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Hydrogen generation, storage and electricity generation from wind energy to grid system

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Hydrogen generation, storage and electricity generation from wind
energy to grid system

By

Jun Chen

A Thesis

Presented to the Graduate and Research Committee

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Abstract

As the world gradually runs out of conventional resources such as petroleum and coal, the use of innovative resources is likely to increase. Thus renewable energy development is seen as an urgent issue. This brings forward the need for a research on methods for storing energy since renewable energies are intermittent. Innovative and large scale of energy storage is necessary also to satisfy the growing demand of a quality electrical grid. Storage of electrical energy in the form of Hydrogen is the primary theme of the present work aimed at wind generated electrical energy. As research has shown storage of Hydrogen involves many challenges. The main problem is to optimize hydrogen production and adopt materials to store large amounts of Hydrogen safely that will be available for consumption. This work evaluates some potential materials such as porous carbons to store hydrogen at relatively high rates of mass fraction. Choices for electrolyzers to generate hydrogen and fuel cells to produce electricity are also discussed to determine the overall efficiency of such a storage system. The Hydrogen corresponding to the storage of energy from a 1.5 MW wind turbine operating for 16 hours is about 487 kg. This amount of Hydrogen can be stored in G212 carbon at 77 K and 5 bar pressure at a cost of about \$ 300,000 that includes costs of associated hardware.

Chapter1. Introduction

As fossil fuels become more expensive and less attractive due to the global CO₂ crisis, it is anticipated that renewable energy use is likely to increase. Currently conventional fuels such as coal though abundant in many parts of the world, are coming under pressure with opportunities for using renewable energies. When possible many would like to use renewable resources. Thus there is an urgent demand for renewable and clean sources, and many scientists are studying ways to spread the use of renewable energies. One of the major difficulties and drawbacks of renewable energies is that they are intermittent and unpredictable. For example the normal load factor for a wind energy turbine is only thirty percent. Thus during the sixteen hours that the windmill does not work, we need to use other forms energy such as coal or natural gas. Another way to solve the problem will be to store wind energy for use during off hours. Thus during a twenty-four hour period while the windmill is working for eight hours, we need to store energy for the sixteen hours that the windmill cannot generate energy and store this energy during off hours.

Most wind energy turbines are connected directly to electrical generators and designed to generate electricity. Unfortunately there are not many means of storing electrical energy except by batteries and devices like super-capacitors. These devices for storing electrical energy are incapable of storing large amounts of energy. For example, a 1.5 MW windmill will need to store energy for 16 hours resulting in the need to store 24 MWh (or 8.64 E07 kJ) for one day on average. One possible medium to store such amounts of energy is Hydrogen. Hydrogen is one of

the most promising clean energy storage options that people are considering. The electrical energy can be used to generate Hydrogen which in turn can be used in a fuel cell to generate electricity.

Hydrogen is a light gas under normal temperature and pressure with a density of 0.08988 kg/m^3 (g/L) at 273 K and 101.325 kPa. It contains the highest energy per unit mass of all the fuels [6] but unfortunately due to its molecular weight and low density, it takes a lot of volume of H_2 to store a given amount of energy. H_2 reacts with O_2 in the air explosively and thus needs controlled combustion. Due to its chemical property, hydrogen will produce only water when reacting with Oxygen in burning process, which will not pollute the environment as traditional fossil fuel sources do as they produce CO_2 . Moreover, hydrogen can be produced abundantly and easily from available water. Therefore, producing large amount of hydrogen can be an opportunity to solve the energy crisis for the current situation by storing energy in the form of H_2 . Hydrogen is known to be a hazardous gas to be handled. Being the lightest gas, and due to its explosive nature (in the presence of O_2) hydrogen needs special handling techniques and special sealing procedures to contain it at any pressure. Due to these difficulties, storage of H_2 requires a great deal of care and the following of safe critical practices that are not exactly the focus of the work.

Use of Hydrogen for the storage of energy is the primary theme of the present work. This thesis will discuss generation, storage of Hydrogen and electricity generation using this stored Hydrogen using efficient fuel cells.

Wind energy is one of the most popular clean energies that a lot of countries are getting interested in. However, as an energy source, wind energy is not steady enough compared to other traditional energies such as coal and natural gas when it comes to practical delivery to the customer. In other words, the difficulty or the missing link for the success of wind energy technology is the store technology to make the availability of wind energy nearly continuous and steady. Thus availability of storage for Hydrogen from wind energy in a suitable storage medium, and use them to generate electricity efficiently are the keys to such technology and are the theme of the current work.

Optimizing the electrical energy storage is especially significant for the whole electrical power grid to operate normally and efficiently. And the needs highly depend on geographical conditions and weather conditions. Therefore, innovative and large scale of energy storage is necessary to satisfy the growing demand of a quality electrical grid. The key point here is to optimize the energy production and consumption by adopting an advanced material to store a great amount of energy economically. Hydrogen is the primary medium to be considered as energy storage medium in this paper.

The whole process of Hydrogen storage technology is briefly discussed here. The process begins with energy generation process; hydrogen generation will be the foundation for the process. Traditionally, Hydrogen has been generated by electrolyzers. During non-peak hours, or when the wind mill energy is not ready to be used by the grid, electrolyzers can produce hydrogen by using electricity from

the wind mill energy. Hydrogen produced then will be stored in a tank made by specific materials, using adsorption in the nano-pores of materials, which is the difficult operation in the whole system. Improving the adsorbed amount of hydrogen stored in the material is an important goal and part of the optimization process. Next, the hydrogen stored will be used to generate electrical power by using a certain type of fuel cell to efficiently and economically meet the demand of load, which will be good for the whole grid interface. Figure 1 shows the general process of how the Hydrogen is generated using energy from wind, stored by adsorption and electricity is generated fuel cells.

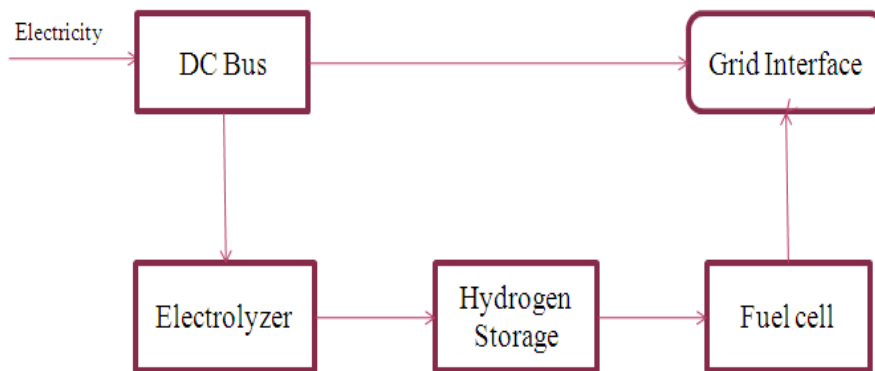


FIGURE 1: FULL SYSTEM LAYOUT OF ELECTRICITY GENERATED FROM WIND

Chapter 2 of this paper is a literature survey that describes the state of art related to Hydrogen generation, hydrogen storage and electricity generation methods for a whole electrical grid system. It will give a general view of how the whole grid system can possibly be established.

Chapter 3 discusses the choices made and methods selected based on concepts of the three sections introduced in chapter 2.

Chapter 4 describe calculations for the system (hydrogen generation, hydrogen storage and electricity generation) the energy aspects related to them. This process uses numerous assumptions to design the whole system.

In Chapter 5 results and cost analysis will be briefly described. Cost analysis will be based on the materials, products and methods adopted under assumptions made in those three sections of the system. Recommendations will be given based on the above discussions.

At the end, conclusions and suggestions will be made based on design calculations and cost analysis results from each part and of the whole electricity system for energy storage.

Chapter2. Literature Survey

The literature from the recent past as relevant to the work is discussed here. There are three parts in this section. The literature review contains three major components of electricity storage as might be applicable to wind energy stage to manage the grid system: hydrogen generation, hydrogen storage and electricity generation.

1. Hydrogen generation

Electrolyzers use water and DC electricity to produce Oxygen and Hydrogen. This process can be set up upon electrical power and with different water availabilities. Electrons flow through the external circuits from the anode to the cathode to generate Hydrogen and hydroxide ions from water [15].

An electrolyzer is typically composed with four components [1]: water supply (at the correct pH), the cell stack, power electronics, and the controller as shown in Figure 2. Water is absorbed by a cell stack, which will be made into Oxygen and Hydrogen as electricity applied.

The most commonly used electrolyzers are of several types such as proton-exchange membrane (PEM), alkaline, and solid oxide electrolyzers. The first two kinds can be well established to the system while solid oxide electrolyzers are not yet proved to be able to perform well in the system. Alkaline is one of the most important types of electrolyzer that can be used in larger scale operations while PEM is mostly used for small scales. Alkaline electrolyzers incorporate bipolar electrodes which are

connected in series between feeder anode and cathode on different ends [15]. This is called filter-press design that allows the build-ups of compact electrolyzers to be suitable for using under relatively high pressures ($\leq 3\text{MPa}$) [15].

