} \]

3.41

where \( n_{H_2,\text{in}} \), \( n_{O_2,\text{in}} \), \( n_{\text{air,in}} \) are the hydrogen, oxygen and air inlet rates (mol/s) respectively, and \( S_{H_2} \), \( S_{O_2} \) is the stoichiometric inlet rates factor.
The flow rate of hydrogen on the fuel side and oxygen (air) on the oxidant side affects the performance of the PEM fuel cell. For instance, if the H$_2$ flow is kept fixed and the O$_2$ stoichiometry is increased, the overall performance of the fuel cell also increases. In the H$_2$/Air fuel cells, which have lower concentrations of O$_2$ on the cathode side than H$_2$/O$_2$ fuel cells, the air flow rates are typically kept about twice the O$_2$ flow rate.

### 3.3.3 Thermal model

A heat balance of a fuel cell can be determined using simple or complex thermal models, depending on the need for accuracy. Assuming a lumped thermal capacitance model, the overall thermal energy balance can be expressed as a linear, first order, non-homogeneous differential equation. If TMODE = 1, the stack temperature is assumed to be constant (T$_{\text{stack,in}} = T_{\text{stack,out}}$). If TMODE = 2, the stack temperature is calculated from the difference of the in/out stack temperature.

(A) **Overall energy balance**

The accumulation of heat is given by:

\[ C_t \cdot dT/dt = Q_{\text{gen}} - Q_{\text{loss}} - Q_{\text{cool}} - Q_{\text{evap}} \quad 3.42 \]

The left hand side of the equation is defined by the thermal capacity ($C_t$) and the stack temperature gradient ($dT/dt$). The first term on the right hand side of the equation 3.42 is the internal heat generation ($Q_{\text{gen}}$), the second term is the total heat loss to the ambient ($Q_{\text{loss}}$), the third term is the auxiliary cooling demand ($Q_{\text{cool}}$), and the fourth term is the evaporation of water at the cathode ($Q_{\text{evap}}$).
(B) Internal heat generation

The internal heat generation \( Q_{\text{gen}} \), is calculated using the energy efficiency \( \eta_e \) to determine the fraction of heat produced from the stack power \( P_{\text{stack}} \) as shown as:

\[
Q_{\text{gen}} = P_{\text{stack}} \cdot \left( 1 - \frac{\eta_e}{\eta_e} \right)
\]

3.43

(C) Heat losses to ambient

Heat loss to ambient \( Q_{\text{loss}} \) is calculated using the overall thermal resistance \( R_t \) of the fuel cell and the temperature difference to the ambient as shown:

\[
Q_{\text{loss}} = \frac{1}{R_t} \cdot (T_{\text{stack}} - T_{\text{amb}})
\]

3.44

(D) Evaporative losses (on cathode side)

The heat consumption from the evaporation of outlet water \( Q_{\text{evap}} \) is calculated from the enthalpy of vaporization \( h_{\text{fg,H2O}} \) and fraction of water vaporized \( X_{\text{vap}} \). It should be noted that the thermal model presented here is on a per stack basis:

\[
Q_{\text{evap}} = X_{\text{vap}} \cdot n_{\text{H2O}} \cdot h_{\text{fg,H2O}} \cdot M_{\text{H2O}}
\]

3.45

(E) Auxiliary cooling requirement

The main cooling of the fuel cell is determined by the heat absorption from the cooling water \( Q_{\text{cool}} \):

\[
Q_{\text{cool}} = V_{\text{cool}} \cdot \rho_{\text{H2O}} \cdot c_{p,\text{H2O}} \cdot (T_{\text{cool, out}} - T_{\text{cool, in}})
\]

3.46

where \( Q_{\text{cool}} \) is the heat absorption from the cooling water, \( V_{\text{cool}} \) is the flow rate of the main cooling of fuel cell, \( \rho_{\text{H2O}} \) is the pressure of the water, \( c_{p,\text{H2O}} \) is the specific heat capacity of water, and \( T_{\text{cool, out}} \) and \( T_{\text{cool, in}} \) is a fixed temperature difference of the in/out flow.
3.4 Advanced alkaline electrolyzer

The electrolyzer model considered for the simulation is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical relationships. An actual alkaline water electrolyzer consists of several electrolyzer cells connected in series. The calculations of the required operation voltage and mass flow rates of hydrogen and oxygen are all conducted on a per cell basis while the corresponding values for the whole electrolyzer unit are simply found by multiplying the number of series cells. A temperature dependent current-voltage curve for a given pressure and a Faraday efficiency relation independent of temperature and pressure form the basis of the electrochemical model. The electrolyzer temperature can be given as input, or calculated from a simple or detailed thermal model [Grasser & Rufer, 2006]. A principle scheme of an electrolyzer is shown in Figure 3.5.

The decomposition of water into hydrogen and oxygen can be achieved by passing an electric current (DC) between two electrodes separated by an aqueous electrolyte with good ionic conductivity. The total reaction for splitting water is:

\[
\text{H}_2\text{O (l) + Electric Energy} \rightarrow \text{H}_2 (g) + \frac{1}{2} \text{O}_2 (g)
\]

For this reaction to occur a minimum electric voltage must be applied to the two electrodes. This minimum voltage, or reversible voltage, can be determined from Gibbs energy for water splitting. In an alkaline electrolyzer the electrolyte is usually aqueous potassium hydroxide (KOH), where the potassium ion \(\text{K}^+\) and hydroxide ion \(\text{OH}^-\) take care of the ionic transport. The anodic and cathodic reactions taking place are:
Figure 3.5: Principle scheme of an electrolyzer

Anode: \[ 2\text{OH}^-(aq) \rightarrow \frac{1}{2} \text{O}_2(g) + \text{H}_2\text{O} (l) + 2 \text{e}^- \]

Cathode: \[ 2\text{H}_2\text{O} (l) + 2\text{e}^- \rightarrow \text{H}_2(g) + 2 \text{OH}^- (aq) \]

In an alkaline solution the electrodes must be resistant to corrosion, and must have good electric conductivity and catalytic properties, as well as good structural integrity while the diaphragm should have low electrical resistance. This can, for instance, be achieved by using anodes based on nickel, cobalt, and iron (Ni, Co, Fe), cathodes based on nickel with a platinum activated carbon catalyst (Ni, C-Pt), and nickel oxide (NiO) diaphragms.

### 3.4.1 Electrochemical model

The electrode kinetics of an electrolyzer cell can be modelled using empirical current-voltage (I-V) relationships. Several empirical I-V models for electrolyzers have been suggested [Amphlett et al. 1996, Lokurlu et al. 2003 & Cataliotti, Graditi & Scrivano, 2007]. In order to properly model the I-V curve for a given temperature, overvoltages and ohmic resistance are taken into account, Rousar [1989] had proposed the equation of the electrolyzer as shown below:
\[ V_{cell} = V_{rev} + r \cdot \frac{I_{ely}}{A} + s \cdot \log \left[ \frac{t \cdot I_{ely}}{A} + 1 \right] \]

where \( V_{cell} \) is the voltage over one electrolyzer cell (V), \( V_{rev} \) is the reversible cell voltage (V), \( r \) is the ohm resistance of electrolyte (Ω), \( A \) is the surface area of electrolyzer (m²), \( I_{ely} \) is the current through the electrolyzer (A), and \( s,t \) is the coefficient for overvoltage on electrodes.

(A) Faraday Efficiency

The Faraday efficiency is defined as the ratio between the actual and theoretical maximum amount of hydrogen produced in the electrolyzer. Since the Faraday efficiency comprises the parasitic current losses along the gas ducts, it is often called the current efficiency. The parasitic currents increase with the decreasing current densities due to an increasing share of electrolyte and, therefore, a lower electrical resistance. Furthermore, the parasitic current in a cell is linear to the cell potential (Equation 3.47). Therefore, the fraction of parasitic currents to total current increases with the decreasing current densities. An increase in temperature leads to a lower resistance, more parasitic current losses, and lower Faraday efficiencies. An empirical expression that accurately depicts these phenomena for a given temperature is:

\[ n_f = \left( \frac{I_{density}}{a_1 + I_{density}} \right)^2 \cdot a_2 \]  

where \( a_1 \) is the Faraday efficiency coefficient (mA / cm), and \( a_2 \) is the Faraday efficiency coefficient (0..1)

69
(B) Hydrogen production

According to Faraday’s law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes which in turn is equivalent to the electrical current in the external circuit. Hence, the total hydrogen production rate in an electrolyzer, which consists of several cells connected in series, can be expressed as:

\[ n_{H_2} = \eta_f \cdot N_{cell} \cdot \left( \frac{I_{doc}}{n \cdot F} \right) \]

3.52

(C) Oxygen production

The oxygen production rate is simply found from stoichiometry (equation 4.49), which on a molar basis is:

\[ n_{O_2} = \frac{1}{2} \cdot n_{H_2} \]

3.53

The generation of heat in an electrolyzer is mainly due to electrical inefficiencies. The energy efficiency can be calculated from the thermoneutral voltage (\(V_{in}\)) and the cell voltage (\(V_{cell}\)).

(D) Energy efficiency

Energy efficiency is given by:

\[ \eta_e = \frac{U_{in}}{U_{cell}} \]

3.54

For a given temperature, an increase in hydrogen production (an increase in current density) increases the cell voltage which consequently decreases the energy efficiency. For a given current density, the energy efficiency increases with increasing cell temperature. The I-V characteristic curve for the electrolyzer is shown in figure 3.6.
Figure 3.6: Electrolyzer – Cell voltage vs. Current for different temperatures

It should be observed that equation 3.54 is only valid for systems where no auxiliary heat is added to the system. If auxiliary heat is added, the voltage may drop into the region between the reversible and thermoneutral voltage and the efficiency would be greater than 100%. In low temperature electrolysis, the cell voltage during normal operation (50-80°C and 40-300 mA/cm²) will always be above the thermoneutral voltage, as shown in figure 3.6. However, some initial heating may be required during start-up if the electrolyzer has been allowed to cool down to ambient temperature.

In order to calculate the overall performance of an electrolyzer system, information about the number of cells in series and/or parallel per stack and number of stacks per unit is needed. The rated voltage of an electrolyzer stack is found from the number of cells in series, while the number of cells in parallel yields the rated current (and H₂ production). The total power is simply the product of the current and voltage.
3.4.2 Thermodynamic model

Thermodynamics provides a framework for describing reaction equilibrium and thermal effects in electrochemical reactors. It also gives a basis for the definition of the driving forces for transport phenomena in electrolytes and leads to the description of the properties of the electrolyte solutions [Kim, Goo & Hae, 2004]. Below is a description of the thermodynamics of the low-temperature hydrogen-oxygen electrochemical reactions used in the electrolyzer model.

The following assumptions can be made about the water splitting reaction:

(a) Hydrogen and air (or oxygen) are ideal gases

(b) Water is an incompressible fluid

(c) The gas and liquid phases are separate

Based on these assumptions the change in enthalpy $\Delta H$, Entropy $\Delta S$ and Gibbs Energy $\Delta G$ of the water splitting reaction can be calculated with reference to pure hydrogen (H$_2$), oxygen (O$_2$), and water (H$_2$O) at a standard temperature and pressure (25°C and 1 atm).

The total change in enthalpy for splitting water is the enthalpy difference between the products (H$_2$ and O$_2$) and the reactants (H$_2$O). The same applies for the total change in entropy. The Gibbs free energy, originally called available energy is the chemical potential that is minimized when a system reaches equilibrium at constant pressure and temperature. As such, it is a convenient criterion of spontaneity for processes with constant pressure and temperature.
(A) Gibbs free energy

The free energy change of the fuel cell reaction is defined as:

$$\Delta G = \Delta H - T \text{_{ely}} \cdot \Delta S$$  \hspace{1cm} 3.55

At standard conditions (25°C and 1 atm) the splitting of water is a non-spontaneous reaction which means that the change in Gibbs energy is positive. The standard Gibbs energy for water splitting is $\Delta G_0 = 237$ kJ mol⁻¹. For an electrochemical process operating at constant pressure and temperature the maximum possible useful work (the reversible work) is equal to the change in Gibbs energy $\Delta G$. Faraday’s law relates the electrical energy (emf) needed to split water to the chemical conversion rate in molar quantities. The emf for a reversible electrochemical process, or the reversible cell voltage, is expressed by reversible voltage.

(B) Reversible voltage (per cell)

The reversible voltage of the fuel cell can be stated as:

$$V_{\text{rev}} = \frac{\Delta G}{n \cdot F}$$ \hspace{1cm} 3.56

The total amount of energy needed in water electrolysis is equivalent to the change in enthalpy $\Delta H$. From equation 3.50, it is seen that $\Delta G$ includes the thermal irreversibility $T \Delta S$ which for a reversible process is equal to the heat demand. The standard enthalpy for splitting water is $\Delta H_0 = 286$ kJ mol⁻¹. The total energy demand $\Delta H$ is related to the thermoneutral cell voltage.

(C) Thermoneutral voltage (per cell)

The thermoneutral voltage (per cell) for the fuel cell can be presented as:

$$V_{n} = \frac{\Delta H}{n \cdot F}$$ \hspace{1cm} 3.57
At standard conditions when $V_{\text{rev}} = 1.229$ V and $V_{\text{in}} = 1.482$, these will change with temperature and pressure. In the applicable temperature range, $V_{\text{rev}}$ decreases slightly with increasing temperature ($V_{\text{rev}}$ @ 80°C, 1 bar = 1.184 V), while $V_{\text{in}}$ remains almost constant ($V_{\text{in}}$ at 80°C, 1 bar = 1.473 V). Increasing pressure increases $V_{\text{rev}}$ slightly under the condition of $V_{\text{rev}}$ at 25°C, 30 bar = 1.295 V), $V_{\text{in}}$ remains constant.

### 3.4.3 Thermal model

The temperature of the electrolyte of the electrolyzer can be determined using simple or complex thermal models depending on the need for accuracy. Assuming a lumped thermal capacitance model, the overall thermal energy balance can be expressed as a linear, first order, nonhomogeneous differential equation. The model can calculate $T_{\text{stack}}$ in 3 different ways:

(A) **MODE 1:** $T$ is given as Input.

(B) **MODE 2:** $T$ is calculated based on a simple quasi-static thermal model.

(C) **MODE 3:** $T$ is calculated based on a complex lumped capacitance thermal model.

(A) **Mode 1**

The thermal energy generated internally due to inefficiencies in the cells is partly stored in the surrounding mass and partly transferred to the ambient. From the basic heat transfer theory [Goetzberger et al. 1993], the overall energy balance on the rate form can be presented as

\[
\dot{Q}_{\text{gen}} = \dot{Q}_{\text{store}} + \dot{Q}_{\text{loss}} + \dot{Q}_{\text{cool}}
\]

\[
\dot{Q}_{\text{stored}} = C_t \cdot \frac{dT}{dt}
\]
\[ \dot{Q}_{\text{loss}} = \frac{1}{R} (T - T_a) \]
\[ \dot{Q}_{\text{gen}} = n_c (U - U_{th}) I = n_c U I (1 - n_e) \]
\[ \dot{Q}_{\text{cool}} = C_{CW} (T_{\text{CW,i}} - T_{\text{CW,o}}) = U \cdot A \cdot \text{LMTD} \]

where \( n_c \) is the number of cells in series, \( U \) is the operation voltage (V), \( U_{th} \) is the thermoneutral voltage (V), \( I \) is the operation current (A), \( \eta_c \) is the energy efficiency, \( C_t \) is the heat capacity of electrolyte (J/K), \( T \) is the temperature of electrolyte (\( ^0\)C), \( R_t \) is the thermal resistance (K/W), \( T_a \) is the ambient temperature (\( ^0\)C), \( C_{CW} \) is the heat capacity of cooling water (J/K), \( T_{\text{CW,i}}, T_{\text{CW,o}} \) is the temperature of cooling water (inlet and outlet) (\( ^0\)C), \( U_A H_X \) is the overall heat transfer coefficient-area product for heat exchanger (W\(^{-1}\)K), and LMTD is the log mean temperature difference (\( ^0\)C).

