
ENG 207-11: English for Engineering
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Dear Dr. Prescott,

We are submitting a multi-disciplinary engineering project report titled “Hydrogen Fuel Cells for Combined Heat-and-Power (CHP) Applications in Commercial and Residential Buildings: An Energy Saving Technology”. The report outlines work involving team members from various engineering disciplines.

This report deals with using hydrogen fuel cells in combined heat-and-power systems to provide a green and feasible solution to the energy crisis in the world. However, hydrogen fuel cells must be environmentally-benign, cost-effective, reliable, and safe in order to be commercialized.

The report illustrates findings from the mechanical, chemical, and civil engineering perspectives. The mechanical aspect of the project deals with thermodynamic efficiency, renewable energy systems, methods to provide and store hydrogen, and CHP cogeneration (see sections 3.3-3.5). The chemical aspect deals with designing the fuel cell, the chemical reactions that occurs inside a fuel cell, converting chemical energy into electrical energy, and properties of hydrogen (see sections 3.1 and 3.2). Finally, the civil engineering aspect is concerned with providing heating for green buildings and the distribution infrastructure of hydrogen (see sections 3.4 and 3.6). In order to carry out the project, the main problems had to be identified. One of the problems is the high cost of using fuel cells. Another problem is finding economical ways to produce, store, and distribute the hydrogen fuel. A primary solution to the fuel cells high cost problem is advising policy makers and increasing awareness among the public about the benefits of using hydrogen fuel cells. As shown in the report, fuel cells costs are gradually decreasing year after year due to growing usage (see appendices (A) and (G)). As for the hydrogen problem, hydrogen can be produced using renewable sources such solar photovoltaic panels (see section 3.4). Also, there are different methods of storing and distributing hydrogen as shown in the report’s findings (see chapter 3). But the two most well-developed and least expensive methods to store and distribute hydrogen are by using pressurized storage tanks and piping networks, respectively.

We used a wide variety of references for our project report including official websites, handbooks, books and e-books, peer-reviewed journal articles, conference proceedings, engineering databases, technical reports, periodicals, video demonstrations, and personal communication with engineering faculty.

Moreover, we wish to acknowledge Dr. David Prescott for providing insightful feedback on all the assignments that contributed to this project. The feedback strengthened the report. Also, we would like to thank Mrs. Jennifer Acorn for showing us how to research and find useful information about our topic using the new library search engine and engineering databases such as IEEE Xplore.

We hope that this report meets the criteria and guidelines assigned for constructing a multi-disciplinary engineering report. Should you have any further questions concerning our project or report, please feel free to contact us by e-mail at: b00031088@aus.edu

Sincerely yours,

Hydrogen Fuel Cells Team
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Glossary

**ALTERNATING CURRENT (AC)** is when the movement of electric charges periodically reverses direction. AC in the form in which electricity is delivered to businesses and residences.

**ANODE** is the electrode at which oxidation, or a loss of electrons, takes place. For fuel cells and other galvanic cells, the anode is the negative terminal.

**AUTOTHERMAL REFORMING (ATR)** is a combination of Steam Methane Reforming and Partial Oxidation.

**BIOPHOTOLYSIS**, also known as biophotoelectrolysis, is the photolysis of a biochemical compound; but especially the production of hydrogen by the action of light on algae or any other organism.

**CATALYST** is a substance, usually used in lesser amounts relative to the reactants, that modifies and increases the rate of a reaction without being consumed in the process.

**CATHODE** is the electrode at which reduction, or a gain of electrons, occurs. For fuel cells and other galvanic cells, the cathode is the positive terminal.

**COMBINED HEAT-AND-POWER (CHP)**, also known as cogeneration, is the combined production of electrical power and thermal energy from a primary source of energy.

**CRYOGENIC TANK** is a tank that is used to store liquid hydrogen at very low temperatures to prevent it from boiling.

**DIRECT CURRENT (DC)** is the unidirectional flow of electric charge. Thermocouples, batteries, fuel cells, and solar cells are common sources of DC.

**ELECTRICAL EFFICIENCY** is defined as the ratio of the useful electrical power output to the total required power input.

**ELECTRODE** is a conductor through which electrons enter or leave an electrolyte. Batteries and fuel cells have a negative electrode (the anode) and a positive electrode (the cathode).

**ELECTROLYSIS** is the separation of a liquid into its chemical components by passing an electric current through it.

**ELECTROLYTE** is a substance that conducts charged ions from one electrode to the other in a fuel cell, battery, or electrolyzer.

**GASIFICATION** is a process that converts organic or fossil based carbonaceous materials into carbon monoxide, hydrogen, carbon dioxide, and methane.

**GREENHOUSE GASES (GHGs)** are atmospheric gases that trap infrared radiation emitted from the earth, lower atmosphere, or clouds and, as a result, cause the greenhouse effect. The primary greenhouse gases in the Earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone.