A survey indicates that electrolytic Hydrogen production shows that the major commercial electrolyzers use “bipolar electrodes filter-press technology” with alkaline electrolysis [15]. Energy efficiency referred to with the higher heating value (HHV) of Hydrogen includes energy consumed by the whole electrolysis process and auxiliary components that vary from 56% (Proton’s PEM) to 73% (Norsk Hydro’s alkaline electrolyzers) [15]. The power for the maximum Hydrogen production rates is derived from 320,000 kg to 380,000 kg per year production, varying from only 2,000 to 2,300 kW [15]. It can be estimated that around 100 times larger electrolyzers in scale will be more effective in coming up with low-cost electricity generated from wind power and other renewable energies in the future [15].

To make the selection of which type of electrolyzers to use to generate Hydrogen for the present system, special emphasis will be given to efficiency and market price.

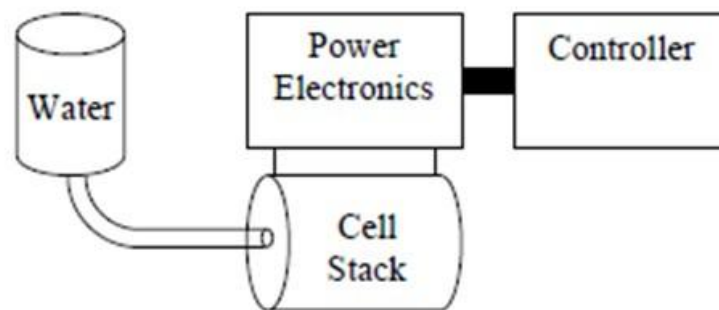


FIGURE 2: ELECTROLYZER CONFIGURATION [1]

2. Hydrogen storage

Hydrogen storage has become more important over the years, especially with the inflexibility of non-renewable energy and due to the pressure on conventional resources. Hydrogen is very difficult gas to handle. It has to be under a certain range of pressure, temperature and special requirements for transportation. Because of the physical and chemical properties of Hydrogen, and the effects of cryogenic temperatures on material behavior safe use of Hydrogen [4] is quite difficult. There are many types of materials have been used for storing Hydrogen in high pressure tanks. Traditionally, the selection of a structural material for Hydrogen storage system is based on mechanical properties such as tensile strength, ductility, impact strength and yield strength. The material must fulfill the requirements of these properties over a certain temperature range [4]. Generally the acceptable materials are those that [4] --

- (1) are best at room temperature, or higher temperature if necessary;
- (2) have been evaluated for suitable fatigue life;
- (3) have many test conditions and the form of the materials;
- (4) testing should include tensile, fracture toughness, crack growth, fatigue, bend, and stress rupture over a certain range of temperatures and pressures;
- (5) the effect of setting the allowable stress for Hydrogen systems.

Usually, metallic as well as nonmetallic materials are both applicable for Hydrogen storage. Historically due to the limited performances of metallic materials, people intended to explore nonmetallic materials to seek a better performance for Hydrogen storage. People have been trying elastomers, plastics, and Teflon for cold gaseous Hydrogen and liquid Hydrogen storage system [4]. However, problems arose in the usage of those traditional materials for Hydrogen storage. Fatigue failure, Hydrogen embrittlement and corrosion are the bottleneck [12].

The conventional way to store Hydrogen in wind towers utilizes steel to build the storage containers. There are a lot of disadvantages of using steel because it will face corrosion, Hydrogen attack, Hydrogen embrittlement etc. as other metallic materials, which is not reliable for an efficient and safe storage especially under high pressure (15 to 20 atmospheres) [12].

In recent years, the best physically and economically effective material is introduced, which is porous carbon. The use of Hydrogen physisorption on porous materials is one of the major methods being considered for Hydrogen storage [4]. To store large amounts of Hydrogen at ambient temperatures and relatively low pressures, the storage materials need to meet the goals of reasonable volume, weight and realistic kinetics for charging and discharging Hydrogen [5]. The U.S. DOE objective is to develop the method of Hydrogen storage, which is to increase the adsorption rate to 9 wt. % by 2015 [5]. To optimize porous materials for Hydrogen adsorption, the major measurements are [5]

- (1) Adsorption amount as a function of pressure;

- (2) The temperature dependence of adsorption;
- (3) The adsorption and desorption characteristics;
- (4) The enthalpies of adsorption.

The adsorption of Hydrogen has under researches over a wide range of materials such as carbon, alumina, metal organic framework and polymer porous materials etc [5].

The most popular Hydrogen storage materials are porous carbon as in the current application. With a large porosity, porous carbon has highly developed internal surface, which can absorb large amount of gases and liquids [6]. As part of the applications of porous carbon, it can be applied as gas storage for catalyst support, electrodes in batteries, absorbents, fluid filters (water and gases) and some types of medical devices [6].

The most commonly used porous carbon materials for Hydrogen storage are Single Walled Carbon Nanotubes (SWCNT) and Multi-Walled Carbon Nanotubes (MWCNT) and they are the most well-known and accepted ones.

As the name indicates, SWCNTs are single walled carbon nanotubes, with inner cavity that is hollow and have plenty of potential Hydrogen adsorption sites [6]. Measurements can be obtained from Anson et al [14]. They have shown in the literature that Hydrogen storage is up to 0.01wt.% at 298K while this value is as high as 1 wt.% at 77K [6].

Compared to Single Walled Carbon Nanotubes, it is known that Multi Walled Carbon Nanotubes have less volume fraction but higher carbon-carbon bonds within the graphene layers than SWCNTs on the other hand [6]. Therefore, it is relatively more difficult to store a large amount of Hydrogen in MWCNTs than in SWCNTs, and almost impossible to store in concentric tubes due to the strong carbon-carbon bonds [6]. Although there is very little work done on MWCNTs compared to SWCNTs in Hydrogen storage field, it is expected that Hydrogen uptake process by MWCNTs is quite low and requires high pressure [6], which can limit applications.

Another limit of utilizing SWCNTs and MWCNTs is that the unit price of each material is too high to build a large storage tanks. As per market prices, the average cost of MWCNTs is approximate \$3.5/g, while it is \$45/g for SWCNTs, which is impractically expensive for large applications. With the limitations that have been discussed above, more porous materials are studied to solve the problem of Hydrogen storage.

Recently a new type of porous carbon material called “Y Carbon” (also known as Carbon Derived Carbons or CDC) has been introduced by Dash, et. al., for Hydrogen storage applications. It is a new kind of porous carbon, which is highly porous, compared to other porous materials. It can be synthesized from four metal carbides: ZrC, TiC, SiC and B₄C [6]. It is claimed that Carbon Derived Carbon has high surface area, which ranges from 500 to 2300 m²/g. The average pore size of CDC is ranging from 0.5 to 1.4 nm, and pore volume is ranging from 0.2 cm³/g to 1.0 cm³/g in general [6]. According to a research done on the characteristics of CDC,

initially it is indicated that up to about 3.0 wt. % or 30kg/m³ Hydrogen can be stored in CDCs [6]. This approximately about twice amount of Hydrogen can be stored in other materials such as MOF-5, and much more than in SWCNTs and MWCNTs under the same circumstances -- at atmospheric pressure and ambient temperature (77K).

Table 1 below shows the theoretical density, apparent density, calculated pore volume and porosity of CDCs for the four different metal carbides discussed above in the text.

Table1. Porosity of CDC for TiC, SiC, ZrC and B4C [6]

Metal carbide	Theoretical density of metal carbide (ρ_{MC}) g/cm³	Calculated apparent density of CDCs (ρ_{CDC})g/cm³	Calculated pore volume (v_p), cm³/g	Porosity, %
ZrC	6.56	0.76	0.86	66.07
TiC	4.92	0.98	0.56	56.16
B ₄ C	2.52	0.54	1.38	75.65
B-SiC	3.21	0.96	0.59	57.26

A theoretical method of porosity calculation is suggested by Dash [6] is given below.

$$p = \rho_{CDC} \times V_P \times 100 \quad (1)$$

$$\rho_{CDC} = \rho_{MC} \times \left(\frac{M_{MC} - M_M}{M_{MC}} \right) \quad (2)$$

$$V_P = 1/\rho_{CDC} - 1/\rho_C \quad (3)$$

Where

p = porosity

ρ_{MC} = theoretical density of metal carbide

ρ_{CDC} = calculated density of CDC

ρ_C = true density of graphitic Carbon = 2.25 g/cm³

V_P = pore volume of CDC

Assuming that ideally Hydrogen occupies the volume of all pores, the weight percentage of Hydrogen adsorbed can be calculated by the following two equations with pore volume ($V_p < 1\text{nm}, \text{cm}^3/\text{g}$) and SSA, the specific surface area of pores $< 1\text{nm} (\text{m}^2/\text{g})$ individually [6].

$$\text{Wt. \% of H}_2 = 4.12 V_p + 0.68 \quad (4)$$

$$\text{Wt. \% of H}_2 = 0.001x \text{ SSA} + 0.91 \quad (5)$$

With this method, we have to know the operating temperature and the state of Hydrogen. Since it is rather difficult to determine whether the Hydrogen is close to liquid or is in some quasi-mixed state, it has to be applied carefully.

