PHD

An Optimal Design Methodology for Hydrogen Energy Storage to Support Wind Power at the University of Bath

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An Optimal Design Methodology for Hydrogen Energy Storage to Support Wind Power at the University of Bath

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Signature:…………………………… Date:.………………………………

SUMMARY

Fossil fuel will eventually become exhausted. Also, fossil fuels produce large amounts of carbon dioxide, which cannot only bring environment pollution, but can also cause global warming. Therefore, clean and renewable energy sources should be investigated.

In this project, renewable wind power was considered. Wind energy is free, clean and available in large quantities, although it is difficult to use due to its stochastic variability. Energy storage can reduce this variability allowing energy production to match energy demand.

In this study, different kinds of energy storage approaches were introduced, compared, and simulated by using half hourly wind data from the Met Office, UK, and half hourly load data from the University of Bath, UK. Hydrogen has higher mass energy density than all other energy storage methods. It is seen as a versatile energy carrier of the future, complementary to electricity and with the potential to replace fossil fuels due to its zero carbon emissions and abundance in nature.

On the other hand, because hydrogen is the lightest element under normal conditions; the same amount of hydrogen must occupy a huge volume compared to other elements. The mature technology for converting hydrogen into electricity has high cost and low efficiency. These are big issues that limit the usage of hydrogen energy storage methods.

Using wind and load data, a new algorithm was developed and used for sizing the wind turbine, and energy storage requirements. The traditional way to supply energy is distributing electricity, but in this PhD research, there are some discussions about a new method, hydrogen transport-hydrogen pipeline.

From the results of the comparison and algorithm, a practical hydrogen energy storage system for the University of Bath network was proposed and designed. In the proposed design the energy from a wind turbine was directed to the load and the remaining excess power was used to produce hydrogen by water electrolysis. The hydrogen was stored in a high pressure compressed tank, and finally a hydrogen fuelled combined cycle gas turbine was used to convert the hydrogen to electricity.

In this thesis, the dynamics of the complete hydrogen cycle energy storage and recovery mechanism are discussed, identifying potential applications such as power smoothing, peak lopping and extending power system controller ranges. The results of calculations of the payback time and revenue verify the feasibility of the designed hydrogen energy storage system.

The main objective of the PhD was to design a practical hydrogen energy storage system for micro-grid applications. During this research, hydrogen energy storage was investigated to show that it does solve the problems arising from renewable energy.

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Contents

List of Abbreviations

Notation	**Description**
AC	alternating current
AFC	alkaline fuel cell
BES	battery energy storage
C	carbon
$CaCO_3$	calcium carbonate
CAES	compressed air energy storage
CaO	calcium oxide
CH_3OH	methanol
CH_4	methane
CO	carbon monoxide
Co	cobalt
CO_2	carbon dioxide
DC	direct current
DG	distributed generation
DI	direct injection
DMFC	direct methanol fuel cell
DOD	depth of discharge
DOE	department of energy
EPRI	electric power research institute
ES	energy storage
Fe	iron
FES	flywheel energy storage
h	hour
H_2-CCGTs	hydrogen-fuelled combined cycle gas turbines
H_2-ICEs	hydrogen-fuelled internal combustion engines
HER	hydrogen evolution reaction
HES	hydrogen energy storage
ICE	internal combustion engine
KOH	potassium hydroxide
LH_2	liquid hydrogen
$LiCoO_2$	lithium cobalt oxide
m	meter
Mo	molybdenum
$NaAlH_4$	sodium aluminium hydride
NaS	sodium sulphur
NiMH	nickel–metal hydride

NO_x	nitrogen oxide
NREL	national renewable energy laboratory
O&M	operation and maintenance
PEMFC	proton exchange membrane fuel cell
PFI	port fuel injection
PHS	pumped hydro storage
PSA	pressure swing adsorption
Pt	platinum
PV	photovoltaic
RE	renewable energy
RFB	redox flow cell
ROW	right of way
SAFC	sulphuric acid fuel cell
SCES	super capacitor energy storage
SMES	superconducting magnetic energy storage
SOFC	solid oxide fuel cell
SWNTs	single walled nano-tubes
Ti	titanium
TiO_2	titanium dioxide
TPD	temperature programmed desorption
UPS	uninterrupted power supply
VRFB	vanadium redox flow batteries
WPS	water pump station
WTGs	wind turbine generators
Zn	zinc
ZrO_2-Y_2O_3	yttrium zirconium

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Chapter 1 Introduction

THE introduction briefly describes the background, the motivation, the objectives, and the contribution of this thesis. It also provides an overview of the thesis layout.

1.1 Background

Nowadays, about 80 % of the energy used in the world is generated by burning fossil fuels. Fossil fuels are formed by dead plants and animals by exposure to heat and pressure in the Earth’s crust over hundreds of millions of years. They are in the form of petroleum, coal, peat, natural gas and other carbon-rich organic compounds. Since the Second World War, energy has been consumed at a very high rate due to rapid development of economics. This consumption has been difficult to meet using only fossil fuels. Furthermore, the carbon dioxide (CO_2) emissions produced during the process of burning fossil fuels is contributing to global climate change. Therefore, alternative energy sources are drawing more interest. Renewable energy (RE) emerges as the times require.

1.1.1 Carbon dioxide Effects

The CO_2 emissions not only bring heavy pollution to the surrounding environment, but also lead to the issue of global warming. The greenhouse effect is a process in which thermal radiation from the sun at high frequencies passes through the atmosphere and is absorbed by the earth, and infrared thermal radiation at lower frequencies emitted by the earth is then absorbed by greenhouse gases, water vapour, carbon dioxide, methane, ozone, and so on [1]. Joseph Fourier discovered the greenhouse effect in 1824 [2], John Tyndall carried out the first reliable experiments on it in 1858 [3], and the first scientific paper about it was written by Svante Arrhenius in 1896, he was the first to calculate the effect of the concentration of CO_2 in the atmosphere on the temperature of the Earth’s surface [4].

Recently, carbon dioxide has become the most important greenhouse gas. Since the industrial revolution in the mid-1800s, the amount of CO_2 which was released by burning fossil fuels for factories and power plants increased significantly, that has enhanced the greenhouse effect. This effect can result in global warming, sea levels rising and reduction of the ozone layer, these are leading to climate change, spread of diseases, impacts on agriculture, and ecosystem change.

1.1.2 Renewable energy

Renewable energy is the term used to describe energy generated from natural resources, such as wind energy, rain, wave and tides, sunlight, terrestrial heat, biomass and hydropower. Besides, those problems referred to previously, another important reason for using renewable energy instead of traditional fossil fuels is the energy security issue. Fossil fuel based energy will be used up in a few decades, for example, the UK has already been a net importer of natural gas since 2004, and oil from 2005 [5]. In 2007, the total energy consumed in the UK amounted to 1914.3×10^9 kWh [6]. However, there was only 65.5 % of the total energy used directly, the reminder was lost in converting and transmitting the energy, or was used by energy industries themselves before it reached the consumers. Generating large amounts of electricity can introduce heavy pollution and high CO_2 emissions if fossil fuels are used.

During the 1940s, 90 % of the UK's electricity was generated from coal 'at its peak'; with oil providing most of the remainder. This situation was changed in 1997 as nuclear power 'at its peak' was used to generate 26 % of the electricity. From about that period onward, new renewable energy sources have begun to contribute to the electricity generated, adding to a small hydro-electricity generating capacity [7][1]; however, this was very limited. Electricity supplied by different fuel types in 1990 and 2007 are compared in Fig. 1-1. From this figure, although renewable energy only contributed about 5.5 % of the electricity in 2007, it is definitely a great improvement, double the amount in 1990 [7]. From the National Grid's 7 years statement, 2011-2017, UK generation will be increased by 31.2 GW in total up until 2017, which includes 16.2 GW increase in CCGT; 22.4 GW increase in wind; 2 GW increase in nuclear; 2.1 GW increase in other renewable; and an 11.5 GW decrease in oil and coal.

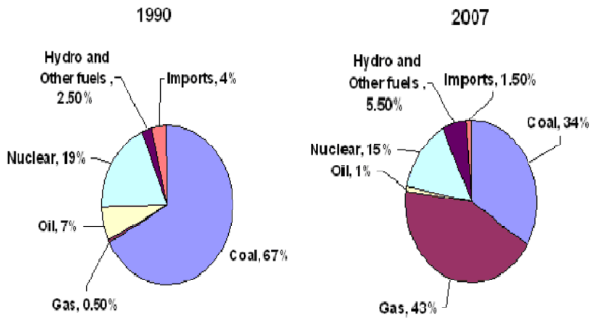


Fig. 1-1 Comparison of electricity supplied by fuel types in 1990 and 2007 [5]

The UK has two key environmental targets from the 2008 climate change act:

1. By 2050, 80 % of CO_2 emissions should be reduced from 1990 levels;
2. The UK will contribute 20 % of the European Union's renewable energy by 2020, mostly from wind power.

1.1.3 Wind power

Energy conversion from renewable energy sources, in particular through wind power with wind turbine generators (WTGs) and solar power by photovoltaic (PV) arrays combined with suitable energy storage can play an important role in the development and operational RE systems.

Wind has been used as an energy source for at least the last 3,000 years, e.g. for sailing boats, and during the 20th century, wind power was used to provide mechanical power to pump water in agriculture. Wind power is proposed to replace the traditional fuels in future plans, because wind is absolutely free, abundant and it generates no pollution, no waste, and will not cause global warming. Besides, wind turbines used to convert wind energy into electricity take up little space. The best places for wind farms are normally in remote areas, like coastal areas, the tops of mountains, remote open plains. Because in these areas, the resources are widely distributed, do not need to be transmitted and thereby has no transmission fee. Additionally, if the wind energy is combined with solar energy, the power provided can be less variable and more reliable. At the end of 2007, worldwide capacity of wind-powered generators was 94.1

GW [8]. But there was only 1 % of electricity produced by wind in the world. In the UK, 8445 MW with 362 operational wind farms and 4158 wind turbines have already been installed, and up to 30 GW will be installed by 2020.

Although there are many advantages of wind power, some drawbacks still limit the use of wind power as the main energy source. The main disadvantage is that wind is unpredictable, so the energy generated from wind might be unreliable. In addition, wind turbines are very expensive; the technology of large size wind turbines has not matured yet; and they can make a lot of loud noise during their operation.

The introduction of wind energy has already brought along the development of increased wind turbine size technology during the past few years. Wind turbine blades and tips are limited by both the strength and stiffness of the materials used. The following Table 1-1 [9-13] provides a brief summarization of this development in wind turbine capacity. From this table, it can be seen that a significant breakthrough in the field of wind turbines is on-going.

Table 1-1 Development of wind turbine size between 1985 and 2000 [9-13]

Year	Capacity (kW)	Rotor diameter (m)
1985	50	15
1989	300	30
1992	500	37
1994	600	46
1998	2000	70
2001/2002	3500	88

1.1.4 Energy storage

Wind energy is difficult to be used due to its stochastic variability. Although the overall energy demand could be easily met by the energy generated from wind turbines, there can be significant mismatches between the instantaneous load and wind power. The intermittence of wind power limits its penetration level in the power industries. Energy storage (ES) can reduce this variability allowing power production to match power demand. In order that wind energy can be efficiently used by consumers, energy storage methods have been considered as solutions to smooth variations in wind power production, so that it can follow the load [9].

There are many methods available to store energy, such as pumped water, compressed air, thermal, flywheels, batteries, capacitors and hydrogen storage. Each of these has its relative advantages and disadvantages.

Batteries can hold charge for quite a long time, several months, but compared to capacitors, have much shorter charge-discharge life cycle [10]. Super capacitors have long life cycle; have high current and power capability and charge-discharge very quickly. Additionally, they also have a wide operational temperature range [11]. But they are low voltage devices, thus they can break down if the voltage is not well controlled. Also, their energy densities are much lower than batteries. Another drawback is that they can only hold charge for a few minutes. Flywheels can store energy very efficiently; have high output power and long life cycle; also, they are not easily affected by temperature. But the current flywheels have low specific energy; self-discharge too quickly; and they may be unsafe due to the high rotating speed [12]. Hydrogen storage is a new technology. It is seen as a versatile energy carrier of the future, complementary to electricity and with the potential to replace fossil fuels due to the fact that it has zero carbon emissions and it is abundant in nature. Compared with other commonly used energy storage methods, such as battery storage, super capacitors and flywheels, hydrogen energy storage is well suitable for seasonal storage applications because it has an inherent high mass energy density, an insignificant leakage from suitable storage tanks, and it is easy to install anywhere. However, there is a space issue of storing hydrogen, as the result of the low density of hydrogen.

1.1.5 Hydrogen storage

Hydrogen was first recognized as a distinct substance in 1766 by Henry Cavendish in the experiment about iron (Fe) and zinc (Zn) in dilute sulphuric acid [13, 14]. Since then, it has been used in many areas, from balloon flight to rocket propulsion. Hydrogen means “water former” in Greek, which was proposed as the element’s name by A. L. Lavoisier in 1783 [14].

Hydrogen is the smallest and simplest member of the family of chemical elements, with atomic number 1 and atomic mass 1.008. Hydrogen is formed from a nucleus consisting of a proton, bearing one unit of positive electrical charge and an electron, bearing one unit of negative electrical charge. Hydrogen is a colourless, odourless and extremely flammable gas. It has the lowest density 0.09 kg m^{-3} of any elements (at 10 bar, 25 ºC). It is much lighter than air that is why it can fly off into space against the earth's gravitational force. The melting point and boiling point are -259 °C and -253 °C at atmospheric pressure, respectively. Hydrogen is an abundant element and it makes up over 90 % of the normal matter of the universe. It can be found in the sun and all other stars. On the earth, hydrogen is plentiful in the form of water in oceans, lakes and rivers.

Hydrogen gas does not usually react with other elements at room temperature, but water and a huge amount of heat can be produced if it is ignited in air, if burning it combines explosively with oxygen in the air.

Producing hydrogen from steam methane (CH_4) reforming has been widely used in industry for several decades [15]. There are also some other ways to produce hydrogen, like water electrolysis. Electrolysis is too expensive to be used in industry, but it is particularly suitable for use with photovoltaic and wind energy systems, especially cheaper with wind energy [16].

Hydrogen storage is an important issue to which scientists from all over the world have directed a lot of effort. Hydrogen is the lightest substance, so it will occupy a huge volume. Therefore, compressed hydrogen, liquid hydrogen, metal hydrides, complex hydrides and carbon based hydrogen storage methods have been investigated to overcome the difficulties [17].

There are different methods for converting hydrogen energy to electricity, for example, fuel cells, hydrogen-fuelled internal combustion engines (H_2-ICEs), direct steam generators, catalytic combustion engines, and hydrogen-fuelled combined cycle gas turbines (H_2-CCGTs) [16]. The advantages and disadvantages of these methods are discussed in the later chapters of this thesis.

1.2 Motivations and objectives

Since the World War II, energy has been consumed at a high rate. Hence the ultimate shortage of fossil fuels is a most crucial issue at the moment. Conventional fossil fuels can produce carbon dioxide, which causes global warming. The pollution of the global environment and the crisis of energy supply sources mean that the future fuels need to be decarbonised. Based on the background referred to in Section 1.1.2, renewable energy can play an increasingly important role alongside traditional fossil fuels in the future. Wind energy was chosen in this study, because the UK has the largest potential wind energy resource in Europe. There is still a long and difficult way to go; therefore, the proportion of energy generated from wind is very small in the current market.

In order to enhance the utilization of wind energy, the author decided to focus on this area—introducing energy storage methods to power systems with wind energy. This work showed that there were considerable seasonal changes in the mean daily wind speed. So as to maximize the harvesting of wind energy, an energy storage approach should possess low cost, high efficiency, and be suitable for seasonal storage. It is expected that the solution will help to enhance the utilization of wind energy and the stability of power systems.

Hydrogen provides the highest available mass energy density of all fuels, but hydrogen to electricity conversion equipment, such as fuel cells, is low efficiency and high-cost. Improving this to meet the requirement of the whole system is an important issue that should be addressed.

The objectives of this research are:

1) To supply an isolated micro-grid with wind generation only, and to minimize the capital cost of the whole system.

   In doing so, a new methodology for optimising the wind turbine size, and a new methodology for using the dynamic energy left on the energy store in order to optimise the energy storage size were developed. An initial hydrogen energy storage system was designed.

2) To explore whether a renewable generation, hydrogen storage system may be applied to other locations.

   In doing so, hydrogen pipelines were studied. Hydrogen can be delivered like nature gas with upgraded pipelines. Hydrogen pipelines and electrical distribution were compared for efficiency, capital costs and operational costs of the optimal wind turbine size and energy storage size.

3) To enhance the efficiency, robustness (fault tolerance), and reduce the cost of the whole system.

   In doing so, different energy storage options were considered. Including flywheels, NaS batteries, and hydrogen energy storage, these are compared in terms of round-trip efficiency, energy loss, life cycle, capital cost, operational cost, payback time, and return on investment. A new methodology for determining the practical number of cycles of energy storage systems is proposed.

4) To improve the performance and reduce the cost of hydrogen energy storage. This is to maximise the benefits of the abundance and green aspects of hydrogen as an energy vector.

In doing so, Hydrogen-fuelled internal combustion engines (ICEs), hydrogen-fuelled combined cycle gas turbines (CCGTs) and fuel cells were studied. The methodologies developed in objectives 1 and 3 were used to find the best technology from these three for The University of Bath. A practical system was designed, and verified for this 5 MW micro-grid.

1.3 Contribution

This PhD work included: investigation of the dynamics of the complete hydrogen cycle energy storage and recovery mechanism; identification of potential applications such as power smoothing, peak lopping and extending the power system controller range; introducing the hydrogen transport method instead of the traditional approach of distributing electricity; and modelling a practical hydrogen energy storage system for micro-grid applications.

To date the original work includes:

1) A new method for optimising the amount of hydrogen energy storage and the wind turbine size for isolated renewable power systems.
2) A comparison between delivering hydrogen energy and distributing electricity to each building at the University of Bath was carried out, using part of the University of Bath network as an example.
3) A case study of the requirements for a power system with wind energy, using the University of Bath site as an example.
4) A new method for determining the dynamic energy left in the energy store, used to size the store accounting for efficiency and energy loss.
5) A new method to determine the lifetime of energy storage methods, given a depth of discharge against life cycle relationship.
6) A realistic energy storage system was designed for the isolated University of Bath network, used as a convenient example system.