(B) Mode 2

In mode 2 the electrolyzer temperature is simply calculated by assuming constant heat generation and heat transfer rates for a given time interval. Therefore, the temperature’s equation can be expressed as:

\[ T = T_{\text{int}} + \frac{\Delta t}{C_t} \left( \dot{Q}_{\text{gen}} - \dot{Q}_{\text{loss}} - \dot{Q}_{\text{cool}} \right) \]

where \( \Delta t \) is the time interval and \( T_{\text{int}} \) is cell temperature at initial condition (\( ^0\)C).

(C) Mode 3

The energy generation term is function of T. From the definition of the log mean temperature, its equation is given as:

\[ \text{LMTD} = \frac{(T - T_{\text{CW,i}}) - (T - T_{\text{CW,o}})}{\ln[(T - T_{\text{CW,i}})/(T - T_{\text{CW,o}})]} \]
For equation 3.62 assuming constant T, it can be proved that the temperature of the cooling water out of the heat exchanger is:

$$T_{cw,o} = T_{cw,i} + (T - T_{cw,i}) \cdot \left[1 - \exp\left(-\frac{UA_{HX}}{C_{cw}}\right)\right]$$

3.65

A linear, first order and nonhomogenous differential equation is expressed for the overall thermal energy balance on the electrolyzer:

$$\frac{dT}{dt} + x'T - y' = 0 \Rightarrow T(t) = \left(T_{ini} - \frac{y'}{x'}\right) \exp(-x't) + \frac{y'}{x'}$$

3.66

with the constants $x'$ and $y'$

$$x' = \frac{1}{\tau_t} + \frac{C_{cw}}{C_t} \cdot \left[1 - \exp\left(-\frac{UA_{HX}}{C_{cw}}\right)\right]$$

3.67

$$y' = \frac{n_C \cdot U \cdot I(1 - \eta_e)}{C_t} + \frac{T_{in}}{\tau_t} + \frac{C_{cw} \cdot T_{cw,i}}{C_t} \cdot \left[1 - \exp\left(-\frac{UA_{HX}}{C_{cw}}\right)\right]$$

3.68

where $t$ is the time(s), $T_{c,in}$ is the cell temperature at the initial conditions (K), and $\tau_t$ is the thermal time constant for the electrolyzer ($\tau_t = R_C C_t$) (s).

3.5 Hydrogen storage model

There are several possibilities for storing hydrogen. The main difficulties with storing hydrogen are its low density and its low boiling point even at high pressure. One method to reduce the volume of the storage is to pressurize the electrolyzer, or in other words, to compress the hydrogen. An electrolyzer can be pressurized up to about 30 bars while higher pressures in the storage tank require additional hydrogen compression. These compressors require electricity and will increase the parasitic loads to the system [Kelly & Briggs, 2002]. The selected pressure in the storage tank
in this study is 30 bars. The equation of state is either the ideal gas or the Van-der-Waal equation of state for real gases. The user can set the hydrogen storage initial state of charge.

Two options for calculating the pressure are:

(A) Mode 1: Ideal gas

(B) Mode 2: Real gas (van der Waals equation)

According to the ideal gas law, the pressure $\rho$ of a gas storage tank can be calculated as:

$$\rho = \frac{n \cdot R \cdot T_{\text{gas}}}{VoI}$$

3.69

According to the Van Der Waals equation of state, the pressure $\rho$ of a real gas in a storage tank can be calculated by Weinmann [1999] as follows:

$$\rho = \frac{n \cdot R \cdot T_{\text{gas}}}{VoI - n \cdot b - a \cdot \frac{n^2}{VoI^2}}$$

3.70

where $n$ is the number of moles of gas, $R$ is the universal gas constant, $VoI$ is the volume of the storage tank (m$^3$), $T_{\text{gas}}$ is the temperature of the gas (K), $a$ is the constant account for the intermolecular attraction forces, and $b$ is the constant account for the volume occupied by the gas molecules.

Note that the ideal gas law is obtained by setting $a$ and $b$ to 0:

$$\rho \cdot VoI = n \cdot R \cdot T_{\text{gas}}$$

3.71
In the Van der Waals equation, \( a \) and \( b \) are defined as

\[
a = \frac{27 \cdot R^2 \cdot T_{cr}^2}{64 \cdot p_{cr}}
\]

\[3.72\]

\[
b = \frac{R \cdot T_{cr}}{8 \cdot p_{cr}}
\]

\[3.73\]

where \( T_{cr} \) and \( p_{cr} \) are respectively the critical temperature and pressure of the substance.

The model simply performs a mass (or moles) balance of gas entering and leaving the storage and calculates the pressure corresponding to the resulting mass of hydrogen in the tank. If the pressure rises beyond a fixed level, the excess of hydrogen is dumped.

### 3.6 Inverter/regulator model

In photovoltaic power systems, two power conditioning devices are needed. The first component is a regulator, which distributes DC power from the solar cell array to and from a battery (in systems with energy storage) and to the second component, the inverter. If the battery is fully charged, or needs only a taper charge, excess power is either dumped or not collected by turning off parts of the array. The inverter converts the DC power to AC and sends it to the load and/or feeds it back to the utility. The power loss for rectifier/inverter modes was stated as follows [Bhide & Bhat, 1992]:

\[
P_{\text{loss}} = P_{in} - P_{out} = P_o + \left(\frac{U_S}{U_{out}}\right)P_{out} + \left(\frac{R_{s}}{U_{out}^2}\right)P_{out}
\]

\[3.74\]

where \( P_o \) is the idling power (W), \( R_{s} \) is the internal resistance constant (\( \Omega \)), and \( U_S \) is the set point voltage (V).
The rectifier/inverter can have either output or input power as input for the calculations (output if the system is connected to a load or input if the system is connected to the electric power net). The rectifier/inverter is disconnected when the input voltage, output voltage or power is zero [Wai & Lin, 2005].

3.7 Summary

The individual component models of the solar hydrogen stand-alone power system have been described in this chapter. These models are mainly based on electrical and electrochemical theories. The models of PV generator, PEM fuel cell and alkaline water electrolyzer are described in detail but the rectifier/inverter and the hydrogen storage tank are presented as simple models. Three PV generator models have been presented. The thermal model is much simpler compare to the one diode and two diode models. For the one or two diode models six parameters must be determined and these parameters are difficult to measure precisely to obtain an acceptable accuracy of the models. The empirical model uses five parameters which can be found in the manufacturer’s data sheet of the PV module.

The models of electrochemical components (PEM fuel cell and alkaline water electrolyzer) presented in this chapter are analytical models that depend on physical and theoretical analysis. Therefore, these models include a high number of parameters that have to be identified. Consequently, to simplify the analysis of these models, water management analysis has to be excluded. Different power conditioning unit models have been presented. The quadratic model relating to the input and output power is expected to give reasonable accurate results and has the advantage of being easy to implement since only three parameters are generating the model.
4. SIMULATION OF SOLAR HYDROGEN HYBRID SYSTEM

4.1 Introduction
The overall aim of this chapter is to describe the simulation of a stand-alone power system that uses solar radiation as the primary energy input and hydrogen as the long term energy storage. The main objective of this chapter is to present a method on how to optimize the operation and control strategies of a typical solar hydrogen system. Thus, it is important in the design to optimize the system configuration, component sizes and control settings. Design via simulation allows the study of different options, considering various influencing parameters and effectively fulfils the system/user requirements. All the components of the system have been modelled in the previous chapter.

4.2 Description of Dynamical Simulation Tool Program

4.2.1 TRaNsient SYstems Simulation program (TRNSYS)
A number of hybrid system simulation packages, such as Matlab/Simulink, INSEL, HYBRID2 and others have been developed by different research teams during the last two decades. Most of these software tools simulate given and predefined hybrid systems based on a mathematical description of the component operation characteristics and system energy flow. In the simulation of this thesis, a simulation program called TRNSYS was used. TRNSYS is a TRaNsient SYstems Simulation program with a modular structure. It allows the user to specify the components that constitute a specific system and the manner in which they are connected. The program can recognize a system organisation and simulate its operation.
The TRNSYS library includes many of the components commonly used in thermal and electrical energy systems, as well as component routines to manage the integration of weather data or other time-dependent forcing functions and output of simulation results. The modular nature of TRNSYS gives the program a large flexibility and makes it possible to add mathematical models not included in the standard TRNSYS library. It is particularly suited for the analysis of solar systems (solar thermal and photovoltaic systems), low energy buildings and HVAC systems, renewable energy systems, and cogeneration or fuel cells [TRNSYS website, 2004].

4.2.2 HYDROGen Energy ModelS (HYDROGEMS)

HYDROGEMS is a collection of HYDROGen Energy ModelS intended for integrated renewable–hydrogen (RE-H₂) energy system simulations. The HYDROGEMS library includes component subroutines for photovoltaic (PV) arrays, wind energy conversion systems (WECS), diesel engine generator systems (DEGS), advanced alkaline water electrolysis, high-pressure hydrogen gas storage, metal hydride (MH) storage, proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC), compressors, power conditioning equipment, and logical control functions. Descriptions of the mathematical models defining the different elements of the HYDROGEMS library are shown in Figure 4.1.

HYDROGEMS have been made compatible to TRNSYS which makes it possible to integrate the component models with a standard library of thermal and electrical renewable energy components. This makes HYDROGEMS particularly useful for system design (or redesign) and optimization of control strategies for integrated RE - H₂ energy systems [HYDROGEMS user guide, 2001].
The following section explains the main HYDROGEMS components used for simulation purpose in this thesis.

1. **TYPE180** is a mathematical model for a photovoltaic (PV) generator based on an equivalent circuit of a one-diode model. The model is primarily intended for PV-arrays consisting of silicon cells but can also be used for other types of materials. The electrical model used in TYPE180 is described in [Duffie and Beckman, 1991].

2. **TYPE170** is a generic mathematical model for a proton exchange membrane fuel cell (PEMFC). The model is largely mechanistic with most terms being derived from theory or including coefficients that have a theoretical basis. The major non-mechanistic term is the ohmic overvoltage that is primarily empirically based. The main equations of the electrochemical model are described in published literature [Amphlett et al., 1995a & Mann et al., 2000].

3. **TYPE160** is a mathematical model for a high pressure alkaline water electrolyzer. The model is based on a combination of fundamental thermodynamics, heat transfer theory, and empirical electrochemical
relationships. A dynamic thermal model is also included. A temperature dependent current-voltage curve for a given pressure and a Faraday efficiency relation independent of temperature and pressure form the basis of the electrochemical model. The electrolyzer temperature can be given as input or calculated from a simple or detailed thermal model.

4 TYPE164 is a compressed gas storage model. The model calculates the pressure in the storage based on either the ideal gas law or van der Waals equation of state for real gases [Çengel and Boles, 1989].

5 TYPE185 is a quasi-static mathematical model of lead-acid battery or Pb-accumulator. The model uses a simple equivalent circuit that relates the electrical currents, voltages, resistance (related to the concentration-overvoltage), and capacity. The main features of the model include gassing current losses, polarization effects (during charging and discharging), and calculation of equilibrium voltage at various states of charge [Saupe, 1993].

6 TYPE175 is a mathematical model for a power conditioning unit. The model is based on empirical efficiency curves for electrical converters (DC/DC) or inverters (DC/AC or AC/DC). The empirical relationship used in TYPE175 was proposed for the simulation model by Laukamp in 1988 [Laukamp, 1988].

4.3 Input and output data of the simulation program

4.3.1 Weather data

The important required weather data for the hydrogen PVFC hybrid system analysed in the work described in this thesis are the solar radiation [W/m²] and the ambient temperature [°C]. These data have to be supplied to the simulation model on an
hourly basis. The solar radiation and ambient temperature are obtained from the
TRNSYS 16 Weather Database.

4.3.2 User load demand data

Accurate simulation studies require higher time resolution for the user load data,
from minutes to hours. Hence, the load duration curve for the intended application
over the study period of interest had to be available on an hourly basis. The duration
curve can take any form, such as load values each hour or considering the load
constant for all hours over the simulation period. In this work, the load was
considered to have basic load priority and was considered to be constant during each
one hour time step.

The size of the system components, the storage and the energy-transforming units
were influenced by the user load demand. Loads that are considered parasitic are, for
example, power required by controllers, or to run fans, and heat required by some
components or parts of the components of the system.

4.3.3 Output system data

The developed simulation model provided sufficient information about the
performance of each component and the system. During the program execution, all
necessary system variables needed for a performance analysis were recorded in a
simulation output file. For example, hourly values of hydrogen fuel produced by
electrolyzer unit, hydrogen fuel consumption by fuel cell back-up generator, energy
generated by the fuel cell to cover the deficit energy from the PV generator to satisfy
the user load demand, energy generated by PV and others.
4.4 Assumptions and simplifications of the system simulations

The main assumptions and simplifications made in the simulation of the solar hydrogen hybrid power system were as follows.

(A) Hydrogen losses

Some hydrogen losses were expected such as hydrogen losses in the electrolyzer or fuel cell during start-up and shutdown, hydrogen losses in the compressor, hydrogen losses in the gas storage tank, and hydrogen losses in the fuel cell during operation, but these will not be included in the simulation. Normally, a combined hydrogen loss of 5% in the compression and storage process can be expected. The losses due to flushing of hydrogen during start up and shutdown of the electrolyzer was around 4%. Although the inclusion of the losses in the PEMFC would make the simulations more accurate, it would not affect the overall results significantly as long as very short fuel cell run times are avoided.

(B) Parasitic loads

Most of the parasitic loads were handled by an auxiliary power supply such as the power needed for the protective current for the electrolyzer during standby operation, the hydrogen purification system, the compressor, the water cooling pump for the electrolyzer and fuel cell, the water rinsing and gas (H₂ and O₂) purification systems, the MPPTs, DC/DC converters, and the DC/AC inverter. These parasitic powers were omitted from the simulation of the system. The inclusion of these losses, of course, would have lead to different results, but will not bring a significant impact to the output of the simulation [Vosen & Keller, 1999].
(C) Oxygen handling system

In an Air/H₂ PEMFC stack, no oxygen purification system is required. In general, the O₂/H₂ PEMFC has a better performance than the Air/H₂ PEMFC, but requires an O₂ storage or purification system. Thus, no oxygen purification or storage systems were included in the system simulations. In other words, it was assumed that the oxygen required by the O₂/H₂ PEMFC always could be supplied in the simulation models.

(D) Protective current for the electrolyzer

In an actual power system, the electrolyzer requires auxiliary power to maintain a protective current during standby operation. This protective current can be obtained by maintaining a minimum voltage across the electrolyzer. The power needed to maintain the voltage depends on the temperature of the electrolyzer. In the simulations, the temperature of the electrolyzer varied from 20-80°C over the year shown in Figure 4.2. In this particular simulation, the electrolyzer operated in the standby mode at an average temperature of 34.8°C.