To illustrate the general idea of Hydrogen storage in carbon derived carbon, it can be shown by the following simple analysis:

(1) Mass as a function of pressure: The amount of Hydrogen adsorption increases with applied pressure [6].

As pressure increases, the weight percent of Hydrogen uptake increases as well (Figure3). It can be seen from the graph that around 760mmHg, the slope of Hydrogen uptake graph gets flatter, and the highest value gets more stable and close to a fixed value [6].

(2) Hydrogen adsorbed at the temperature of 77K is preferred.

From measurements of Hydrogen sorption by Dash [6], it compares interpolation of isotherms at temperatures of 87K and 77K individually by using Clausius Clapeyron equation [6].

The result of the manner shows that the volume adsorbed of Hydrogen has higher value at lower temperature, 77K than 87K at the same pressure level.

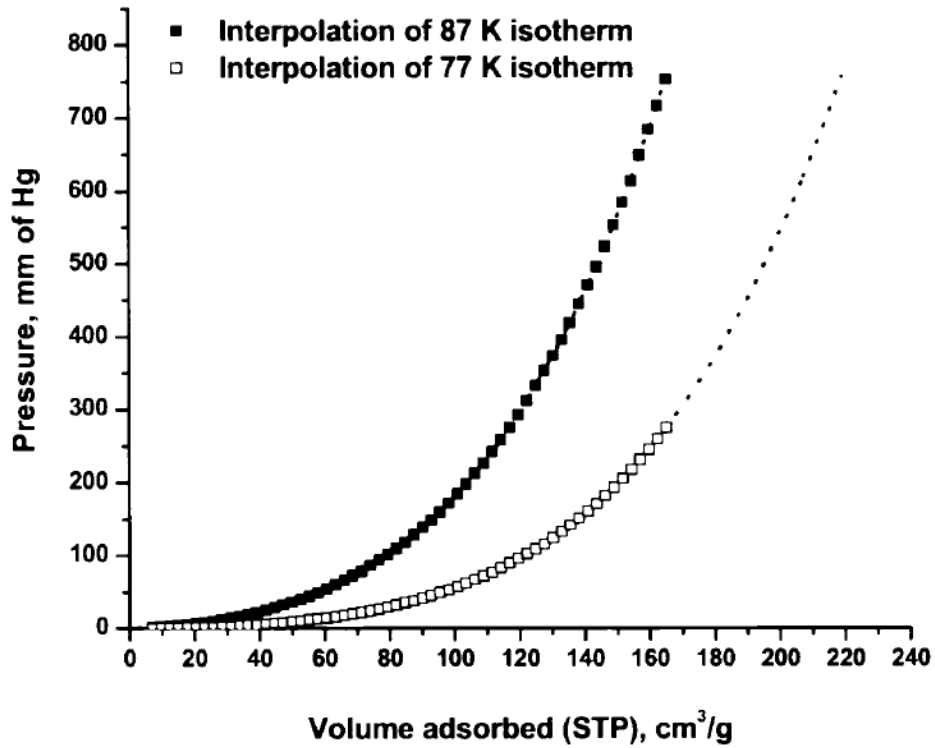


FIGURE 3: INTERPOLATED ISOTHERMS COLLECTED AT 77K AND 87K [6]

(3) Hydrogen physisorption is not directly proportional to specific surface area (SSA) [6]. Instead, smaller pores perform higher storage capacity, and they also have higher surface area. Therefore it suggested that the storage capacity is dominated by pore size but not just the total SSA. Small pores, which range from 0.6-0.7nm are the most efficient sizes for Hydrogen sorption [6].

To intuitively see the performing differences of the major types of carbon derived carbon and other porous carbon materials for Hydrogen uptake, Figure 4 and Figure

5 show the relation between pressure changes and the amount changes of gravimetric uptake of Hydrogen individually. From the data shown in the graphs, we can directly estimate the weight percent of different CDC materials.

The Hydrogen uptake for

- TiC-CDC (H_2 treated) will get close to 3.15 wt.%
- TiC-CDC will get close to 2.7 wt.%
- SiC-CDC will be close to 2.25 wt.%
- B_4C -CDC will be close to 2.1 wt.%

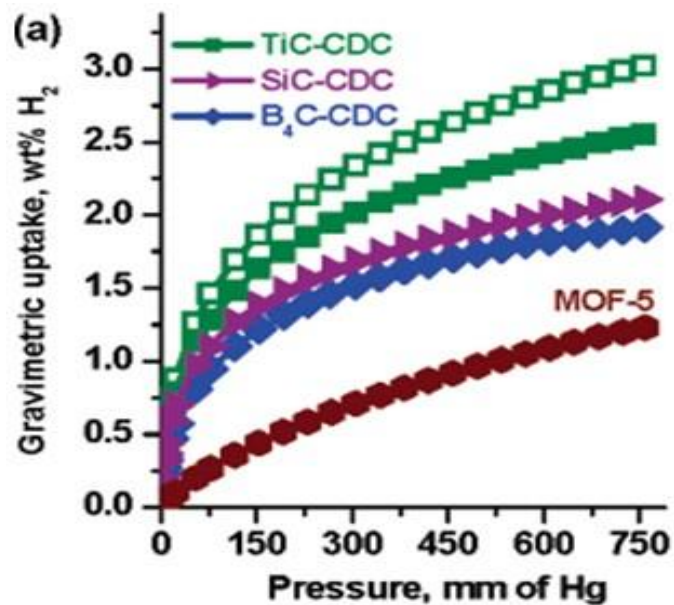


FIGURE 4: EXPERIMENTAL RESULT OF PRESSURE VS. WT. % UPTAKE FOR CDC AND ACTIVATED CARBON MOF-5 [6]

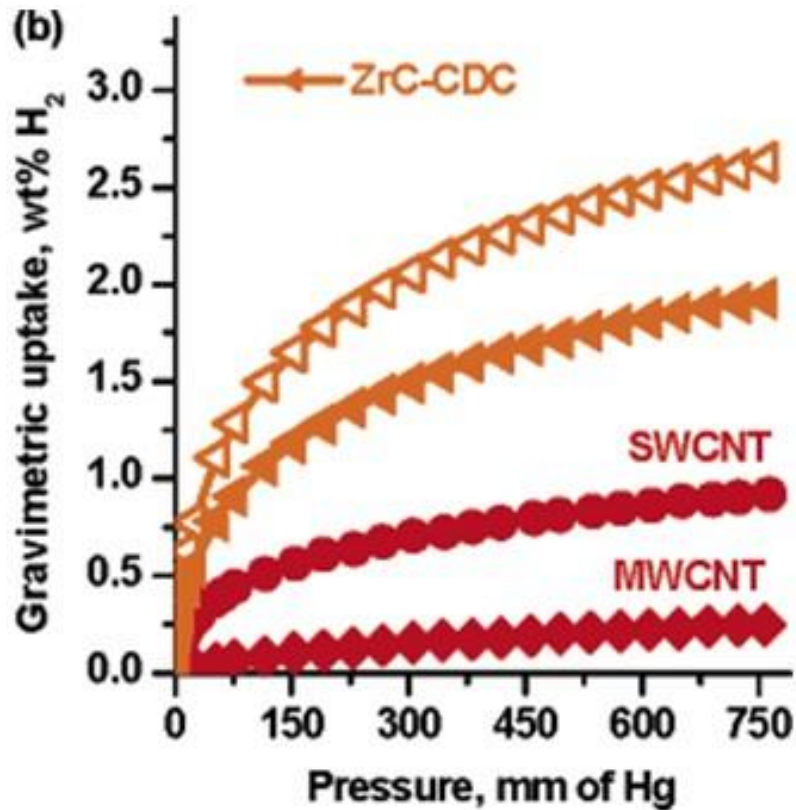


FIGURE 5: EXPERIMENTAL RESULT OF PRESSURE VS. WT. % UPTAKE FOR CDC AND OTHER POROUS CARBON MATERIALS [6]

Even though the author Dash [6] claims in the dissertation that the Hydrogen sorption capacity could be as high as 3 wt. % at 77K and 1 atmosphere, and could get even have higher adsorption rate with pressure increases, however in reality, the adsorption rate of CDC is not as high as the results shown due to some practical limits. As confirmed privately instead, it will be only 1/10 of the amount as claimed in the research [6] that can be absorbed, which is around 0.3 wt. % at 77K and 1 atmosphere according to Y-Carbon Ltd Corp. Thus, the performance of CDC is not at all satisfactory for Hydrogen storage for wind mill electricity to manage the grid. Therefore, a substitute porous material is considered.