**IGNITION ENERGY** is the minimum amount of energy required to ignite a combustible vapor, gas, or dust cloud.

**MICRO-CHP** refers to the application of a small-scale CHP system in a typical family residence or a small office building.

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1 Terms explained in the glossary are in **bold** font type in the report
THE SECOND LAW OF THERMODYNAMICS asserts that processes occur in a certain direction and that energy has quality as well as quantity.

PARTIAL OXIDATION (POX) is the process whereby hydrogen is produced through the partial combustion of oil or natural gas with oxygen gas to yield carbon monoxide and hydrogen.

PHOTOLYSIS, also known as photoelectrolysis, is the process of splitting water into hydrogen and oxygen using electric current generated from direct solar energy.

STEAM METHANE REFORMING (SMR) involves the endothermic conversion of methane and water vapor into hydrogen and carbon monoxide.

SUSTAINABLE DEVELOPMENT is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

THERMOCHEMICAL PROCESSES involve the study of heat and energy accompanying chemical reactions and/or physical transformations.

THERMOCHEMICAL WATER SPLITTING refers to the conversion of water into hydrogen and oxygen by a series of thermally-driven chemical reactions.
1 Introduction and Analysis of Situation

Supplies of fossil fuels are becoming increasingly scarce, expensive, and unstable as global energy demands keep rising and are expected to double by the year 2050 [1, 2]. As a result of heavy consumption of inexpensive, energy-dense fossil fuels, carbon dioxide and other greenhouse gases (GHGs) concentration levels in the atmosphere have reached the danger zone. This recklessness of the human race is going to have very serious consequences in the short-run if not faced with a serious and immediate stand. We are already facing some of these consequences depicted in global warming, climate change, acid rains, depletion of ozone layer, draughts, floods, rising sea level, and thawing permafrost all over the globe. For these and many other reasons, the utilization of the planet’s immense supplies of clean renewable energy has become more important than at any other time in the human history. Therefore, a steady and economic transition from a fossil fuel-based to a renewable-based economy has become a necessity for the wellbeing and continuity of the human race. This project report is an attempt to demonstrate how combined heat-and-power (CHP) hydrogen fuel cell systems used in the residential and commercial sectors could significantly facilitate this transition if provided with sufficient support from policy makers and the public.

In this project report we will try to answer two fundamental questions. The first question is: Why is replacing conventional combustion-based power plants that provide power and heat for the residential and commercial sectors with CHP hydrogen fuel cells advantageous? The second question is: How will the hydrogen powering the CHP fuel cells be produced, stored, and distributed?

36% of the total energy consumption in the US is directed to the residential and commercial sectors [3]. The energy consumed by residential and commercial applications comes mainly from coal-fired centralized power plants. These power plants:

1. Release large quantities of toxic pollutants to the environment.
2. Typically have low efficiencies of around 30%.
3. Are based on the limited supplies of fossil fuels in nature.
4. Are noisy and unsuitable for residential locations.

All these factors and others prompt us to develop a sustainable (refer to sustainable development), efficient, environmentally-benign, and quiet alternative energy system. Hydrogen fuel cells that provide both heat and power from CHP systems for residential and commercial applications are a strong candidate for this position, according to an interview with Dr. Mehmet Orhan. However, some technological, economical, and social problems are yet to be resolved in order for hydrogen fuel cells to step into the commercialization stage.
2 Identification and Discussion of Problems

2.1 Hydrogen Safety

Like any other fuel or energy carrier, hydrogen poses risks if not properly handled and controlled. Because hydrogen has the smallest molecule among all other elements, it has a greater tendency to escape through small openings than other liquid or gaseous fuels. Hydrogen has a very low ignition energy (0.02 mJ), about one order of magnitude lower than other fuels. Hydrogen has a flame velocity seven times faster than that of natural gas or gasoline [4]. Hydrogen flame is nearly invisible, which may be dangerous because people in the vicinity of a hydrogen flame may not even realize there is a fire. All these reasons make the safety of hydrogen gas storage in fuel cells a very sensitive issue. Moreover, liquid hydrogen presents another set of safety issues such as risk of cold burns and the increased duration of leaked cryogenic fuel. A large spill of liquid hydrogen has some characteristics of a gasoline spill; however, it will dissipate much faster. Another potential safety issue is violent explosions of liquid hydrogen expanding into vapor form in case of a pressure-relief-valve failure [4].

2.2 Dependence on Fossil Fuels

One of the major concerns about the development of fuel cells is the overdependence of nations on fossil fuels for producing power. This situation is more evident in the Middle East where oil and natural gas resources are very abundant. As a result, the governments of these countries do not grant sufficient resources to the research and development of hydrogen power and fuel cells. Hence, this slows down the development and commercialization of fuel cells.