1.4 Outline of the thesis

Chapter 1

This chapter introduces renewable energy, wind energy, energy storage, and hydrogen storage. Hydrogen storage, as the energy storage chosen in this research, is mainly proposed for the improvement of the stability and utilization of wind energy. Then the motivations of the work presented in this thesis are stated, and main contributions of the work are summarized. At the end of this chapter, activities, skills and trainings related to the work are listed.

Chapter 2

In this chapter, a survey of many different energy storage methods is reviewed. Their advantages, drawbacks, and applications are identified and compared. There are further studies of three kinds of promising candidates, flywheels, Sodium Sulfur (NaS) batteries and hydrogen storage, chosen from many in preparation, for the future research work. Finally, an overview of power systems with energy storage is presented in Chapter 2.

Chapter 3

In this chapter, a survey showing details of the hydrogen storage method is presented. This chapter focuses on the process of the hydrogen storage approach which contains hydrogen production, hydrogen storage and the stage of hydrogen to electricity conversion. Different methods of storing hydrogen and kinds of energy conversion devices are compared for work following on from Chapter 3.

Chapter 4

This chapter studies the designing of a power system with wind energy and energy storage for the University of Bath network. Real, half hourly wind data and load data were used for the simulation. A new algorithm was developed for determining the wind turbine and energy storage size for an off-grid power system is presented in this chapter. The flow diagram of this algorithm is given, and a detailed energy flow chart is drawn out in the chapter. Also, the efficiencies and energy losses are calculated in Chapter 4.

Chapter 5

In this chapter, a new method of delivering hydrogen gas through upgraded tubes to a set of sub-generators is compared with traditional electricity transmission, by using half hourly wind and load data for the University of Bath site. Delivering hydrogen gas is just like delivering natural gas to each building by using upgraded natural gas pipelines. Half hourly data of four buildings chosen in the University of Bath in 2009 was used to verify the feasibility from the view-point of efficiency, capital cost, requirements of wind turbine and hydrogen storage size. Results are given for comparison in this chapter.

Chapter 6

This chapter shows comparisons between hydrogen energy storage, flywheels, and battery energy storage methods in terms of cost, efficiency, life cycle, payback time and revenue. The NaS battery was adopted in this chapter to complete these comparisons, based on the survey of batteries in Chapter 2. Half hourly wind and load data for the University of Bath network in 2006 was used here for the simulations. The simulation results and discussions are given in this chapter.

Chapter 7

In this chapter, the detailed power system with wind energy and hydrogen energy storage is designed. Each component chosen for the designed of a 5 MW off-grid power system with wind energy is described. The development of hydrogen energy storage systems by introducing H_2-ICEs and H_2-CCGTs is given, and the parameters of this system are summarized in this chapter.

Chapter 8

This chapter summarizes all the main conclusions and results obtained in the thesis. Further discussions about those conclusions and results are given. An overview of possible future work is presented in the chapter.

1.5 Activities

The author organised the following teaching, conferences, presentation, and workshop activities into the research to support this PhD study:

Session Chairman-Energy storage session, EuroPES 2011, the tenth IASTED European Conference on Power and Systems, Crete, Greece, 22/06/2011-24/06/2011

Transfer viva-"Hydrogen storage in wind power systems to balance the generation and demands", University of Bath, 03/2010

Seminar-"Hydrogen storage in wind power systems to balance the generation and demands", Power Point Presentation, University of Bath, 17/11/2008

Lab Demonstrator:

2007-2008—Electrical Systems & Control: DC-motor speed control;
& Signals, Systems & Communications—Amplitude Modulation/Demodulation
2008-2009—Operating Systems & Structured Programming;
& Mouse Project
2009-2010—Operating Systems & Structured Programming;
& Mouse Project
2010-2011—Signal Processing 1: Digital Spectral Analysis;
& Signal Processing 1: FIR Filtering
2011-2012—Operating Systems & Structured Programming;

& Mouse Project

2012-2013—Mouse Project

Conferences:

- Flexnet Assembly Meeting Steams, University of Bath, 19/05/2008-20/05/2008

- UK-SHEC 2010 3rd Workshop-Hydrogen energy futures, University of Bath, 10/05/2010-11/05/2010

- UKRC Sustaining Women's Career Progress in Science Engineering & Technology Conference, University of Bath, 30/09/2010

- UK-SHEC 2010 4th Biannual Workshop, "Hydrogen storage used in power system with wind turbines", Power Point Presentation, STFC Rutherford Appleton Laboratory, 09/11/2010-10/11/2010

- Paper-"A new methodology for designing hydrogen energy storage in wind power systems to balance generation and demand", Power Point Presentation, Supergen 09, 1st International Conference on Sustainable Power Generation and Supply, Nanjing, China, 06/04/2009-07/04/2009

- Poster- "Hydrogen and Hybrid Storage System as Balancing Components in a Wind Power Supplied Micro-grid", Poster Presentation, Sustainable Energy & the Environment Research Showcase, University of Bath, 17/09/2008

- Poster-"Electricity Supply to the University of Bath using Wind Energy and Hydrogen Storage to Balance Supply and Demand", Poster Presentation, Meeting of Minds Conference, University of Bath, 10/06/2010

- Paper- "Hydrogen energy storage in isolated microgrids with wind generation", Power Point Presentation, UPEC 2010, 45th International Universities' Power Engineering Conference, Cardiff, Wales, UK, 31/08/2010-03/09/2010

- “Comparison of different energy storage approaches in micro-grids with wind farm for energy balance”, Power Point Presentation**,** 5th International Renewable Energy Storage Conference, IRES 2010, Berlin, German, 22/11/2010-24/11/2010

- Paper-“Long-term hydrogen storage approach for a 5 MW Micro-power generator using wind turbines”, Power Point Presentation, EuroPES 2011, the tenth IASTED European Conference on Power and Systems, Crete, Greece, 22/06/2011-24/06/2011

1.6 Skills & trainings

SUPERGEN Flexnet Course on Power System Engineering and Economics, Supergen, Edinburgh, Scotland, 07/04/2008-10/04/2008

Residential South West Universities GRADschool 2010, Brecon beacons, Wales, 24/05/2010-27/05/2010

These presentation, communication, time managing, and other skill courses & trainings were completed for helping this PhD research:

Course	**Date**
Essential personal effectiveness in the PhD	22-Nov-2007
A doctor in three years: project and time managing your PhD	27-Nov-2007
Creative thinking & problem solving	18-Jan-2008
Writing quality papers	28-Jan-2008
Teaching in labs and tutorials and problem classes	05-Feb-2008
Presenting yourself	08-Feb-2008

Presentation skills: presenting research at meetings, seminars & conferences	14-Feb-2008
Teaching in labs and tutorials and problem classes	15-Feb-2008
Communication skills - getting your message across	19-Feb-2008
Overcoming overload: rapid reading in research	25-Apr-2008
Information skills: Copyright/plagiarism/referencing	22-Oct-2008
Information skills: Endnote	13-Nov-2008
Managing stress in PhD	18-Nov-2008
Presentations: Conference abstracts & posters	09-Dec-2008
Enterprise: Collaborating with commercial organisations	08-Jan-2009
Ethics 1 (good research practice)	E-learning module
Excel advanced: Conditional Logic and Lookup Tables	27-Apr-2010
Information skills: literature and data searching for engineering and design	27-Apr-2010
Planning conference posters	28-Apr-2010
Reading for academic writing - for the sciences	19-May-2010
Writing your thesis (less painfully) for engineering & design	03-Jun-2010

Chapter 2 Overview of energy storage

THIS chapter summarises the applications and development of the energy storage approaches, pumped hydro storage (PHS), Compressed air energy storage (CAES), battery energy storage (BES), flywheel energy storage (FES), Superconducting magnetic energy storage (SMES), Super capacitor energy storage (SCES) and hydrogen energy storage (HES).

2.1 Introduction

As described in the issues discussed in Chapter 1, energy storage is a method to balance the power and load in electrical power systems. It can add stability to intermittent wind generation, contribute to power smoothing, peak looping, and reduce cost fluctuation, etc. This chapter gives an overview of most of the energy storage methods, in order to identify these techniques and their applications. This review is based on the following main areas: efficiency, cost, advantages, disadvantages and applications.

Energy storage was introduced into power systems with wind power, as wind power technology has become mature. As electrical energy generated by wind turbines cannot be stored directly, converting electrical energy into other forms of energy is generally considered as a good solution.

The advantages of electricity generated from wind turbines are: wind energy is an environmental friendly and a free energy source from nature; it is abundant in nature; it has no harmful emissions and low operation cost; the life cycle of wind turbine is about 20-25 years; and the operational and maintenance fees are only about 3 % to 5 % of the total cost. Furthermore, the construction time is short. However, there are still some drawbacks which can restrict the wider commercial use of wind energy.

The main drawback is that wind is unpredictable and intermittent, so the power generated from wind is unreliable. When wind is strong, more power is generated which could exceed the customers' demand and the extra wind power is a waste; alternatively, when wind is weak, the power generated may not meet the demand. Although the overall demand could be easily met by energy generated from wind turbines, there can be significant mismatches between the peak load and maximum wind power generation periods. Also, compared with fossil fuels, wind energy is still quite expensive.

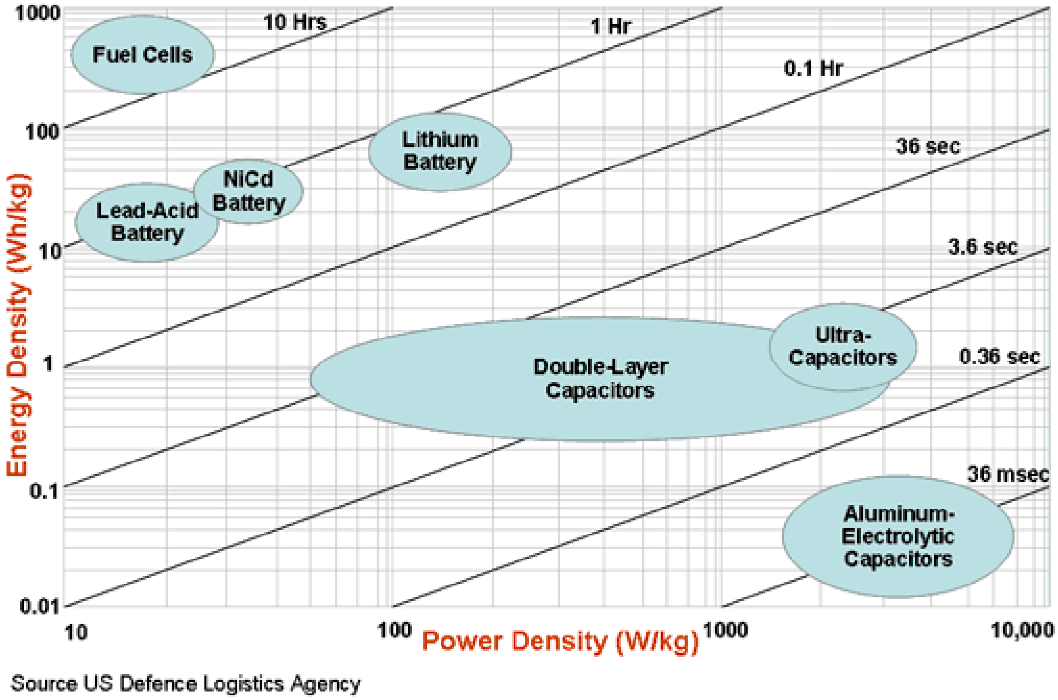
To increase the proportion of the energy generated from wind turbines in the network, it is necessary to evaluate the possibility of these generators participating in the ancillary services market. To contribute to voltage amplitude and frequency stabilization of networks, an energy storage system must be associated with the wind generator [12]. Due to significant fast fluctuations of wind, batteries are not suitable for power systems with wind energy, because of their short cycle lives. On the other hand, various storage methods such as flywheel energy storage systems are well adapted because of their high speed dynamics, long life cycle and good efficiency [18]. However, these have high self-discharge rates and so only provide short-term storage systems.

Energy storage technologies cannot only solve the intermittency problem of wind energy, but they are also very economical. Energy storage devices utilise the excess electricity from wind turbine generations to store energy into another form, like electro-chemical storage, thermal storage, hydraulic storage, pressure storage, mechanical storage, electro-magnetic storage, and electro-static storage [19]; and release energy to consumers when there is a shortage of wind. In addition, electrical energy generated during off-peak hours (10:00 pm to 6:00 am) can be stored, and then discharged, to the grid during peak hours (6:00 am to 10:00 pm).

Since other researchers in the department are working on different energy storage methods, such as flywheels and batteries, a cross comparison could be carried out in further studies. The most commonly used energy storage technologies are described below.

2.2 Energy storage technologies

The optimal size of the energy storage device is determined by differing characteristic requirements, like high energy density, power density and efficiency, low cost, long life cycle, etc. The ideal characteristics of the energy storage method required in a power system are largely based on which application it will be applied to. For example, grid stabilization, power quality, load shifting, frequency regulation, and so on. In this research, the author focuses on load shifting at the distribution level, where the energy density and power density of the storage device are quite important. The Ragone Plot of electrochemical devices, Fig. 2-1 and energy storage, Fig. 2-2, are introduced here to compare their performance based on the relationship between energy and power of the energy storage device.



Source US Defence Logistics Agency

Fig. 2-1 Ragone plot of electrochemical devices [20]

As shown in Fig. 2-1, fuel cells have the highest energy density, but much lower power density; batteries have higher energy density than the capacitors. Among batteries, lithium batteries show both higher energy density and higher power density than lead-acid and NiCd batteries.

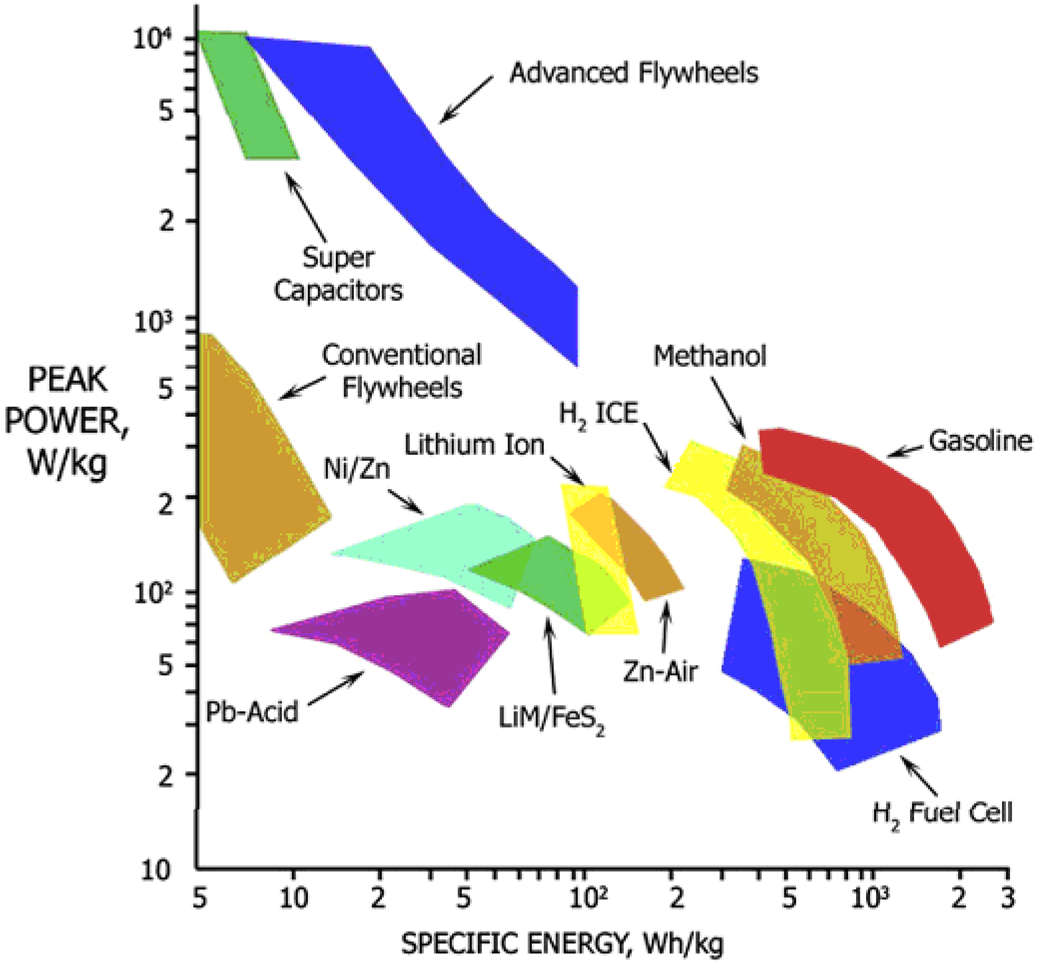


Fig. 2-2 Ragone plot of energy storage [20]

Fig. 2-2 shows that flywheels and super capacitors have quite high power density, but very low energy density; and even the most advanced lithium ion batteries still have much lower energy density than fuel cells, hydrogen fuelled combustion engines, and conventional fuels. These feature differences indicate that a) different energy storage devices are suitable for different applications, or b) combining some of them can make better performance in some applications compared to using just one technology. Among them, hydrogen fuelled internal combustion engines (ICEs) have good energy density and moderate power density; therefore, it can be a good fit to a wide range of applications.

2.2.1 Pumped hydro storage (PHS)

The PHS method stores energy in the form of gravitational potential energy of water. Water is pumped from a lower elevation reservoir to a higher elevation. This system uses excess electricity production, in periods of low demand, to pump water to a deposit situated at a certain height, recovering it at a later time through a turbine when it is required to cover peak load periods [21]. Fig. 2-3 shows how the pumped storage stations work.