Since carbon derived carbon is not ideal for large capacity Hydrogen storage, an alternative porous carbon material named G212 is considered to take up the slack of Hydrogen storage under the same operational pressure and temperature.

G212 is a well-known commercial activated porous carbon, which is produced from coconut shells, and has been applied to the industries of air filtration and water purification etc. The sample that has been tested in the research is provided by PICA Ltd., Vierzon, France. As mentioned in the literature, the Hydrogen adsorption uptakes of carbon G212 are about 1.8 wt. % at 1 bar and up to 3.88 wt. % at 20 bar [7]. The apparent density of carbon G212 is 0.38g/cc min (PICA). Figure 6 shows the Hydrogen uptake comparisons for different porous carbon materials at 77K with pressure changes from one to twenty bar.

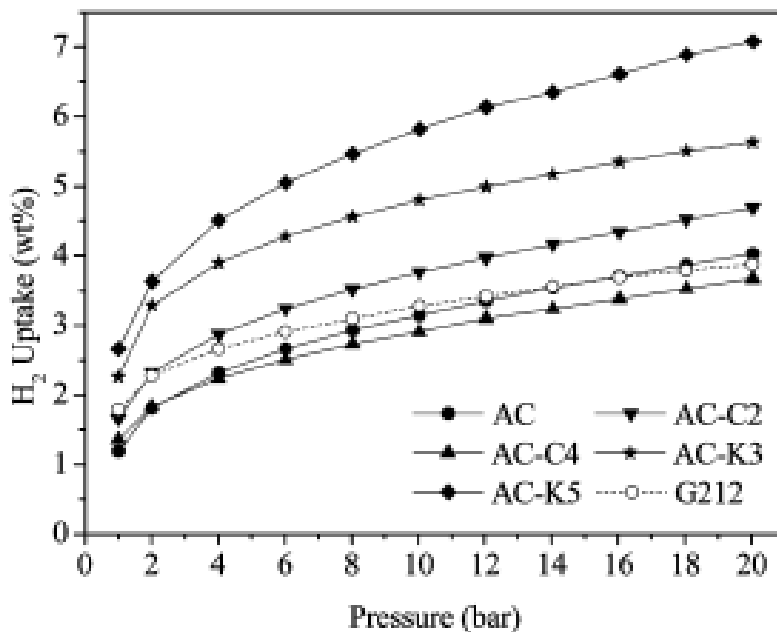


Figure 6: Hydrogen uptake of different porous carbon materials under pressure changes at 77K

The literature [7] result indicates that if the pore diameter is between 1 to 2 nm would have more Hydrogen uptake at 20 bars than at 1 bar. Moreover, this could result in more types of porous carbon material to perform high capacity storage of Hydrogen. However, as seen from the previous studies, small pores (0.6-0.7nm) are the most efficient sizes for Hydrogen sorption [6]. A study done by Panella et al. [5] has investigated that the maximum adsorption of a series of porous carbon under the same pressure but different temperatures results in a great adsorption differences. At 77K, the maximum capacity of Hydrogen adsorption is less than 4.5 wt. %, while this value dramatically decreasing to less than 0.5 wt. % at 298K. Another study done by Zhou et al. [5] indicates that temperature plays an important role in the Hydrogen storage process. Under the same pressure conditions, higher temperature will results in lower Hydrogen uptake capacities than those with lower temperature for most kinds of porous carbon materials such as activated carbon AX-21, MWCNT and SWCNT. Therefore, regarding the performance of G212, an operating temperature of 77K is suggested for a better Hydrogen storage result.

At temperature of 77K and 1 atmosphere, the amount of Hydrogen adsorbed (mmol/g) reaches the highest value, while this value decreases as temperature increases. It can be observed that the adsorption amount of Hydrogen is very little at 240K. Figure 7 shows the plot of temperature versus the amount of Hydrogen adsorbed [5]. In the plot, the Hydrogen adsorption rate tremendously dropped to around 0.18 wt. % from 1.2 wt. % at 77K, and decreased to 0.024 at 190K, which is a large difference.

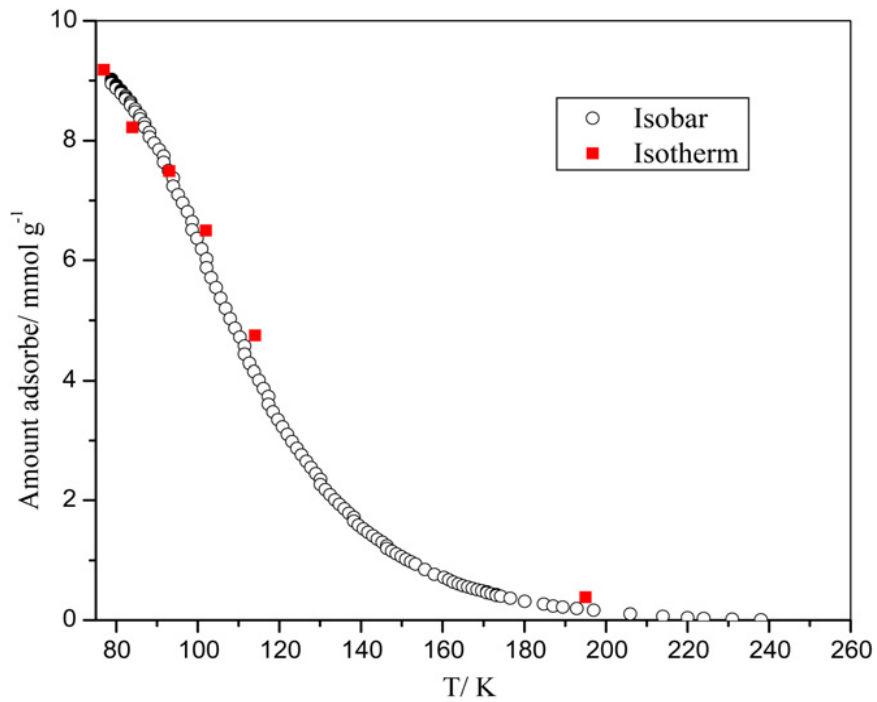


FIGURE 7: ADSORPTION ISOBARS FOR HYDROGEN DESORPTION (ONLY EVERY 45TH POINT INCLUDED FOR CLARITY) FROM CARBON G212 AT 100 kPa: HEATING RATE 0.3 K MIN⁻¹ AND 100 kPa DATA FROM ADSORPTION ISOTHERMS [5]

The series plots in Figure 8 are an additional explanation specifies the adsorption amount changes with the pressure changes from 0 to 1 atmosphere under different temperature conditions. It can be directly observed from the graph that Hydrogen adsorption amount is the highest at 77K, and lowest at 114K, and also increases as the pressure gets close to 1 atmosphere [8].

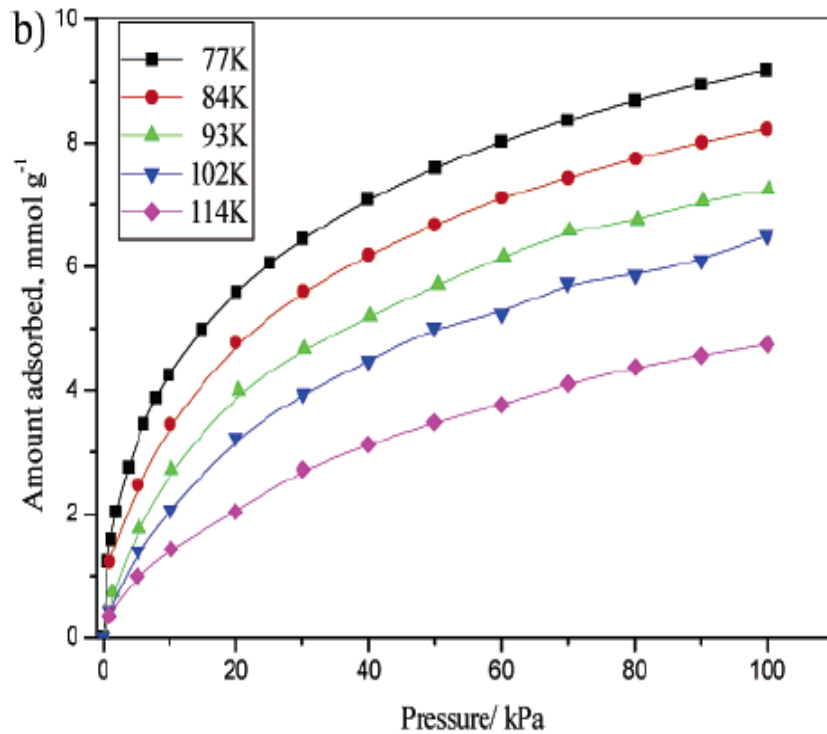


FIGURE 8: HYDROGEN ADSORPTION ISOTHERMS FOR G212 AT TEMPERATURE RANGE 77-114 K [8]

3. Electrical Power Generation using Fuel Cells

Fuel cells convert gaseous fuels such as natural gas, gasified coal and Hydrogen into electricity with an electrochemical process [10]. Fuel cells operate like batteries but no need to be recharged and do not consume electrode mass. They can continuously produce power to the system when gases and oxidant are supplied. Fuel cells are considered to be utilized in the electricity generation system because of their advantages, which includes [10]:

- High efficiency, not limited by Carnot cycle of a heat engine

- Low noise and less pollutant outputs
- Suit long transmission lines to distribute generated power at users
- Permits modular construction to suit different load capacities

Fuel cells have been widely used by industries and military. The most common type is PEM fuel cells. PEM fuel cells have high efficiency as others do, but their price is about \$1,000 to \$1,500 per kW due to market price, which is too expensive to be widely used for large scale electricity generation. There is a type of fuel cell named Solid Oxide Fuel Cell (SOFC) is another choice of fuel cells. SOFC is the third generation fuel cell, which is regarded as one of the most efficient and tolerated power generation system. It especially performs excellent at dispersed power generation [10]. The overall efficiency of SOFC is approximately 60% for single cycles under 1000°C, and 85% for the total system [10]. Moreover, the fuel cell output can reach as high as 100 kW or even higher [10].