2.3 Utilizing Waste Energy is Still Uncommon

During the CHP fuel cell reactions, the by-products are water and waste heat (further explained in sections 3.2 and 3.3). This waste heat could be used to heat up the domestic water supply or to provide space heating. If this waste heat is taken into account, the total efficiency of a fuel cell increases to 90%. However, the problem remains that the concept of “recycling” energy is still uncommon.
2.4 Higher Per-Unit-Power Cost Relative to Combustion-Based Systems

Lastly, current figures show that the cost per-kilowatt of electricity from hydrogen fuel cells is still quite high compared to power from combustion-based systems. The graph in Appendix (A) determines the expected trend over the years for the cost per-kilowatt of the commonly-used polymer electrolyte membrane fuel cell (PEMFC) (see section 3.2). Consequently, we can prove that it would require a couple of years for CHP fuel cells to reach a competitive cost to deliver electricity at residential areas [5].
3  Findings and Solutions

3.1  Why Hydrogen?

Fuel cells and hydrogen have the potential to reduce oil, gas, and coal usage as well as reduce harmful effects on the environment. Many companies, academic and governmental laboratories, universities and institutions, and engineer teams are eager to participate in this rapidly developing field. There are several reasons as to why there is a need to switch to a hydrogen-based economy [6]. Some of the main reasons are listed below:

1. Hydrogen is the most abundant element in the universe. Actually, hydrogen makes up about 75% of all matter [7].
2. The energy content of hydrogen is the highest per-unit-weight of any fuel [7].
3. Hydrogen is non-polluting. The only byproducts of hydrogen when it combines with oxygen in a fuel cell are heat and water.
4. Hydrogen could be harnessed in a clean and efficient way from water by means of breaking water into its oxygen and hydrogen components [8].

A full list of hydrogen physical and chemical properties is found in Appendix (F). Since fuel cells can use hydrogen as a fuel, they are viewed by many as the most promising solution for our critical global environment and energy problems [6].

3.2  Hydrogen Fuel Cells: Concept and Applications

3.2.1  Concept

Hydrogen fuel cells are a state-of-the-art technology capable of revolutionizing energy production in the future. Hydrogen fuel cells provide power that is clean, efficient, and quiet. This represents a promising alternative to the current combustion-based systems that consume gasoline and other fossil fuels.
A fuel cell uses the chemical energy stored in hydrogen to produce electricity along with water and heat as the only byproducts. A single fuel cell consists of an electrolyte and two electrodes: cathode and anode. The electrons are drawn from the anode to the cathode through an external circuit. As the electrons flow through the circuit, they produce electricity in the form of direct current (DC). A single fuel cell produces very small amounts of electricity, around 0.7 volts. So, usually cells are stacked and placed in series or parallel circuits to increase the output and meet the application’s power requirements. A fuel cell produces electricity without causing any pollution or noise, which makes it suitable for residential and commercial applications.

Figure (1) shows the chemical reaction that happens inside a fuel cell. The hydrogen protons pass through the membrane, while the electrons flow through the external circuit producing electric current. The hydrogen protons then react with oxygen to produce water. So, the outputs are electricity, water, and heat.

The design of a fuel cell system is complex and it can vary depending on the application. But in general, a fuel cell system consists of three basic components [9]:

1. Fuel cell stack: It is the main component of a fuel cell power system. A typical fuel cell stack may consist of hundreds of fuel cells. The power produced by a fuel cell depends upon many factors, such as fuel cell type, cell size, the temperature at which it operates, and the pressure at which the gases are supplied to the cell.

2. Current inverters and conditioners: Fuel cells produce electricity in the form of direct current (DC). Therefore, a current inverter is used to change the electricity to alternating current (AC). This is because a fuel cell is intended for residential
and commercial applications that use (AC) power. Moreover, the AC power must be conditioned to meet the needs of the applications.

3. Heat recovery system: Fuel cells generate heat, especially those that operate at high temperatures, such as solid oxide and molten carbonate systems. So this heat is used to produce steam or hot water which can drive a steam turbine to generate electricity. This method improves the overall efficiency of the system.

3.2.2 Types

The main difference in fuel cell types is the electrolyte. There are around 20 different types of cells, but the most common types applicable to residential and commercial applications are PEM and SOFC. PEM fuel cells can be used in small residential units as a result of their suitable size, weight, and volume. On the other hand, SOFC fuel cells can be used for commercial buildings’ applications since they are big and have higher power outputs and elevated operation temperatures. Appendix (B) provides a comprehensive comparison between the most common fuel cell technologies [10].