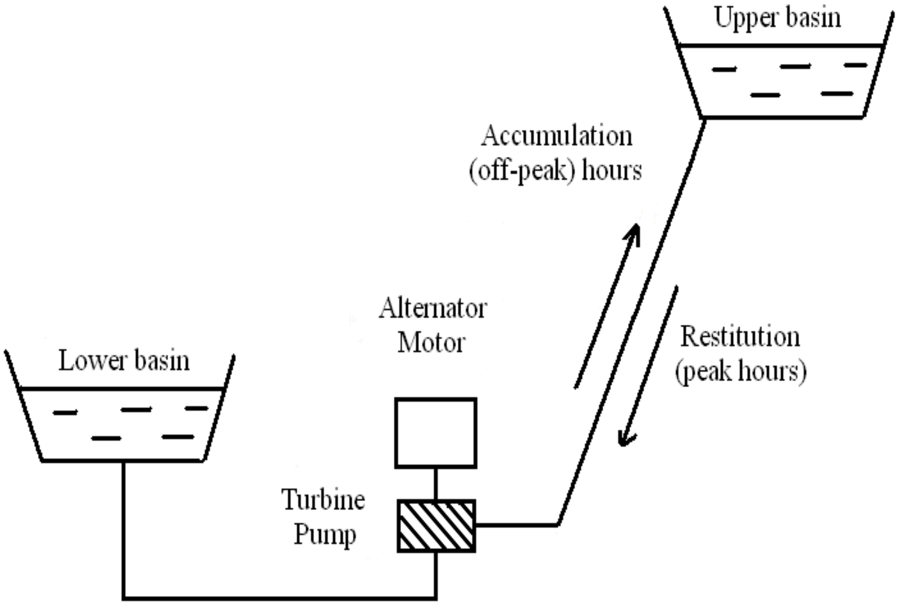


Fig. 2-3 Illustration of a pumped hydro storage device [22]

The first PHS system was built in 1910 [23]. Pumped storage has large capacity and this technology is normally used for high-power applications. Considering the evaporation losses from the exposed water surface and conversion losses, the efficiency of this technology is approximately 70 % to 85 % [22].

The typical size of PHS is normally between 100 MW and 3000 MW, the capacity of PHS is the highest of all the common energy storage methods [10]. In the world, there are over 200 units and 100 GW of PHS plant installed, which includes about 32 GW installed in Europe, 21 GW in Japan, 19.5 GW in the USA and rest in Asia and Latin America [24] [10]. Although PHS is already a mature technology with large capacity, high efficiency, and low capital cost, this technology is still limited by geography, long construction time and environmental issues.

2.2.2 Compressed air energy storage (CAES)

CAES is a method to store energy in the form of compressed air in an underground cavern. CAES is operated at high pressures about 40-70 bar, at ambient temperatures. The first commercial scale CAES station using an underground compressed air reservoir was 290 MW in Huntorf, Germany, since November 1978 [25]. Electric Power Research Institute (EPRI) designed an advanced CAES system, which is shown in Fig. 2-4, by using an advanced turbine technology.

A CAES unit mainly consists of five basic components:

1) Compressor train
2) Motor generator
3) Turbine expander train
4) Recuperator
5) Underground cavern

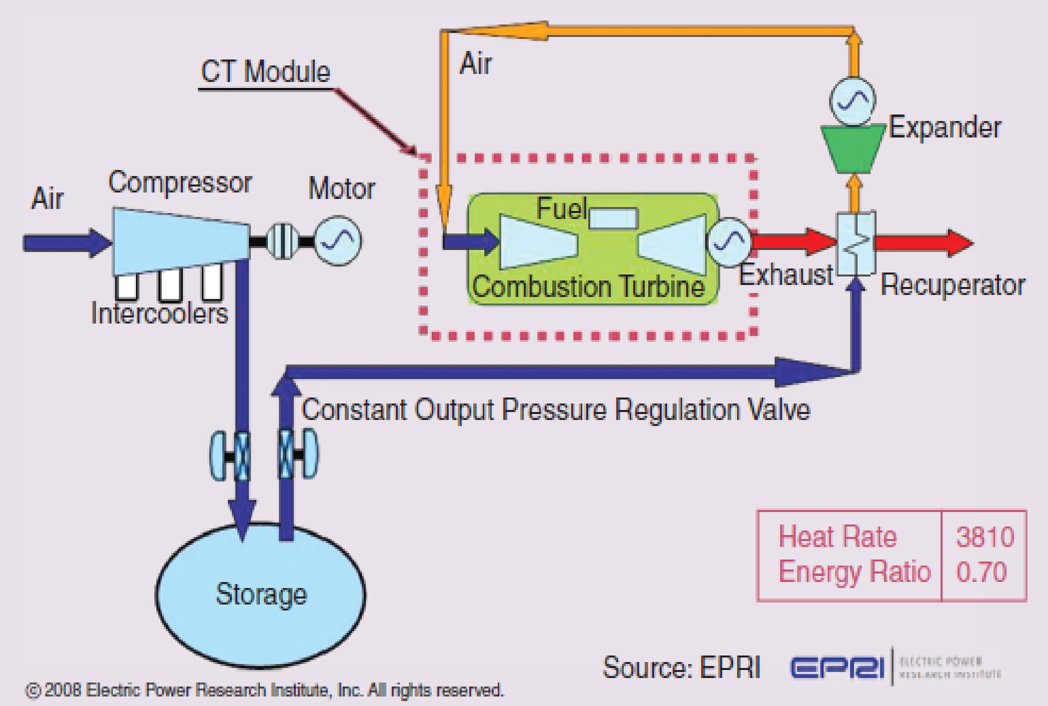


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Fig. 2-4 An advanced compressed air energy storage plant [26]

The excess power is used in an electric motor to drive a compressor to compress air. The compressed air should be cooled down and stored in the cavern; when air needs to be extracted from the cavern, it needs to be preheated firstly in the recuperator. The heated air is then mixed with small quantities of oil or gas, which is burned in the combustor. The hot gas from the combustor is expanded in the turbine to generate electricity. It takes only a few minutes to achieve this. Therefore, short start-up time is an advantage of CAES. A typical CAES plant can provide a normal start-up in 10-12 minutes [27].

CAES and PHS are both suitable for large-scale and long-period storage applications. Compared to PHS, CAES systems also have both high power and energy density, but lower efficiency. The efficiency of a compressor is approximately 79 %, and the round trip efficiency is around 42 % - 54 % [28]. Currently, CAES is still limited for commercial availability. Also, like PHS, this technology requires suitable geographic sites as well.

2.2.3 Flywheel energy storage (FES)

Energy in flywheel energy storage systems is stored in the form of kinetic energy. The excess electricity drives an electric motor which increases the speed of the flywheel, and then electricity is obtained by running the motor as a generator which causes the flywheel to slow down [29]. Flywheel energy storage systems have good high speed dynamics, long life cycle and good efficiency [18]. Fig. 2-5 shows the cross section of a class flywheel energy storage system: 1) flywheel; 2) stator of the radial magnetic bearing with water cooling; 3) redial magnetic bearings; 4) thrust magnetic bearing; 5) stator of the electrical machine with water cooling; 6) inner rotor part; 7) outer rotor part; 8) vacuum housing.

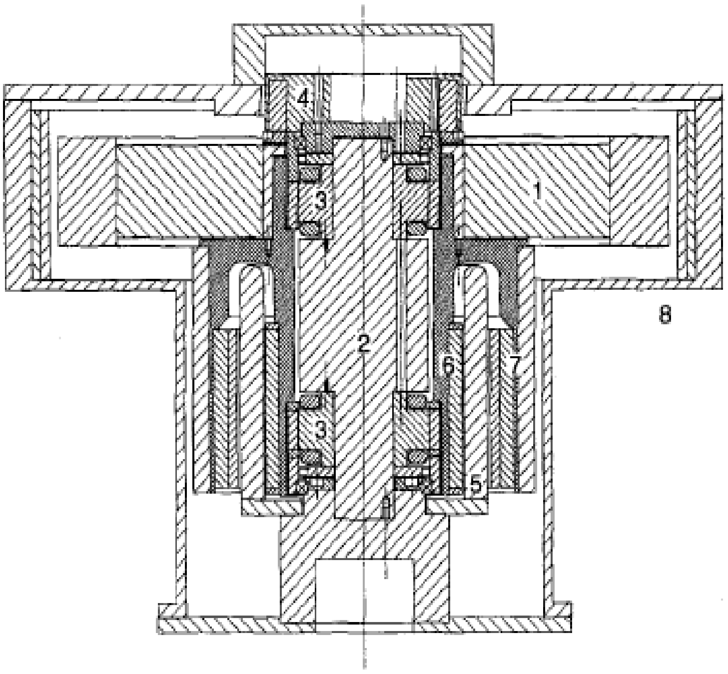

Fig. 2-5 Cross section of a typical flywheel energy storage system [30] [31]

In the case of fixed-speed wind generator, the flywheel energy storage system must be connected to alternating current (AC) grid; on the contrary, in the case of variable-speed wind generator, the generation and energy storage systems can be coupled via a direct current (DC) bus [12] [32]. The energy stored in a flywheel can be calculated by the equation below:

$$E = \frac{1}{2} I\omega^2 \qquad \text{Eq. 2-1}$$

Where, E is energy; I is moment of inertia; and ω is rotational velocity [2].

High capacity flywheels are required in an electrical power system. The maximum energy can be stored depends on the tensile strength of the materials of flywheels. Nowadays, the highest capacity flywheels are made of fibre reinforces composites, because of their high tensile strength [29]. A typical flywheel can store energy, equal to about 1 kWh of electricity [29]. Although the efficiency of this is quite high about 95 %, the friction loss is about 0.1 % per hour, the flywheels self-discharge very quickly around 20 % per hour [33].

Traditional flywheels have quite low energy density; advanced flywheels can be designed for high energy or high power. High-power flywheels are suitable for applications requiring short discharge time; and high-energy flywheels are more suitable for longer discharge time. Safety issues are an important consideration during the operation of flywheels due to mechanical stress failure.

2.2.4 Superconducting magnetic energy storage (SMES)

SMES systems store energy in super conducting magnetic coils immersed in a very cold liquid, such as liquid helium, contained in highly insulated thermal bottles [19]. The coils are not very large. Power is stored in SMES by inducing DC electricity into a coil with the zero resistance magnetically. Fig. 2-6 shows that the construction of a typical SMES.

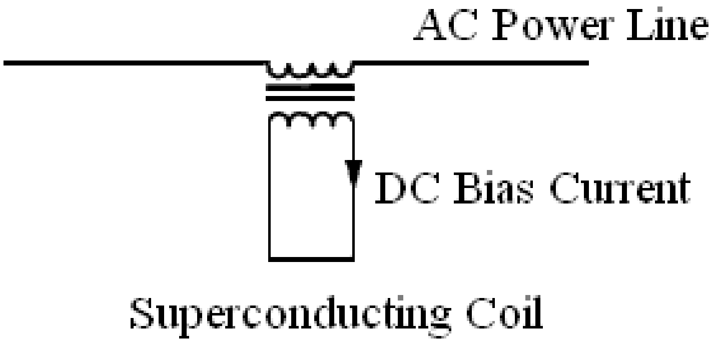

Fig. 2-6 Schematic construction of a super-transductor [34]

Ferrier introduced an idea that a single large SMES can be used to accommodate the daily variation in power system in France in 1969 [35], although it was discovered in 1911 [36]. In 1972, Boom and Peterson first explored the small SMES for power system damping control [37] [38]. SMES stores energy in a magnet field instead of converting to another energy form, so it has a high instantaneous efficiency, about 95 % for a charge-discharge cycle [22] and it is robust, very reliable and noiseless during operation [19]. For the same reason, SMES can respond very rapidly.

SMES devices are still under development, and they can only be used for grid stabilization currently [39]. Seven SMES units have been installed by American Superconductor in upper Wisconsin for power quality applications and reactive power support [40]. American Transmission Company provides these units, which are 3 MW/0.83 kWh and each can provide 8 MVA [41]. These units can be operated either independently or combined. This technology has a long life cycle, rapid response, and high power density, but it also has a relatively low energy density and high-cost. Moreover, the major disadvantage of this system is the refrigeration requirement [22].

2.2.5 Battery energy storage (BES)

A battery energy storage system includes the battery, DC/AC converter, charger, transformer, and AC switchgear. Energy is stored in chemical form in batteries. Batteries can store large amounts of energy in small volume and weight compared to the other energy storage methods. There are many common types of batteries: Lead Acid, Nickel-metal hydride, Lithium-ion, Sodium-Sulfur, Alkaline and Nickel Cadmium [42]. There are some more advanced batteries, like high temperature batteries, Metal-air batteries, and flow batteries, which have attracted more attention and have already become mature technologies [43]. The lithium-ion battery is introduced as the most commercially used battery in the world at present, and the Redox flow battery (RFB) is also discussed below as an alternative potential type of battery technology.

I) Lithium-ion battery

Lithium-ion batteries have three components: anode, cathode, and electrolyte. The anode of lithium-ion battery is normally made of a carbon material, lithiated metal oxides as the cathodes, and lithium salt in a solvent is used as the electrolyte [44]. The principle of the lithium-ion battery is that lithium ions move from the anode to the cathode, when it is discharging; and the lithium ions move back, when charging. Complete discharge can reduce lithium-ion batteries' life cycle. Fig. 2-7 shows the most commonly used Lithium-ion battery, with carbon as the anodes and $LiCoO_2$ as the cathodes.

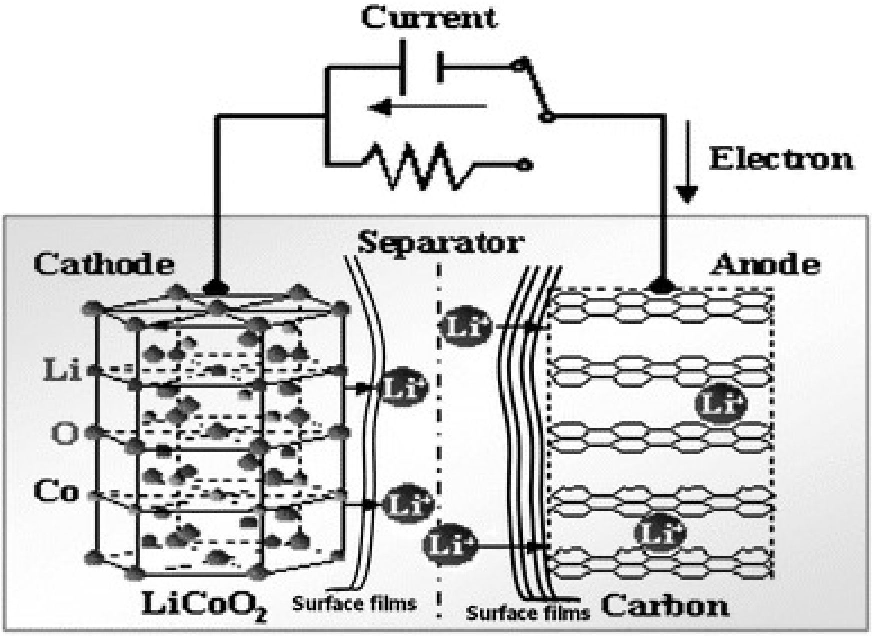

Fig. 2-7 Illustration of a Li-ion battery [45]

Lithium-ion batteries' self-discharge rate is very low, at around 5 % per month, and they are extremely low maintenance. Lithium-ion cells have high energy density about 80-150 Wh/kg, and moderate power density ranging from 500-2000 W/kg [46]. The nearly 100 % efficiency and long life cycle make lithium-ion batteries very commonly used. Their light weight and small size make lithium-ion batteries more suitable for portable/mobile applications. Lithium-ion batteries should not be frequently completely charged and discharged. Therefore, a protection circuit is required, making the whole system more expensive. For small-scale mobile/portable applications, lithium-ion batteries are a mature technology, but there have not been any large-scale lithium-ion batteries used in power systems with renewable energy yet.

II) Redox flow battery (RFB)

RFB is an innovative battery energy storage method for stationary storage in power systems with renewable energy generations. Redox means reduction oxidation. RFB stores energy by driving the electro-active species which dissolved in the electrolyte to flow through a reactor that converts chemical energy directly to electricity [47]. Compared to the traditional batteries, RFB has low cost, high efficiency nearly 90 %, long life cycle at least 20 years, very low maintenance cost, and it is flexible operated, and suitable for large scale application [48]. It has been installed for the wind farms in Hokkaido, Japan, Huxley Hill wind farms in Australia, and text systems in USA [49]. The disadvantage of this is that it is a new technology, still under development, that is why it is not considered in this research. Fig. 2-8 shows a RFB unit.

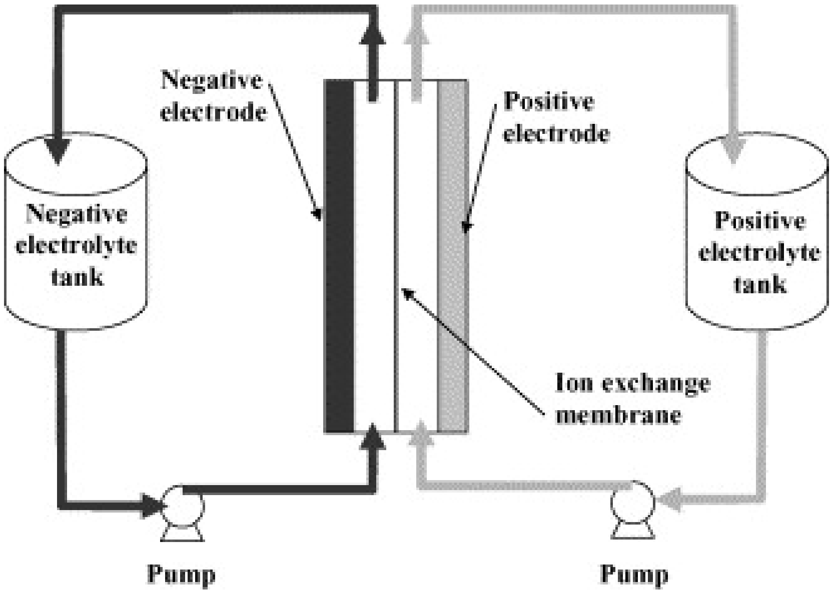

Fig. 2-8 A redox flow battery unit [48]

The efficiency of battery energy storage systems varies, but most of them have high efficiencies. Batteries usually have low losses, high energy density, but low power density. Some more commercial and promising batteries are presented and compared later in this chapter. There are still some drawbacks that limit batteries' development. The main disadvantages of most of the battery energy storage systems are high initial cost and low number of cycles.

2.2.6 Super capacitor energy storage (SCES)

In SCES systems, energy is stored in the form of an electric field between two electrodes. Traditional capacitors used in electronic circuits cannot meet the volume and weight requirements of energy storage, so the development of high energy density capacitors (super capacitors) has been investigated [11].

Fig. 2-9 illustrates a double layer super capacitor. Super capacitors have much lower energy density than batteries, but they are very durable and their efficiencies are very high, approximate 95 %; however, 5 % energy is self-discharged per day, which means the stored energy can be lost very quickly [22].