The major features of SOFC are the high-temperature operation and all solid state construction [11]. SOFC have been produced into different geometries such as tubular, planar, banded and flat- plate etc [11]. Figure 9 is the single cell configurations of SOFC.

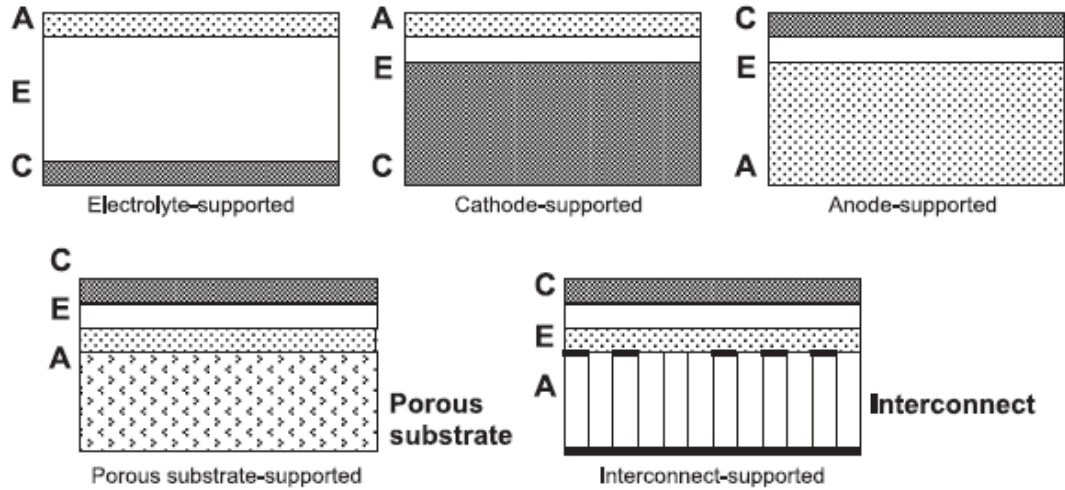


FIGURE 9: SINGLE CELL CONFIGURATIONS OF SOFC [11]

Figure 10 is a schematic of how Hydrogen is transferred in SOFC

- At the anode side of a SOFC, Hydrogen is fed and the oxidant/air is provided at the cathode side [13].
- The gases diffuse through the anode side and the cathode electrodes towards the interface of the electrolyte [13]

It is expected that SOFC fuel cells can be available at market prices of \$500/kW investment. Major impediments for the application of the SOFC cells are the lack of broad experience with them at wide operating conditions for long periods and the fact that they need to be operated at 1273 K. The high temperature is a major problem.

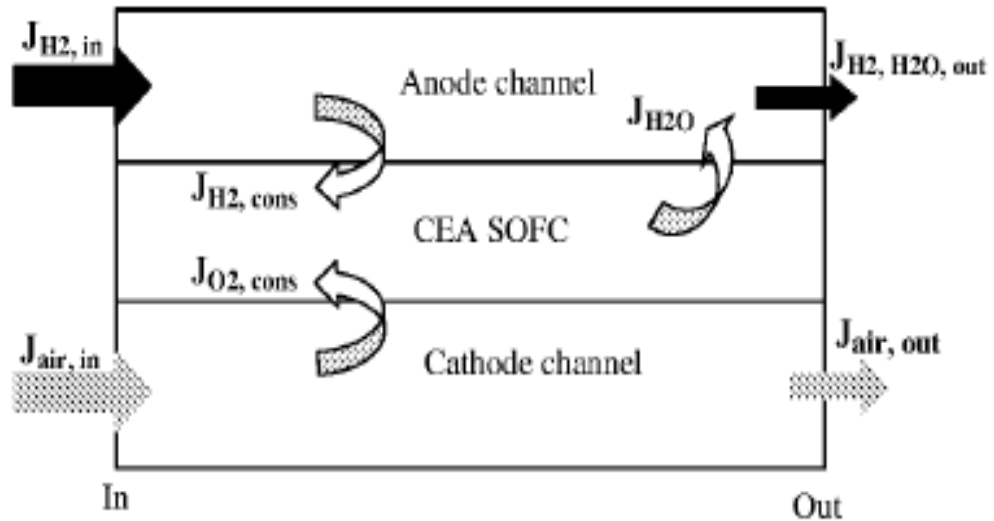


FIGURE 10: MASS TRANSFER IN SOFC ANODE FLOW [13]

Low voltage DC current flows out of fuel cells, which a conversion from DC to AC will be required to make the grid compatible. This can lead to a power losses, therefore more than one fuel cell may have to be used for the system.

Planar design is most commonly used and able to deliver the cheapest SOFC unit. The net power rating for planar SOFC is approximated 1 MW/m^3 in Hydrogen [10].

The next chapter describes the consolidation of systems chose for generation of H_2 , storage and regeneration of electricity.

Chapter3. Methods used and Materials Chosen

The choices made for the generation of Hydrogen from wind energy electricity, the storage of Hydrogen in G212 carbon and the regeneration of electricity on demand using SOFC fuel cells is considered here in a little more detail. The present design considers a 1.5 MW windmill that will need storage of energy for 16 hours resulting in the storage of 24 MWh equivalent of energy. To efficiently generate the amount of Hydrogen in large capacities, alkaline electrolyzer is selected for the present application. Electrolyzers produced by Norsk Hydro offers “minimal downtime, compact size, flexible solutions” for electrolyzers that can meet different demands according to the company. According to Norsk Hydro, the maximum output capacity of one single electrolyzer is 485 Nm³/hr of Hydrogen and 242,5 Nm³ /hr of Oxygen. Larger capacity plants can be readily obtained by multiplying the number of units. The maximum capacity for one electrolyzer is 500 Nm³/hr. It is claimed as the largest atmospheric pressure water electrolyzer in the world, which can fit the Hydrogen technologies considered here. With assumptions made (1.5 MW power rate operates for 16 hours), calculations of the amount of Hydrogen needed (487kg) are presented in Chapter4.

Once the Hydrogen is produced, a high efficiency storage material for storing the Hydrogen is needed. As proposed in an earlier section, CDC and G212 are the candidates for large capacity Hydrogen storage. Thus, we can compare carbon derived carbon with carbon G212 in several ways to show the advantages that carbon G212 has in Hydrogen storage. In this case, we assume the operating

pressure is 1 bar. Again, it has to be taken at 0.3 wt. % for CDC due to its practical performance limits. The amount of Hydrogen adsorbed in carbon G212 is 10.661 ± 0.185 mmol/g at 77K [8], this can be converted into 1.2 wt. %. With 24 MWh (1.5 MW power rate operating for 16 hours as indicated before), calculations shown in Chapter 4 will compare CDC with carbon G212 in how much porous carbon is needed for each material and their expenses. The unit prices chosen for each material comes from the current market price.

In addition, G212 can also be introduced to another application on improving its Hydrogen storage rate. With this result of G212, if BMW adopts G212 to their BMW Hydrogen 7 Series of cars, the company would greatly benefit by the high adsorption rate of Hydrogen storage. As introduced by BMW, Hydrogen 7 car directly uses Hydrogen as fuel, which is different from other traditional fuel cell vehicles. It injects Hydrogen into the air intakes of cars to be combusted in the cylinders of engine. The company claims to store liquid Hydrogen in an approximately 30 gallon (or 110 liters), bi-layered and highly insulated tank. The storage tank holds the maximum of 8 kg (or 18 lbs) of liquid Hydrogen, which allows traveling for 125 miles (201Km) per tank [9].