3.3 Combined Heat and Power (CHP) Generation

3.3.1 Overview of CHP Systems

CHP, or cogeneration, systems utilize waste heat from gas engines, steam turbines, reciprocating engines, nuclear power plants, fuel cells, etc. to generate useful thermal power. This thermal power could be used for applications ranging from the industrial sector where thermal energy is required for some industrial processes (e.g., the paper industry) to the residential and commercial sectors (e.g., space and water heating). According to the second law of thermodynamics, any machine that produces useful energy such as mechanical work or electrical current is bound to lose some of its fuel’s internal energy in the form of waste heat. According to this law, it is impossible to utilize all of the internal energy content of the source fuel. CHP systems, however, attempt to minimize this waste heat as much as possible by utilizing a portion of it for other uses. So in theory, we cannot convert all of the waste heat to a useful form of energy. The utilized thermal energy, however, has to be high in temperature (i.e., high
in quality) in order to be useful in other applications. Utilizing CHP in an already existing system increases its efficiency from 30-50% to 70-90% [11].

The major components necessary for a CHP system include a prime mover, an electrical generator, electrical controls, and a heat recovery system. The heat recovery system in a CHP system could be a simple heat exchanger, a duct burner, or a boiler. These heat recovery devices extract energy from the exhaust hot gases and use this energy to heat and/or vaporize water and/or to superheat steam [12]. CHP systems increase efficiency, reduce costs, and reduce greenhouse gas emissions. The advantages CHP systems have over conventional systems make them very attractive to industrial leaders, policy makers, as well as home and small-business owners [13]. For small-scale applications, such as home water and space heating, the CHP system is called **micro-CHP**. Micro-CHP systems are popular in Western Europe and Japan. And even though their current portion of the CHP market is roughly 1% [14], micro-CHP systems are increasing in popularity due to initiatives led by the US Department of Energy and the Environmental Protection Agency [12]. In conclusion, due to the rapid technological advances in the CHP field, CHP systems will continue to grow due to the fact that they merge conventional power generation and thermal power production into a single efficient and cost-effective system.

### 3.3.2 CHP Systems and Hydrogen Fuel Cells

Even though combustion-based CHP systems are very attractive due to their environmental, economical, and energy-saving advantages over conventional single-output combustion-based systems, their use in buildings is limited due to many factors, such as GHG emissions, noise, and efficiency relevant to load [11]. Hydrogen fuel cells-based CHP systems, on the other hand, overcome most of these limitations imposed by combustion-based CHP

<table>
<thead>
<tr>
<th>Fuel cell type</th>
<th>Operating temperature (°C)</th>
<th>Waste heat utilization options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton exchange membrane (PEMFC)</td>
<td>80</td>
<td>Hot water</td>
</tr>
<tr>
<td>Phosphoric acid (PAFC)</td>
<td>200</td>
<td>Low pressure steam</td>
</tr>
<tr>
<td>Molten carbonate (MCFC)</td>
<td>600</td>
<td>High flow pressure steam and hot water</td>
</tr>
<tr>
<td>Solid oxide (SOFC)</td>
<td>800–1000</td>
<td>High flow pressure steam and hot water and air conditioning</td>
</tr>
</tbody>
</table>

Table 1: Different Applications of Waste Heat from Different Types of Fuel Cells [15]
systems. This makes fuel cells-based systems very attractive for users and developers and stronger candidates to receive funding allocated for CHP R&D. Table (1) lists the four most commonly used fuel cell types in CHP applications along with their corresponding operating temperatures and proposed waste heat applications.

A schematic of a CHP fuel cell system installed in a residence is shown in Figure (2). The fuel cell provides heat and power to the residence. It is worth noting that in case the fuel cell system can’t provide the energy requirements of the residence, power is imported and bought from the grid. On the other hand, if the energy produced by the fuel cell is more than the residence requirements, power is exported and sold to the grid.

### 3.4 Hydrogen Production

Even though it’s the most abundant element in the universe, hydrogen is rarely found in a directly-harvestable state on Earth. This is why hydrogen production is one of the leading challenges for the development of a hydrogen-dependent combustion-free economy. Continuous research is being conducted in order to resolve some of the technological and economical difficulties the current methods of hydrogen production face. These production technologies are covered in Figure (3). We will briefly investigate these technologies in this section.
3.4.1 Thermal Production Technologies

Unfortunately, most of the hydrogen produced in our economy today comes from fossil fuels, as shown in Figure (4). Fossil fuels are hydrocarbons that contain extractable hydrogen; however, the greenhouse gas emissions that accompany this extraction process make fossil fuels highly unsustainable and harmful to the environment.

Hydrogen is extracted from coal through gasification. Equation (1) below is an unbalanced equation that resembles a coal gasification process:

\[
CH + O_2 + H_2O \xrightarrow{\text{Heat}} CO + CO_2 + H_2 + \text{Other Species} \ldots \ldots \text{Equation (1)}
\]

---

2 Figure (3) is based on data sourced from [2, 16, 17].
3 Equation (1) is based on equations and relations listed in [16, 17]
Coal gasification to produce hydrogen is more complex, costly, and harmful to the environment in comparison to natural gas technologies. In general, coal gasification is more suitable for large-scale centralized hydrogen production projects [17].