4.5 Weather and user load characteristics of the system under study

The daily electrical load profiles vary with time, depending on the activity patterns and the type of appliances used. The reference location for the simulation study was a small village in Kuching, Sarawak (1° 29’ N, 110° 43’ E). In cloudy weather, the electricity demand in winter is usually higher than the summer with 5kW maximum load. For the cloudy weather, the minimum and average load of the system was 2.08W and 3.34kW, respectively. Also, for sunny weather, the minimum and average load of the system was 2.68kW and 4.05kW, respectively. The yearly average load energy was 11.83MWh and 6.12MWh for sunny and cloudy weather, respectively.
Figure 4.2: The temperature of the electrolyzer over a year

Figure 4.3: Monthly radiation and clearness index in Kuching

The monthly global solar radiation and clearness index in Kuching for the system under study are shown in Figure 4.3. The optimum tilt angle was estimated according to the major share of solar radiation over the year in the northern hemisphere. The yearly average ambient temperatures are 26.56 °C in Kuching.
4.6 Sizing of the solar hydrogen hybrid system components

4.6.1 Consistency check

The energy was balanced within each time step throughout the entire simulation run. The total amount of produced energy (PV generator, fuel cell, and storage output) must equal the total amount of consumed energy (user load, electrolyzer, storage input, and losses). Checking the energy balance at each time step assures that the model is internally consistent. The overall energy balance equation is given by:

\[ P_{PV} + P_{FC} - P_{EL} - P_{LOAD} \pm P_{BAT} - \sum_i P_{LOSS,i} = 0 \]  

where \( P_{PV} \) is the PV generator output power (W), \( P_{FC} \) is the output power from PEMFC (W), \( P_{EL} \) is the input power to alkaline water electrolyzer (W), \( P_{LOAD} \) is the user load power demand (W), \( \pm P_{BAT} \) is the battery discharge or charge power (W), \( \sum_i P_{LOSS,i} \) is the all power losses in the system (W).

The power losses \( P_{LOSS} \) in the energy balance equation for the system under study comprise only the losses in the power conditioning units during energy conversion between the different units of the system. Power line losses are neglected.

4.6.2 PV generator

The essential parameters for system sizing were the average daily solar radiation energy and the load consumption energies. These parameters can be used to calculate the peak power of the PV generator and the amount of energy to store, in order to
assure the autonomy of the system. To size the PV power generator, the equation which been derived by Ding & Buckeridge [2000] were defined as:

\[
A_{PV} = \frac{E_{LD}}{\eta_{sys} \times E_{SD}}
\]

4.2

\[
P_{PV,STC} = E_o \times \eta_{PV,STC} \times A_{PV}
\]

4.3

where \( A_{PV} \) is the PV generator surface area (m\(^2\)), \( E_{LD} \) is the daily mean load energy consumption (kWh/d), \( E_{SD} \) is the daily mean solar radiation energy (kWh/m\(^2\)/d), \( \eta_{sys} \) is the total system efficiency taking into account the PV conversion efficiency, wires, diodes, chemical conversion, electricity regeneration, PCU, etc (%), \( \eta_{PV,STC} \) is the PV generator rated efficiency around 10-15 (%), \( P_{PV,STC} \) is the PV production power at standard test conditions (Wp), \( E_o \) Solar radiation at STC (1kW/m\(^2\))

In Kuching, the daily average solar radiation energy was 6.2kWh/m\(^2\)/d and the daily average load energy consumption was 32.4kWh/d. Assuming that the PV rated efficiency was 13.8% and the total system efficiency was 4.8%. The system efficiency depended on the components efficiency and on the periods of time at which the solar energy is enough to satisfy the user load demand.

\subsection{4.6.3 PEMFC and Electrolyzer}

Two simple equations were used to determine the power of the electrolyzer and fuel cell components.

\[
P_{FC,\text{rated}} = P_{LDM}
\]

4.4

\[
P_{EL,\text{rated}} = P_{PV,STC} - P_{LDI}
\]

4.5
where $P_{EL,\text{rated}}$ is the rated power of electrolyzer (W), $P_{FC,\text{rated}}$ is the rated power of fuel cell (W), $P_{PV,\text{STC}}$ is the rated PV power at standard test conditions (W), $P_{LDi}$ and $P_{LDM}$ is the minimum and maximum load power, respectively (W).

The rated power of the electrolyzer was identical to the maximal excess power of the PV generator over the minimal load power. As the fuel cell power production depended on the maximum load power.

4.6.4 Storage tank volume

The sizing of the solar hydrogen hybrid system to satisfy long-term autonomy was based on the yearly average value of solar radiation energy and the load demand. Accordingly, the PV generator was sized according to the solar radiation energy and the load demand. The storage sizing method used the PV generator sizing and the monthly solar radiation energy to determine the storage tank volume. This method can be applied to all sites and all load demands.

The hydrogen amount produced by the system during each month was calculated by using the value of the PV generator surface area and assumed the efficiency of PV, PCU and electrolyzer to be 10%, 90% and 70%, respectively. This method also estimated the hydrogen production was completely stored firstly before it supplied power to the user load. The monthly average value of hydrogen production over one year was calculated from the monthly average values by the same manner as for the monthly average solar radiation energy over one year.
4.7 Control strategies for solar hydrogen hybrid power systems

Table 4.1: Definition of the parameters in the fuel cell controller, the electrolyzer controller and the compressor controller.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cell (TYPE 170)</td>
<td></td>
</tr>
<tr>
<td>FC&lt;sub&gt;low&lt;/sub&gt;</td>
<td>Battery SOC at which fuel cell is switched on (%)</td>
</tr>
<tr>
<td>FC&lt;sub&gt;high&lt;/sub&gt;</td>
<td>Battery SOC at which fuel cell is switched off (%)</td>
</tr>
<tr>
<td>t</td>
<td>Time at which FC&lt;sub&gt;low&lt;/sub&gt; and FC&lt;sub&gt;high&lt;/sub&gt; is switched (h)</td>
</tr>
<tr>
<td>V&lt;sub&gt;H2, FC&lt;/sub&gt;</td>
<td>Hydrogen flow supply rate set point (Nm&lt;sup&gt;3&lt;/sup&gt;/hr)</td>
</tr>
<tr>
<td>τ&lt;sub&gt;FC&lt;/sub&gt;</td>
<td>Fuel cell switch variable (0= Off, 1 = On)</td>
</tr>
<tr>
<td>Electrolyzer (TYPE160)</td>
<td></td>
</tr>
<tr>
<td>EL&lt;sub&gt;low&lt;/sub&gt;</td>
<td>Battery SOC at which electrolyzer is switched off (%)</td>
</tr>
<tr>
<td>EL&lt;sub&gt;up&lt;/sub&gt;</td>
<td>Battery SOC at which electrolyzer is switched on (%)</td>
</tr>
<tr>
<td>E&lt;sub&gt;ly&lt;/sub&gt;</td>
<td>Electrical mode of operation for the electrolyzer</td>
</tr>
<tr>
<td>1= fixed power input (W)</td>
<td></td>
</tr>
<tr>
<td>2= fixed current input (A)</td>
<td></td>
</tr>
<tr>
<td>3= variable current input (A)</td>
<td></td>
</tr>
<tr>
<td>P&lt;sub&gt;ly,sp&lt;/sub&gt;</td>
<td>Power set point for E&lt;sub&gt;ly&lt;/sub&gt;&lt;sub&gt;mode&lt;/sub&gt; = 1 (W)</td>
</tr>
<tr>
<td>I&lt;sub&gt;ly,sp&lt;/sub&gt;</td>
<td>Current set point for E&lt;sub&gt;ly&lt;/sub&gt;&lt;sub&gt;mode&lt;/sub&gt; = 2 (A)</td>
</tr>
<tr>
<td>I&lt;sub&gt;idle&lt;/sub&gt;</td>
<td>Idling current at low insolation for SOC &gt; EL&lt;sub&gt;low&lt;/sub&gt; (A)</td>
</tr>
<tr>
<td>STARTCLK</td>
<td>Time at which the electrolyzer is switched to the idling mode (h)</td>
</tr>
<tr>
<td>STOPCLK</td>
<td>Time at which the electrolyzer is switched to the standby mode (h)</td>
</tr>
<tr>
<td>γ&lt;sub&gt;EL&lt;/sub&gt;</td>
<td>Electrolyzer switch variable (0= Off, 1 = On)</td>
</tr>
<tr>
<td>Compressor (TYPE 185)</td>
<td></td>
</tr>
<tr>
<td>ρ&lt;sub&gt;up&lt;/sub&gt;</td>
<td>Pressure in hydrogen buffer at which compressor is switched on (bar)</td>
</tr>
<tr>
<td>ρ&lt;sub&gt;low&lt;/sub&gt;</td>
<td>Pressure in hydrogen buffer at which compressor is switched off (bar)</td>
</tr>
</tbody>
</table>

The system energy balance was checked at each time step of the simulation. The input data such as solar radiation and ambient temperature were fed in to calculate the amount of energy that can be generated by the PV generator. The value of PV energy was compared with the load demand energy to determine the distribution of energy flow between the storage unit and the load. This section described a set of control strategies for solar hydrogen hybrid power systems. Definitions of the key control parameters for the system under study were summarized in Table 4.1.
Figure 4.4: The basic control scheme for the fuel cell and electrolyzer in a solar hydrogen system, with the battery SOC thresholds and logical variable indicated.

The system under study had two controller valves to protect the hydrogen storage tank from over pressure inside the tank and to regulate the hydrogen flow supply rate to the fuel cell unit. The on/off switching of the electrolyzer and fuel cell in a solar hydrogen system that used a rechargeable battery as energy buffer, can be based on the SOC of the battery. Figure 4.4 shows the on/off switching set points for the electrolyzer and fuel cell, $E_{L_{up}}$, $E_{L_{low}}$, $F_{C_{low}}$, and $F_{C_{up}}$, respectively. It also shows the control signals for the electrolyzer and fuel cell, $\gamma_{EL}$ and $\gamma_{FC}$, which are discrete variables that can only attain the value 0 (off) or 1 (on).

The solar hydrogen system control was based on the state of charge of the battery. However, such a control being very complex to simulate with TRNSYS since such a controller didn’t exist in TRNSYS library yet, an approximation of the system was developed basing the control strategy on the state of charge of the hydrogen store. This can be achieved using the Master Level Controller (type 105 in the library of TRNSYS) which was designed to control a stand-alone power system including the
PV source, an electrolyzer, a fuel cell, a hydrogen storage device and another auxiliary power source that consists of multiple units.

The decisions of the controller were based on the mini-grid busbar power balance, assuming that the minimum number of PV was operating and that the fuel cell and electrolyzer were idling:

1. Electrolyzer status

   • If the electrolyzer is currently OFF (Idling):
     - If SOC < EL_{low}, switch ON:
     - Operate with \( P_{ely, set} = P_{PV} + P_{FC, min} - P_{Load} \)
     - Else, remain OFF (Idling)

   • Else (electrolyzer is currently ON):
     - If SOC > EL_{up}, switch OFF (Idling)
     - Else, keep operating and \( P_{ely, set} = P_{PV} + P_{FC, min} - P_{Load} \)

   • Constraints on \( P_{Ely, set} \): If \( P_{Ely, set} > P_{Ely, max} \) then \( P_{Ely, set} = P_{Ely, max} \)

2. Dump

   • If \( P_{Ely, max} \) was reached: \( P_{dump} = P_{PV} + P_{FC, min} - P_{Load} - P_{Ely, set} \)

POWER DEFICIT (PBUSBAR < 0)

(a) Switch off fuel cell if necessary, based on the H\textsubscript{2} storage tank level

   • Switch Fuel cell to idling mode if the fuel cell is currently ON and SOC < FC_{low}

   • Keep idling if the fuel cell is currently OFF and SOC ≤ FC_{up}
(b). Electrolyzer and Dump

• If the fuel cell is currently OFF (idling):
  
  - Assuming the electrolyzer is idling \((P_{PV} + P_{FC,min} - P_{Load} - P_{Ely,min}) \geq 0\)
  
  - Electrolyzer operates at \(P_{Ely, set} = P_{PV} + P_{FC,min} - P_{Load}\)
  
  - No dumped power: \(P_{dump} = 0\)

• Else (the fuel cell is currently ON):

Assuming the electrolyzer is idling and the fuel cell is at maximum power.

\(((PPV + PFC,max - PLoad − PEly,min) \geq 0)\)

- Assume electrolyzer is idling

- Set fuel cell power: \(P_{FC, set} = P_{Load} + P_{Ely,min} - P_{PV}\)

- If \(P_{FC, set} < P_{FC, min}\) then impose \(P_{FC, set} = P_{FC, min}\)

- Set Electrolyzer power to use all power that would be dumped: \(P_{Ely, set} = P_{PV} + P_{FC,max} \cdot P_{Load}\)

Of course this model was far from being ideal. One can see from these equations that the fuel cells can run on partial load in this system, which was not the case in the real solar hydrogen system where fuel cells ran only at fuel power, it should give a good first approximation of the actual system.

In addition to the on/off switching of the fuel cell and electrolyzer, the battery to be protected from overcharging (at high SOC) or undercharging (at low SOC) was needed. Thus, a pair of battery protection thresholds for high and low SOC was included in the basic control strategy. According to this control strategy, if the fuel cell was switched on, then the electrolyzer must be in the switched off position. The switching off of the electrolyzer actually defined that the electrolyzer was switched
to the standby mode operation, because it can never be completely switched off, as this will damage the electrodes. The control time step (Δt) was one hour for this long-term operation. Thus, the battery module which represents a storage unit for short-term operation, to provide a more stable power response to transient changes in load demand or to stabilize the fuel cell operation, was not considered here.

4.7.1 Fuel cell controller

When the fuel cell was switched on it can be operated in a constant current mode. This was achieved by maintaining a constant hydrogen supply flow rate $V_{H2,FC}$. Since the I-V characteristic for the fuel cell was temperature dependent, a constant $V_{H2,FC}$ will yield a variable power output. However, because the fuel cell had a fairly low thermal capacity, it will reach its maximum operation temperature relatively fast. Thus, the assumption that the fuel cell operated at a constant $V_{H2,FC}$ and consequently at a constant power was not a bad one. This was particular true if the fuel cell was switched on for several hours at a time.

4.7.2 Compressor controller

A compressor was included in the simulations to compress hydrogen from a short-term low pressure H$_2$ buffer (after the electrolyzer) up to a long term high-pressure H$_2$ storage. The compressor controller unit used a simple on/off switching strategy based on the two parameters $\rho_{up}$ and $\rho_{low}$. 
4.7.3 Electrolyzer controller

The electrolyzer controller model included the basic on/off-switching scheme described in Figure 4.4 Note that the power set points $P_{EL,sp}$ ($E_{ly\_mode} = 1$) and $I_{EL,sp}$ ($E_{ly\_mode} = 2$) were fixed inputs, while the current $I_{\text{excess}}$ or $I_{\text{idle}}$ ($E_{ly\_mode} = 3$) were variable inputs.

When the electrolyzer was switched on it can be operated in three distinct electrical modes.

1. Mode 1= Fixed electrolyzer power mode ($E_{ly\_mode} = 1$)
2. Mode 2= Fixed electrolyzer current mode ($E_{ly\_mode} = 2$)
3. Mode 3= Variable electrolyzer current mode ($E_{ly\_mode} = 3$)

(A) Mode 1

In this mode ($E_{ly\_mode} = 1$), the electrolyzer operated at a fixed power. This mean that if the power from the MPPTs minus the power to the user loads inverter was less than the power required by the electrolyzer inverter, the battery must cover the power deficit. In the opposite case, the excess power was used to charge the battery.

(B) Mode 2

In this mode ($E_{ly\_mode} = 2$) the electrolyzer operated at a fixed current which mean that the electrolyzer required an almost fixed amount of power. During operation in $E_{ly\_mode} = 2$, the electrolyzer power was not completely constant. This was because the I-U characteristic for the electrolyzer was temperature dependent. Nevertheless, the difference between mode 1 and mode 2 was quite small. The current balance on the busbar (subscript b) in $E_{ly\_mode} = 2$ was
\[ I_{\text{bat}} = I_{\text{MPPT}} - I_{\text{ely},b} - I_{\text{load},b} \]  

where \( I_{\text{bat}} \) is the net battery (\( I_{\text{bat}} > 0 \) is a charging current) (A), \( I_{\text{MPPT}} \) is the total current from all of the MPPTs (A), \( I_{\text{ely},b} \) is the current to electrolyzer converter (A), and \( I_{\text{load},b} \) is the current to user load converter (A).