FIGURE 11: BMW HYDROGEN 7 [CORPORATE LITERATURE]

Since the Hydrogen storage material has been selected, the next step is to propose the general design of the Hydrogen tank. Figure 12 shows the overview of Hydrogen tank. Firstly, an insulation layer has to be built outside of the gas container, which uses polystyrene Styrofoam to insulate the outer walls of the container. A secondary insulation layer is built around the original G212 materials tank. This second insulation is a hollow space for liquid Nitrogen (at 77 K at 1 atm) to flow through, which can physically cool down the temperature of the Hydrogen stored inside. The core of this design is the main part the storage of Hydrogen. With the Hydrogen from the electrolyzer cooled down to 77K, Hydrogen flows into the storage tank and is stored approximately at 77 to 80K. Liquid nitrogen flows into the system originally at 77K, and it increases to around 79K as Hydrogen simultaneously stored in the tank. The tank has two different outlets which allow nitrogen and Hydrogen to flow outside of the tank. Temperature of Hydrogen flows

out of the storage tank is approximately at 80K, which can be used by SOFC fuel cell to generate electric power.

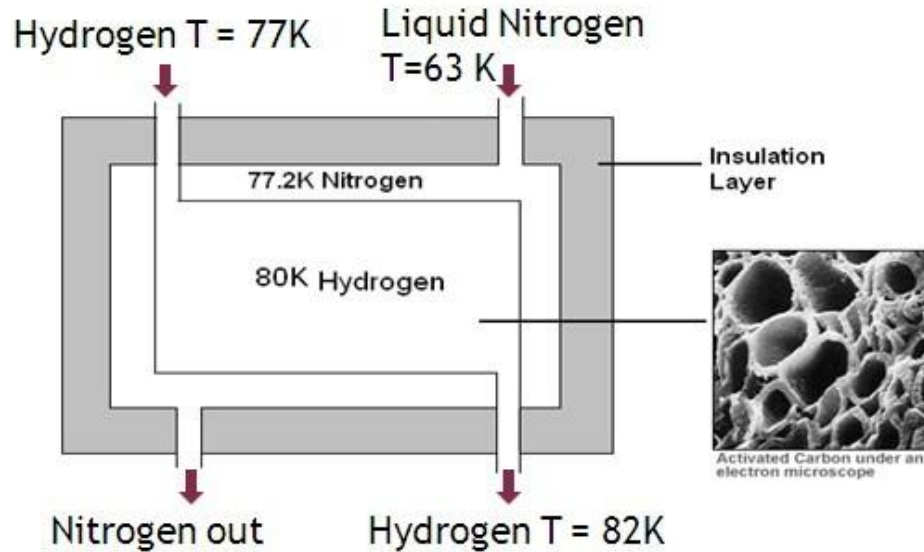


FIGURE 12: STRUCTURE OF HYDROGEN STORAGE TANK WITH POROUS CARBON G212

Calculations in Chapter 4 will elaborate that with 77K and 1 bar assumptions, the total volume of carbon G212 required to build the Hydrogen storage tank for 487 kg Hydrogen (corresponding to 24 MWh of energy to be stored coming in at power rates of as much as 1.5 MW from the wind mill) is 129 m^3 . This corresponds to a tank of approximately $5\text{ m} \times 5\text{ m} \times 5\text{ m}$ ($\sim 17\text{ ft} \times 17\text{ ft} \times 17\text{ ft}$) which is quite practical and manageable. The net weight of G212 required will be about 49,020 kg which assumes only 1 wt % storage capability of Hydrogen in G212 porous carbon. There is reason for optimism since G212 could store 3 wt % of Hydrogen if the tank pressure was increased to 10 bar (150 psi) and the carbon need could be as little as

16,300 kg and the tank size will correspondingly be smaller, about 43 m³ (4m x 4m x 4m).

Using the stored Hydrogen, as it is released from the storage tank just by depressurization and heating to atmospheric temperature if necessary, electricity generation can be done using SOFC fuel cells. SOFC is the only kind of fuel cell which has the potential for a wide range of applications, small power systems, automobile auxiliary power to distributed power plants [11], for systems in the range from 100kW to 500kW.

The next chapter delves into the calculational details for the three component energy storage system described above.

Chapter4. Calculations for the Generation and Storage of Hydrogen

A three-component system for the generation of Hydrogen, storage of Hydrogen at 77 K in G212 porous carbon at up to 3 wt % and the generation of electrical power using SOFC fuel cell was described in the previous chapter. The numerical details for sizing and designing these components are considered here.

The conversion efficiencies of electrolyzers are in the range of 52% to 82% if the higher heating value is adopted [3]. Electrolyzers selected for this work are high efficiency units that can achieve 80% efficiency. Ideally 1 kg of Hydrogen can be produced by 8.9 liters of water and 39.4kWh (HHV) of electrical energy [2], which includes the total energy to dissociate water under 1 atmosphere and 298 K.

With HHV= 39.4kwh/kg, it takes 49.25 kWh and 11.13 liters of water to produce 1 kg Hydrogen.

As mentioned earlier, since we assume that this effort is aimed at saving the energy storage for a 1.5 MW wind mill for 16 hours resulting in the storage of 24 MWh equivalent of energy,

For 1.5 Mw power rate, time=16 hrs, $1.5 \times 10^3 = 1,500 \text{ kW}$

$$1,500 \times 16 = 24,000 \text{ kWh}$$

$$\frac{1 \text{ kg}}{49.25 \text{ kWh}} = \frac{m_{H_2}}{24,000 \text{ kWh}} \quad (6)$$

Therefore Hydrogen mass needed for 24 MWh equivalent of energy is:,

$$m_{H_2} = 487.3\text{kg}$$

The mass of Hydrogen is around 487 kg and this value will be used through the following calculations for Hydrogen storage and electricity generation.

To calculate the amount of porous G212 or other materials need for Hydrogen storage in CDC and G212, following equations can be used. Hydrogen adsorption rate for different conditions is obtained from experiment and can be directly applied in the calculations.

Porosity:
$$p = 1 - \frac{\rho_{bulk}}{\rho_{part}} \quad (7)$$

Weight percent:
$$\frac{m_{H_2}}{m_C} = wt. \% \quad (8)$$

Mass of graphitic carbon:
$$m_C = \frac{m_{H_2}}{wt. \%} \quad (9)$$

Volume of graphitic carbon:
$$V_C = \frac{m_C}{\rho_C} \quad (10)$$

Volume of porous carbon:
$$V_{por} = \frac{V_C}{(1-p)} \quad (11)$$

(1) Carbon derived carbon storage calculations

Select the density of CDC ($\rho_{CDC} = 0.76 \text{ g/cm}^3$, $p = 0.6607$) in Table 1. ρ_C is the true density of graphitic Carbon which equals to 2.25 g/cm^3 ($2,250 \text{ kg/m}^3$), adsorption rates are referred to Figure 13, we can therefore calculate:

- At 77K, 1bar

$$\text{Weight percent stored} = \frac{m_{H_2}}{m_C} = 0.3 \text{ wt.}\% = 0.003$$

$$\text{Mass of Carbon} = m_C = \frac{487 \text{ kg}}{0.003} = 162,333 \text{ kg}$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{162,333 \text{ kg}}{2,250 \text{ kg/m}^3} = 72 \text{ m}^3$$

$$\text{Volume of CDC} = V_{tot} = \frac{V_C}{(1-p)} = \frac{72 \text{ m}^3}{(1-0.6607)} = 212 \text{ m}^3$$

$$\text{Mass of CDC} = \rho_{CDC} \times V_{tot} = 760 \text{ kg/m}^3 \times 212 \text{ m}^3 = 161,273 \text{ kg}$$

$$\text{Unit price of CDC} = \$2/\text{lb.} \times \frac{1 \text{ lb}}{0.45 \text{ kg}} = \$4.44/\text{kg}$$

$$\text{Total price of CDC} = \$4.44/\text{kg} \times 161,273 \text{ kg} = \$716,052$$

- At 77 K, 5bar

$$\text{Weight percent stored} = \frac{m_{H_2}}{m_C} = 0.342 \text{ wt.}\% = 0.00342$$

$$\text{Mass of carbon} = m_C = \frac{487 \text{ kg}}{0.00342} = 142,398 \text{ kg}$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{142,398 \text{ kg}}{2,250 \text{ kg/m}^3} = 63 \text{ m}^3$$

$$\text{Volume of CDC} = V_{tot} = \frac{V_C}{(1-p)} = \frac{63m^3}{(1-0.6607)} = 187 m^3$$

$$\text{Mass of CDC} = \rho_{CDC} \times V_{tot} = 760 \text{ kg/m}^3 \times 187 m^3 = 141,759 \text{ kg}$$

$$\text{Unit price of CDC} = \$2/lb. \times \frac{1lb}{0.45kg} = \$4.44/kg$$

$$\text{Total price of CDC} = \$4.44/kg \times 141,759kg = \$ 629,411$$

- At 77K, 20bar (this pressure of 20 atm could be more difficult to handle)

$$\text{Weight percent} = \frac{m_{H_2}}{m_C} = 0.4wt.\% = 0.004$$

$$\text{Mass of carbon} = m_C = \frac{487kg}{0.004} = 121,750kg$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{121,750kg}{2,250kg/m^3} = 54 m^3$$

$$\text{Volume of CDC} = V_{tot} = \frac{V_C}{(1-p)} = \frac{54m^3}{(1-0.6607)} = 159 m^3$$

$$\text{Mass of CDC} = \rho_{CDC} \times V_{tot} = 760 \text{ kg/m}^3 \times 159 m^3 = 121,203 \text{ kg}$$

$$\text{Unit price of CDC} = \$2/lb. \times \frac{1lb}{0.45kg} = \$4.44/kg$$

$$\text{Total price of CDC} = \$4.44/kg \times 121,203kg = \$538,144$$

(2) Carbon G212 storage calculations

The apparent density of G212 is 0.38 g/cm³ (provided by PICA); porosity of G212 can be calculated by:

$$p = 1 - \frac{\rho_{b u l l}}{\rho_{p a r t i c l e}} \quad (7)$$

$$= 1 - \frac{0.38}{2.65} = 0.86$$

For normal particles, density ($\rho_{particle}$) is assumed to be approximately 2.65 g/cm³ in general.