Hydrogen is extracted from oil and natural gas through three main thermochemical processes [16]:

1. **Steam Methane Reforming (SMR).**
2. **Partial Oxidation (POX).**
3. **Autothermal Reforming (ATR).**

In these processes, methane, ethanol, propane, or gasoline are fed into the system to produce hydrogen along with GHG pollutants and byproducts [18]. Table (2) compares the benefits and challenges of the three technologies.

<table>
<thead>
<tr>
<th>Technology</th>
<th>SMR</th>
<th>ATR or POX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>High efficiency</td>
<td>Smaller size</td>
</tr>
<tr>
<td></td>
<td>Emissions</td>
<td>Costs for small units</td>
</tr>
<tr>
<td></td>
<td>Costs for large units</td>
<td>Simple system</td>
</tr>
<tr>
<td></td>
<td>Complex system</td>
<td>Lower efficiency</td>
</tr>
<tr>
<td></td>
<td>Sensitive to natural gas qualities</td>
<td>H₂ purification</td>
</tr>
<tr>
<td>Challenges</td>
<td></td>
<td>Emissions/Fining</td>
</tr>
</tbody>
</table>

Appendix (D) shows a schematic of a typical reformer to extract hydrogen from a gaseous fossil fuel. Usually, capture, storage, and then disposal of CO₂ emissions from fossil fuels-based hydrogen production is required. However, capture and disposal of CO₂ is rarely implemented due to additional costs [16]. This makes fossil fuels-based hydrogen production unsustainable and harmful to the environment.

3.4.2 **Electrolysis Production Technologies**

**Electrolysis** is the only well-developed method to date that can be used for large-scale hydrogen production in a post-fossil-fuel era [12]. Production of hydrogen by water electrolysis is based on an essentially simple process that is very efficient and does not involve any moving parts [12]. Hydrogen produced from water electrolysis virtually has 0% GHG emissions if the source of the electric current used in the electrolyzer is renewable energy. This makes water electrolysis based on renewable
energy sources the only permanent sustainable solution to the world’s energy crisis [2]. The cost, efficiency, and emissions resulting from the source of the required electricity are critical factors when evaluating the benefits of hydrogen production via water electrolysis [10, 19]. Researchers and developers are trying to come up with efficient integrated systems that combine renewable energy sources such as solar energy, wind energy, and hydroelectric energy with electrolyzers and fuel cells to have a 100% environmentally-friendly energy system, as shown in Figure (5).

Such systems are closed systems since the water produced from the fuel cell is reused in the electrolyzer unit. Also, oxygen emitted from the electrolyzer unit is reused in the fuel cell. This makes these systems very attractive and truly sustainable since all you need to generate electric power is a renewable source, such as sunlight [20]. Figure (6) shows the conceptual schematic of a system already built and in-use by SCHATZ Energy Research Center for several applications [21].

3.4.3 Photolytic Production Technologies

Photolytic processes are divided into three main groups:

1. Photolysis.
2. Biophotolysis.
3. Thermochemical Water Splitting.
All three processes utilize light to drive the electrolysis process. Figure (6) was an example of hydrogen production by photolysis. Figure (7) provides a schematic of what a typical biophotolysis hydrogen production system looks like. Photolytic production technologies hold a lot of promise for the future and are very attractive since they are all mainly based on sunlight.

![Figure 7: Biophotolysis Hydrogen Production System [16]](image)

3.5 **Hydrogen Storage and Distribution**

3.5.1 **Hydrogen Storage**

One of the characteristics of hydrogen is its low density. Therefore, storing hydrogen requires large volumes of storage tanks. As a result, hydrogen is stored as a gas in highly pressurized tanks or as a liquid in cryogenic tanks. The most three common technologies of storing hydrogen are cryogenic tanks, metal hydrides, and pressurized tanks [4]. Liquid hydrogen is stored inside cryogenic tanks. Liquid hydrogen, however, requires large amounts of energy to keep the hydrogen at low temperatures. As a result, the tanks require special insulation to maintain the temperature. All of which adds a lot to the total cost.

Alternatively, hydrogen can be stored in a solid state by forming metal hydrides capable of releasing hydrogen from them when needed. Metal hydrides have the advantage of storing hydrogen in a safe nonflammable state. A number of properties have to be considered in metal hydrides such as ease of activation, heat transfer, safety, weight, and cost. Cost is the main issue in metal hydrides, which is why they are not
common yet. A recent research has found a new catalyst that is able to release hydrogen from the solids while minimizing the energy required. It is still under research but it shows a promising solution in the near future [22].

By far, the most cost-effective and reliable technology to store hydrogen is by using pressurized tanks. And even though pressurized tanks pose some safety issues, using durable and high-quality materials with constant maintenance and checkups ought to resolve that. Large stationary hydrogen tanks are used at the production plant or at the start and end of a pipeline. Similarly, small stationary tanks are used at the end-use (e.g., near buildings or at homes). These tanks can store the hydrogen required for the fuel cells to operate continuously.