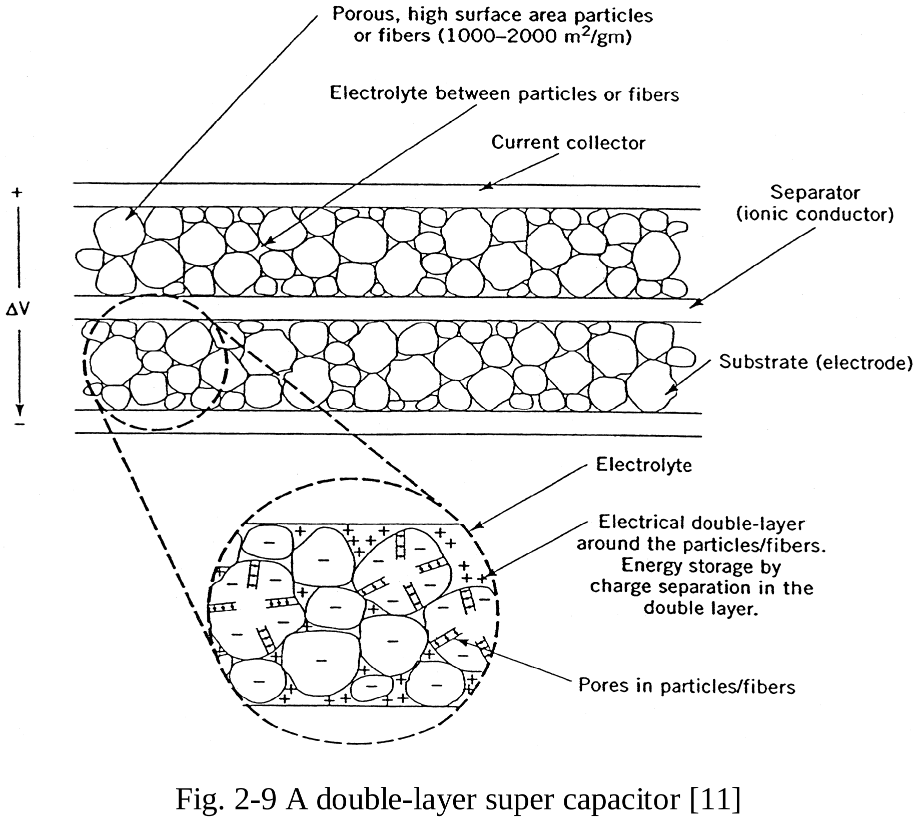

Fig. 2-9 A double-layer super capacitor [11]

Super capacitors can provide high power density and quite low energy density. SCES can be charged substantially faster than conventional batteries. Similar to flywheels, they can be used for power quality applications. This technology is still under development for large-scale systems, and there are no available commercial large-scale SCES systems in the world currently.

2.2.7 Hydrogen energy storage (HES)

In 1891, the Danish scientist Poul la Cour had already built a windmill to introduce hydrogen into power systems with energy storage. Hydrogen stored in a wind turbine tower had been first suggested by Lee Jay Fingersh at the National Renewable Energy Laboratory (NREL) [50]. Hydrogen storage has been introduced into power systems with wind energy as an energy storage method, mainly because hydrogen has the highest mass energy density.

A typical hydrogen energy storage system combines hydrogen production, storage and recovery. The hydrogen energy storage process is that water is split into hydrogen and oxygen by supplying direct current to the electrodes in electrolysis cells; hydrogen is then compressed into a tank, so energy can be stored as the form of hydrogen gas; finally, hydrogen energy is converted back to electricity by fuel cells and other equipment. The round trip efficiency of this combination is relatively low, theoretically only about 20 % - 50 %, including water electrolysis, and gas compression, shown in Fig. 2-10, and PEM fuel cell, shown in Fig. 2-11.

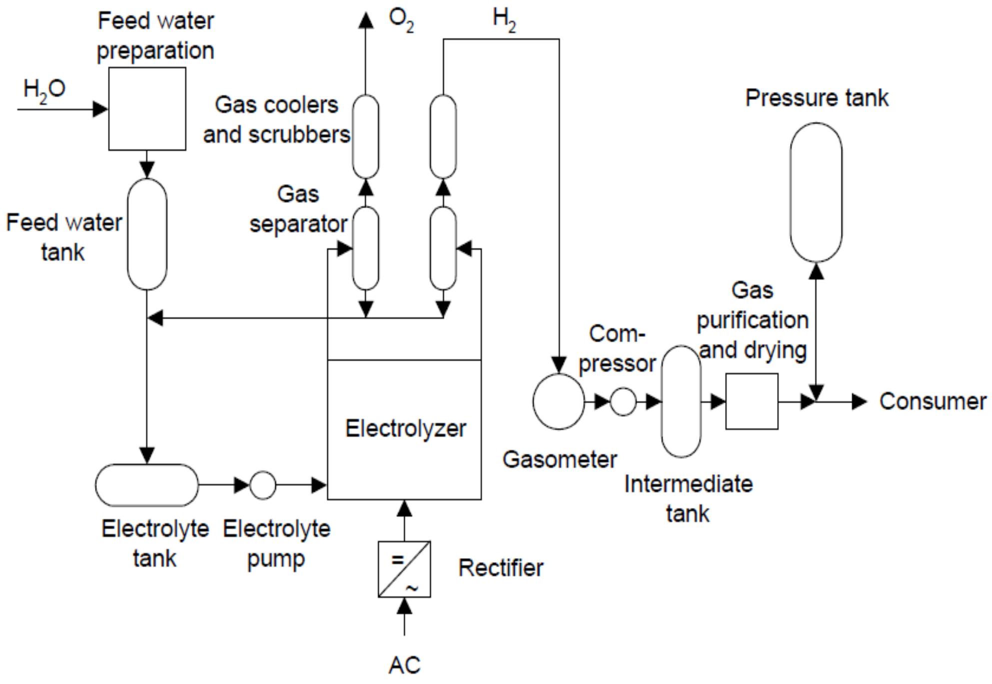

Fig. 2-10 A conventional alkaline electrolyser plant [51]

There are many competitive hydrogen storage methods, such as compressed hydrogen, liquefied hydrogen and metal hydride. For static applications, volume is not a key problem, and then pressurized tanks are the simplest solution. The current available pressures for the pressurized tanks are up to 350 bar. Fuel cells are devices normally used currently to convert hydrogen energy back to electricity; as a result of its easy operation and higher efficiency, than other hydrogen to electricity conversion devices, for example, hydrogen driven internal combustion engines. Fig. 2-11 shows the general principle of a PEM fuel cell.

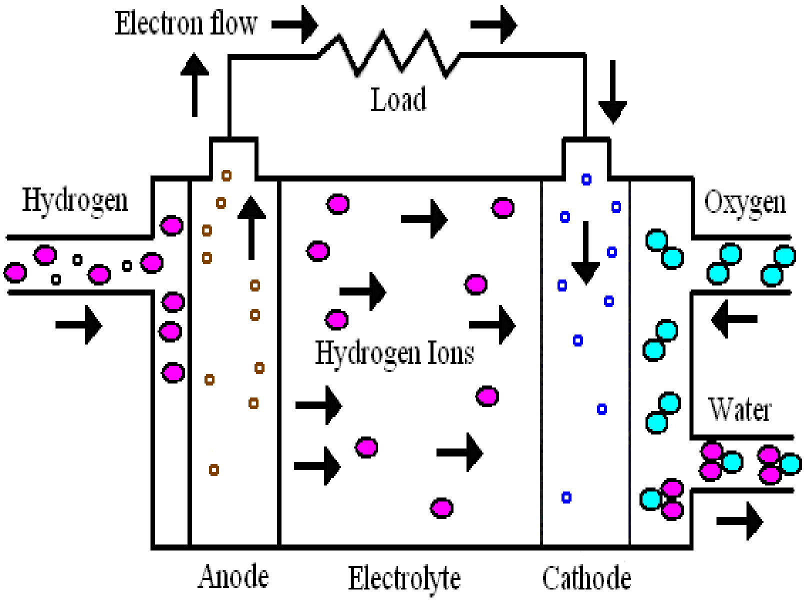

Fig. 2-11 Illustration of a PEM fuel cell [22]

Hydrogen energy storage systems are suitable for very large-scale storage in isolated systems with expensive grid extension. There are some demonstration projects with hydrogen energy storage combined with other energy storage devices in Norway, UK, Denmark, Greece, Spain, etc.

2.3 Applications of energy storage

Wind power is becoming one of the most important topics in many countries. In order to increase the penetration of the wind energy, smooth the power, reduce the cost, and so on, many energy storage systems have been investigated for different applications.

Kaldellis and Kavadias [52] investigated the use of two water reservoirs for a long-term economic wind generation power system; a micro-hydroelectric power plant and a water pump station (WPS) are used, to store the energy generated from the wind farm in low demand periods. Kaldellis et al. found that a wind-hydro energy station is most suited for a small to medium size island, using calculations and analysis which were based on real wind speed and demanded load data of the medium size island of the East Aegean Sea—Ikaria in Greece. Ikaria has a population of 9,000 people, and covers an area of 255 km^2. The penetration of the wind rises to exceed 90 % by using the hydro station as an energy storage method [53]. PHS works for a long-term, large capacity power system. It has high efficiency, high wind utilisation, and long life cycle, etc, but it is limited to locations with specific geological features.

Three CAES plants have been built and operated in the world: a 290 MW in Huntorf, Germany; a 110 MW in McIntosh, United States; and a 25 MW in Sesta, Italy [54]. Although none of them has been built for the purpose of storing the exceed energy from wind power generation, the Huntof CAES plant was developed with the wind turbine generators in Germany [55]. Obviously, CAES with wind energy is a competitive energy storage method for large capacity power systems, for its lower cost, but like PHS, it needs a specific geography as well.

Flywheel energy storage systems with wind generations are more popular than the two methods discussed above. A low-cost 60 kg m^2 flywheel connected to a 45 kW wind turbine in order to smooth the wind power has been investigated by Hardan et al. in the UK [56]. Flywheels possess quick response, high efficiency, low cost, etc, that is why it has been widely investigated for renewable energy. On the other hand, flywheels lose energy very quickly, so it cannot handle the long-term energy storage application. Therefore, it is normally used in power systems with wind energy with other energy storage methods.

SMESs are still under development. There are many scientists modelling and doing simulations about it, but haven’t used it as a dependent energy storage method in power system with wind energy.

BESs and SCESs are popular methods in power system with wind energy nowadays. NaS batteries have developed very well in Japan. In 2009, a 34 MW NaS battery system was installed with a 51 MW wind generation in Japan [57]. A 275 kW and A 200 kW, 800 kWh Vanadium Redox Flow batteries (VRFB) were installed in the Tomari wind farms of Hokkaido, Japan, and at the Huxley Hill wind farm on King Island, Tasmania, Australia [58].

Hydrogen has the highest energy density, which makes it attract lots of attentions. There are quite a number of wind-hydrogen systems installed all over the world. A stand-alone demonstration power system with a wind turbine (600 kW) and hydrogen energy storage was launched at the island of Utsira in Norway. This hydrogen energy storage system includes water electrolysis (10 Nm/m^3), compressed gas storage (2400 Nm^3, 200 bar), hydrogen engine (55 kW), and a proton exchange membrane fuel cell (PEMFC) (10 kW) [59]. A flywheel, a synchronous generator, and a battery system are also employed to ensure the voltage and frequency stability of this system. The system can supply 2-3 days full energy for 10 households. The theoretical efficiency of hydrogen storage system is around 53 % at maximum, while the electrolyser's efficiency is around 73 %, but in practice the electrolyser's efficiency is down to 50 % at the island of Utsira. In general, in this wind-hydrogen system, only 20 % of the wind energy is used, which can be improved by installing a suitable and efficient electrolysers. Gabriele and Paolo also studied on a wind-hydrogen system, but with carbon physisorption storage instead of compressed gas. This hydrogen energy storage system has 10.8 % gravimetric capacity and 32.5 g/l volumetric capacity at 6 MPa (60 bar). But the whole system's efficiency is only around 10 % [60].

2.4 Theoretical comparison of storage

From the literature survey above, it can be seen that PHS and CAES methods are limited to suitable geographical environments; SMES methods are too expensive, because SMESs need a refrigeration system and advanced materials. Besides, this technology is still under developing for the large-scale system. SCES methods have too low energy density, and lose energy too quickly. Batteries and flywheels are already mature technologies and are used commercially nowadays.

2.4.1 Comparison of different types of batteries

There are many kinds of batteries, such as Lead Acid, Lithium-ion, NaS, and Nickel–Metal Hydride (NiMH), etc. A comparison of the characteristic of the four common batteries is given in Table 2-1.

NaS batteries were chosen for the further comparisons between batteries, flywheels and hydrogen energy storage, because they have high energy and power density, high efficiency, and they have already been used in power systems with renewable energy.

Table 2-1 General comparisons in three batteries [39, 56, 62-66][61]

Electrical energy storage technology	**Lead Acid**	Lithium-ion	**Sodium Sulfur**	**Nickel–Metal Hydride**
Advantages	1. Mature technology 2. Familiar 3. Inexpensive 4. Ready availability	1. High energy density 2. High efficiency, nearly 100 % 3. Long life cycle 4. Low self-discharge 5. Low maintenance cost 6. Recyclable	1. High energy and power density 2. Relatively high efficiency 3. Long life cycle 4. Relatively well established	1. Relatively mature technology 2. Relatively rugged 3. Higher energy density 4. Better life cycle than lead-acid batteries 5. Less toxic components Ni-Cd
Disadvantages	1. Low specific energy and specific power 2. Short life cycle 3. High maintenance requirements 4. Environmental hazards 5. Capacity falls with decreasing temperature below 25 °C	1. Expensive 2. Deep discharging has a detrimental effect on its lifetime	1. Relatively expensive 2. Small volume manufacturing 3. Safety issues related to high temperature	1. More expensive than lead-acid 2. Limited long-term potential for cost reductions due to material costs
Major applications	Automobile and Uninterrupted Power Supply (UPS)/ Telecom/ Substation reserve power	Cell phones/ laptops/ cameras/ power tools/ medical/ electric vehicles/ grid storage	Peak shaving for T&D upgrade deferral and small load levelling applications	Utility / Telecom backup and consumer electronics

2.4.2 Comparison of ES methods for micro-grid applications

Water electrolysers and fuel cells are used to produce hydrogen energy and generate electricity in hydrogen energy storage system and the HES systems including these two parts were used to carry out the comparison here. The applications of energy storage can be classified as bulk energy storage, distributed generation (DG) and power quality [33]. Table 2-2 shows a general comparison of the three common energy storage methods, NaS batteries, Flywheels, and hydrogen energy storage systems, for many different aspects of distributed generation applications. For example, scale, output, life cycle, efficiency, advantages and disadvantages, etc.

Table 2-2 Comparisons of common ES methods [39, 62, 66-68]

	NaS battery	**Flywheel**	**Hydrogen Electrolyser/Fuel cell**
Application scale	Small to medium	Small to large	Small to large
Term	Short to medium	Short	Medium to long
Outputs range	1 MW~20MW	1 KW~100 MW	------
Commercial maturity	Prototype units ordered	Commercial products	Prototype units ordered
Replacement period (years)	15	20	20/6
Efficiency	75 % [62]	95 % [33]	30.1 %
Self-discharge	0.1 % / day [33]	20 % / day [33]	0.000033 % /day
Advantages	1. High energy and power density 2. Relatively high efficiency 3. Long life cycle 4. Relatively	1. High power density 2. Long life cycle 3. Quick recharge 4. Independent power and energy sizing	1. High mass energy density 2. Infinite 3. Create no environmental impact 4. Long storage time

	well-established	5. Create no environmental impact in use	
Disadvantages	1. Relatively expensive 2. High temperature produces unique safety issues 3. Sodium should be handled as a hazard material	1. Low energy density 2. High self-discharge rate 3. potentially dangerous failure modes	1. High cost of fuel cell 2. Large volume and heavy 3. Low efficiency of fuel cell 4. Low volume density
Potential improvements	Lower cost	1. Lower cost 2. Higher energy densities 3. Lower self-discharge rate	1. Lower cost 2. Higher efficiency

NaS batteries and hydrogen storage systems are suitable for long-term storage, which means they can be used for this study purpose. Flywheels have the better price, but they self-discharge too quickly. Hydrogen energy storage systems are good candidates, but the cost of the fuel cells is too expensive, and the efficiency of the fuel cells is also too low. Other devices instead of fuel cells to generate electricity can be introduced to improve the whole hydrogen storage system.

2.5 Summary

Different energy storage methods including PHS; CAES; BES; FES; SMES; SCES; and HES were introduced into wind power systems to increase the utilization of wind, smooth the power, and reduce the cost. Each method has been briefly analysed, discussed and cross-compared in this chapter. The main advantage of hydrogen energy storage is the highest energy mass density of all the fuels so far.

From the comparisons of Table 2-1 and Table 2-2, it can be concluded that:

- Flywheels are quite cheap, but lose energy in a very short period, and therefore, it is not suitable for long-term storage applications;
- NaS batteries are more suitable amongst these three technologies for the reason that it is cheaper than hydrogen and can hold energy for a long time, but this system needs a high temperature, and contains hazard materials, which is not environmental friendly;
- Hydrogen storage is a good candidate. Compared to other mature energy storage methods, it is chosen here because it is suitable for large-scale, long-term storage and it has no environmental impact. Hydrogen is a seasonal energy storage method. Although it has very low efficiency, it can hold energy for a few months with little loss. Hydrogen can be released by either a combustion engine or a fuel cell. Fuel cells have higher efficiency than combustion engine, but are too expensive. Hydrogen is much more suitable for stand-alone generation application. Therefore, it was chosen for the further investigation in this study.

Chapter 3 The process of hydrogen storage systems

THIS chapter has a review of hydrogen production, hydrogen storage and equipment for converting hydrogen to electricity. The choice of components can be decided, after these comparisons.

3.1 Introduction

Compared to the traditional fuels, like CH_4, methanol (CH_3OH) and gasoline, hydrogen (H_2) has the lightest weight, zero carbon content and highest energy density, as shown in Table 3-1. As hydrogen is a very abundant element on the earth, it can be produced anywhere with a supply of water and electricity, biomass or solar energy. Its combustion essentially produces water vapour without releasing CO_2 or carbon monoxide (CO).