- At 77K, 1bar

$$\text{Weight percent} = \frac{m_{H_2}}{m_C} = 1.2 \text{ wt. \%} = 0.012$$

$$\text{Mass of carbon} = m_C = \frac{487 \text{ kg}}{0.012} = 40,583 \text{ kg}$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{40,583 \text{ kg}}{2,250 \text{ kg/m}^3} = 18 \text{ m}^3$$

$$\text{Volume of G212} = V_{t o t} = \frac{V_C}{(1-p)} = \frac{18 \text{ m}^3}{(1-0.86)} = 129 \text{ m}^3$$

$$\text{Mass of G212} = m_{G212} = \rho_{G212} \times V_{t o t} = 380 \text{ kg/m}^3 \times 129 \text{ m}^3 = 49,020 \text{ kg}$$

$$\text{Unit price of G212} = \$4/\text{lb.} \times \frac{1 \text{ lb}}{0.45 \text{ kg}} = \$8.88/\text{kg}$$

$$\text{Total price of G212} = \$8.88/\text{kg} \times 49,020 \text{ kg} = \$435,298$$

- At 77K, 5bar

$$\text{Weight percent} = \frac{m_{H_2}}{m_C} = 2.8 \text{ wt. \%} = 0.028$$

$$\text{Mass of carbon} = m_C = \frac{487 \text{ kg}}{0.028} = 17,393 \text{ kg}$$

$$\text{Volume of carbon} = V_c = \frac{m_c}{\rho_c} = \frac{17,393\text{kg}}{2,250\text{kg/m}^3} = 8 \text{ m}^3$$

$$\text{Volume of G212} = V_{\text{tot}} = \frac{V_c}{(1-p)} = \frac{8\text{m}^3}{(1-0.86)} = 55 \text{ m}^3$$

$$\text{Mass of G212} = m_{G212} = \rho_{G212} \times V_{\text{tot}} = 380 \text{ kg/m}^3 \times 55 \text{ m}^3 = 20,982 \text{ kg}$$

$$\text{Unit price of G212} = \$4/\text{lb.} \times \frac{1\text{lb}}{0.45\text{kg}} = \$8.88/\text{kg}$$

$$\text{Total price of G212} = \$8.88/\text{kg} \times 20,982\text{kg} = \$186,320$$

- At 77K, 20bar (this 20 atm or 300 psi pressure could be difficult to handle or make the system more expensive)

$$\text{Weight percent} = \frac{m_{H_2}}{m_c} = 3.88\text{wt.}\% = 0.0388$$

$$\text{Mass of carbon} = m_c = \frac{487\text{kg}}{0.0388} = 12,552\text{kg}$$

$$\text{Volume of carbon} = V_c = \frac{m_c}{\rho_c} = \frac{12,552\text{kg}}{2,250\text{kg/m}^3} = 6 \text{ m}^3$$

$$\text{Volume of G212} = V_{\text{tot}} = \frac{V_c}{(1-p)} = \frac{6\text{m}^3}{(1-0.86)} = 40 \text{ m}^3$$

$$\text{Mass of G212} = m_{G212} = \rho_{G212} \times V_{\text{tot}} = 380 \text{ kg/m}^3 \times 40 \text{ m}^3 = 15,142 \text{ kg}$$

$$\text{Unit price of G212} = \$4/\text{lb.} \times \frac{1\text{lb}}{0.45\text{kg}} = \$8.88/\text{kg}$$

$$\text{Total price of G212} = \$8.88/\text{kg} \times 15,142\text{kg} = \$134,461$$

Temperature variations are considered in the comparisons for G212 since it will give us a more specific idea of how the temperature will affect the results of materials need.

- At 140K, 1bar

$$\text{Weight percent} = \frac{m_{H_2}}{m_C} = 0.18 \text{ wt. \%} = 0.0018$$

$$\text{Mass of carbon} = m_C = \frac{487 \text{ kg}}{0.0018} = 270,556 \text{ kg}$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{270,556 \text{ kg}}{2,250 \text{ kg/m}^3} = 120 \text{ m}^3$$

$$\text{Volume of G212} = V_{t, o \bar{r}} = \frac{V_C}{(1-p)} = \frac{120 \text{ m}^3}{(1-0.86)} = 859 \text{ m}^3$$

$$\text{Mass of G212} = m_{G212} = \rho_{G212} \times V_{tot} = 380 \text{ kg/m}^3 \times 859 \text{ m}^3 = 326,420 \text{ kg}$$

$$\text{Unit price of G212} = \$4/\text{lb.} \times \frac{1 \text{ lb}}{0.45 \text{ kg}} = \$8.88/\text{kg}$$

$$\text{Total price of G212} = \$8.88/\text{kg} \times 326,420 \text{ kg} = \$2,898,610$$

- At 190K, 1bar

$$\text{Weight percent} = \frac{m_{H_2}}{m_C} = 0.024 \text{ wt. \%} = 0.00024$$

$$\text{Mass of carbon} = m_C = \frac{487 \text{ kg}}{0.00024} = 2,029,167 \text{ kg}$$

$$\text{Volume of carbon} = V_C = \frac{m_C}{\rho_C} = \frac{2,029,167 \text{ kg}}{2,250 \text{ kg/m}^3} = 902 \text{ m}^3$$

$$\text{Volume of G212} = V_{t, o \bar{r}} = \frac{V_C}{(1-p)} = \frac{902 \text{ m}^3}{(1-0.86)} = 6,442 \text{ m}^3$$

$$\text{Mass of G212} = m_{G212} = \rho_{G212} \times V_{tot} = 380 \text{ kg/m}^3 \times 6,442 \text{ m}^3 = 2,447,884 \text{ kg}$$

$$\text{Unit price of G212} = \$4/\text{lb.} \times \frac{1 \text{ lb}}{0.45 \text{ kg}} = \$8.88/\text{kg}$$

$$\text{Total price of G212} = \$8.88/\text{kg} \times 2,447,884 \text{ kg} = \$21,737,210$$

Firstly, from Hydrogen adsorption characteristics of both Carbon Derived Carbon and carbon G212, a comparison of the adsorption rate for both materials can be plotted with pressure changes from 1 bar to 20 bar in Figure 13. As pressure increases, the adsorption rate of Hydrogen is increasing as well. CDC has a higher adsorption rate in general over the pressure range from 1 to 20 bar, while G212 has faster changes as the pressure gets larger.

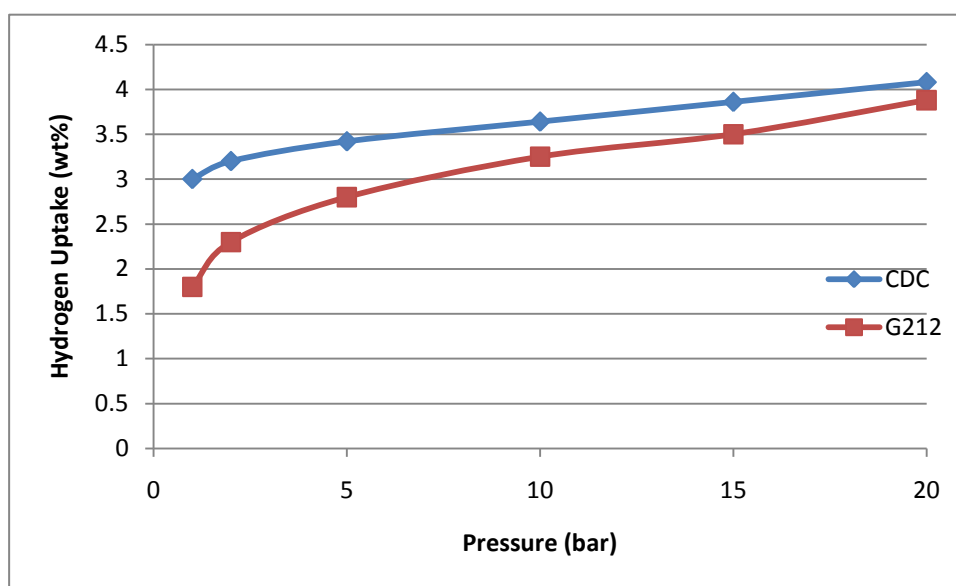


FIGURE 13: HYDROGEN UPTAKE OF CDC AND G212 WITH PRESSURE CHANGES FROM 1-20 BAR

Descriptions of temperature variations of CDC at higher temperatures are not available since there is very little work of it has been done so far. In addition, with the practical performance of CDC at 77K and 1 atmosphere, the adsorption rate at higher temperature is not seen competitive with G212 under the same condition.