3.5.2 Hydrogen Distribution

Hydrogen can be transported by either mobile trucks or by using pipelines. Underground pipelines are the most developed and least expensive option for the distribution of hydrogen. Special attention must be paid to the sealing of the pipes to avoid any leakage due to the low density of hydrogen. Economically, pipelines are not that expensive since “most studies show that the cost of large scale transmission of hydrogen is about 1.5-1.8 times that of natural gas [4].” According to the US department of energy, currently there are around 1200 miles of hydrogen pipelines in the US [23]. On the other hand, other methods of distribution such as highly pressurized hydrogen trucks and liquid hydrogen trucks exist. However, these methods are expensive and uncommon.

3.6 Residential and Commercial Buildings Heat and Power Requirements

According to the US Energy Information Administration statistics in 2010 about electricity consumption [24], the average home in the US consumes about 1.31 kilowatt-per-hour, and the maximum consumption achieved was 1.90 kilowatt-per-hour. This can be easily supplied by a fuel cell, as evident in the table in Appendix (B). Appendix (C) provides detailed data on typical residential usage. One can notice that space cooling has the highest percentage. Similarly, water and space heating together are almost as high as cooling. So, using fuel cells for combined heat and power would decrease the
electricity consumption while providing water and space heating. Commercial buildings consumption varies greatly and cannot be easily generalized. However, many big companies are already using fuel cells to generate their needs of electricity, such as Coca-Cola, FedEx, Wal-Mart, Bank of America, eBay, and Google [25]. A breakdown and a comparison of the typical residential and commercial energy (electricity and heating) requirements are shown in Appendix (H).

3.7 Fuel Cells versus Power Plants

In the United States, currently more than half of the electricity is produced by combustion-based power plants. This method of generating electricity is both harmful to the environment and inherently inefficient. It converts only about one third of the fuel’s potential energy into usable power. We illustrate this concept clearly in Figure (8)\(^4\). The rest of the energy is lost in the form of waste heat and during the transmission process which is often thousands of miles from the point of generation to the point of use [26].

The graph shown in Appendix (E), by the World Coal Association, analyzes the carbon dioxide emissions along with the efficiency curve of typical power plants. We can interpret from it that the best practical efficiency of a state-of-the-art plant is 45% with emissions of 550 grams of carbon dioxide per kilowatt generated [27].

In comparison to power plants, reasons why fuel cells are a better and more efficient choice are as follows:

1. Electricity is generated through an electrochemical process that does not involve combustion and produces negligible amounts of pollutants [26].
2. Since fuel cells could be installed directly in buildings; there is no loss of electricity during the transmission process in contrast to power plants.

\(^4\) Figure (8) is based on data sourced from [4, 6]
3. The heat produced as a byproduct of the electrochemical reaction could be used for space and water heating [26].

4. CHP fuel cell systems operate at 90% efficiency and can cut the energy costs by as much as 50% [26].

To illustrate the points mentioned above, a comparison of the electrical efficiencies of power plants, combustion engines, and fuel cells is given in Figure (9).

![Figure 9: Typical and Maximum Electrical Efficiencies of ICEs, FCs, and Power Plants](image)

3.8 **Challenges in the Commercialization of Fuel Cells**

Manufacturers of fuel cells and their components established their first fuel cell-powered products by 2004 and have now reached the market in significant numbers. A study by PricewaterhouseCoopers (PwC) estimated that the global market for fuel cells has reached $30 billion in 2011. However, there’s a lot of performance and cost-related issues we need to overcome before the widespread commercialization of fuel cells according to experts. "For product launches within the next few years, cost and technical issues will pose significant barriers," says Daniel Benjamin, an analyst at ABI Research (Oyster Bay, NY). "Initial consumer fuel cell products will focus primarily on stationary power generation and portable electronics. However, they may not function as well as the power systems they're replacing, yet [they] will be more expensive." [28].

Consequently, the following are few of the uncertainties to the success of fuel cells and their development:

---

5 Figure (9) is based on data sourced from [2, 4, 12]
1. Fuel cells must obtain mass-market acceptance to succeed. This acceptance depends largely on price, reliability, longevity of fuel cells, and the accessibility and cost of fuel [20].

2. The durability of fuel cell systems has not been established. Fuel cell power systems will be required to achieve the same level of durability and reliability of current combustion engines. For stationary applications, more than 40,000 hours of reliable operation in a temperature at -35°C to 40°C will be required for market acceptance [29].

3. Governments’ reluctance to adopt hydrogen fuel cells can greatly hinder their development [20].

4. Many of the reactions involved in fuel cells require platinum as a catalyst. Platinum is a scare natural resource and the major suppliers to the world platinum market are Russia, Canada, and South Africa. Shortage of this key component is not expected but the changes in government policies can affect the supplies in the future. Progress is being made in reducing the amount of catalyst required in fuel cells and in the use of lower-cost materials instead of platinum [20].