A fixed electrolyzer current set points \( I_{\text{ely},sp} \) yielded a fixed converter current \( I_{\text{ely},b} \). Thus, the charging or discharging of the battery depended only on \( I_{\text{MPPT}} \) and \( I_{\text{load},b} \). It should also be noticed that no current was supplied to the busbar from the fuel cell converter when the electrolyzer was switched on.

(C) Mode 3

In this mode (\( \text{Ely}_{\text{mode}} = 3 \)) the electrolyzer utilized only the excess power available on the busbar, which mean that no current passed in/out of the battery during operation shown in equation 4.7. However, if \( I_{\text{excess},b} \) was lower than a lower critical current \( I_{\text{idle},b} \) the current deficit must be drawn from the battery (equation 5.3). If \( I_{\text{excess},b} \) was above a specified maximum current, the simulation will be stopped.

The current balance on the busbar in \( \text{Ely}_{\text{mode}} = 3 \) were based on the following calculations:

\[
\text{if } I_{\text{excess},b} > I_{\text{idle},b} \text{ then } I_{\text{excess},b} = I_{\text{MPPT}} - I_{\text{load},b} \text{ and } I_{\text{ely},b} = I_{\text{excess},b} \quad 4.7
\]

Else

\[
\text{if } I_{\text{excess},b} \leq I_{\text{idle},b} \text{ then } I_{\text{bat}} = I_{\text{MPPT}} - I_{\text{load},b} - I_{\text{idle},b} \text{ and } I_{\text{ely},b} = I_{\text{idle},b} \quad 4.8
\]

where \( I_{\text{excess},b} \) is the excess current on the busbar (A) and \( I_{\text{idle},b} \) is the idling current drawn by the electrolyzer converter (A).
(D) Standby mode

Once the electrolyzer had been installed in an actual system it can never be completely switched off, as this will damage the electrodes. Therefore, in the simulations performed here, switching off the electrolyzer actually mean that the electrolyzer was switched to the standby mode.

(E) Additional controls

The additional logical control statement included in the electrolyzer controller is:

1. If the fuel cell is switched on ($\gamma_{FC} = 1$), then the electrolyzer is switched off ($\gamma_{EL} = 0$).
2. The electrolyzer can only operate during the day (between STARTCLK and STOPCLK).
3. If the solar radiation during daytime is less than a minimum value close to zero ($G < G_{min}$), then the electrolyzer is switched to the idling mode. (The idling mode is used together with STARTCLK and STOPCLK to avoid abrupt start ups and shutdowns).

Two operation hour set points are proposed in this thesis:

1. STARTCLK - hour of the day at which the electrolyzer is switched to the idling mode
2. STOPCLK - hour of the day at which the electrolyzer is switched to the standby mode

The purpose of this feature was to avoid start-ups and shutdowns. Ideally, STARTCLK and STOPCLK should be the actual sunrise and sunset hours respectively. However, the STARTCLK parameters can only be fully utilized in
connection with a weather forecasting system. That was, if the weather forecast predicted a sunny day, the electrolyzer should be switched on to its idling mode at STARTCLK, otherwise it should remain in the standby mode.

The main purpose of the idling mode included in electrolyzer controller was to prevent the electrolyzer to be switched to the standby mode when a short disruptions of solar radiation ($G < G_{\min}$) during the middle of the day occurs (provided that $\text{SOC} > \text{EL}_{\text{low}}$). Instead, the user can specify an idling current $I_{\text{idle}}$ at which the electrolyzer was to operate when the situation ($G < G_{\min}$) occurs. However, as the case in actual system, $I_{\text{idle}}$ should always be greater than the minimum electrode protective current.

Furthermore, when the electrolyzer operated on the excess power on the busbar ($E_{\text{ly,mode}} = 3$), another check must also be performed. If the excess power on the busbar (at some point during the course of the day) was less than minimum power required in the standby mode, the electrolyzer must operate in the idling mode.

### 4.8 Simulation results

Simulation results of the solar hydrogen hybrid system were divided into two parts; short- and long-term performance analysis. Short-term analysis concentrated only on the fuel cell and battery and illustrated how the battery can operate with the fuel cell unit to meet the transient changes in the load demand. In long-term performance analysis, the simulation based on the models investigated the energy analysis of the solar hydrogen hybrid system topologies based on Kuching (Malaysia) weather condition.
Figure 4.5: Solar hydrogen hybrid system modelling with TRNSYS

To well visualize the simulation of the system for long-term operation, figure 4.5 represents the whole modelling of the solar hydrogen hybrid system, comprising the system components, as well as the printers and plotters used for the analysis using TRNSYS. The TRNSYS system includes a data file (wind speed, solar radiation and load data every hour) 60kW of PV arrays, a Master Controller, the hydrogen system (an electrolyzer of 70kW, 70m$^3$ of hydrogen storage facility, 10kW of fuel cells and the corresponding power conditioning devices) and different calculators required for the modelling of the system. This is simply due to the fact that the Master Controller used in TRNSYS is designed to control only one fuel cell at the time.

Figures 4.6 show simulation results for solar hydrogen system in Kuching site. The solar radiation varied according to the season. During the period of low solar
Figure 4.6: Simulation results of the solar hydrogen system in Kuching site
radiation (raining weather), the SOC of hydrogen storage dropped because the hydrogen production during the daytimes was lower than the consumption during the nighttimes. In sunny day, the hydrogen production was higher than the hydrogen consumption, thus, the SOC of hydrogen storage increased. From these figures in 4.6, the fuel cell and electrolyzer operated almost all the year. Thus, the numbers of start operations for these components were approximately equal to the number of the days of the year. At night, the fuel cell operated to compensate the deficit in PV generator energy. During the day’s light, the electrolyzer operated to produce hydrogen which was stored to be consumed nightly.

4.8.1 Electrolyzer control

Three arbitrarily selected days (17-19 September) with different insolation and user load profiles described in Figure 4.7 were selected for the two scenarios. Sunday 17 September was a day with high insolation, while the user load was at constant low. On Monday 18 September the insolation level was lower and more irregular, while the user load was higher, compared to the Sunday. On Tuesday 19 September the insolation was quite high, except for a drop around noon, while the user load was about the same as on Monday.

The electrolyzer control actions depended on the mode of operation. This can be illustrated by looking at two different scenarios. In both of these two scenarios, the SOC thresholds were the same (EL\textsubscript{up} = 90\% and EL\textsubscript{low} = 80\%) while the electrolyzer day time operation period was 5am -9pm. (STARTCLK = 5h and STOPCLK = 21h).
(A) Scenario 1

Figure 4.7: Power from MPPTs and power to user load inverter (17-19 September)

Figure 4.8: Fixed electrolyzer current mode (E_{\text{mode}} = 2) for scenario 1 (17 – 19 September)
Figure 4.9: Variable electrolyzer current mode \((E_{\text{ly,mode}} = 3)\) for scenario 2 (17 – 19 September)

In this scenario the electrolyzer was operated in the fixed current mode \((E_{\text{ly,mode}} = 2)\). Hence, a significant amount of current passed in/out of the battery shown in Figure 4.8a. The power required by the electrolyzer was almost constant. On Sunday the electrolyzer was switched on at 11am as the battery SOC passed 90% while it was switched off at 6pm because the battery SOC at that time dropped below 80%.

On Monday the SOC never reached 90%, hence the electrolyzer was never switched on. On Tuesday there was less power available from the MPPTs than on Sunday and the electrolyzer was not switched on before 12pm, while it was switched off at 4pm shown in Figure 4.8b.
(B) Scenario 2

In this scenario, the electrolyzer was operated in the variable current mode ($\text{Ely}_{\text{mode}} = 3$). Hence, practically no current passed in/out of the battery in Figure 4.9a. The power required by the electrolyzer varied, depending on the excess power available on the busbar Figure 4.9b On Sunday the electrolyzer was switched on at 11am as the battery SOC passed 90% but it was not switched off until 9pm because the SOC was still greater than 80% (it was switched off at 6pm in scenario 1). However, at 9pm STOPCLK was reached, and the electrolyzer was switched off. In the hours 6-9pm on Sunday, the excess power on the busbar dropped below a minimum, and the electrolyzer was switched to the idling mode in Figure 4.9b.

On Monday the SOC never reached 90%, hence the electrolyzer was never switched on. On Tuesday there was less power available from the MPPTs, and the electrolyzer was not switched on before 12pm. This is similar to that observed in scenario 1. However, since the electrolyzer in scenario 2 only operated on the excess power on the busbar ($\text{Ely}_{\text{mode}} = 3$), the battery SOC did not drop below 80%. Thus, the electrolyzer did not need to be switched to the idling mode before 6pm. The electrolyzer was switched off at 9pm (STOPCLK) on Tuesday (as on Sunday) Figure4.9b.

(C) Scenario 3

In this scenario the electrolyzer was operated in the fixed current mode ($\text{Ely}_{\text{mode}} = 2$). On 2 October 2006 the electrolyzer was switched on at 10am and off at 12pm, due to the disruption in insolation (power from the MPPTs) which caused the battery SOC to drop below 80%.
Figure 4.10: Fixed electrolyzer current mode (E_y mode = 2) for scenario 3 (2 October)

At 2pm the insolation increased, and as a result the SOC rose again. At 4pm the SOC was above 90% and the electrolyzer was switched on for a second time that day. It was switched off at 6pm in Figure 4.10b. On disadvantages with the control scheme chosen in this scenario was the increased charging/discharging activity in the battery in Figure 4.10a. However, the main drawback was that the battery SOC temporarily drops below EL_{low} during the middle of the day, which caused the electrolyzer to be switched off for several sunshine hours. As result, no hydrogen was produced; even through the sun was shining.
(D) Scenario 4

Figure 4.11: Variable electrolyzer current mode ($E_{ly, mode} = 3$) for scenario 4 (2 October)

In this scenario the electrolyzer operated in the variable current mode ($E_{ly, mode} = 3$). The electrolyzer was switched on at 10am and off at 9pm. In other words, it operated continuously for 11 hours shown in figure 4.11b. In comparison, the electrolyzer run time was only 5 hours in scenario 3. Another advantage with $E_{ly, mode} = 3$ was that only a small amount of current was drawn from the battery in Figure 4.11a.

At 1pm, the electrolyzer was switched to the idling mode, due to the temporary disruption in insolation and some currents were drawn from the battery. A closer look at the battery conditions at 12pm revealed that the final SOC is higher in scenario 4 than in scenario 3. As a consequence, the battery SOC in scenario 4 will reach $E_{ly, up}$ earlier in the morning of the next day than in scenario 3.
Figure 4.12: Hydrogen flow from the electrolyzer (input to H₂ buffer), hydrogen flow through the compressor (output from H₂ buffer), and pressure in the H₂ buffer for scenario 5 (11-12 September)

(D) Scenario 5

In this scenario the control actions of the compressor that compressed the hydrogen gas from the low-pressure H₂ buffer up to the high pressure H₂ storage was illustrated. Two days (11-12 September) were arbitrarily selected in figure 4.12. In scenario 5 the compressor was switched on when the pressure ρ was greater than 5 bars (ρ > ρ_up), while it was switched off when the pressure dropped below 3 bar (ρ < ρ_low).

4.8.2 Fuel cell control

An example of a four days period (4-7 August 2006) with low insolation shown in figure 4.13 was selected to illustrate the on/off switching of the fuel cell. Two different fuel cells modes of operation were investigated below in scenario 6 and 7. In both of these two scenarios the battery SOC threshold for the on/off switching of the fuel cell were the same (FC_low = 45% and FC_up = 55%).
(F) Scenario 6

Figure 4.13: Power from the MPPTs and user load for a 4-day period with low insolation (4-7 August 2006)

Figure 4.14: High fuel cell H₂ supply ($V_{H2,FC} = 4 \text{Nm}^3\text{h}^{-1}$) for scenario 6 (4-7 August 2006)
Figure 4.15: Low fuel cell H₂ supply ($V_{H₂,FC} = 1.5$ Nm$^3$h$^{-1}$) for scenario 7 (4-7 August 2006)

In this scenario a relatively high hydrogen flow rate set point ($V_{H₂,FC} = 4$ Nm$^3$h$^{-1}$) was chosen. The average fuel cell power at this setting was about 5.3kw. The fuel cell was switched on three times. Each time the fuel cell was switched off, ac current was drawn from the battery to supply the user and hence the battery SOC slowly dropped below 45% in Figure 4.14a

In scenario 6 the fuel cell needed to be switched on/off three times, due to the low insolation the first three days of the period shown in figure 4.14b. The fuel cell run time (number of operations hours) each time was 9, 12, and 15hours. Hence the total hydrogen consumption for the period was $4 \times 36 = 144$ Nm$^3$. 

110
(I) Scenario 7

In this scenario a quite low hydrogen flow rate set points \( V_{H2,FC} = 1.5 \text{ Nm}^3\text{h}^{-1} \) was chosen. This gave an average fuel cell shown in figure 4.15b. The fuel cell run time in this scenario was 80h, which is about twice that of the total run time in scenario 6.

Hence, the total hydrogen consumption in scenario 7 was \( 1.5 \times 80 = 120 \text{ Nm}^3 \). This was not directly comparable to scenario 6 (144 Nm\(^3\)) because the final battery SOC in scenario 6 was slightly higher than scenario 6. However, the results indicate that, for given set of FC\(_{low}\) and FC\(_{up}\), there should exist an optimal \( V_{H2,FC} \).

4.8.3 Typical week simulation results

The week (16 – 22 October) selected here was a week with a typical user load profile show in figure 4.16. The load was lower during night time than day time, while it remained constant during the weekend. Furthermore, the load profile had a small peak in the morning, before it settled at a relatively constant level later in the day.

The solar radiation varied independently of the load. Hence, the power from the PV-arrays (conditioned in the MPPTS) will vary stochastically with time. The insolation during the week (16 – 22 October) varied from medium high (Monday) to low (Tuesday – Thursday) and back to high (Friday – Sunday).

During the period with low insolation the battery SOC dropped below 45% (FC\(_{low}\)), and the fuel cell was switched on. About 8 hours later, on Thursday afternoon, the SOC was greater than 55% (FC\(_{up}\)), and the fuel cell was switched off. The SOC did not reach 90% (EL\(_{up}\)) until Saturday morning. At that time the electrolyzer was switched on.
Figure 4.16: Total power from MPPTs and power to user load inverter (16 – 22 October)

Figure 4.17: Control actions for fuel cell and electrolyzer in variable current mode (16 – 22 October) for battery SOC and voltage

Figure 4.18: Control actions for fuel cell and electrolyzer in variable current mode (16 – 22 October) for net battery current, current to electrolyzer, and current from fuel cell converter
Figure 4.19: Control actions for fuel cell and electrolyzer in variable current mode (16 – 22 October) for battery SOC, electrolyzer power and fuel cell power

During the weekend, when the user load was at a constant low, the insolation was high. Since the electrolyzer in this case operated in the variable current mode ($E_{ly,mode} = 3$), practically all of the power from the MPPTs could be used to run the electrolyzer shown Figure 4.18. This gave an ideal simulation for high hydrogen production.

An analysis of the battery SOC and voltage shown in Figure 4.17 and charging/discharging current showed that battery in essence experiences one complete cycle (from high to low to high SOC) at relatively moderate currents.

The advantage of operating the electrolyzer in the variable current mode ($E_{ly,mode} = 3$) was that a high (and constant) battery SOC is maintained during the daytime, even when the electrolyzer was switched on. This fact was clearly illustrated by the shaved peaks of the SOC curve on Saturday and Sunday.

The depth of the battery cycle depended mainly on $F_{C}^{low}$ and $V_{H2,FC}$. From a battery SOC point of view, the specific fuel cell settings chosen seemed to be acceptable shown Figure 4.19.
4.8.4 Typical year simulation results

A summary of annual results for a typical simulation was given in Figure 4.21. The simulation system was performed at one hour time steps, which for the reference year 2004 (leap year) gave a total of 8,784 hours.