Table 3-1 Comparison of some fuels [63]

Fuel	**H_2**	**CH_4**	**CH_3OH**	**Gasoline**
Molar mass (g mol^{-1})	2	16	32	100~105
Carbon content (mass %)	0	75	37.5	85~88
Enthalpy (MJ kg^{-1})	143 (Product is water)	50	19.9	44.4

(Note：under standard condition，the working temperature and pressure are 25 °C (298 K), 1 bar)

A comparison of the thermophysical properties of hydrogen (in both liquid and gaseous states) with gasoline and natural gas is tabulated in Table 3-2. As a mixture, gasoline has different boiling points, the range of which is called the distillation range. Comparison shows that for a given amount of energy, hydrogen weighs about one-third of the weight of fossil fuels, occupies 3.8 times the volume of gasoline in liquid form and occupies 3.6 times the volume of natural gas in gaseous form. Its high flame speed and wide flammability limits make hydrogen a very good fuel for internal combustion engines, gas turbines and jet engines. A high ignition temperature and low flame luminosity also make hydrogen a safer fuel than the others. Furthermore, it is also non-poisonous and recyclable.

Table 3-2 Properties of gasoline, natural gas and hydrogen [64]

	Gasoline	**Natural gas**	**Hydrogen**
Density (g cm^{-3})	0.73	0.78×10^{-3}	0.84×10^{-4} (gas) 0.71×10^{-1} (liquid)
Boiling point (°C)	Distillation range 30-204	-156	-253 (20K)
Gravimetric energy density (kJ kg^{-1})	4.45×10^{4}	4.8×10^{4}	12.5×10^{4}
Volumetric energy density (kJ m^{-3})	32×10^{6}	37.3×10^{3}	10.4×10^{3} (gas) 8.52×10^{6} (liquid)
Flammable limits (% in air)	1.4-7.6	5-16	4-75
Flame speed (m s^{-1})	0.4	0.41	3.45
Flame temperature in air (°C)	2197	1875	2045
Ignition temperature (°C)	257	540	585
Flame luminosity	High	Medium	Low

(Note：under standard condition，the working temperature and pressure are 25 °C (298 K), 1 bar)

Hydrogen is not a primary energy; it is an energy carrier, which is called a secondary energy. Further comparison made between various common fuels is shown in Fig. 3-1. The figure also shows that hydrogen has the highest energy density of all the combustion fuels, about 120 MJ kg^{-1}, which is nearly three times of that of traditional gasoline. However, the volume energy density of hydrogen is only about 0.01006 MJ L^{-1}.

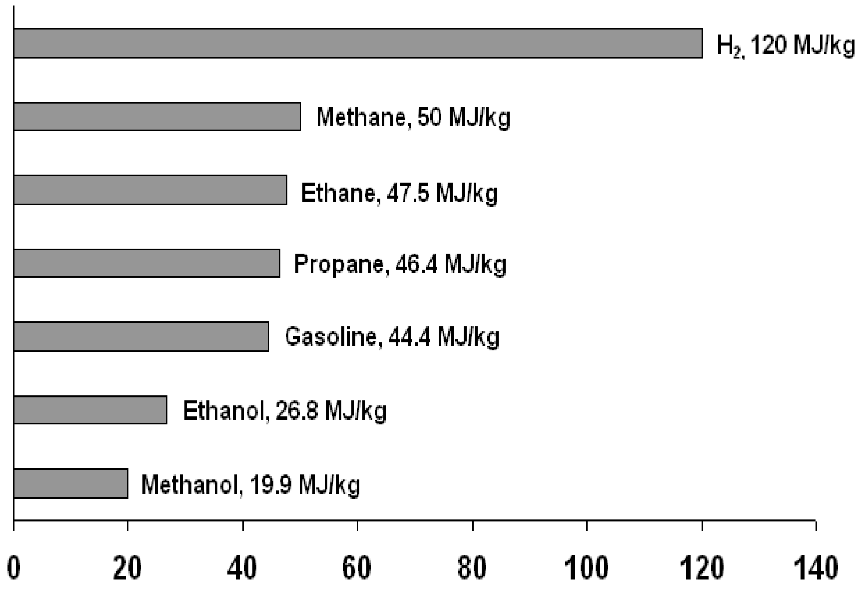

Fig. 3-1 Heating energy content by mass of several common fuels [65]

In the hydrogen energy storage system, it is envisaged that hydrogen could be produced from non-fossil energy sources, and can be used in every application where fossil fuels are used today.

Hydrogen is now widely regarded as a promising energy solution in the twenty-first century, capable of assisting in issues of environmental emissions, sustainability and energy security, etc. Hydrogen has the potential to provide for energy in transportation, distributed heat, power generation and energy storage systems with little or no impact on the environment. The significant disadvantage for transportation is the low density of hydrogen, which can result in a huge volume. Take a normal hydrogen powered vehicle as an example. It requires 4 kg of hydrogen to enable it to cruise at the sustaining speed for 400 km [63], which occupies a very large volume. Therefore, if hydrogen were to be extensively used, the storage within a certain volume would be a key issue, that needs to be addressed particularly for mobile applications. This can be demonstrated by how much volume these energy sources (gasoline, liquid hydrogen, compressed hydrogen, and metal hydrides) occupy to produce the same 1 GJ of energy, shown in Fig. 3-2. It can be clearly seen that all hydrogen sources take considerably more volume than gasoline for the same energy.

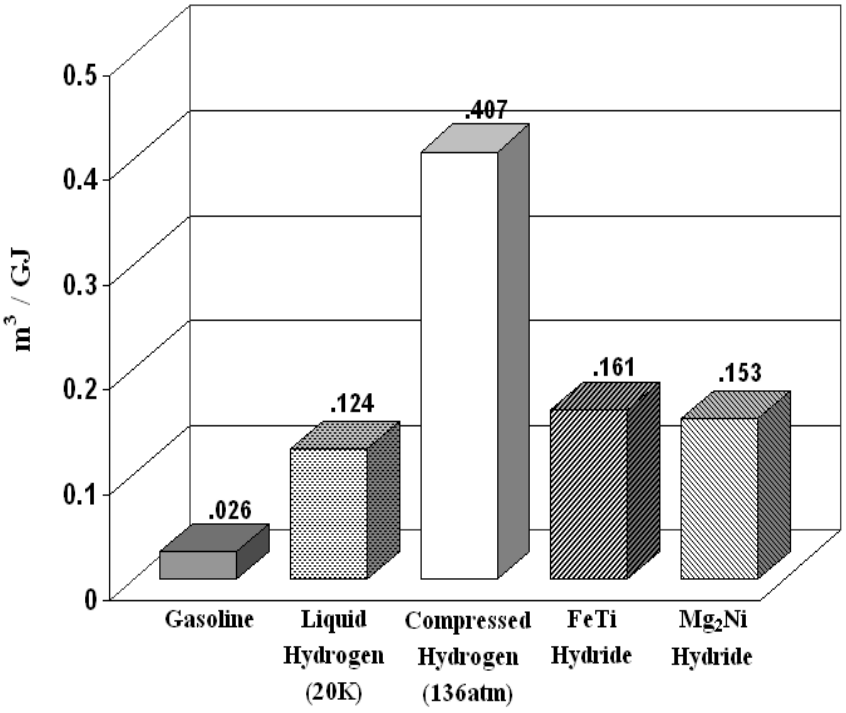

Fig. 3-2 The volume the energy sources occupies for producing 1 GJ of energy

As a fuel, hydrogen can be employed to power three main types of energy conversion devices: fuel cells for producing electrical power; hydrogen steam turbines for electrical power; and internal combustion engines (ICE) for electrical or mechanical power. There is no doubt that hydrogen is the energy of the future.

3.2 Procedures for setting up a hydrogen system

3.2.1 Hydrogen production procedures

Hydrogen is the most abundant element in the universe, but hydrogen does not normally exist in nature as a pure element. It must be produced in an energy intensive process. Hydrogen production has been growing rapidly at 8 ± 10 % per annum for many years [66]. Approximately half the hydrogen produced is used in ammonia manufacture and most of the remainder, about 37 % is used for petroleum processing (e.g. hydrocracking and hydrodesulphurisation of oil); and nearly 8 % for methanol production [67].

There are three main sources for hydrogen production, fossil fuels, biomass, and water. The modern method used to produce hydrogen from processing fossil fuels is by the reactions of natural gas or light oil fractions with steam at high temperatures, which is called steam reforming. The majority of hydrogen (about 90 %) is produced in this way [68]. Coal gasification and water electrolysis are other industrial methods of hydrogen production. Fig. 3-3 displays the relative contribution of each hydrogen production source. It shows that natural gas plays an important role in making up nearly half of the hydrogen production sources.

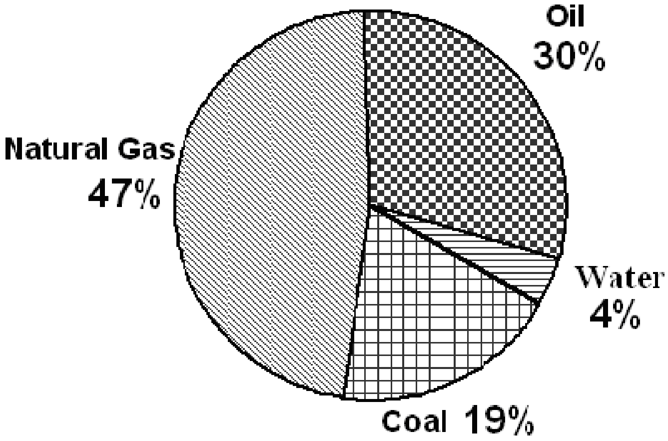

Fig. 3-3 Contributions of various hydrogen production sources [69]

3.2.2 Fossil fuels as a source of hydrogen production

a) Steam reforming of fossil fuels

Steam reforming of CH_4 is the most common method for hydrogen production at present. Steam reforming converts CH_4 or other hydrocarbons into hydrogen and carbon monoxide by using steam with a catalyst. It is an endothermic, catalytic process carried out within a temperature range of 700 °C -850 °C and a pressure up to 3.5 MPa (35 bar) [69]. Nickel is normally used as a catalyst in this reaction. High hydrogen to oxygen ratios in fossil fuels makes them good candidates for the reforming process.

The reaction for steam reforming of CH_4 is:

$$CH_4\,(g) + H_2O\,(g) \rightarrow CO\,(g) + 3H_2\,(g) + 191.7\ \text{kJ mol}^{-1} \qquad \text{Eq. 3-1}$$

where g indicates the gaseous condition.

This reaction needs absorb 191.7 kJ mol^{-1} of heat from the ambient environment. Additional hydrogen can be recovered by adding more water at a lower temperature, about 130 °C. In this process, the step will give 40.4 kJ mol^{-1} of heat out:

$$CO\,(g) + H_2O\,(g) \rightarrow CO_2\,(g) + H_2\,(g) - 40.4\ \text{kJ mol}^{-1} \qquad \text{Eq. 3-2}$$

The steam reforming reaction has two steps. First, separate hydrogen from carbon in natural gas by employing the high temperature steam and take hydrogen from methane as shown above. In this step, carbon monoxide is produced. Second, convert carbon monoxide with steam to hydrogen and carbon dioxide. This process is efficient and economical, but it has a big disadvantage. The production of hydrogen is accompanied by the emissions of large quantities of CO_2.

b) Thermal cracking of natural gas

Hydrogen can be produced from natural gas by an advanced process called thermal cracking [70]. Thermal cracking is the simplest and oldest method for the petroleum refinery process. In this process, a methane-air flame is used to heat up the firebrick to 1400 °C. The air is then turned off and the methane alone decomposes to carbon and hydrogen on the hot firebrick until the temperature drops to about 800 °C. The mixture of methane-hydrogen gas is separated and then hydrogen gas is purified.

c) Partial oxidation of hydrocarbons

Partial oxidation of hydrocarbons is an exothermic reaction. This reaction does not need external energy. It utilized the incomplete combustion of oxygen at moderately high temperature and high pressure. The non-catalytic partial oxidation typically occurs with flame temperatures of 1300 -1500 °C [67]. Catalysts can be used to lower temperatures. A common reaction for this process is:

$$2\ C_8H_{18}\ (l) + H_2O\ (g) + 23/2\ O_2\ (g) \rightarrow 8\ CO\ (g) + 8\ CO_2\ (g) + 19\ H_2\ (g) \quad \text{Eq. 3-3}$$

where l indicates the liquid state; g indicates the gaseous condition.

CH_4 is a by-product in this reaction. The pressure and temperature can influence the amount of methane. If the operating pressure is limited, temperature can be increased to reduce the methane.

d) Coal gasification

Gasification of hydrocarbon fuels is an effective way of thermal hydrogen production. It is also a very efficient way of extracting energy. This method is low cost, reliable and highly efficient [71]. The process of gasification is more complex and contains many chemical reactions. This technology has been in suspension for a period of time, because of the impact of hydrogen production from natural gas and oil. Recently, it has been reused by employing synthetic gas cleaning technologies. During the coal gasification process, coal is reacted with steam at 30 bar and >700 °C, the mixture of gas is mostly CO, CO_2 and H_2. A small amount of methane is produced. The methane becomes a major product as the pressure is increased to a certain extent. The CO_2 gas can be removed by adding a CO_2 acceptor to the mixture. The principle is putting the mixture through calcium oxide (CaO) or lime, and then CO_2 can quickly react with CaO to produce calcium carbonate ($CaCO_3$). In a separate reactor, $CaCO_3$ is heated up to get CO_2. The pressure swing adsorption (PSA) method can be used to purify hydrogen. The hydrogen can achieve 99.5 % purity finally [72].

3.2.3 Water as a source of hydrogen

On the Earth, hydrogen is plentiful in the form of water in the oceans, lakes and rivers. Besides, there are no other by-products except oxygen during water electrolysis. Therefore, water electrolysis is a clean, cheap and promising process for hydrogen production.

a) Direct electrolysis

From 1800, William Nicholson and Anthony Carlisle first introduced water electrolysis. In this method, hydrogen is separated from oxygen in water by employing electricity. This process uses direct electric current. An electrical power source is linked to two electrodes, which are placed in the water. An electrolyser is a low-voltage, direct-current device [50]. Oxygen is liberated at the anode and hydrogen is at the cathode. A simple water electrolysis device is shown in Fig. 3-4. The amounts of hydrogen and oxygen depend on how much electrical charge is put in the water. The best theoretical electrolysis voltage is 1.23 V, but in fact, the operational voltage should be higher than this, about 1.65 V- 2.2 V [73].

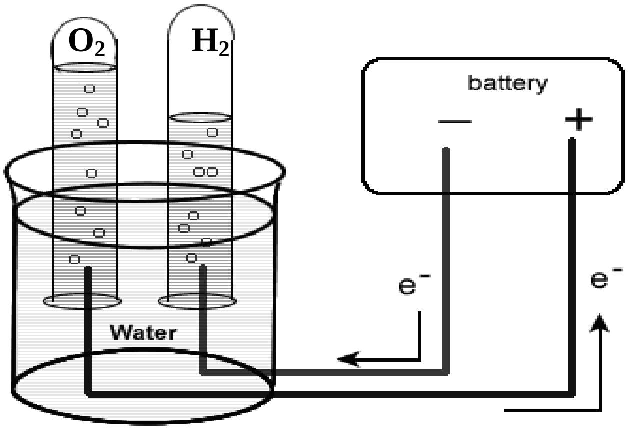

Fig. 3-4 Water electrolysis device includes battery and electrochemical cell

Electrolysis can produce high purity hydrogen. The electrochemical reactions taking place in this process can be described as follows:

$$\left.\begin{array}{l}\text{Cathode}: 4H_2O\,(l) + 4e^- \rightarrow 2H_2\,(g) + 4OH^- \\ \text{Anode}: 4OH^- \rightarrow 2H_2O\,(l) + O_2\,(g) + 4e^- \\ \text{Overall}: 4H_2O\,(l) + \text{Electricity} \rightarrow 2H_2\,(g) + O_2\,(g) + \text{heat}\end{array}\right\} \quad \text{Eq. 3-4}$$

On the cathode, a reduction reaction occurs. Electrons are given to hydrogen ions; on the anode, an oxidation reaction occurs. The main factor influencing the efficiency is the materials of the electrodes. The Department of Energy (DOE) 2010 efficiency target for water electrolysis is 75 %. To increase the efficiency the energy consumption of the hydrogen evolution reaction (HER) should be decreased. Ionic activators have a significant influence on energy consumption, which means HER can be enhanced by developing materials for the cathodes. The inter-metallic phases along the platinum-molybdenum (Pt-Mo) phase diagram have been investigated as potential cathode materials for the production of hydrogen by water electrolysis [74]. Inter-metallic compounds titanium-platinum (TiPt) and molybdenum-platinum ($MoPt_2$) were considered as good candidates for cathode materials. Besides, kinetic investigation proved that $MoPt_2$ inter-metallic revealed higher electro-catalytic activity, which was further enhanced by adding small quantities of Mo-Cobalt(Co)-based compounds as an ionic activator [75]. The common electrolysis technologies are alkaline based, proton exchange membrane, and solid oxide [67]. The costs of hydrogen produced from alkaline, proton exchange membrane, and solid oxide electrolysers are US$ 400-600/kW, US$ 2000/kW, and US$ 1000-1500/kW, respectively. The cost of hydrogen produced by water electrolysis with PV is about US$ 41.8/GJ (US$ 5/kg); and the cost will reduce to US$ 20.2/GJ (US$ 2.43/kg) if hydrogen is produced by water electrolysis combined with wind turbine generations [76].

The electrolysis reaction is very slow in pure water, because of the lower conductivity of pure water. Electrolytes are introduced in this process to enhance the efficiency. Besides, seawater can be used here to achieve higher efficiency and lower cost, if the industry is located by the sea. This method has high efficiency, about 75 %, and is even better at a higher temperature and high pressure. The efficiency drops to about 30-45 % when considering a process that converts the heat into hydrogen through electrolysis [77]. Water electrolysis is an energy-intensive process. 1 kg of hydrogen produced requires 53.4-70.1 kWh of energy [78].

b) Direct thermolysis

Thermolysis is also called high temperature electrolysis or steam electrolysis. So steam is employed in this method. The direct decomposition of water to hydrogen and oxygen can only occur above 2200 °C [79]. This high temperature is not feasible at an industry level. Heat and electricity can be used in a hybrid process to split water into hydrogen and oxygen, and the operation temperature can be reduced to 800 °C [80]. High temperature electrolysis is more efficient than room temperature electrolysis as the energy is supplied partly from heat, unlike at room temperature method where all the energy is supplied by electricity [81]. Besides, the electrolysis reaction is more active at higher temperatures. The rate of the steam molecules splitting increases at higher temperatures. The electrode in this process is a hollow tube made of electrolyte Yttrium Zirconium (ZrO_2-Y_2O_3). Inside is cathode, outside is anode. The reaction can be described by:

$$H_2O\ (l) + \text{Heat} \rightarrow a\ H_2O\ (g) + bH_2\ (g) + cO_2\ (g) \qquad \text{Eq. 3-5}$$

Where, a, b and c are mole fractions.