By determining the above challenges we can conclude that “[the] commercialization of hydrogen fuel cells is not the utilities, but making the fuel cells themselves cheaper, more durable, and more reliable, by solving all the mechanical issues,” as illustrated by Terry Poles, director of fuel cells at Engelhard Technologies. He further discloses that “[n]o one has yet developed a perfect fuel cell that is competitive for a significant market application.” [28]. Appendices (A) and (G) show cost and number of fuel cell units installed over the years, respectively.

3.9 **Hydrogen and Fuel Cells Safety**

The risks and hazards of a fuel cell operating on hydrogen are of the same order of magnitude as an internal combustion engine operating on gasoline or a space heater operating on natural gas [2]. Based on a proper understanding of how fuel cells work (see section 3.2) and what the properties of hydrogen are (see section 3.1), safety
measures could be taken in order to eliminate these risks and hazards. Some of these safety measures include [30]:

1. Protection against mechanical hazards such as moving parts, falling or ejected objects, and loss of stability.
2. Protection against electrical hazards such as static electricity, electrical equipment and supply, and electromagnetic compatibility.
3. Protection against fire and explosion hazards by considering the following aspects:
   a. Ensure an explosive atmosphere never exists, either as a result of a leak, air ingress forming an explosive atmosphere inside the equipment, or having gas mixtures in the explosive range.
   b. The next line of defense is the avoidance of ignition sources in areas where a flammable atmosphere may occur.
   c. The last line of defense is preventing the explosion from propagating to surrounding areas using precautions such as explosion venting, explosion suppression, isolation systems, containment systems, and blast walls.
   d. The employment of a hydrogen detection system for early detection of leaks.
4. Protection against pressure-related hazards such as strength and material of pressure vessels, allowable limits of pressure equipment, and wear.
5. General health and safety requirements such as external temperatures, noise, vibrations, and external radiation.
6. Operational and maintenance considerations such as failure of the power supply, regular inspection of the system, and a plan for emergencies.
4. **Evaluation and Conclusions**

Hydrogen is used because it acts as an energy carrier. Renewable sources are intermittent by-nature, making them unreliable. Hydrogen solves that problem by effectively storing renewable energy during demand off-peak hours to be used during demand peak hours. While there are many ways to produce hydrogen, the most environmentally-friendly way is by using renewable sources. And even though renewable sources have very low running costs, they still have high initial capital costs. Although, there are some risks associated with using hydrogen, these can be solved by regular maintenance and using high quality materials. Combined heat-and-power fuel cell systems provide many benefits as summarized below.

4.1 **Efficiency**

Since CHP fuel cell systems utilize up to 90% of the total energy in a fuel, they save large amounts of money in addition to being environmentally-friendly. On average, they can be twice as efficient as a power plant.

4.2 **Environmental Benefits**

Fuel cell CHP systems are quiet and do not generate any pollution or greenhouse gases, which makes them a good solution for residential and commercial areas.

4.3 **Flexibility**

CHP systems are quite flexible due to a lack of moving parts. Hence, they can be installed almost anywhere. Moreover, they can decentralize power generation to the user, allowing each house to have its own fuel cell. Additionally, if the fuel cells generate more than required, it can be easily sold back to the grid.

4.4 **Savings**

CHP hydrogen fuel cell systems have high costs, so governments can give grants and subsidies that will help prompt people to adopt them. In addition, finance by private-sector partners is another option since the system pays for itself with the savings it acquires.
5 Recommendations

We recommend utilizing hydrogen fuel cells in combined heat-and-power systems to generate electricity and heating requirements at residential and commercial buildings in order to save energy, reduce GHG emissions, reduce costs, and provide a sustainable, long-lasting solution for the world energy crisis. Also, since hydrogen is the most abundant element in the universe and on earth, it can be produced from water through a photolysis system. So, this gives us the potential to produce unlimited supplies of energy as long as the sun and water exist. Finally, a photolysis hydrogen-production system has no harmful impacts on the environment at all, which will prompt governments to shift from the current fossil fuels-based economy to a clean and sustainable hydrogen-based economy. We recommend adopting the solutions we reached in our findings, conducting more research on the subjects of fuel cells and hydrogen, funding private and academic efforts to come up with innovative solutions to the current technological challenges, and increasing the public awareness about hydrogen fuel cells and their advantages over conventional systems.
6 References