(A) Solar radiation and user load

As indicated by the power output from the maximum power points tracker (MPPTs) for the PV arrays, the periods with most stable solar radiation input occurred during the months April – September, where April was a particularly good month shown in Figure 4.20. The same solar radiation was used as input in all of the simulations presented in this chapter. These mean that the total powers from the MPPTs to the busbar were approximately the same in all of the simulations.

(B) Battery condition

A plot of the variation of the battery SOC and voltage showed how these generally are at a higher level during the sunny and raining period. However, on a few occasions (in February and December) the SOC rose to unacceptable high levels, and some energy (0.16MWh) needed to be dumped to an external source. However, this situation occurred only when the electrolyzer was switched off depends on the intermittent weather condition. A closer look at the battery conditions revealed that the SOC in Figure 4.21 was in the range 80 – 90% about 52% of the time. The battery SOC operating range was 44-99%, while the average SOC was 75%. The corresponding battery voltages were 225-260V, and 233V. Finally, it should be noted that the battery had about 7 deep discharges (SOC < 50%) during the period of March to October, but operated in this range only 9% of the time.
(C) Fuel cell and electrolyzer operation

A plot of the power produced by the fuel cell (input to the converter) and the power consumed by the electrolyzer (output from the converter) showed that the electrolyzer operates much more often than the fuel cell in Figure 4.22. In fact, the electrolyzer had 156 starts and the 61 starts for the fuel cell. Another interesting note was that the fuel cell only needed to be switched on four times during the period of March to October. The fuel cell operating power fixed at 6kw, while the electrolyzer which operated in the power range 0.8-21.7kw, had an average power of 7.5kw. The total electrolyzer run time for the period of March to October was 1,411 hours, while the total standby time was 4,469 hours. The average run time was 9 hours. In other words, when the electrolyzer was switched on, it remains switched on for several hours. This was a direct result of the fact that the electrolyzer was operated in the variable current mode ($E_{ly\text{mode}} = 3$).

(D) Hydrogen storage

The fluctuations in the pressure of the high-pressure hydrogen storage ($H_2$ storage) varied with hydrogen produced by the electrolyzer and the hydrogen consumed by the fuel cell. The pressure in the $H_2$ storage was lowest (7 bar) around March and at highest (114 bar) around October shown in figure 4.23. Thus, the utilization of the $H_2$ storage capacity was good, as the maximum pressure was rated to the 120 bars. The pressure in the $H_2$ buffer varied between 3 to 5 bars. In the simulations, as in actual system, the final pressure of the $H_2$ storage at the end of the year $\rho_{H_2,\text{final}}$ should equal to the initial pressure at the beginning of the year $\rho_{H_2,\text{ini}}$. For a given system with a known user load and solar radiation input, the only way to make $\rho_{H_2,\text{final}} = \rho_{H_2,\text{ini}}$ can be used as a measure in the optimization of the control strategy.
Figure 4.20: Total power from the MPPTs (upper curve) and power to the user load inverter in the simulation system

Figure 4.21: Typical annual results for a simulation for battery SOC (upper curve) and battery voltage

Figure 4.22: Typical annual results for a simulation for fuel cell power (upper curve) and electrolyzer power
Figure 4.23: Typical annual results for a simulation for pressure levels in high pressure H₂ storage and H₂ buffer

4.8.5 Total system analysis

The annual energy consumptions/production and efficiencies of the various components and subsystems of the simulation scenario results showed that about one third of the energy produced by the PV arrays went to the production of hydrogen in the electrolyzer, one third went to battery charging, and one third directly went to cover the user load. The overall system efficiency was about 58%.

The hydrogen system efficiency was about 21% which is somewhat low. The reason for this that the fuel cell was operated at a high hydrogen flow set point $V_{H₂,FC}$ which gave a high power supply, but low energy efficiency. The optimal setting of $V_{H₂,FC}$ was investigated later. The battery had the capacity (300 kWh at 220V) to supply the user continuously with power for about 4-5 days (average user load was about 501 kWh per day) without receiving any power from the PV arrays or fuel cell. This explained why such a large amount of energy passed through the battery. The average energy efficiency of the battery was about 91%.
The total volume of the high-pressure H₂ storage tanks was 26.8 m³, which gave a maximum capacity of about 2,900 Nm³, while the H₂ consumption in the fuel cell was about 3,350 Nm³. In other words, there was a hydrogen deficit about 650 Nm³ over the year. However, as it will be demonstrated below this deficit can be turned into a surplus by carefully choosing an optimal control strategy.

### 4.8.6 Optimal control strategies

**(A) Electrolyzer mode of operation**

An analysis of the basic control strategy for the electrolyzer showed that the overall system performance depended on the setting of the battery SOC thresholds $E_{\text{Lup}}$ and $E_{\text{Llow}}$ and on the electrolyzer mode of operation $E_{\text{Lmode}}$. A comparison between a wide and a narrow electrolyzer hysteresis ($\Delta E_{\text{L}} = E_{\text{Lup}} - E_{\text{Llow}}$) for the fixed current mode ($E_{\text{Lmode}} = 2$) was performed in scenario 3 ($\Delta E_{\text{L}} = 10\%$) and scenario 4 ($\Delta E_{\text{L}} = 5\%$). The results showed how a reduction in $\Delta E_{\text{L}}$ gave an increase in the number of electrolyzer starts from 135 to 238, but decreased the average run time from 6.0 to 3.4 h.

**(B) On/Off switching for the electrolyzer**

The electrolyzer was in the standby mode all year around. The energy required to operate the electrolyzer in the stand by mode was not included in the simulation, but a simple calculation showed that a hydrogen quantity of 63 NM³ can produce about 84 kWh of electricity energy from the fuel cell. This energy from the fuel cell was not sufficient to cover the energy that would have been required to operate the electrolyzer four months in the standby mode. Figure 4.24 illustrated the simulation result for the electrolyzer in stand by mode.
(C) Hydrogen supply flow set point for the fuel cell

The difference between a high and a low hydrogen supply flow set point $V_{H_2,FC}$ was illustrated in Figure 4.24. The overall system performance for three values for $V_{H_2,FC}$ was presented. The results show that a low $V_{H_2,FC}$ that was a low fuel cell power output $P_{FC}$ gave relatively few fuel cell starts and a long average fuel cell run time. The opposite was true for a high $V_{H_2,FC}$. Furthermore, a reduction in $V_{H_2,FC}$ also reduced the annual hydrogen consumption in the fuel cell. Since the hydrogen productions in the electrolyzer were about the same, the final pressure in the $H_2$ storage was bound to be greater.

An analysis of the above results was best explained by performing an overall energy balance on the busbar:

$$E_{MPPT} + E_{FC} - E_{Ely} + E_{batch} - E_{bat,dch} - E_{load} - E_{dumped} = 0$$

where $E$ is the annual energy flow and the subscripts symbolize the maximum power point trackers, the fuel cell, the electrolyzer, the battery charging and discharging, the user load and the dumped energy respectively.
(D) Full storage scenario

In this scenario the H₂ storage and the battery were both almost full (99%) and the power from the PV arrays exceeds the total load. If this scenario occurred when the electrolyzer and compressor were running the following control actions must be taken:

1. H₂ in the high pressure storage is vented out through a safety valve.
2. The PV arrays are disconnected.
3. The electrolyzer is switched off.
4. The compressor is switched off.

If this scenario occurred during a period when the electrolyzer was shut down for the season (that was only a protective current was maintained), it was sufficient to disconnect the PV arrays until the battery SOC dropped to an acceptable level. In the simulations the control actions needed in this scenario were simplified compared to those needed in an actual system. In the first case (the electrolyzer is running) only control action number 1 was taken (H₂ is vented out). This occurred at \( f_{\text{H2}} = 0.99 \). In the second case (electrolyzer switched off for the season) the excess power was simply dumped from the busbar (to an imagined resistive load). This occurred at SOC = 99%

(E) Empty storage scenario

In this scenario the H₂ storage and the battery were both almost empty and the total load exceeds the power from the PV arrays. With the assumption that the fuel cell was allowed to operate all year round, this scenario will always occur when the fuel cell is running. Thus, if this scenario occurred the following control actions must be taken:
1. The load is disconnected (blackout)
2. The fuel cell is switch off.

In the simulations, no advanced control scheme was followed if this scenario occurred. Instead, the simulation was simply stopped. This scenario usually occurred when the initial level in the H₂ storage f₁₁₂,ini was set too low. A quick fix to this problem was to simply reset f₁₁₂,ini to at a higher value. The simulation was then rerun. A criterion for a successful simulation was that there were no or very few occurrences of full storage scenario. The above process was therefore repeated until a satisfactory simulation result was found (f₁₁₂,final ≥ f₁₁₂,ini). Usually, only 2-3 iterations were needed.

4.9 Conclusions

The main conclusions that can be drawn from the above simulations are:

1. It is more optimal to operate the electrolyzer in a variable power mode (where it runs on the excess power on the busbar) than in a fixed power or fixed current mode (where it uses battery power if needed).
2. If the electrolyzer must operate in a fixed current or fixed power mode it should run at a moderate power and not at full power. This will significantly reduce the use and, hence the wear of the battery.
3. The upper electrolyzer threshold EL_up should be set relatively high (90%) and the hysteresis ΔEL should be quite small (5%). However, the setting of ΔEL is most crucial if the electrolyzer is operating in a fixed power or fixed current mode.
4. A smart control strategy for on/off switching of the electrolyzer is recommended. A weather forecasting system should be included. This system could indicate the electrolyzer to go from the standby mode to the idling mode (needed for warm-up) only on days that are expected to give high insolation. A solar clock that tells the system to switch back to the standby mode at sunset is also recommended.

5. It is recommended the fuel cell operate at the highest energy efficiency possible (at the lowest H₂ supply flow feasible). In a system that does not permit frequent operation medium high power (at a medium high efficiency).

6. For a fixed fuel cell hydrogen supply flow (and fixed power) the lower fuel cell threshold FClow should be relatively low, but always higher than the lowset allowable battery SOC (45%), while the hysteresis ΔFC should be quite small (5%). However, care must be taken so that the fuel cell run time does not drop below a minimum number of hours (2h) or that no other system component limits are violated.
5. BALANCING COST OF SOLAR HYDROGEN STAND-ALONE POWER SYSTEM

5.1 Introduction

Recent advances in hydrogen fuel cell technologies have enabled new energy options for supplying electrical power in stand-alone remote areas. This study showed the way to design the aspects of a hybrid power system that will target remote users. It emphasized the hydrogen hybrid power system to obtain a reliable autonomous system with the optimisation of the components size and the improvement of the capital cost.

Assuming that reliable, low-maintenance systems can be designed, solar hydrogen power systems are expected to first become competitive in remote locations in which electricity is expensive because there are no links to power grids serving the main urban areas. This investigation also examined the conditions under which these systems might be economically competitive in these areas. The aim of this analysis was to determine under which conditions solar PV systems could feasibly power electrolyzers to generate and store hydrogen for remote power generation using fuel cells.

The system concerned with an investigation of the cost related to hydrogen hybrid system. A methodology was developed for calculating the correct size of the system and for optimizing the management. The main power for the hybrid system comes from the photovoltaic panels, while the fuel cell and secondary batteries are used as backup units at night time.
5.2 Method of system analysis

In this investigation, the optimization software Hybrid Optimization Model for Electric Renewables (HOMER) was used to analyse a small 20kWp remote village power system. HOMER is a design model that determines the optimal architecture and control strategy of a hybrid system. It can also determine the sensitivity of the outputs to changes in the inputs. It performs an hourly time series analysis on each of hundreds or thousands of different system configurations.

HOMER performs comparative economic analyses on a distributed generation power systems. Inputs to HOMER like load profile and solar radiation data will perform the hourly simulation of every possible combination of components entered and rank the systems according to user-specified criteria, such as cost of energy (COE) or capital costs. Furthermore, HOMER can perform “sensitivity analyses” in which the values of certain parameters such as fuel cell cost are varied to determine their impact on the COE.

To obtain the input data for HOMER, hydrogen component information was collected from research literature and manufacturers. These data with the HOMER can also calculate the present and future of hydrogen system costs and efficiencies in term of

1. The technology’s investment costs and technical features;

2. Their useful life and maintenance requirement;

3. The qualities of energy required annually;

4. The cost of the energy produced by the various plants.
5.3 Solar hydrogen system description and their associated costs

As for medium-scale systems, such as small villages, the renewable systems may only contribute a fraction of the energy, with the primary load being served by a diesel generator. The cost of energy is often high in these regions because diesel is a relatively expensive means of producing electricity. Because of the extreme remoteness of most of these communities and the lack of roads, the delivered cost of diesel fuel is high, ranging from $0.26 to $0.79 per litre. In addition, the high operations and maintenance (O&M) costs of diesel-generating stations contribute to electric generation costs that average nearly $0.40/kWh and can be as high as $1.00/kWh [Hollmuller et al., 2000]. Furthermore, the environment pollution from the diesel generator’s emission is the other important issue to be concerned.

Therefore in this chapter, it will examine the technical feasibility and balancing cost of an autonomous solar hydrogen renewable energy system at two locations in this study. The first location was Kuching, Sarawak (1° 29’ N, 110° 43’ E). The other location will be in Perth, Western Australia (31° 58’ S, 115° 49’ E). Both systems used the same systems’ size of the electrolyzer, fuel cell, hydrogen storage and rechargeable batteries to supplement the PV arrays. They were examined to determine

1) Whether hydrogen systems are competitive today;
2) At what cost hydrogen systems will become economically competitive;
3) When hydrogen systems are likely to become competitive.

The schematic figure for the system is listed in Figure 5.1. The assumptions and system properties are described in detail as follow.
Figure 5.1: Schematic of the remote village load

(A) Operating Principle
The theory of operation was to use the PV system to directly meet the load whenever possible to minimize the losses in the battery and fuel cell. When excess PV energy was available, power was supplied first to the batteries, and then to an electrolyzer, which consumed water to generate hydrogen for storage. The batteries or the fuel cell was then used to meet the load when the solar energy was insufficient. HOMER decided whether to use energy from the battery, fuel cell, or both based on the replacement cost and O&M of the devices. Because this analysis neglected O&M and because the fuel cell was not replaced during its lifetime, HOMER used the full extent of the fuel cell capacity for this system before using the rechargeable batteries.

(B) Load
Load data were obtained from system specifications. The station had an annual average AC load of 180 kWh/d. The summer load average (October through March) was 240 kWh/d, and the winter average (April through September) was 120 kWh/d.
in Perth. The daily load profile was not available, so HOMER was used to estimate load profile using the duty cycles available in the specifications. Daily and hourly noise values of 12.2% were employed in HOMER; resulting in a maximum load of $20W_p$. HOMER also allowed input of the operating reserve for the system. The operating reserve was the surplus generation capacity used to compensate for rapid fluctuations of load and sunshine. The amount of operating reserve was specified as a percentage of hourly load and renewable resources. For the results reported here, the operating reserve was required to be 10% of the hourly load, plus 25% of the PV power output.