A solar furnace can be introduced in this process to achieve the required temperature, which is needed to split the water steam molecules into hydrogen and oxygen. It is much cheaper than the normal water electrolysis, because it saves more electricity. This process does not need a catalyst and produces no environmental pollution. The purity of hydrogen gas is also quite high.

c) Thermo-chemical process

The thermo-chemical method dissociates the water molecules to hydrogen and oxygen by adding a catalyst. This process is achieved by heating up water to a moderate temperature. It is very difficult to keep water in the liquid form during this process, so as to avoid direct steam themolysis. The efficiency varies from 17.5 % to 75.5 % [66]. It can be represented chemically as below, in which AB is catalyst:

$$\left.\begin{array}{l} AB + H_2O\,(l) + heat \rightarrow AH_2\,(g) + BO \\ AH_2 + heat \rightarrow A + H_2\,(g) \\ 2BO + heat \rightarrow 2B + O_2\,(g) \\ A + B + heat \rightarrow AB \end{array}\right\} \qquad \text{Eq. 3-6}$$

d) Solar energy

Solar energy is absolutely free. It does not need additional fuel, has no pollution and produces no waste. Solar energy is the cheap, clean and abundant. It can be used to split water for the hydrogen production. Solar energy can be employed in a variety of methods: photolysis, photovoltaic-electrolysis, photochemical and photoelectrochemical [82]. Water is a very stable compound. Under standard conditions, it takes 285.57 kJ of energy to decompose 1 mol of water into hydrogen and oxygen. In photolysis, a photocatalyst is employed. A typical catalyst is titanium dioxide (TiO_2) [83]. This method is direct, easy operated and no pollution produced, but it has a very low efficiency. The photolysis process can be described as follows [69], X stands for a photocatalyst:

$$\left.\begin{array}{l} H_2O\,(l) + X + Light \rightarrow Reduced\ X + 2H^- + 1/2\,O_2\,(g) \\ Reduced\ X + 2H^- \rightarrow X + H_2\,(g) \\ H_2O\,(l) + X + Light \rightarrow H_2\,(g) + 1/2\,O_2\,(g) + X \end{array}\right\} \qquad \text{Eq. 3-7}$$

A photovoltaic cell and an electrolyser can be combined to generate hydrogen. This process is called Photovoltaic-electrolysis. The Photovoltaic cell converts sunlight directly into electricity. The principle of the remaining is similar to that of water electrolysis. The combined device is placed in water and begins to generate hydrogen when exposed to sunlight.

There are also some new technologies such as photochemical and photoelectrochemical methods. Photocatalysts, free electrons and holes are employed. The photocatalysts can be recovered, which leaves no side products. The holes made by the light have very strong oxidizability; the free electrons made by the light have very strong reducibility. Therefore, water can be very easily decomposed into hydrogen and oxygen by the utilization of free electron-hole pairs [84].

3.2.4 Biological methods for hydrogen production

Hydrogen can be produced using biological methods by using sunlight, biological components and a bioreactor. Algae have been used as the biological component until now. Hans Gaffron first discovered the potential of algae when he did research at the University of Chicago in 1939. He observed that a kind of green algae called chlamydomonas reinhardtii, would sometimes switch from producing oxygen to creating hydrogen, but only for quite a short time [85]. However, the reasons were not found out until the late 1990s. Professor Anastasios Meils discovered that deprivating the algae of sulphur is the cause for this phenomenon, as the amount of sulphur can interrupt its internal oxygen flow, increasing the hydrogenise, which can make it switch to the production of hydrogen [86]. Specific organisms, algae and bacteria are introduced in these processes along with the development of the technology. These processes mostly operate in water at ambient temperature and pressure. Sunlight and water are used to produce hydrogen by photosynthesis. They are inexhaustible, but these processes create waste and have environmental pollution. Although the efficiency of this method is not too high at the moment, about 7-10 % from sunlight to hydrogen, this efficiency can achieve the economic target of the DOE [87]. There are two major biological components: biomass and microbe.

a) Biomass

Biophotolysis is the method producing hydrogen from biomass, which is abundant, clean and renewable. Biomass resources are huge and various: crops, animal waste, tree, sewage and some other industrial waste. The basis of this technology is decomposition. Heat up the biomass in water to a temperature of approximately 700 ºC to gasify it into CO_2 and H_2, and then purify the synthesis gas to get pure hydrogen. In reference [88], green algae are shown to be better for hydrogen production than cyan bacteria, as the latter has more energy intensive enzymes.

b) Microbe

Hydrogen production from microbe was first discovered through observing hydrogen production in the dark by using photosynthetic bacteria by Nakamura in 1937 [89]. Gest and Kamen proved photosynthesis could generate hydrogen by using micro-organisms [90]. This technology utilizes metabolism of the micro-organism to produce hydrogen. It normally has two methods: photosynthetic microbe and anaerobic organism. Hydrogen is produced from microbe by utilizing the fermentation of anaerobic organisms: employing anaerobic or nitrogen fixation bacteria to decompose some small molecular organisms. The combination of both kinds of bacteria not only reduces the light energy demand of the photosynthetic bacteria, but also increases hydrogen production [91].

Fermentative evolution is more advantageous than photochemical evolution for the mass production of hydrogen by micro-organisms, the reason for which is that fermentative bacteria can help hydrogen production [101-103].

3.3 Hydrogen storage methods

Although hydrogen is abundant, clean and has the highest mass energy density, it is still the lightest substance. This makes it occupy a much larger volume at the same mass with other fuels, which makes storing hydrogen a big issue. The hydrogen phase diagram, Fig. 3-5, shows different hydrogen states under different environmental conditions.

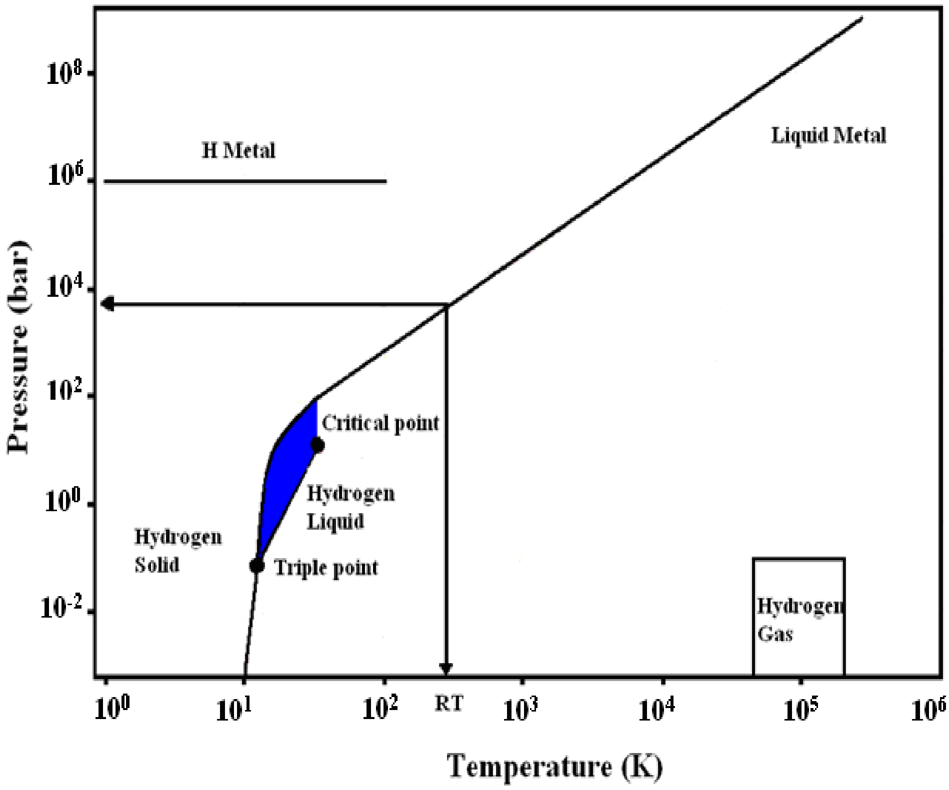

Fig. 3-5 Hydrogen phase diagram [92, 93]

There are basically five options for hydrogen storage: compressed and stored in a pressure tank; cooled to a liquid state and kept cold in an insulated tank; physisorpted in carbon; complex compounds and absorbed on interstitial sites in a host metal. The characteristics of the basic 5 storage methods are listed in Table 3-3. ρ_m is the gravimetric density, ρ_v is the volumetric density, T is the working temperature, P is the pressure, and RT is room temperature.

Table 3-3 The five basic hydrogen storage methods and phenomena [17]

Storage method	**ρ_m [mass %]**	**ρ_v [kg H_2 m^{-3}]**	**T [^{0}C]**	**P [bar]**	**Phenomena and remarks**
High compressed gas	12	< 4	RT	800	Compressed gas (molecular H_2) in light weight composite cylinders (tensile strength of the material is 20000 bar)
Liquid hydrogen in cryogenic tanks	Size dependent	70.8	-252	1	Liquid hydrogen (molecular H_2), continuous loss of a few percentage per day of hydrogen
Adsorbed hydrogen	≈ 2	20	-80	100	Physisorption (molecular H_2) on materials e.g. carbon with a very large specific surface area, fully reversible
Absorbed on interstitial sites in a host metal	≈ 2	150	RT	1	Hydrogen (atomic H) intercalation in host metals, metallic hydrides working at RT are fully reversible
Complex compounds	< 18	150	> 100	1	Complex compounds ($[AlH_4]^-$ or $[BH_4]^-$), desorption at elevated temperature, adsorption at high pressures

(Note：under standard condition，the working temperature and pressure are 25 °C (298 K), 1 bar)

3.3.1 Compressed gas

The density of hydrogen is 70.6 kg m^{-3} at –262 °C in solid state, 70.8 kg m^{-3} at –253 ºC in liquid state and 0.09 kg m^{-3} at 0 °C and a pressure of 1 bar in gas state. Compared to other available fuels, hydrogen stores the most energy per unit mass, but has the lowest density, and so has the lowest volumetric energy; therefore, how to store hydrogen is an urgent problem that needs to be solved. Storing hydrogen in a gas state under high pressure has been done for many years. As an example, hydrogen can be compressed to 14.5 kg m^{-3} under 200 bar and 15 °C (288 K) or liquefied to 70.8 kg m^{-3} under 1 bar and -253 °C (20 K) [94]. Hydrogen can be compressed into high-pressure containers and delivered by pipelines, which need excellent seals. This approach can be considered as an easy method to operate, and it is also quite an efficient system, the efficiency of which is around 90 %. Safety is a big issue for this storage method, as high pressure is required for this technology.

The storage tanks can either be made of steel, aluminium or copper alloys that may be encased in fiberglass. The steel tanks are most commonly used for static applications where weight is not a major consideration. The common commercial high pressure compressed gas cylinder is under 200 bar (3000 psi) [95], the density is 14.5 kg/m^3 [94]. Higher capacity can be achieved by increasing the pressure, and the highest pressure is developed to 800 bar (12000 psi) by now, in the meantime, the density can reach to 36 kg m^{-3} [95]. Beattie-Bridgeman equation of state shows that higher gas density becomes increasingly difficult to attain with higher pressure, which is presented in Fig. 3-6.

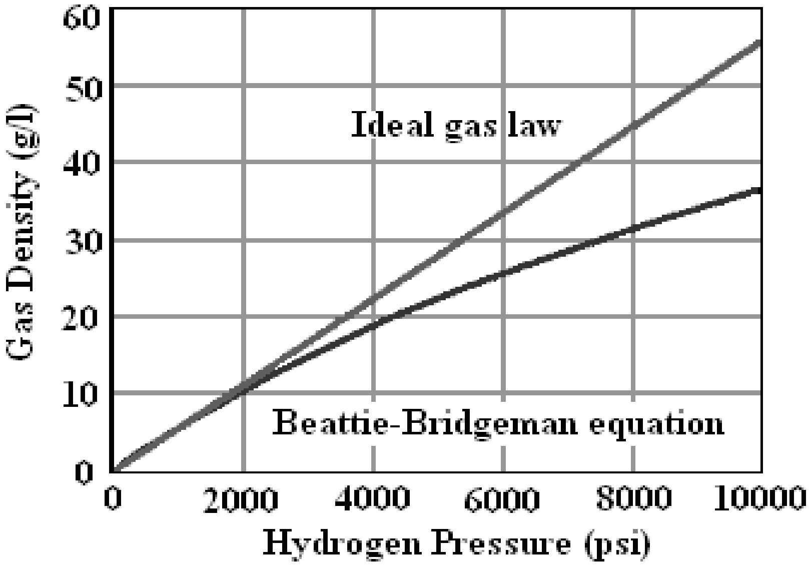

Fig. 3-6 Gas density vs. hydrogen pressure under Beattie-Bridgeman equation [96]

Fig. 3-7 shows the energy required for compressing hydrogen at different pressures under adiabatic, multistage, and isothermal conditions. From this figure, higher pressure requires more energy. A multistage compressor consumes about 7.5 % energy to compress hydrogen at 200 bar, and 12 % at 800 bar.

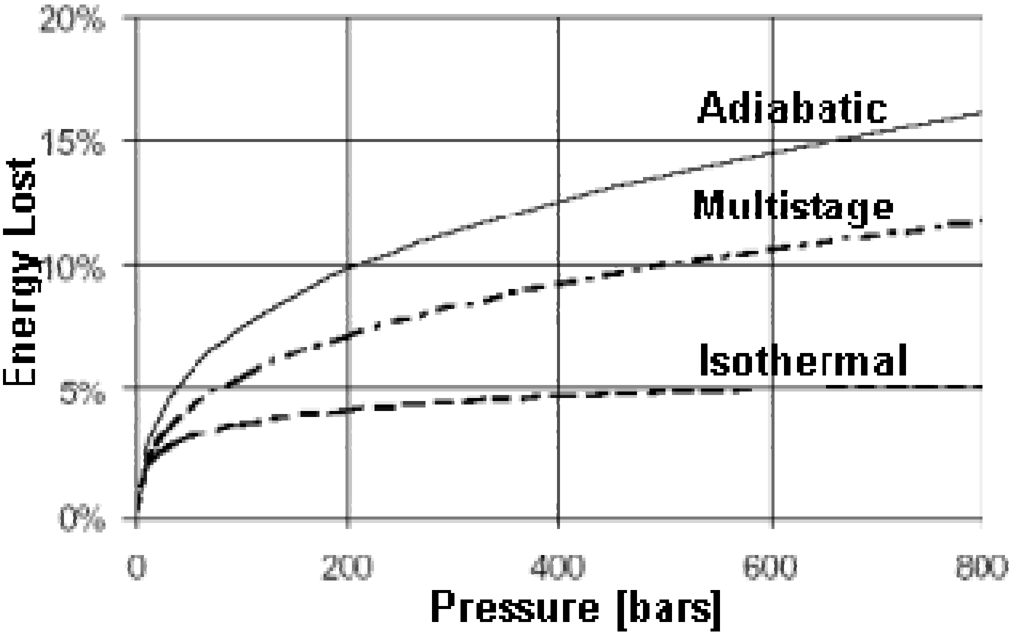

Fig. 3-7 Energy required for the compression of hydrogen at different pressure levels [97]

Without considering the operational losses, the main loss in compressed gas method is permeation. Fick's first law for diffusion provides the relationship between the hydrogen flux *J* and the concentration gradient across the plate (container wall). Sievert's law states that the concentration *C* is proportional to the square root of the pressure. Combining these relationships at steady state provides an expression for the rate of permeation of hydrogen by diffusion [98]:

$$J = D\frac{\Delta C}{l} = \frac{DS\sqrt{P}}{l} \qquad \text{Eq. 3-8}$$

Where, P is the pressure, l is the thickness of the cylinder wall, J is the permeation rate (mol H_2 s^{-1} m^{-2}), D is the diffusivity of hydrogen in the plate material, and *S* is the solubility of hydrogen in the plate material (also called Sievert's parameter). There is a parameter table for *DS*.

The following equation can be used to design the cylinder wall thickness *l*. The wall thickness of a cylinder capped with two hemispheres is given by the following equation [17]:

$$l = \frac{\Delta p * d}{2 * \sigma_v + \Delta p} \qquad \text{Eq. 3-9}$$

Where, *d* is the outer diameter of the cylinder, Δp is the overpressure, and σ_v is the tensile strength of the material.

A simulation for one large storage system to get the leakage of compressed hydrogen over time was carried out. It was simulated with the ambient temperature at 25 °C (298 K) and pressure at 300 bar. “316 Stainless Steel” was chosen as the vessel wall material, $DS = 2.3 \times 10^{-15}$, and $\sigma_v = 5800$ bar [99].

3.3.2 Liquid hydrogen

Hydrogen liquefaction is an energy intensive process. It requires amounts of energy equal to about one third of the energy stored in liquefied hydrogen [100]. The principle of this process is the same with the high compressed gas method. Hydrogen does exist in a liquid state only at extremely cold temperatures of -253 °C. Therefore, in order to exist as a liquid, hydrogen must be pressurized and cooled to a very low temperature, -252.87 °C (-423.17 °F / 20.27 K) at ambient pressure in cryogenic tanks. Once liquefied, it can be maintained as a liquid in cooled and pressurized containers which have to be quite large since liquid hydrogen (LH_2) has a very low density. Although LH_2 storage in liquid state has high storage capacity, the energy utilization efficiency is low due to the energy lost during liquation process.

LH_2 occupies a relatively small volume compared to the compressed gas. The volumetric capacity of liquid hydrogen is 0.070 kg L^{-1}, compared to 0.030 kg L^{-1} for the 700 bar gas tanks. High purity hydrogen can be obtained by this technique. A small amount of hydrogen, about 1.5 % per day, could be lost continuously due to evaporation [101, 102]. The strict pressure and temperature requirements make this technology extremely expensive compared to the others.

A hybrid tank concept combining both high-pressure gaseous and cryogenic storage is studied by Sang Sup Han [103]. These hybrid (cryo-compressed tanks) insulated pressure vessels are lighter than hydrides and more compact than ambient-temperature, high-pressure vessels. Since the required temperature is not as low as it for LH_2 storage, less energy penalty is paid for liquification and there are less evaporative losses in hybrid tanks.

3.3.3 Physisorption in carbon

Physisorption happens on the surfaces of the solid materials. The principle of this process is enhancing the hydrogen density of solid interface. The non-polar surface makes carbon a good hydrogen storage material [104, 105]. Carbon exists in different forms such as meso-carbon, nano-tube and active graphite. Hydrogen is adsorbed in pore, tube and inter-layers carbon. Maximum storage capacity is 1.2 mass% at room temperature 25 °C and 4.5 mass% at -196 °C (77 K), the pressure of both are at 10 bar [106].