7 Appendices

### Appendix (B): Comparison of Fuel Cell Technologies [10]

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Common Electrolyte</th>
<th>Operating Temperature</th>
<th>Common Polymer Electrolyte Membrane (PEM)</th>
<th>Size</th>
<th>Efficiency</th>
<th>Typical Stack Operating Temperature</th>
<th>Applications</th>
<th>Disadvantages</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM Fuel Cell</td>
<td>Aqueous solution of potassium hydroxide</td>
<td>90-100°C (194-212°F)</td>
<td>Nafion (PFSA)</td>
<td>&lt;1kW-100kW</td>
<td>60%</td>
<td>80°C-90°C (176°F-194°F)</td>
<td>Backup power, portable generation</td>
<td>Expensive catalysts, sensitive to fuel impurities, low temperature waste heat</td>
<td>High temperature enables CHP, increased tolerance to fuel impurities</td>
</tr>
<tr>
<td>AFC Fuel Cell</td>
<td>Phosphoric acid and sodium carbonate, or potassium carbonate, in a matrix</td>
<td>50-200°C (122-680°F)</td>
<td>Perfluorosulfonic acid (Nafion)</td>
<td>10-100 kW</td>
<td>40%</td>
<td>300°C</td>
<td>Military, space</td>
<td>High temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
<td>High temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
</tr>
<tr>
<td>MCFC Fuel Cell</td>
<td>Solution of lithium, sodium, and carbonate, or potassium carbonate, in a matrix</td>
<td>600-700°C (1112-1292°F)</td>
<td>Perfluorosulfonic acid (Nafion)</td>
<td>100 kW module</td>
<td>45-50%</td>
<td>600°C</td>
<td>Electricity, fuel cell, stand-alone</td>
<td>High temperature, high temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
<td>High temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
</tr>
<tr>
<td>AFC Fuel Cell</td>
<td>Solid Oxide Fuel Cell (SOFC)</td>
<td>700-1000°C (1292-1822°F)</td>
<td>Perfluorosulfonic acid (Nafion)</td>
<td>1 kW-2 MW</td>
<td>60%</td>
<td>700°C</td>
<td>Hybrids, GT cycle</td>
<td>High temperature, high temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
<td>High temperature corrosion and breakdown of cell components, long start-up time, low power density</td>
</tr>
</tbody>
</table>

31
Appendix (C): Typical Residential Power Percentage Consumption in the US\textsuperscript{6}

\begin{center}
\includegraphics[width=\textwidth]{chart.png}
\end{center}

\begin{itemize}
\item Space Cooling: 17.9
\item Lighting: 15.3
\item Water Heating: 9.3
\item Space Heating: 9.1
\item Refrigeration: 7.9
\item Clothes Dryers: 7.2
\item Cooking: 4
\item Dishwashers: 3.8
\item Freezers: 2.3
\item Clothes Washers: 2
\item Other — Miscellaneous Uses: 1.7
\item Total: 18.9
\end{itemize}

\textsuperscript{6} Based on data from [31]
Appendix (D): A Typical Fossil Fuel Reformer [32]
Appendix (E): Efficiency and Emissions of Power Plants [27]

Source: IEA “Focus on Clean Coal” (2006)
### Appendix (F): Properties of Hydrogen at Ambient Pressure and Temperature [12]

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular weight</td>
<td></td>
<td>2.016</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>0.0838</td>
</tr>
<tr>
<td>Higher heating value</td>
<td>MJ/kg</td>
<td>141.90</td>
</tr>
<tr>
<td></td>
<td>MJ/m³</td>
<td>11.89</td>
</tr>
<tr>
<td>Lower heating value</td>
<td>MJ/kg</td>
<td>119.90</td>
</tr>
<tr>
<td></td>
<td>MJ/m³</td>
<td>10.05</td>
</tr>
<tr>
<td>Boiling temperature</td>
<td>K</td>
<td>20.3</td>
</tr>
<tr>
<td>Density as liquid</td>
<td>kg/m³</td>
<td>70.8</td>
</tr>
<tr>
<td>Critical point</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>K</td>
<td>32.94</td>
</tr>
<tr>
<td>Pressure</td>
<td>Bar</td>
<td>12.84</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>31.40</td>
</tr>
<tr>
<td>Self-ignition temperature</td>
<td>K</td>
<td>858</td>
</tr>
<tr>
<td>Ignition limits in air</td>
<td>(vol. %)</td>
<td>4–75</td>
</tr>
<tr>
<td>Stoichiometric mixture in air</td>
<td>(vol. %)</td>
<td>29.53</td>
</tr>
<tr>
<td>Flame temperature in air</td>
<td>K</td>
<td>2,318</td>
</tr>
<tr>
<td>Diffusion coefficient</td>
<td>cm²/s</td>
<td>0.61</td>
</tr>
<tr>
<td>Specific heat ($c_p$)</td>
<td>kJ/(kg·K)</td>
<td>14.89</td>
</tr>
</tbody>
</table>
Appendix (G): Number of Stationary Fuel Cells (≥10 kW) and their Corresponding MW per Year [33]
Appendix (H): Breakdown of Residential and Commercial Buildings Power and Heat Requirements in the US [34]

(a) Residential buildings

(b) Commercial buildings