(C) Resources
Solar radiation and clearness data for these locations were derived from the TRNSYS 16.0 weather TMY2 (Typical Metrological Year) database. The annual average global radiation in Perth and Kuching was 5.344 kWh/m²/day and 4.649 kWh/m²/day respectively, with an annual average clearness index of in Perth and Kuching was 0.614 and 0.46, respectively. The overleaf figures showed all the sites’ solar radiation that needed for the simulation study.
Table 5.1: Perth Solar radiation data (latitude 31°58’ South, longitude 115°49’)

<table>
<thead>
<tr>
<th>Month</th>
<th>Clearness Index</th>
<th>Daily Radiation (kWh/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.698</td>
<td>8.350</td>
</tr>
<tr>
<td>February</td>
<td>0.666</td>
<td>7.300</td>
</tr>
<tr>
<td>March</td>
<td>0.612</td>
<td>5.690</td>
</tr>
<tr>
<td>April</td>
<td>0.576</td>
<td>4.200</td>
</tr>
<tr>
<td>May</td>
<td>0.530</td>
<td>2.990</td>
</tr>
<tr>
<td>June</td>
<td>0.527</td>
<td>2.570</td>
</tr>
<tr>
<td>July</td>
<td>0.541</td>
<td>2.820</td>
</tr>
<tr>
<td>August</td>
<td>0.532</td>
<td>3.490</td>
</tr>
<tr>
<td>September</td>
<td>0.576</td>
<td>4.880</td>
</tr>
<tr>
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<td>0.601</td>
<td>6.220</td>
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<td>November</td>
<td>0.641</td>
<td>7.480</td>
</tr>
<tr>
<td>December</td>
<td>0.675</td>
<td>8.250</td>
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</table>

Figure 5.3: Daily radiation and clearness index in Perth

Table 5.2: Kuching Solar radiation data (latitude 1°29’ North, longitude 110°43’)

<table>
<thead>
<tr>
<th>Month</th>
<th>Clearness Index</th>
<th>Daily Radiation (kWh/m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>0.401</td>
<td>3.970</td>
</tr>
<tr>
<td>February</td>
<td>0.434</td>
<td>4.460</td>
</tr>
<tr>
<td>March</td>
<td>0.440</td>
<td>4.610</td>
</tr>
<tr>
<td>April</td>
<td>0.482</td>
<td>4.950</td>
</tr>
<tr>
<td>May</td>
<td>0.499</td>
<td>4.880</td>
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<tr>
<td>June</td>
<td>0.534</td>
<td>5.050</td>
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<tr>
<td>July</td>
<td>0.509</td>
<td>4.870</td>
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<tr>
<td>August</td>
<td>0.495</td>
<td>4.950</td>
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<tr>
<td>September</td>
<td>0.458</td>
<td>4.740</td>
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<tr>
<td>October</td>
<td>0.459</td>
<td>4.720</td>
</tr>
<tr>
<td>November</td>
<td>0.451</td>
<td>4.490</td>
</tr>
<tr>
<td>December</td>
<td>0.421</td>
<td>4.100</td>
</tr>
</tbody>
</table>
(D) Operations and Maintenance

In this analysis, the operations and maintenance costs was considered for the fuel cell and electrolyzer. For the fuel cell, the O&M was assumed to cost around $.0033/hour/kW. The O&M for the electrolyzer system was estimated to be 7% of the annual capital cost per year, or $245/yr.

(E) PV Arrays

This scenario was modelled with PV panels fixed at a slope of 15° in Kuching and 25° in Perth. The installed cost of a 1-kW (peak) PV array ranges between $6.00/W and $10.00/W. The baseline capital cost of the PV in this study was $8.00/W. Lifetimes were assumed to be 20 years.

(F) Fuel Cells

A PEM fuel cell was selected for this study. The cost of fuel cells varied widely depending on scale, power electronics requirements, and reformer requirements. A
survey performed by [Korpaas, Hildrum & Holen, 2003] identified three types of fuel cells that currently sell for between $3,000/kW and $6,000/kW. One high-temperature membrane technology currently being pursued is expected to have a membrane life of greater than 20,000 hours and an overall installed fuel cell system cost of less than $1,500/kW for initial commercialization by 2008 and ultimately $400/kW for large markets by 2010. Stationary fuel cells are targeted to last 30,000 to 40,000 operating hours, during which the membrane will likely have to be replaced one or more times.

Stationary fuel cells are targeted to last 30,000 to 40,000 operating hours, during which the membrane will likely have to be replaced one or more times. This study was assumed the fuel cell would last 30,000 hours. The baseline capital cost used for this study is $5,000/kW for the radio repeater (because of its very small scale). The efficiencies of PEM fuel cells running on pure hydrogen were roughly 40% to 50% (lower heating value) at rated power with slightly higher values at partial load. The electrical efficiency used for this study was held constant at 45% to compensate for parasitic losses, which occur at partial load.

(G) Electrolyzers

Proton exchange membrane (PEM) electrolyzers from Proton Energy Inc. were used to obtain a cost estimate of a stand-alone (“hydrogen by wire”) electrolyzer. The system used to obtain a $/kW cost for electrolyzers is six units of Hogen 40 6-kW electrolyzer. It included the PEM stack, power electronics, and control system. The current production cost of the Hogen 40 was approximately $16,000 or $2,700/kW. Projected costs were expected to be approximately $700/kW within 10 years. Cost
reductions were expected to stem from improvements in the PEM stack, power electronics, control system, and manufacturing improvements such as replacing fittings with welded tube assemblies. These costs assumed the production of 500 units per year. A profit margin of 30% was added to these costs to estimate the purchase price of the electrolyzer [Xin, Khambadkone & Soy, 2005]. The total cost was around $3,500/kW. The installation cost was deemed to be negligible because the HOGEN 40 was a self-contained unit. The efficiency of electrolyzers using the higher heating value was estimated to be between 70% and 85%. A constant value of 83% (70% using the lower heating value) was used for this study. The electrolyzer was assumed to last 20 years.

Feed water and cooling water were required for the electrolyzer. To avoid contaminating the electrolyzer, feed water should be purified and deionised. Small, remote systems may use a storage tank; larger systems (rest areas, homes) can draw from existing water lines. Water treatment systems need regular maintenance such as filter cartridge replacement. The cost of a filter cartridge system and O&M for the remote village was neglected as the water use in the electrolyzer was small. The PV-fuel cell-battery system used approximately 4 gallons per year, and the system that consumes the most water was the PV-fuel cell system, which uses approximately 35 gallons per year. In addition, a water recycling system between the fuel cell and electrolyzer could also reduce the amount of water needed if necessary.

Conventional electrolyzers produced hydrogen at low pressure (100-200 psi). Compressors were used to elevate the pressure for gas storage. However, 2,500-3,000 psi production pressures have been demonstrated recently at Proton energy and
were expected to be in production in the very near future; targets are upward of 6,000 psi. In addition, The U.S. Company, Avalence, had demonstrated an electrolyzer technology that can produce hydrogen at pressures up to 10,000 psi. Such technologies will likely eliminate the need for compressors. Accordingly, this study assumed that a compressor was not required.

(H) Hydrogen Storage

Hydrogen can be stored several ways. Small amounts of hydrogen are most commonly stored as a compressed gas or as a metal hydride. Compressed gas storage is currently the most cost-effective for small-scale system tanks, so it is used for this study. The small-quantity prices were around $1,320/kg with long-term targets of $165/kg [Connelly, 2004]. These cost reductions of small-scale storage are likely to result from automotive research into compressed hydrogen storage.

(I) Inverter

An inverter converts DC voltage and current, from the PV / fuel cell system into AC Sine wave power. For this study, the inverter costs were included the costs of Sunnyboy inverter, isolation transformer, AC disconnect switch, DC disconnect switch, combiner box, 15 ADC 600V fuse. The Sunny boy inverters were reliable, easy to install and have an efficient design, with over 95% peak efficiency for the inverter, and overall efficiency including transformer losses, in excess of 93% [Goh, 2004]. The rest of the electric power was converted into heat. It was assumed that the capital costs and the replacement costs were the same; details were shown in Table 5.3.
(J) Rechargeable Battery

Normally batteries are used to store excess electricity for the RE system and to operate the system when power from RE system is insufficient or absent. With the existing of electrolyzer and fuel cell in the stand-alone power system, rechargeable batteries just acted as secondary sources to start up the system components when emergency cases occurred [Golovatov & Berber, 2003]. Two manufacturers that have deep cycle lead acid batteries in their line up that are frequently used in renewable energy applications: Rolls Battery and Trojan Battery Company. An overview of the prices of these selected batteries for this study is given in Table 6.4.

A deep cycle battery is designed to provide a steady amount of current over a long time period of time. It can provide a surge when needed and it has the ability to be deeply discharged and charged many times during its service life. This is what makes a deep cycle battery ideal for powering electrical equipment for long periods of time. The advantage of lead acid batteries is their interesting costs, the facility of maintenance and the fact they are be recycled at a high rate. (97% of the lead is recycled and reused in new batteries).

A battery charger allows the PV generator to charge the battery if the electricity from the RE system is insufficient; and it is used for maintenance. The purchasing costs of the battery included the prices of the battery, the battery charger and the battery strings. The remote village used 15 units of Trojan T-105 deep-cycle batteries with two in parallel for a nominal voltage of 12V. Each 6V battery had a rated capacity of 360Ah. The average cost of the battery system was $930 per battery, or $166/kWh.
Table 5.3: The selected input data in HOMER concerning the inverters

<table>
<thead>
<tr>
<th>Inverter Size (kW)</th>
<th>Capital Costs ($)</th>
<th>Replacement ($)</th>
<th>O &amp; M ($/yr)</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>12,083</td>
<td>12,083</td>
<td>115</td>
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<tr>
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<tr>
<td>30</td>
<td>27,155</td>
<td>27,155</td>
<td>340</td>
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Table 5.4: The different batteries used in HOMER

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Num of battery</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O &amp; M ($/yr)</th>
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<tr>
<td>Trojan L16P</td>
<td>1</td>
<td>385</td>
<td>345</td>
<td>5</td>
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<tr>
<td>Trojan T-105</td>
<td>1</td>
<td>165</td>
<td>109</td>
<td>5</td>
</tr>
<tr>
<td>Surrette 6CS25P</td>
<td>1</td>
<td>1,080</td>
<td>1,020</td>
<td>25</td>
</tr>
<tr>
<td>Surrette 4KS25P</td>
<td>1</td>
<td>1,190</td>
<td>1,135</td>
<td>30</td>
</tr>
</tbody>
</table>

5.4 Economic analysis

In this part, the capital, replacement and O&M costs of the main components present in a solar hydrogen hybrid system was illustrated. The capital costs included the cost to purchase, to install, and to transport the components and the training costs. The capital costs also encompassed the costs of a feasibility study that included system design and engineering and site investigations. Also take in account the feasibility costs in the economic inputs window of HOMER. PV modules have an anticipated 20 year lifetime. Therefore project lifetimes (the length of time over which the costs of the system occur) of 20 years were chosen. The project lifetime was used to calculate the annualized replacement cost and annualized capital cost of each component, as well as the total net present cost of the system [Gilreath, Singh & Rastgoufard, 2003].
(A) The Annual Real Interest Rate

The annual real interest rate is the discount rate used to convert between one-time costs and annualized costs. The annual real interest rate is related to the nominal interest rate by the equation given below:

\[ i = \frac{i' - f}{1 + f} \]

where \( i \) is the real interest rate, \( i' \) is the nominal interest rate (the rate at which could be loaning), \( f \) is the annual inflation rate.

According to National Renewable Energy Laboratory (NREL) recommendation, assume the nominal interest rates of 5% and 10% and the inflation rate was around 1.5%; so it will deal with the annual interest rates of respectively 3.4% and 8.4%. So in HOMER simulation, assume that all prices inflate at the same rate. To analyse the economic soundness of the different studied systems, the levelized cost of energy (COE) and the Net Present Value (NPV) will be included.

(B) Levelized COE

The COE that is the ratio between the total cost per year of the system and the power it supplies over the same period. The costs to be included are of two types:

(I)Fixed costs of construction and installation
(II)Variable operating and maintenance costs

To evaluate the fixed costs, those are the depreciation value of the equipment, the assumption of the lives of the system and of the principal components were needed. The fixed costs are calculated at year zero, so need to discount them back to every year. Similarly, the replacement costs had to be firstly discounted to year zero, and
then discounted back to every year so as to be summed to capital expenses [Chowdhury & Rahman, 1988]. Levelized replacement costs in the systems included replacement of rechargeable batteries. The levelized COE ($/kWh) can therefore be obtained from:

\[
Levelized \ COE = \left( \frac{C_F \times CRF + C_{OM} + C_R \times PVF \times CRF}{N_{kw}} \right)
\]

where \( C_F \) is the initial capital cost, \( C_{OM} \) is the annual operating and maintenance costs, \( C_R \) is the replacement costs, PVF is the present worth factor (based on discount rate \( i = 5\% \)), \( N_{kw} \) is the annual generation, CRF is the capital recovery factor (also based on discount rate \( i = 5\% \))

CRF is calculated using the following equation:

\[
CRF = \frac{i}{1-(1+i)^{-L}}
\]

where \( i \) is the annual real interest rate, \( L \) is the project lifetime (assume 20 years).

(C) The Net Present Value

The Net Present Value (NPV) gives an indication on how profitable a certain project is. The NPV of the project is the value of all future cash flows, discounted at the real interest rate. Under the NPV method, the present value of all cash inflows is compared against the presented value of these cash flows, called the NPV, determines whether or not the project is generally an acceptable investment. Positive NPV values are an indicator of a potentially feasible project.

\[
NPV = \sum_{j=1}^{L} \frac{B_j - C_j}{(1-i)^j}
\]

where \( B_j \) are the total annual benefits in year \( j \) and \( C_j \) are the total annual costs in year \( j \), \( i \) is the annual real interest rate, \( L \) is the lifetime of the project.
Many activities consist of an initial investment, followed by an annual net benefit that is constant in time. In that case, the calculation of the net present value is highly simplified making use of the capital recovery factor.

\[
NPV = -I \times \frac{B - C}{CRF}
\]

where I is the initial investment.

5.5 System cost optimization

The theory of system operation for this system was to use the PV arrays supplemented by the fuel cell or batteries to meet the load. HOMER will decide whether to use energy from the battery, fuel cell, or both based on the replacement cost and O&M of the devices. In this simulation, HOMER used the full extent of the fuel cell capacity for this system before using the batteries. When excess PV energy was available, power was routed first to the batteries (in a load following strategy), then to the electrolyzer. Usually, batteries were used to store energy for the short term (efficiency 70%) and hydrogen allowed the energy storage over the seasons. The round trip efficiency were about 40% (electrolyzer 80% + gases storage 100% + fuel cell 50%).

In the optimization process, HOMER simulated every system configuration in the search space and displayed the feasible ones in a table, sorted by total net present cost. Hence it showed a subset of these overall optimization results by displaying only the least-cost configuration within each system category or type. The focus of the site analysis was on low-hydrogen-penetration systems in which a relatively small hydrogen component was used to supplement the PV array. Another possible system configuration was to use a high-hydrogen-penetration system that relied
primarily on the PV array and fuel cell to provide the village power. To limit the simulation time to a reasonable figure, separate simulations were performed to examine the feasibility of low- and high-hydrogen-penetration systems.

(A) Perth results

The least cost solution of system architecture for the PV-FC-BAT system in Perth consisted of 90kW BP solar panels, 10kw PEMFC, 70kW electrolyzer, 80kg H₂ Tank, 15 units of Battery Trojan L16P and 20kw inverter. The electrolyzer was designed in such way that it provided enough electricity to completely store the energy produced by the PV arrays, so that the load was covered during the month of June (the month of the least radiation). So with this data, a PV array typically produced very few electricity. This causes the huge increased of the total system cost investment. For the final low-hydrogen-penetration simulation, HOMER examined 120 possible solutions by the combining components listed figure 5.5. The components of the high-penetration system were identical to the low-hydrogen-penetration system except that 50% of the fuel cell waste heat was routed to the thermal load, which increased the overall efficiency of the fuel cell to about 63%.