Dillon et al. [107] first introduced carbon nano-tubes method for hydrogen storage in 1997. The storage capacity depends on the surface area of the nano-tube, pore geometry and pore size distribution as well as the storage pressure and temperature [63].

The hydrogen gas molecules run onto the surface of the hydrogen storage materials. This process is called physisorption. Actually, a gas molecule can interact with several surface atoms of a solid [17]. The advantages of this method are low operating pressure, low cost and simple operation. However, the density of hydrogen is relatively low and the process can only be carried out below room temperature at 25 °C. Because of the porous structure of carbon, activated carbon, graphite and carbon nano-tubes can be also used in this process. The drawback is that the process is difficult to control and optimize.

Activated carbon is well known as one of the best adsorbents for gases due to its large surface area and abundant pore volume [108]. The storage capacity of carbon nano-tubes and carbon nano-fibers, which is less than 0.7 wt%, at ambient temperature 25 °C and high pressure (about 100 bar) is smaller than the capacity of activated carbon [109]. However, Chambers et al. [110] researched on herringbone type graphite nano-fibers, and the result showed that it can absorb hydrogen up to 67 wt% at 101 bar and 27 °C (300 K). The achievement has been unable to be validated by other researchers so far. In recent publications [122-124], almost all experimental results indicated that hydrogen storage by carbon nano-materials was only 0.1-2.0 wt%, The maximum storage capacity for activated carbon with a BET surface area of 2564 m^2 g^{-1} was reported as 4.5 wt% at -196 °C (77.4 K) [111]. The BET method is used for calculating physical adsorption of gas molecules on the surface areas of solids [112]. Adsorption of hydrogen usually takes place in micro-pores, in order to enhance the hydrogen storage capacity; many improvements have been investigated recently to obtain micro-porous carbonaceous materials. Macro-pores have practically no influence on the adsorption capacity, but they are important for gas compression and adsorption/desorption reaction rates [113].

In Fig. 3-8, hydrogen Temperature Programmed Desorption (TPD) mass signal is plotted against the temperature [107]. Graphite, activated carbon and arc single walled nano-tubes (SWNTs) were researched on. SWNTs show better hydrogen desorption properties than activated carbon and graphite, because SWNTs adsorb larger amounts of hydrogen than graphite and activated carbon under the same duration and temperature conditions. The result is that 4 wt% hydrogen could be stored in SWNTs at room temperature 25 °C (298 K), which has been achieved before [107].

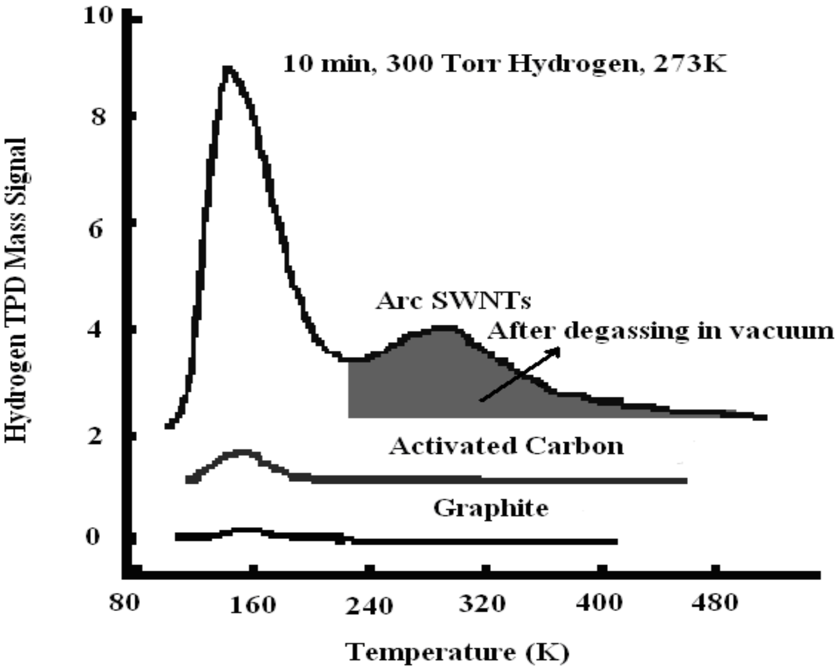

Fig. 3-8 Adsorption on physisorption vs temperature [107]

3.3.4 Complex hydrides

Complex hydrides are different from the alloying hydrides. They can be dissolved in suitable solvents without decomposition. They are non-conducting in their pure state, and most of them are irreversible. For their lightweight and high hydrogen storage capacities, they are considered as good hydrogen storage candidates. This leads hydrogen storage into a brand new field. Normally, multi-component alloys result in slow hydrogen sorption kinetics and high hysteresis. Back in 1997, Bogdanovic and Schwickardi [114] found that the adsorption and desorption pressure-concentration isotherms for Sodium aluminium hydride ($NaAlH_4$) had a horizontal pressure plateau at 180 °C and 210 °C, which means no hysteresis. The results showed that $NaAlH_4$ is a good candidate for its high hydrogen sorption kinetic in complex hydrides area.

3.3.5 Absorbed on interstitial sites in a host metal

Many metals and alloys are able to react spontaneously with hydrogen. These materials, either a defined compound or a solid solution, are designed as metallic hydrides. Metal hydrides have the potential for reversible on-board hydrogen storage and release hydrogen at low temperatures and low pressures. Reversible metal hydrides hydrogen storage can be used in a wide range of applications, for example, vehicles, boats and laptops. From the first discovery of hydrogen in experiments about iron and zinc in dilute sulphuric acid, scientists have been very interested in the area of metal hydride hydrogen storage. Metals can absorb more hydrogen like the 'sponges' [115], which results in that metal hydrides are widely investigated in the area of hydrogen storage for their high storage capacities.

In the element periodic table, nearly 50 metals can absorb hydrogen. The experiments were carried out by putting some solid materials into containers with condensation hydrogen inside. An excellent hydrogen storage material must possess: low cost, no pollution, safety, easy preparation and activation, high gravimetric density and volumetric density, light weight, high absorption and desorption kinetics, good reversibility, low thermodynamic stability, high plateau pressure, high life cycle, low operation temperature and low hysteresis, etc [63].

The metal hydride method has been widely investigated, because it is an easy and safe approach for hydrogen storage. The hydrogen storage capacity of this method is quite high. The storage process is reversible and does not self-discharge [116]. Compared to the other methods, it does not need complex containers to obtain high purity hydrogen. But most metal hydrides are easily oxidised, hard to be activated and expensive. Fig. 3-9 compares the primary properties of some metal hydrides, complex hydrides, carbon nano-tubes and other hydrogen storage materials. The comparison is based on both hydrogen mass density ρ_m and volume density ρ_v.

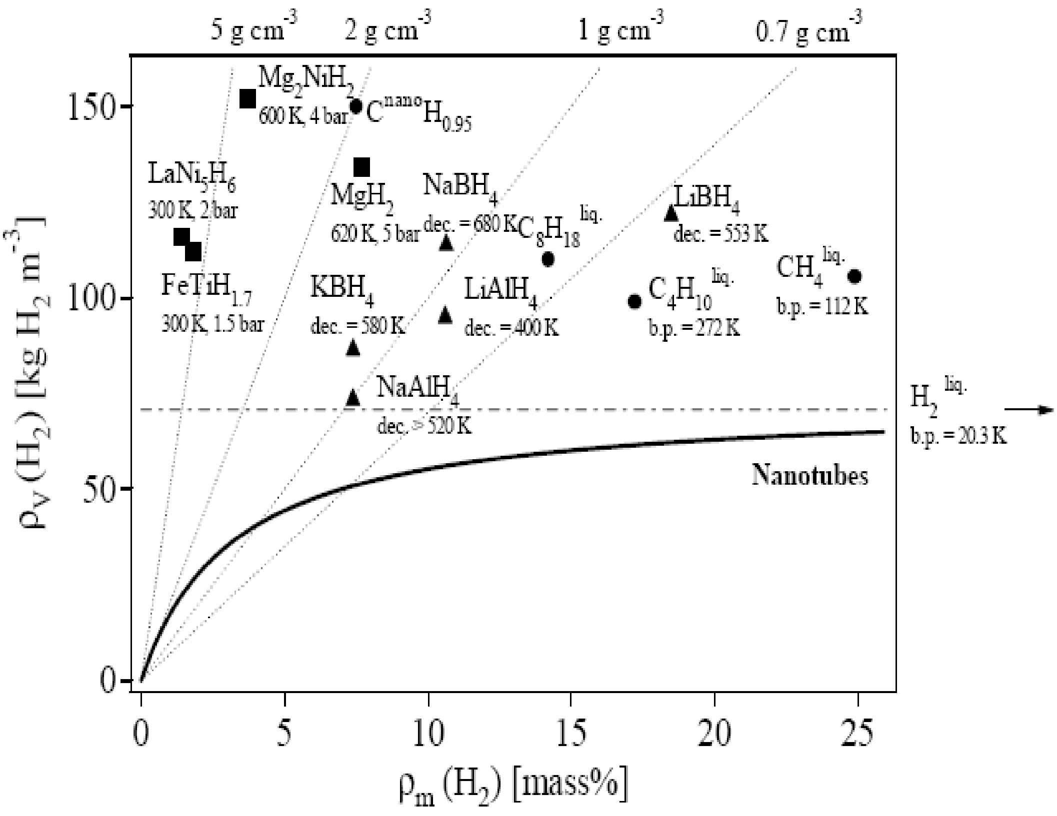

Fig. 3-9 Hydride hydrogen capacities [17]

The hydrogen economy requires two types of hydrogen storage system: one for transportation, and the other for stationary applications. Both applications have different requirements and constraints. The transportation sector is expected to be the first high-volume user of hydrogen in the future hydrogen economy. The hydrogen storage requirements for transportation applications are far more stringent than those for stationary applications.

3.3.6 Discussion

These operating requirements for the "ideal" hydrogen storage system for transportation applications include the followings [117]:

—multi-cycle reversibility, at least 500 cycles,
—low operation pressure, less than 4 bar,
—operation temperature is easy to meet, around -50 to 150 °C,
—fast kinetics,

—high gravimetric density, greater than 9 wt%,
—high volumetric density, greater than 0.07 kg L^{-1},
—safety,
—low cost, less than £15 per kg.

The comparison among different storage methods is summarized in Table 3-4. The thickness of the compressed gas cylinder was chosen to be 5 mm, and then the leakage characteristics of the compressed gas were simulated. The energy loss in compressed gas is relatively low, and therefore yields higher conversion efficiency. Activated carbon also has a high efficiency; however, a very low temperature is required during the process. During the storage period, the hydrogen leakage rate should also be considered, because it is a part of the dynamic efficiency of the system. As shown in Table 3-4, the compressed gas method has a very low leakage rate compared to the other methods.

Table 3-4 Some parameters of hydrogen storage methods [118, 119]

		Energy intensity (MJ kg^{-1})	Efficiency	Leak rate (/day)
High pressure compressed gas	350 bar	13	0.80	--
	700 bar	16	0.76	--
Low pressure compressed gas (< 200 bar)		< 10	~90 %	--
Liquid		30-200	0.625-0.77	1%
Activated carbon (77 K)		~5	0.917-0.933	0.2%
Hydrides	Low temperature (<100 °C)	---	0.9-0.933	---
	High temperature (>300 °C)	>227	0.79-0.83	---

Nowadays compressed hydrogen technology can reach 800 bar. Although higher pressure can achieve a smaller volume, it can also result in lower efficiency. For stationary applications, weight and volume restrictions of hydrogen energy storage are less critical than those for vehicles; stationary hydrogen storage systems can occupy a large area, be operated at high temperatures and pressures, and have extra capacities to compensate for slow kinetics. Nevertheless, hydrogen storage for stationary applications also represents a major scientific and technical challenge, especially in the area of storage materials. Therefore, low pressure compressed hydrogen at 150 bar was chosen for this study, and the efficiency of this is about 91.5 %.

3.4 Devices for converting hydrogen back to electricity

There are many kinds of devices for converting hydrogen back to electricity, such as fuel cells, H_2-ICEs, direct steam generation by hydrogen/oxygen combustion, catalytic combustions, and H_2-CCGTs [16]. PEMFCs and solid oxide fuel cells (SOFCs) are more competitive, due to the fact that PEMFCs have high current density, a low working temperature of around 80 ° C, long stack life, and fast start-up [120]; and SOFCs have high efficiency, low cost, and long-term stability. Therefore, both of them are suitable for large power station applications [121]. The efficiency of fuel cells decreases with increasing power output. Therefore, their efficiencies and economics are interrelated. For the same power output, a more efficient fuel cell is bigger and thus more expensive [122].

3.4.1 Fuel cells

There are different types of fuel cells, with different electrolytes, such as alkaline fuel cell (AFC), direct methanol fuel cell (DMFC), sulphuric acid fuel cell (SAFC), SOFC, and PEMFC, etc. SOFCs and PEMFCs are chosen in further comparisons as they are more suitable for the large scale applications with distributed generations than the other kinds of fuel cells [121]. In reality, efficiencies of fuel cells vary with load. The polarization curve Fig. 3-10 shows the efficiency of the fuel cells at any operating current. Fuel cells can achieve their highest theoretical output voltage at the condition with no load, and the output voltage decreases when the current increases. The dropped voltage gives the total energy losses, affecting the electrical efficiency of the fuel cell.

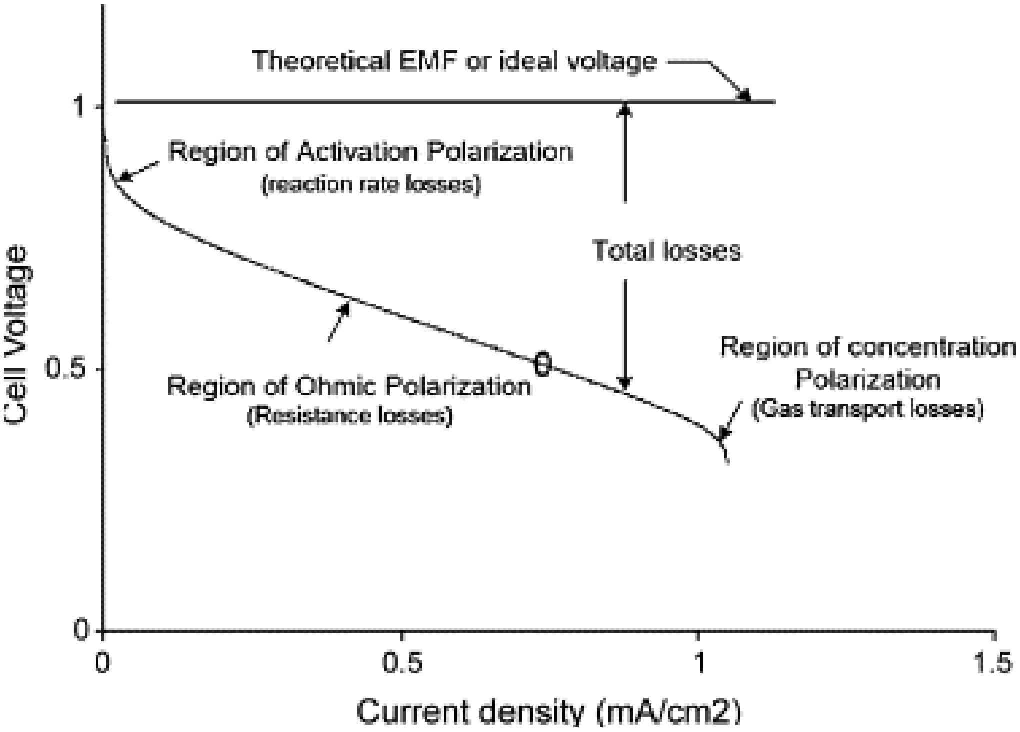

Fig. 3-10 Typical fuel cell polarization curve [123]

i) **PEMFC:** Proton exchange membrane fuel cells use polymer membrane as the electrolytes. It draws the most attention due to its low operating temperature of approximate 50-80 ºC and quite high efficiency of about 50 %. The life cycle of PEMFCs exceeds 3000 h [124]. And PEMFCs can be used in the power ranges from a few kW up to hundreds of kW for generation and light industry applications [125]. The disadvantages are that purer hydrogen is needed as the fuel; the practical efficiency is low; and the cost is very high. The capital investment cost is US$ 2900 per kW, and the operation and maintenance (O&M) cost is about US$ 500 per kW-yr [126], which is about US$ 0.057 per kWh.

ii) **SOFC:** Solid oxide fuel cells have solid oxide or ceramic electrolytes. There are many kinds of oxide based ceramic materials which can be used in SOFCs. The most common one is stabilised zirconia with conductivity based on oxygen ions, especially yttria-stabilised zirconia

(Y_2O_3-stabilised ZrO_2 or YSZ), $(ZrO_2)_{0.92}(Y_2O_3)_{0.08}$ for example. The solid ceramic electrolyte makes the operation temperature quite high, about 600-1000 °C [121]. SOFCs have a wide range of applications with the outputs from some hundreds of kW to tens of MW for distributed generations and industrial co-generation [125]. The efficiency of it is 70 % with an additional 20 % as heat recovery [127]. The life cycle of SOFCs is very long, at least 40,000 h [128, 129]. Mature market cost of pure SOFC plants to date is around US$ 1000 to US$ 1200 per kW [130]. Its O&M cost is US$ 0.0156 per kWh, which is nearly US$ 137 per kW-yr [131].

The efficiency of heat engines normally follows the Carnot cycle efficiency, which can be calculated by

$$\eta = 1 - \frac{T_L}{T_H} \qquad \text{Eq. 3-10}$$

Where, η is the thermodynamic efficiency, T_L is the lower temperature, and T_H is the higher temperature.

Fuel cells differ from conventional heat engines; therefore, the Carnot cycle is not applicable for fuel cells. The thermodynamic efficiency of fuel cells is [132]

$$\eta = \frac{\Delta G^o}{\Delta H^o} \qquad \text{Eq. 3-11}$$

Where, η is the thermodynamic efficiency, ΔG^o is Gibbs free energy, and ΔH^o is Enthalpy.

As the Gibbs free energy drops while temperature increasing, the thermodynamic efficiency of fuels cells decreases with increasing temperature.