Next, with temperature increases slightly, the amount adsorbed decreases in a great amount rapidly, the efficiency of Hydrogen storage changes a lot from 77K. This requires much more storage material and higher costs of the material.

With calculations based on different pressures and temperatures for each material, it can be concluded that with higher temperature, the adsorption rate decreases tremendously, which physically requires a larger amount of porous carbon materials and higher costs. On the other hand, pressure changes will greatly increase the Hydrogen adsorption amount and requires less storage materials, which leads to lower costs on the purchases.

Considering different situations may be applied to Hydrogen storage, 1 atmosphere and 77K is used for the system with analyzing purpose as assumed previously. To summarize the comparisons of Hydrogen store in CDC and G212, see table 2 below. From economic point of view, it can save almost half of the expenses on purchasing porous materials for Hydrogen storage with G212 at 1 bar and 77K than using CDC.

Table 2. Comparison data for Carbon derived carbon (CDC) with G212 for 1.5 MW power for 16 hours of storage

	Wt.%	m_{H2} (kg)	m (kg)	Volume of porous material (m³)	Unit Price(\$/kg)	Total price(\$)
CDC	0.3	487	161,273	212	4.44	716,052

G212	1.2	487	49,020	129	8.88	435,298
G212	2.8	487	17,429	55	8.88	154,766

With the amount of Hydrogen stored for using, 487 kg Hydrogen can be generated into around 1.11MW power by planar SOFC. The cost of this kind of SOFC produced by General Electric Company is around \$800/kW. Utilizing this type of SOFC, the cost of electricity generation will be approximated at \$888,000 in total, which is less than a million dollars and is considered reasonable for 24MWh storage. The amount of G212 and the associated costs will be even smaller if the G212 is operated at 77K and 5 bar requiring only \$155,000 worth of G212. The tanks will have to be stronger but the pressures in question are not high at 5 bar.

Chapter5. Cost analysis of the system

As mentioned earlier, with no loss of generality, the current calculations are done for 24 MWh of windmill generated electrical energy storage using electrolysis based Hydrogen generation. For the wind energy to be generated and stored at 1.5 MW operating for 16 hours needs 487 kg Hydrogen based on the calculations of the previous chapter. The current chapter analyses the cost implications of the storage and the related equipment.

The average price (equipment investment cost) of an electrolyzer is about \$400/kW - \$600/kW. To store 487 kg of Hydrogen using carbon G212 in this case, it costs about \$435,298 for the porous carbon and associated costs of tank, etc. With specific geometry and dimension requirements, the cost of polystyrene or other insulation can be calculated by multiplying the total area of the outer tank and the unit price of the insulation layer, which is about \$21/ft² (\$226/m²).

The following table is a cost summary from calculations from the earlier Hydrogen storage section. It compares the porous carbon amount required to store Hydrogen and cost of each material under 77K and for at pressures ranging from 1 to 20 bar.

Table 3. Comparison data of CDC and G212 with pressure changes from 1-20 bar

Pressure (bar)	P = 1 bar	P = 5 bar	P =20 bar
Amount of CDC required (kg)	161,273	141,759	121,203
Costs of CDC (\$)	716,052	629,411	538,144
Amount of G212 required (kg)	49,020	20,982	15,142
Costs of G212 (\$)	435,298	186,320	134,461

Table 4 is a comparison of the amount of G212 required and costs with 1 bar pressure with temperature range from 77K to 190K. It is apparent from the results that with higher temperatures, the amount of G212 required to store a certain amount of Hydrogen (in this case 487kg) increases rapidly. This inherently makes the costs of G212 go up quickly even with temperature increases slightly above 80 K. Thus it makes sense to operate the storage tank and the associated G212 liquid Nitrogen (77 K) cooled around and maintained around 80 K.

Table 4. Comparison data of G212 with temperature changes from 77-190K

Temperature (K)	77	140	190
Amount of G212 required (kg)	49,020	326,420	2,447,884
Costs of G212 (\$)	435,298	2,898,610	21,737,210

One of the DOE designs for the storage of Hydrogen was a high pressure tank located inside the turbine tower. We can compare the above costs with a conventional 1.5MW wind turbine tower [12]. The cost of a 1.5 MW wind turbine tower is estimated at \$271,863, and that does not include the cost of high pressure tanks and related gas control equipment. While tank storage of Hydrogen cannot be compared to storage in porous carbon materials, storage of Hydrogen as compressed gas will require a significant amount of energy to compress to the desired high pressure.

Solid oxide fuel cells cost about \$800/kW of initial investment as sold by General Electric Company. To this we need to add operation and maintenance costs (~80/kW per year). The cost of electricity generation will be approximated at \$888,000 in this application. Table 5 is a summary of the major items that make up costs of 24 MWh energy storage systems.

Table 5. General costs of the system

	Item	Price (\$)
1	Water (\$/kgal)	5.50
2	Electricity (\$/kWh)	0.06
3	DC Bus usage	76.00
4	Solid Oxide Fuel cell	\$ 888,000

5	Electrolyzer	\$400/kW - \$600/kW
6	Storage tank (G212)	\$ 360,377
7	Liquid nitrogen	\$ 1,000
8	Outer insulation of the tank	\$226/m ²

The work described here is aimed at looking at the feasibility and cost implications of storing 24 MWh equivalent electrical energy generated by windmills. Wind energy is quite variable and may hardly match the load usage patterns. Thus storage of energy generated by windmills is an essential feature even when smart grid systems will be available in the future. Electrical energy is difficult to store at these magnitudes in an economic manner. Thus it is proposed to convert the electrical energy generated into Hydrogen using electrolyzers, store the Hydrogen as adsorbed and re-generate electrical energy as and when needed using SOFC fuel cells.

For the energy from the windmill to be stored, equivalent of 1.5 MW power operating for 16 hours will require the Hydrogen generation of about 500 (~ 487) kg needs to be generated and this require the use of 49,020kg of liquid Nitrogen (~77 K) cooled G212 porous carbon with 2.8 wt % storage capability at 80 K and 5 atm built into insulated storage tanks. The amount of G212 and the associated costs will be even smaller if the G212 is operated at 77 and 5 bar requiring only \$155,000 worth of G212. The tanks will have to be stronger but the pressures in question are not high at 5 bar.

As and when electricity is needed, this 500 kg of Hydrogen safely stored in G212 carbon can generate 1.11MW of power for the sixteen hours to be delivered to the grid interface and power system. The use of G212 carbon and SOFC fuel cells can economically reduce costs and improve the overall efficiency of the storage and the whole grid system.

Chapter6. Summary and Conclusions

To optimize the whole electrical power grid to operate it efficiently especially with larger anticipated capacities of renewable energies such as wind energy, it will be important to increase storage technologies in general and the use of Hydrogen storage capacity in particular. This will improve the performance of the whole windmill electric generation and grid system.

Handling and storage of Hydrogen is dangerous and requires safe but well established practices. Traditional materials do not have the capacities needed to store Hydrogen. Conventional porous carbons such as SWCNTs and MWCNTs are too expensive to build up tanks full of CNTs, while the reasonable price of materials such as carbon derived carbon have lower adsorption rates and thus are not ideal as a candidate for Hydrogen storage.

Porous carbons such as G212 carbon could make an economic alternative and have been described in detail in this work and is selected as the ‘container’ (adsorption storage medium) to store Hydrogen. Use of G212 carbon in the system, the costs can be cut in half of the expenses to build Hydrogen storage tank with G212 compared to some other systems. Moreover, the performance of Hydrogen adsorption of G212 is relatively satisfactory at 2.8 wt % at 5 bar (5 atm or 75 psia) pressure compared to current widely applied materials and compressed gas storage options.

Using SOFC fuel cells it is possible to generate electricity with stored Hydrogen. The performance of SOFC fuel cells is expected to be stable, and is much cheaper than PEM fuel cells. They will be used widely for the electrical grid industry since they are commercially available despite difficulties of having to operate at very high temperatures.

The porous carbons such as G212 described in this work with up to 2.8 wt % storage around 80 K and 5 atm pressure can provide an economic alternative for the safe storage of Hydrogen which can be useful in many scenarios but can make a major impact with windmill generated electrical energy storage.

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Vita

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