The PV-FC-BAT system was highly oversized and required $936,830 as investment costs and created electricity at a cost $1.408/kWh. This clearly more expensive when compare with the conventional diesel system which only needs $1.007/kWh shown in Table 5.5. But for PV-FC-BAT system, it reduced a lot of pollutant emission especially for carbon dioxide. The PV-Diesel-Bat system still produced the amount of 28,080 (kg/yr) of Carbon dioxide although its renewable fraction reached 0.832. So it was a good opportunity to replace the diesel generator by the hydrogen power/storage system in future.
### Sensitivity Results

<table>
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<td>90</td>
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<td>80</td>
<td>$344,300</td>
<td>$1,112,685</td>
<td>1.418</td>
<td>1.00</td>
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<td>4.20%</td>
<td></td>
<td></td>
</tr>
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<td>15</td>
<td>30</td>
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<td>0.00</td>
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<td>1.00</td>
<td>0.00</td>
<td>4.25%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5.5:** HOMER optimization simulation results of the PV-FC-Battery system sample in Perth

![Cash Flow Summary](image)

**Figure 5.6:** Typical daily load profiles (demand in kW) of the PV-FC-Battery system sample in Perth

139
Table 5.5: The lists results for the total least cost solution of hybrid system in Perth

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>PV-Diesel-Bat</th>
<th>PV-FC-Bat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Capital</td>
<td>$652,830</td>
<td>$936,830</td>
<td></td>
</tr>
<tr>
<td>Operating Cost ($/yr)</td>
<td>$14,667</td>
<td>$17,681</td>
<td></td>
</tr>
<tr>
<td>Total NPC</td>
<td>$840,328</td>
<td>$1,162,855</td>
<td></td>
</tr>
<tr>
<td>Levelized COE</td>
<td>$1.007/kwh</td>
<td>$1.408/kWh</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.6: The capital cost for each system relative to the PV-FC-Battery system in Perth.

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O &amp; M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
<th>Total ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>630,000</td>
<td>196,347</td>
<td>0</td>
<td>0</td>
<td>-110,092</td>
<td>716,345</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>30,000</td>
<td>27,479</td>
<td>54,662</td>
<td>0</td>
<td>-2,289</td>
<td>109,851</td>
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<tr>
<td>Battery</td>
<td>1,830</td>
<td>6,793</td>
<td>767</td>
<td>0</td>
<td>-369</td>
<td>9,021</td>
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<tr>
<td>Converter</td>
<td>15,000</td>
<td>6,259</td>
<td>0</td>
<td>0</td>
<td>-1,165</td>
<td>20,094</td>
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<td>Electrolyzer</td>
<td>140,000</td>
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<td>0</td>
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<td>Hydrogen Tank</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>120,000</td>
</tr>
<tr>
<td>Total System</td>
<td>936,830</td>
<td>295,385</td>
<td>55,429</td>
<td>0</td>
<td>-124,788</td>
<td>1,162,855</td>
</tr>
</tbody>
</table>

(B) Kuching results

For Kuching simulation study, the system architecture still remained the same shown in Table 6.7 to have better significant comparison with the Perth one. The technical design for the PV consisted of a 20kw inverter that mean a capacity equal to the peak load. Further, the 90kWp PV panel was sufficient to carry the daily load and an electrolyzer with the capacity of 70kW that could provide the system with at least 3 days of autonomy.

The system was oversized due to the intermittent character of the solar radiation and so the investment were high with the COE 1.363$/kWh. It was slightly cheaper than the Perth system due to the four season’s weather condition. In Kuching, the constant solar irradiation can be obtained for whole year except in the raining session.
Figure 5.7: Typical daily load profiles (demand in kW) of the PV-FC-Battery system sample in Kuching

Table 5.7: The capital cost for each system relative to the PV-FC-Battery system in Kuching

<table>
<thead>
<tr>
<th>Component</th>
<th>Capital ($)</th>
<th>Replacement ($)</th>
<th>O &amp; M ($)</th>
<th>Fuel ($)</th>
<th>Salvage ($)</th>
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<tbody>
<tr>
<td>PV</td>
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<td>716,345</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>30</td>
<td>29,204</td>
<td>59,507</td>
<td>0</td>
<td>-633</td>
<td>118,077</td>
</tr>
<tr>
<td>Battery</td>
<td>1,83</td>
<td>6,164</td>
<td>767</td>
<td>0</td>
<td>-140</td>
<td>8,621</td>
</tr>
<tr>
<td>Converter</td>
<td>15</td>
<td>6,259</td>
<td>0</td>
<td>0</td>
<td>-1,165</td>
<td>20,094</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>120</td>
<td>50,072</td>
<td>0</td>
<td>0</td>
<td>-9,32</td>
<td>160,752</td>
</tr>
<tr>
<td>Hydrogen Tank</td>
<td>120</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>120</td>
</tr>
<tr>
<td>Total System</td>
<td>916,83</td>
<td>288,136</td>
<td>60,274</td>
<td>0</td>
<td>-121,35</td>
<td>1,143,890</td>
</tr>
</tbody>
</table>

Table 5.8: PV-FC-Battery System Architecture in Kuching

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td></td>
<td>90kW</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td></td>
<td>10kW</td>
</tr>
<tr>
<td>Battery Trojan L16P</td>
<td></td>
<td>15 units</td>
</tr>
<tr>
<td>Inverter</td>
<td></td>
<td>20kW</td>
</tr>
<tr>
<td>Rectifier</td>
<td></td>
<td>20kW</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td></td>
<td>60kW</td>
</tr>
<tr>
<td>H₂ Tank</td>
<td></td>
<td>80kg</td>
</tr>
</tbody>
</table>
Figure 5.8: The power output of PV-FC-Battery system in Kuching

Table 5.9: The lists results for the total least cost solution of hybrid system in Kuching

<table>
<thead>
<tr>
<th>Cost</th>
<th>PV-Diesel-Bat</th>
<th>PV-FC-Bat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Capital</td>
<td>$653,220</td>
<td>$916,830</td>
</tr>
<tr>
<td>Operating Cost ($/yr)</td>
<td>11,794</td>
<td>17,762</td>
</tr>
<tr>
<td>Total NPC</td>
<td>$802,985</td>
<td>$1,143,889</td>
</tr>
<tr>
<td>Levelized COE</td>
<td>$0.957/kWh</td>
<td>$1.363/kWh</td>
</tr>
</tbody>
</table>

Replacement of the conventional system by a PEMFC can keep the system reliability of supply at the same level while decreasing the environmental impact of the whole system. Furthermore, gas (H₂ and O₂) storage that can be sized for seasonal operation thus increasing the performance ratio of the PV part. The AC primary load profile, stored hydrogen, battery state of charge and other results in Kuching system were attached in the appendix section.
5.6 System comparison

In this study considered two extremes of technology: inexpensive lead acid batteries and diesel generator and costly hydrogen power system (fuel cell, electrolyzer and hydrogen tank). The advantages of adding a fuel cell to the system were long lifetime (relative to batteries) and relatively inexpensive long-term storage. Table 5.10 summarizes the most important findings for the base system, solar-diesel and solar hydrogen system based on Perth and Kuching weather. The base system (diesel only) produced 64,787 kWh/year and released 96.8tCO₂ per year. All RE systems in table 5.10 at least produced 83 to 100% renewable electricity and reduced the GHG emissions.

Depending on the choice and maturity of batteries and diesel generator, fuel cells may or may not be economically competitive for systems at this moment. From Table 5.10, it showed that the COE of the PV-FC-Battery system was about 50% higher compared with the PV-FC-Battery system. On an economic basis, if fuel cells and electrolyzer costs dropped to approximately 30% of their current values, hydrogen systems could theoretically entirely replacing the conventional diesel/batteries under many conditions, despite their lower round-trip efficiency and relatively high cost. However, at present prices for fuel cells and electrolyzers, most optimum systems have batteries because their fast discharge rates facilitate smaller fuel cells. When using inexpensive lead acid batteries, fuel cells and electrolyzer costs need to drop to at least 25% of their current values to become economically competitive. Even then, the increased complexity of including a hydrogen system will likely favour the choice of systems without hydrogen systems.
Table 5.10: The summary of the different hybrid power system in Perth and Kuching

<table>
<thead>
<tr>
<th>System Configuration</th>
<th>solar-diesel (Perth)</th>
<th>solar hydrogen (Perth)</th>
<th>solar-diesel (Kuching)</th>
<th>solar hydrogen (Kuching)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV panels (kW_p)</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Diesel generator (kW)</td>
<td>15</td>
<td>15</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Fuel cell (kW)</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Electrolyzer (kW)</td>
<td>-</td>
<td>70</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>Hydrogen Storage (kg)</td>
<td>-</td>
<td>80</td>
<td>-</td>
<td>80</td>
</tr>
<tr>
<td>Inverter (kW)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Batteries (units)</td>
<td>10</td>
<td>10</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Investment ($</td>
<td>840,328</td>
<td>1,162,855</td>
<td>805,577</td>
<td>1,143,889</td>
</tr>
<tr>
<td>Levelized COE ($/kWh)</td>
<td>1.007</td>
<td>1.408</td>
<td>0.960</td>
<td>1.363</td>
</tr>
<tr>
<td>Ren Fraction</td>
<td>0.832</td>
<td>1.00</td>
<td>0.832</td>
<td>1.00</td>
</tr>
<tr>
<td>GHG emission reduction (tCO2/year)</td>
<td>28.2</td>
<td>-15.9</td>
<td>18.2</td>
<td>-16.9</td>
</tr>
</tbody>
</table>
5.7 Summary

This chapter has focused on the economic costs of hydrogen investment, and only briefly discussed the broader picture of full environmental and social costs. However, it should be recognized that at present there is an inherent bias toward hydrogen investment options that have the highest environmental and social costs. This is because many of these costs are “externalities” that are not presently valued in energy and fuel markets. Thus, in deciding on hydrogen investments as the development of the hydrogen economy unfolds, analyzing these options in ways that value as many of their actual environmental and human health impacts as possible will be important.

During the day, the PV array produces much more power than needed by the load, with the surplus going to the electrolyzer. Overnight, the fuel cell serves the load while drawing hydrogen from the storage tank. In the winning system, the hydrogen tank starts the year full and ends the year empty. That system would therefore probably not be able to serve the load as well in its second year as in its first. Introduction of an electrolyzer, powered by the PV generator is used to produce the fuel for the PEMFC.

The round-trip efficiency of the hydrogen storage system is less than 50%. Because so much power is lost in the storage system, the energy production of the PV array must greatly exceed the electrical load. The fuel cells could be economically competitive in hybrid systems in 2010. As fuel cells will likely reach the price point, considering installed stationary fuel cell targets are $400/kW by the year 2010.
6. Conclusions and future recommendations

6.1 Summary of findings and conclusions

The system studied was mainly focused on the use of solar radiation as energy input to the hydrogen energy system. Hydrogen production from renewables had autonomous operation, with re-electrification through fuel cells when the PV arrays were not operated at night time or intermittent weather. In addition, the main focus was put on modelling and simulation the hydrogen energy stored operation.

The objective of this thesis had been achieved. The system that was analyzed has given a picture of the potential of using solar hydrogen systems for optimizing renewable energy in Kuching and Perth. This study had illustrated the potential of a hydrogen and fuel cell storage system for electricity from solar photovoltaic energy in the remote villages compared with a PV/diesel/battery system. With the analysis, this system not only worked effectively but also to provide a global environmental friendly solution for the future.

Replacing diesel and battery generation in stand-alone power system with a hydrogen energy system in the renewable energy market will be the trends in future, especially for the locations where electricity transportation and distribution losses are high. In a solar hydrogen system, efficiency losses along the hydrogen energy chain amplify emissions associated with systems. CO$_2$ specific emissions can be reduced significantly. The difference between the battery and the fuel cell system laid in the environmental concerns of the two energy storage systems. It concluded that the fuel cell system is a more
environmental system than the battery because the material that used together with the high reliability and effective operation gives a greater lifetime.

6.2 Modelling of solar hydrogen stand-alone power system components

Detailed descriptions of the individual component models required to simulate a solar hydrogen hybrid system are presented. These models were mainly based on electrical, electrochemical and thermodynamics relations. However, a number of empirical relationships for some models were also used. The models of PV generator, PEM fuel cell, alkaline water electrolyzer, and power conditioning units were discussed in details, while rechargeable battery and storage tank were presented by the simple models. All of the models, with lack of data could be run in simpler modes. Several short-term simulations were performed, such that the I-V characteristics, hydrogen production and consumption rates, and other physical processes of the individual component models are evaluated. Below was a list of the main conclusions that could be drawn from the evaluation of the key solar hydrogen components models:

1. PV generator

Three PV generator models were studied in this thesis: one-diode, two-diode analytical model, and thermal model.

1 A one-diode was more than accurate enough for both long-term and short-term simulation purposes, as long as the PV operating range was limited to voltages less than or equal to the maximum power point.
2. A two-diode model was not recommended due to the complexity of parameter numbers.

3. A thermal model that accounted for dynamic behaviour of the temperature of a PV-array was only required for short-term simulations for one day in Kuching. The inclusion of wind speed in the calculations was not essential in this study. Thus, the linear model was used in this work.

2. PEMFC

The PEMFC were modelled by using analytical equations and including empirical aspects, when the theoretical analysis was either too complicated or the parameters are not accessible. The parameters of these models were determined for practical units. A simplified empirical relationship describing the I-V fuel cell characteristics for comparing the voltage drop off. \( \text{H}_2/\text{O}_2 - \text{PEMFC} \) had less voltage-drop-off compared with \( \text{H}_2/\text{Air} - \text{PEMFC} \) at high current densities.

3. Electrolyzer

The thermal behaviour of an electrolyzer was modelled using a lumped capacitance model. This model will be accurate if an empirical relationship for the overall heat transfer in the heat exchanger was included at high electrical current densities.

4. Rechargeable Battery

A relatively simple steady-state model can be used to simulate the battery charging / discharging with reasonable accuracy for SOC in the range of 40 to 100%. The advantage
of a simple battery model was that the parameters easily can be retrofitted to an actual battery of a system in full operation.

5. Power conditioning units

In this thesis, three empirical PCU models, which are linear, quadratic, and piecewise linear, were studied. The quadratic model was used to represent all the PCUs. Two different inverter types, Sunny and Trace, were used in the hydrogen PVFC hybrid system.

6.3 Simulation of solar hydrogen stand-alone power system

In this study, a complete model for solar hydrogen stand-alone power system had been implemented in computer codes and utilized to predict its operational performance through numerical simulation. The TRNSYS simulation environment had been selected for this work because it included an advanced library for the system components called HYDROGEMS. This library had been developed by Institute for Energy Technology, Norway and comprised a number of hydrogen energy models, which were used in solar hydrogen hybrid systems technology.

6.4 Optimization of the operation of solar hydrogen system

Optimization of the operation of solar hydrogen systems that could be drawn from the integrated system simulations is:

1. An electrolyzer that has to be used in a solar hydrogen system, or any other kind of system based on intermittent energy, should be designed to operate in a variable power mode.
2. An electrolyzer that is designed to operate in a fixed power mode only should always run at moderate power and not at full power, as this will reduce wear of the battery.

3. It is recommended that the fuel cell possibly operates at the highest energy efficiency. In a system that does not permit frequent operation at low battery SOC, the H$_2$ supply should be fixed so that the fuel cell operates at a medium high power.

In order to design and optimize the practical and energy efficient solar hydrogen system the following step are recommended:

1. The expected solar radiation and wind speed for the site in selection should be determined from long-term data.

2. The user load should be determined and measured to reduce the load to a minimum.

3. A system configuration based on the components characteristics should be selected and followed by a detailed analysis of the operation of the system.

4. A systematic methodology on modelling and verification of the models and the simulation which had been developed in chapter 4 and 5 should be performed.

5. It is possible to redesign the system configuration if this step shows that it can reduce the sizes of the initially selected components.

6. Determine the economical cost analysis for several alternatives were recommended in chapter 6.

7. A combined optimization of the design and operation (step 4-6) was investigated.

Instead, it is recommended that a combined optimization be performed for a few selected alternative designs based on the needs and requirements of the user and on the availability of the resource.
6.5 Recommendation for improved design and future work

The design of a solar hydrogen stand-alone power system for a given location with a known insolation is extremely dependent on the load. To enhance the performance of solar hydrogen stand-alone power system, the following recommendations for future work are proposed:

- Replacement of the low-pressure electrolyzer with a high-pressure electrolyzer

This electrolyzer could eliminate the need for a compressor to compress hydrogen into high pressure and, thus the volume of the gas storage tank is decreased. Other concept is to store the hydrogen in metal hydride (MH), that replacing the compressed hydrogen gas storage with low pressure ambient temperature metal hydride storage. The greatest advantage of the MH-storage is that it can be coupled directly to a low pressure electrolyzer, thus eliminating the compressor. It is not possible to give an absolute recommendation about which of these two concepts to chose. The choice of the suitable concept should be based on the type of application. For the application with small power requirements, hydrogen storage in low-pressure near-ambient temperature metal hydrides seems to be a favourable option.

- Inclusion of a wind turbine or micro-hydro

Adding other renewable sources, such as a wind turbine or micro-hydro to the system. The additional renewable sources would reduce the required PV generator area, and reduce the hydrogen storage volume, and may even eliminate the need for PV entirely. A trade-off between PV generator area, wind generator size and micro-hydro is an
interesting challenge for systems located at sites with high average wind speeds and strong water flow stream.

- Investigate the application of H₂/O₂ PEM fuel cell and Air/H₂ PEM fuel in power generation sector.

  The H₂/O₂ PEM fuel cell has a better performance than the Air/H₂ PEM fuel cell which is used in this work, but requires a storage tank for oxygen and a purification system. Thus, it is recommended to study using H₂/O₂ PEM fuel cell with the solar hydrogen hybrid system and evaluate the system according to the cost point of view.

- Design and optimization of stand-alone fuel cell power systems.

  The investigation of this topic is appropriate for remote power applications and would involve investigation of energy storage technologies, system dynamic response, and optimal fuel cell/battery sizing. Preliminary investigation reveals that weekly simulation of battery state-of-charge is necessary to accurately size the component.

- Comparison of SOFC (high temperature) and PEMFC (low temperature) technology for small-scale stationary applications.

  These two types of fuel cells are considered to be the most attractive and viable options for small-scale stationary applications. The relative advantages of one over the other would be an attractive option for further research study.
o Define the hydrogen production and storage from renewable energy sources

Hydrogen from Renewable Energy Sources is the only fully sustainable pathway. Renewable energy-based hydrogen produced from this is an important issue for consideration and a more detailed investigation in terms of performance, economics and practicality would be necessary.

o Designing a new power conditioning units that can match the characteristics for the fuel cell.

A practical limitation on the system design is the voltage operating range of the available power conditioning units, which are designed mainly for lead-acid batteries rather than fuel cells. As a result, an optimum energy utilization of the fuel cells could not be achieved.

o Establish a simulation tool for the different control strategies in computerised form.

With the establishment of the simulation tool, the actual system costs of the hybrid renewable system can be calculated and the optimal goal function can be chosen in real-time mode, by the sophisticated control algorithm.
REFERENCES


27 HYDROGEMS user guide 2001, Institute for Energy Technology


41 Masters, GM 2004, Renewable and efficient electric power systems, John Wiley & Sons.


APPENDICES

Appendix A: Components Simulation Parameters

This appendix contains manufacturer specifications and data sheets for the system components of the solar hydrogen hybrid system under study.

(A) PV Model

Below is a list of the parameters of the equations of the main component models developed in chapter 4 and used in the software simulation in chapter 5.

\[
I = I_L - I_D - I_{SH} = I_L - I_0 \left[ \exp \left( \frac{q}{\gamma k T_c} (V + IR_s) \right) - 1 \right] - \frac{V + IR_s}{R_{SH}}
\]

The PV parameters below are for a single PV module (150 cells in series) of the PV array

One-diode model (equation 4.1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{c,ref}$</td>
<td>25°C</td>
</tr>
<tr>
<td>$G_{T,ref}$</td>
<td>1000 W/m²</td>
</tr>
<tr>
<td>$I_{SC,ref}$</td>
<td>2.664 A</td>
</tr>
<tr>
<td>$V_{OC,ref}$</td>
<td>87.72 V</td>
</tr>
<tr>
<td>$I_{mp,ref}$</td>
<td>2.448 A</td>
</tr>
<tr>
<td>$V_{mp,ref}$</td>
<td>70.731 V</td>
</tr>
<tr>
<td>$\mu_{Voc}$</td>
<td>-0.3318 V/K</td>
</tr>
<tr>
<td>$T_{c,ref}$</td>
<td>44°C</td>
</tr>
</tbody>
</table>

Two-diode model (equation 4.10)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{gap}$</td>
<td>1.17 eV</td>
</tr>
<tr>
<td>$k_0$</td>
<td>0.002631 A/m²/W</td>
</tr>
<tr>
<td>$k_1$</td>
<td>690</td>
</tr>
<tr>
<td>$k_2$</td>
<td>0.014</td>
</tr>
<tr>
<td>$R_S$</td>
<td>0.0145 Ω</td>
</tr>
<tr>
<td>$R_{SH}$</td>
<td>10 Ω</td>
</tr>
<tr>
<td>$\beta_0$</td>
<td>$5.59 \times 10^{-4} \text{C}^{-1}$</td>
</tr>
<tr>
<td>$\gamma_1$</td>
<td>1 V/J</td>
</tr>
<tr>
<td>$\gamma_2$</td>
<td>2 V/J</td>
</tr>
</tbody>
</table>
Thermal Mode (equation 4.14)

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>30 J/Km²</td>
</tr>
<tr>
<td>$U_L$</td>
<td>50000 J/m²</td>
</tr>
<tr>
<td>$T_{a, NOCT}$</td>
<td>20 °C</td>
</tr>
<tr>
<td>$T_{C, NOCT}$</td>
<td>44 °C</td>
</tr>
<tr>
<td>$G_{T, NOCT}$</td>
<td>800 W/m²</td>
</tr>
</tbody>
</table>

Mono-crystalline Photovoltaic Module Electrical Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power ($P_{max}$)</td>
<td>85W</td>
</tr>
<tr>
<td>Voltage at $P_{max}$, ($U_{mpp}$)</td>
<td>18.0V</td>
</tr>
<tr>
<td>Current at $P_{max}$, ($I_{mpp}$)</td>
<td>4.72A</td>
</tr>
<tr>
<td>Warranted minimum ($P_{max}$)</td>
<td>80.8W</td>
</tr>
<tr>
<td>Short-circuit current ($I_{sc}$)</td>
<td>5.0A</td>
</tr>
<tr>
<td>Open-circuit voltage ($U_{oc}$)</td>
<td>22.1V</td>
</tr>
<tr>
<td>Temperature coefficient of current</td>
<td>(0.065±0.015)%/°C</td>
</tr>
<tr>
<td>Temperature coefficient of voltage</td>
<td>-(80±10)mV/°C</td>
</tr>
<tr>
<td>Temperature coefficient of power</td>
<td>-(0.5±0.05)%/°C</td>
</tr>
<tr>
<td>NOCT</td>
<td>47±2°C</td>
</tr>
</tbody>
</table>

(B) Fuel Cell

The fuel cell parameters below are for a single fuel cell (of the 26 cells placed in series per stack) in the PEMFC stack. The parameters given here are for a high and low temperature. A linear interpolation to find the parameters for operation between these temperatures can be used:

<table>
<thead>
<tr>
<th>Power Data</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical rated power</td>
<td>2kW (2 × 1kW)</td>
</tr>
<tr>
<td>Maximum electric power</td>
<td>3kW (2 × 1.5kW)</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>2 × ca. 48V</td>
</tr>
<tr>
<td>Rated electric current</td>
<td>34A</td>
</tr>
<tr>
<td>Rated electric voltage</td>
<td>30V</td>
</tr>
<tr>
<td>Maximum electric current per stack</td>
<td>60A</td>
</tr>
<tr>
<td>Hydrogen consumption at rated electric power</td>
<td>Ca. 1.6Nm³/h (every stack 0.8Nm³/h)</td>
</tr>
<tr>
<td>CHP coefficient at operating point</td>
<td>0.92</td>
</tr>
<tr>
<td>Power peripheral supply</td>
<td>Max. 10A at 24V$_{DC}$</td>
</tr>
<tr>
<td>Fuel Gas Supply</td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Operating pressure of hydrogen</td>
<td>20 – 40kPa</td>
</tr>
<tr>
<td>Maximum operating pressure of hydrogen</td>
<td>50kPa</td>
</tr>
<tr>
<td>Connection pressure of hydrogen</td>
<td>500kPa</td>
</tr>
<tr>
<td>Tube/flexible tube diameter for hydrogen supply</td>
<td>High-grate steel, outside diameter 10mm</td>
</tr>
<tr>
<td>Hydrogen loss through sink cycle</td>
<td>40kPa per purge (0.3s) ca. 570ml</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width × depth × high</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permissible ambient temperature</td>
</tr>
<tr>
<td>Permissible relative humidity</td>
</tr>
</tbody>
</table>

(C) Electrolyzer

The parameters are for the alkaline electrolyzer as a whole:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.25 m²</td>
</tr>
<tr>
<td>a₁</td>
<td>-9.5788 m²/A</td>
</tr>
<tr>
<td>a₂</td>
<td>0</td>
</tr>
<tr>
<td>R</td>
<td>0.167kW⁻¹</td>
</tr>
<tr>
<td>τ₁</td>
<td>29 h</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Supplier</th>
<th>Hydrogen Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>30 Cells of 150cm², Zero gap Alkaline Technology</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>30bar</td>
</tr>
<tr>
<td>Nominal Voltage and Intensity</td>
<td>60V- 60A</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>2 to 40°C</td>
</tr>
<tr>
<td>Electrolyte Temperature</td>
<td>85°C (max)</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>KOH (30 wt. %)</td>
</tr>
<tr>
<td>Maximum Power</td>
<td>3.6kW</td>
</tr>
<tr>
<td>Module Conversion Efficiency</td>
<td>3.9kWh/Nm³</td>
</tr>
<tr>
<td>Current Density</td>
<td>400mA/cm² (max)</td>
</tr>
<tr>
<td>Hydrogen Production</td>
<td>0.8Nm³/h at 30bar</td>
</tr>
<tr>
<td>Purity of the Hydrogen</td>
<td>99.8%</td>
</tr>
<tr>
<td>Oxygen Production</td>
<td>0.4Nm³/h</td>
</tr>
<tr>
<td>Purity of the Oxygen</td>
<td>99.5%</td>
</tr>
<tr>
<td>Water Cooling of Cells</td>
<td>0.40L/h at 15°C</td>
</tr>
</tbody>
</table>
Appendix B: Oxygen and Air Usage

From the basic operation of the fuel cell, we know that four electrons are transferred for each mole of oxygen. So the charge equation is given as:

\[ \text{charge} = 4F \times \text{amount of O}_2 \]

Dividing by time, and rearranging the equation to be:

\[ \text{O}_2 \text{ usage} = \frac{I}{4F} \text{ moles / s} \]

This is for a single cell. For a stack of \( n \) cells, the equation for the \( \text{O}_2 \) usage is shown as:

\[ \text{O}_2 \text{ usage} = \frac{In}{4F} \text{ moles / s} \]

However, it would be more useful to have the formula in kg/s, without needing to know the number of cells, and in terms of power, rather than current. If the voltage of each cell in the stack is \( V_c \), then the equation for the power is stated as:

\[ P_e = V_c \times I \times n \Rightarrow I = \frac{P_e}{V_c \times n} \]

Substituting this into the previous equation:

\[ \text{O}_2 \text{ usage} = \frac{P_e}{4 \times V_c \times F} \text{ moles / s} \]
Changing from moles/s to kg/s, the equation becomes:

\[
\text{O}_2 \text{ usage} = \frac{32 \times 10^{-3} \times P_e}{4 \times V_c \times F} \text{ kg/s} = 8.29 \times 10^{-8} \times \frac{P_e}{V_c} \text{ kg/s}
\]

This formula allows the oxygen usage of any fuel cell system of given power to be calculated. If \( V_c \) is not given, it can be calculated from the efficiency, and if that is not given, the figure of 0.65V can be used for a good approximation.
Appendix C: Definitions of system performance indices

The long-term performance analysis of a hybrid system is important in order to understand its operation and to compare systems of different sizes and architectures. The analysis is done in two steps, accounting for two different aspects of the overall performance: energy system balances are established in order to determine mean operating efficiencies for each component and describe the performance of the hybrid system; then indices of system performance are calculated to be able to compare between the different topologies of the hybrid system. The so-called yields are normalised performance indicators obtained by dividing the relevant energy balances by a nominal reference value. Brief definitions of all parameters are described hereunder.

Energy System Balances

Simulation results of the hybrid system are used to calculate a certain number of parameters that characterize the system operation.

Total input energy $E_{in} = E_{PV,\text{out}} + E_{FCN}$ of a solar hydrogen stand-alone power system is defined as the sum of all contributions from the different energy sources, where $E_{PV,\text{out}}$ (kWh) is the total output energy of the PV generator, and $E_{FCN} = 3 \times (H_{2,\text{cons}} - H_{2,\text{prod}}) \times \eta_{fc} \times \eta_{\text{PCU,FC}}$ is the integral amount of energy that is drawn from the hydrogen storage by the fuel cell unit during the entire simulation duration. $E_{FCN}$ (kWh) is a net quantity; as it is positive when $H_{2,\text{cons}} > H_{2,\text{prod}}$ or zero when $H_{2,\text{cons}} \leq H_{2,\text{prod}}$. $H_{2,\text{cons}}$ and $H_{2,\text{prod}}$ (Nm$^3$) are the hydrogen consumption from the hydrogen tank by the fuel cell and the hydrogen production supplied by the electrolyzer to the hydrogen tank, respectively. $\eta_{fc}$ and $\eta_{\text{PCU,FC}}$ are efficiencies of the fuel cell and associated PCU, respectively. The number 3 in the
equation means that 1Nm³ from hydrogen corresponds to approximately 3kWh. The total input energy $E_{in}$ (kWh) serves as a reference value for the PV fraction of the total input energy $F_{in, PV}$.

PV generator fraction of the total input energy $F_{in, PV} = E_{PV, out} / E_{in}$ is the fraction of the total input energy that is produced by the PV generator.

Useful energy $E_{use} = E_L + E_{ELN}$ of a solar hydrogen stand-alone power system is the total output energy of the system which is supplied to a user load. $E_L$ (kWh) is the energy consumed by the user load and $E_{ELN} = 3 \times (H_{2, prod} - H_{2, cons}) \times \eta_{fc} \times \eta_{PCU, FC}$ is the net stored energy in the hydrogen storage during the entire simulation duration. $E_{ELN}$ (kWh) is also a net quantity; as it is positive when $H_{2, prod} > H_{2, cons}$ or zero when $H_{2, prod} \leq H_{2, cons}$.

PV generator part of the useful energy $E_{PV, use} = F_{in, PV} \times E_{use}$ is obtained from multiplying the PV generator fraction of the total input energy by the useful energy.

PV generator nominal energy $E_{PV, STC} = E_s \times A_{PV} \times \eta_{PV, STC}$,

where $E_s$ is the solar radiation (W/m²), $A_{PV}$ is the PV generator area (m²), and $\eta_{PV, STC}$ is the PV generator efficiency at Standard Test Conditions.

Mean operating efficiencies of all components are the quotient of energy output over energy input. These efficiencies can be easy calculated by knowing the input and output energy from all components. The overall balance of system BOS component performance can be calculated by $\eta_{BOS} = (E_L + E_{ELN} - E_{FCN}) / E_{PV, out}$.

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