3.4.2 Hydrogen-fuelled internal combustion engines

The first operational hydrogen-fuelled internal combustion engine was introduced by Reverend W. Cecil in 1820 [133]. Sixty years later, N. A. Otto used a synthetic producer gas, which includes more than 50 % hydrogen, as the fuel for the internal combustion engine in the 1860s and 1870s [134]. Hydrogen has very low ignition energy, so the amount of energy needed to ignite hydrogen is much less than it needed for the same amount of gasoline.

In most cases, H_2-ICEs have been designed as naturally aspirated engines using ambient external mixture formation port fuel injection (PFI). In the present work, the high pressure direct injection (DI) H_2-ICEs are investigated as they can overcome some disadvantages of the normal H_2-ICEs, such as the low power output and low volumetric efficiency [135]. The peak output is determined by volumetric efficiency, fuel energy density, and pre-ignition. For most applications, pre-ignition is the limiting factor in determining the peak power output [136]. The maximum output of the engine can reach about 20 % higher than that of gasoline engines [137]. To date, the largest power output of commercial hydrogen driven internal combustion engine is 200 kW, created by MAN Truck & Bus Company N.V. in Rotterdam, The Netherlands [138].

The theoretical thermodynamic efficiency of an Otto cycle engine depends on the compression ratio of the engine and the specific-heat ratio of the fuel. The equation of the thermodynamic efficiency is shown below [139]:

$$\eta = 1 - \frac{1}{(\frac{V_1}{V_2})^{\gamma - 1}} \qquad \text{Eq. 3-12}$$

Where, γ is the specific-heat ratio of the fuel, which is based on the molecular structure of the fuel, like hydrogen's is 1.4, and gasoline's is 1.1; V_1/V_2 is the compression ratio of the engine; η is the theoretical thermodynamic efficiency.

The theoretical thermodynamic efficiency can be increased by improving either the compression ratio or the specific-heat ratio. Hydrogen has much higher specific-heat ratio than gasoline. Under the normal condition, 25 °C and 1 bar, the specific-heat ratio of hydrogen is 1.4, and gasoline's specific-heat ratio is 1.1. Besides, the energy needed for igniting hydrogen-air is much lower than it needed to ignite the hydrocarbon-air, which is shown in Fig. 3-11. The figure also shows the comparison of the Minimum ignition energy of hydrogen-air, methane-air, and heptane-air in relation to ϕ at atmospheric pressure.

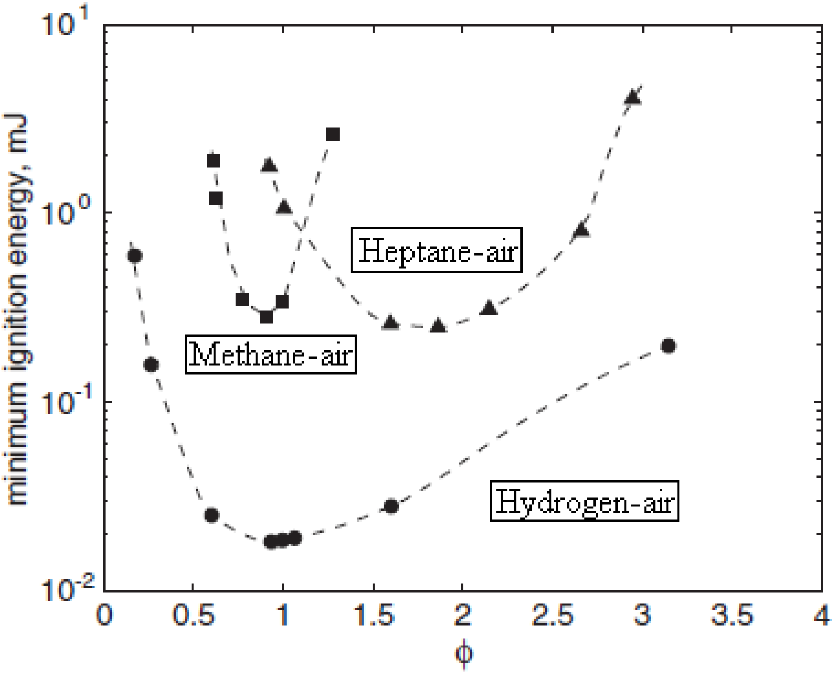

Fig. 3-11 Minimum ignition energy at atmospheric pressure [136]

ϕ is defined as the ratio of the actual fuel/air mass ratio to the stoichiometric fuel/air mass ratio, for example, the stoichiometric fuel/air mass ratio for gasoline is 14.7:1, and it for hydrogen is 34:1. Therefore, the efficiency of H_2-ICEs is 20 % to 25 % higher than that of traditional gasoline ICEs.

3.4.3 Hydrogen-fuelled combined cycle gas turbines

The first combined cycle power plants with a power output of between 200 and 350 MW were built in the US in the 1970s, and the design efficiency was around

42.5% [140]. The first CCGT plant in the UK was started up in 1991. The combined cycle gas turbine includes gas turbine and steam turbine. A standard commercial CCGT normally consists of two gas turbines and one steam turbine, which means 2/3 and 1/3 of the electric production capacity, respectively [141]. The normal CCGT produced by Siemens with two gas turbines and one steam turbine can produce the electricity between 505 MW and 848 MW, and the standard size of the CCGT with only one gas turbine and one steam turbine is between 290 MW and 530 MW.

Enel, Italy's largest utility, has been working on a hydrogen programme, in Fusina, near Venice. This plant has a 12 MW hydrogen fuelled CCGT, which is the first industrial-scale hydrogen fuelled CCGT in the world. This hydrogen power plant generates sufficient clean electricity, which can supply the electricity for 20,000 households [142]. Enel reported that the Fusina hydrogen plant invested 50 million euros. The capacity of the Fusina hydrogen plant is 16 MW, the overall efficiency is 41.6 %. It can generate 60 million kWh of energy every year, and it is the world's first industrial-scale hydrogen-fired power plant.

A simple gas turbine includes: a compressor, a combustor and a turbine. The gas turbines have attracted many interests in recent years, because of their low capital costs, compact sizes, high flexibility and reliability, better environmental performance, and they are fast starting and loading and require lower manpower operating [143]. However, they do not have a high efficiency (40-45 %), especially at part load [125]. The efficiency of a combined gas turbine is much higher than that of the either part of the CCGT, which is about 55-60 % [144].

3.5 Summary

Compared to the traditional fuels, like CH_4, CH_3OH and gasoline, hydrogen has the lightest weight, zero carbon content and the highest mass energy density, which makes it a very good candidate as an energy carrier. Various sources such as fossil fuels, biological components and water are available for hydrogen production. The water electrolysis method is considered to be a good solution for this study, because it is a well-developed method and it has a high efficiency (75 %).

Different hydrogen storage methods were carefully compared in this chapter. A quite low operating temperature is required for liquid and activated carbon storage methods, while hydrogen stored and released is relatively slow for hydrides storage. Therefore, the compressed gas approach is chosen as the best solution for this study due to its relatively high conversion efficiency, ease of operation and low leakage rate.

Many kinds of hydrogen to electricity conversion devices were considered here. H_2-ICEs, H_2-CCGTs, and fuel cells have similar efficiencies, but fuel cells are quite expensive; the large output H_2-ICEs are still under development; and H_2-CCGTs technology is not that mature. Therefore, the mature technology of fuel cells and low cost H_2-CCGTs were chosen for this PhD research.

Chapter 4 Selecting wind turbine size with hydrogen storage in off-grid systems

THIS chapter introduces a new optimal methodology to determine the wind turbine and energy storage sizes for a 5 MW micro-grid—the University of Bath network.

4.1 Introduction

In the wind power system, the production of electrical energy depends on the wind speed, if wind turbines have already been chosen; however, the wind power does not often match the consumers' demand. A "balancing system" needs to be introduced into the system to optimize the power produced to the demand, shown in Fig. 4-1. The purpose of this balance system is to store excess energy when wind power is higher than demand and to release the stored energy when the demand is higher. In this study, excess wind energy is converted from AC to DC, and then goes through the control strategy: part of the energy is utilized to produce hydrogen, while the rest is used to compress hydrogen into the cylinder.

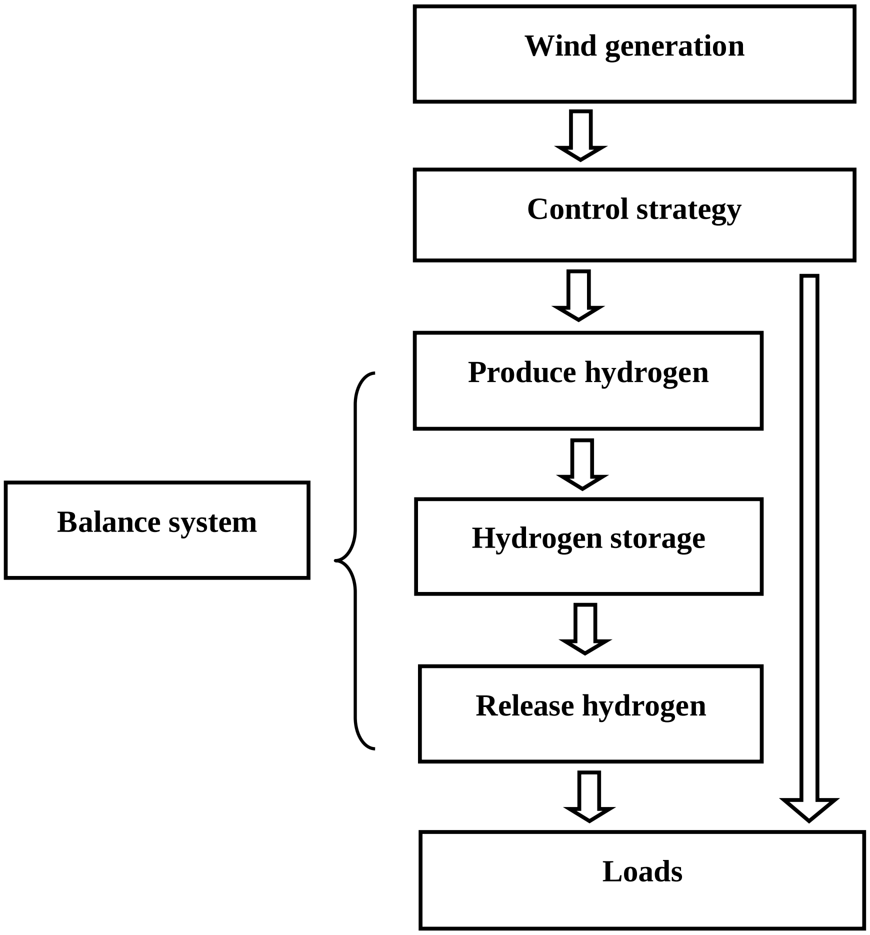

Fig. 4-1 Optimised wind power system by introducing a balance system

4.2 Data processing

Half-hourly wind data in 2006 and 2007 was used for this research, which was observed by the Met Office, UK. There is six recent years free hourly data from all the stations can be ordered by school and university students from the Met Office official website. There are a large amount of weather stations covering the whole UK area, and the weather stations do not only measure wind speed, direction, but also air temperature; atmospheric pressure; rainfall, and so on. The data from Bristol Lulsgate airport weather station was chosen in this research as it is the nearest one from the University of Bath, only about 30 km away from Bath. Table 4-1 is taken as an example of the data, and the METAR decoding in Europe describes how it works. EGGD shows the data observed from Bristol Lulsgate airport; Visibility is recorded as a four figure, 0000 means the visibility is less than 50 meters, 9999 indicates the visibility is 10 km or more, and the letter by the end indicates the direction; although wind speed is the only parameter which is considered in this research.

Table 4-1 Example of half hourly weather data from the Met Office

Time	Date	Platform	Wind	Visibility	Temperature and dew point
0150Z	01/01/06	EGGD	26012KT	9999	06/05
1220Z	01/01/06	EGGD	30007KT 270V330	9000S	07/05
1050Z	10/01/06	EGGD	19017G28KT	6000	08/06

Wind data is normally taken at 10 meters. The first three numbers stand for which direction the wind blows from, and the next two numbers show the mean wind speed in KT, where KT is wind speed unit, knot (1 knot equals 0.514 metres per second (m s^{-1})). Therefore, 26012KT indicates wind is blowing from the southwest at 12 knots. If the direction is varying, V could be used: 30007KT 270V300 shows that wind is blowing from the southeast at 7 knots but wind direction is varying from 270 to 300 degree. If wind is gusting, then it is shown by the letter G. For example, 19017G28KT shows the wind is blowing from 190 degree at 17 knots but gusts to 28 knots. If wind direction is ‘variable’, then the first 3 figures are replaced by VRB; and dead calm can be indicated by 00000KT.

Raw half hourly wind data from the Met Office is for wind speed at 10 m above ground, however, the hub of a wind turbine is much higher than this. Wind speed varies with the change of the height. Near the Earth’s surface, air flows slower due to the friction from the terrain, buildings, and the others. The friction is reduced, and so the wind is stronger, when further away from the ground. There are normally two ways used to calculate the wind speed [145]: One is the power law relation shown as below [146, 147]:

$$v_h / v_0 = (H_h / H_0)^{\mathrm{n}} \qquad \text{Eq. 4-1}$$

Where, v_0 is the original raw wind speed at 10 m, v_h is the adjusted wind speed at the turbine hub; H_h is the hub height, reasonably being assumed to be 100 m, and H_0 is the original measurement height (10 m) of the raw wind speed data; n is the friction coefficient, and depending on stability, it will vary from 0.09 when it is very unstable, to 0.41 when it is very stable [147], which is typically chosen to be 1/7 [148].

The other one is the logarithmic law [148], which is described in Eq. 4-2, and not like the power law, it is theoretically valid for neutral atmospheric conditions only:

$$\mathrm{V(z)=V_R}\frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_R}{z_0}\right)} \qquad \text{Eq. 4-2}$$

Where, $\mathrm{V_R}$ is the original raw wind speed at 10 m; V(z) is the adjusted wind speed at the turbine hub; Z is the hub height, reasonably assumed to be 100 m; $\mathrm{Z_R}$ is the original measurement height (10 m) of raw wind speed data; $\mathrm{Z_0}$

is the roughness length, typically 0.01 m. Roughness length Z_0 is not a physical length; it is a parameter, which can be considered as a length-scale of the roughness of the surface of the ground.

The conversion of raw data was carried out according to the power law relation in this study, and the friction coefficient value is chosen to be 1/7. Fig. 4-2 indicates that most wind turbines start generating electricity at wind speeds about 2-4 m s^{-1}, which is called the cut-in speed, and shut down to prevent damage at 25 m s^{-1}, which is called the cut-off speed. The rated output power, which means the maximum power they can generate, occurs when wind speed is around 14 m s^{-1} [149] [150].

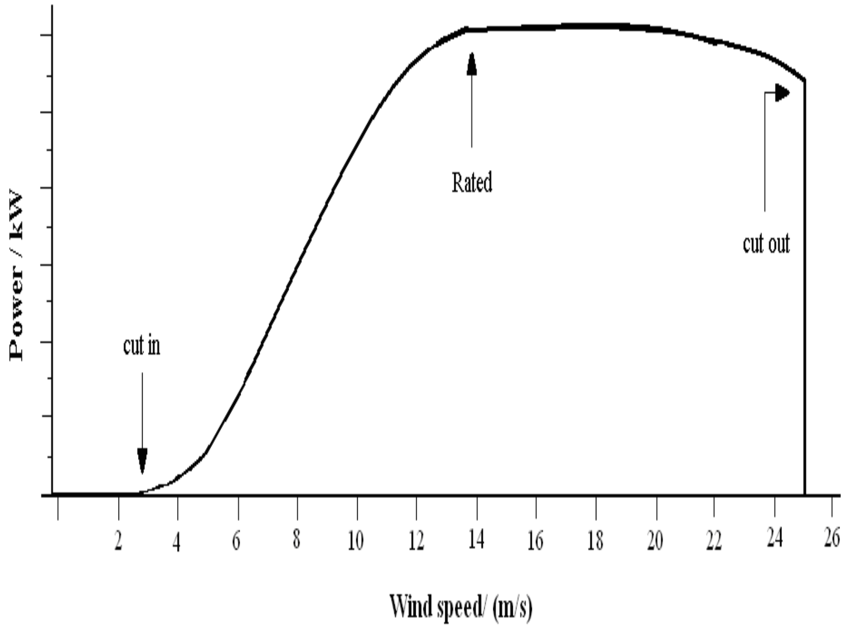

Fig. 4-2 Wind power versus wind speed curve [14-16]

During these years' development of the wind turbine technology, the blade sizes of the typical modern wind turbines and their rated output powers are shown in Fig. 4-3 [151].

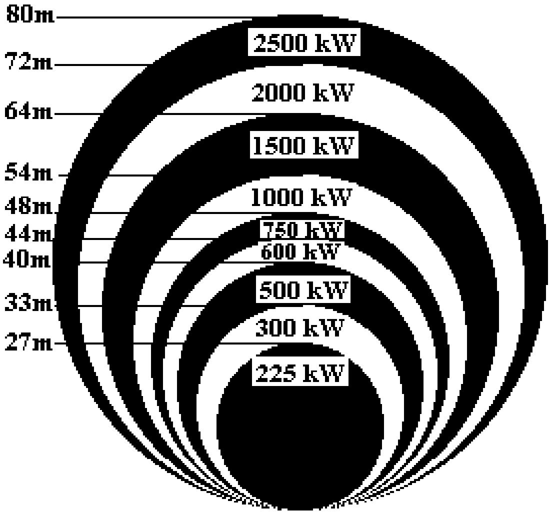

Fig. 4-3 Typical modern wind turbine blade sizes and corresponding rated powers

4.3 New methodology to size the wind turbine and energy storage

A whole year's half hourly wind and load data is taken for calculation from 1st January 2006 to 31st December 2006. The University of Bath consumed in total 13651765 Kilowatt-hours (kWh) of energy during the year 2006. Hydrogen energy storage is employed as the energy storage approach in this chapter. The energy generated from the wind turbine was consumed directly by the load to some extent, and the excess energy was stored as hydrogen , when wind energy is exceed; only part of the stored energy was converted back to make up shortfalls during the periods when the wind turbine could not supply the load. The efficiency is quite low about 30.1 %, including: AC to DC, 98 %; water electrolysis, 76 %; compressed hydrogen, 91.5 %; fuel cell, 46 %; DC to AC, 98 %; transformer, 98 %.

4.3.1 Sizing the wind turbines

The optimized methodology is introduced here to size the wind turbines. This simulation can be described easily in a flow diagram, which is shown in Fig. 4-4. Also, the methodology is described as follows.

I) Flow diagram of the optimized methodology

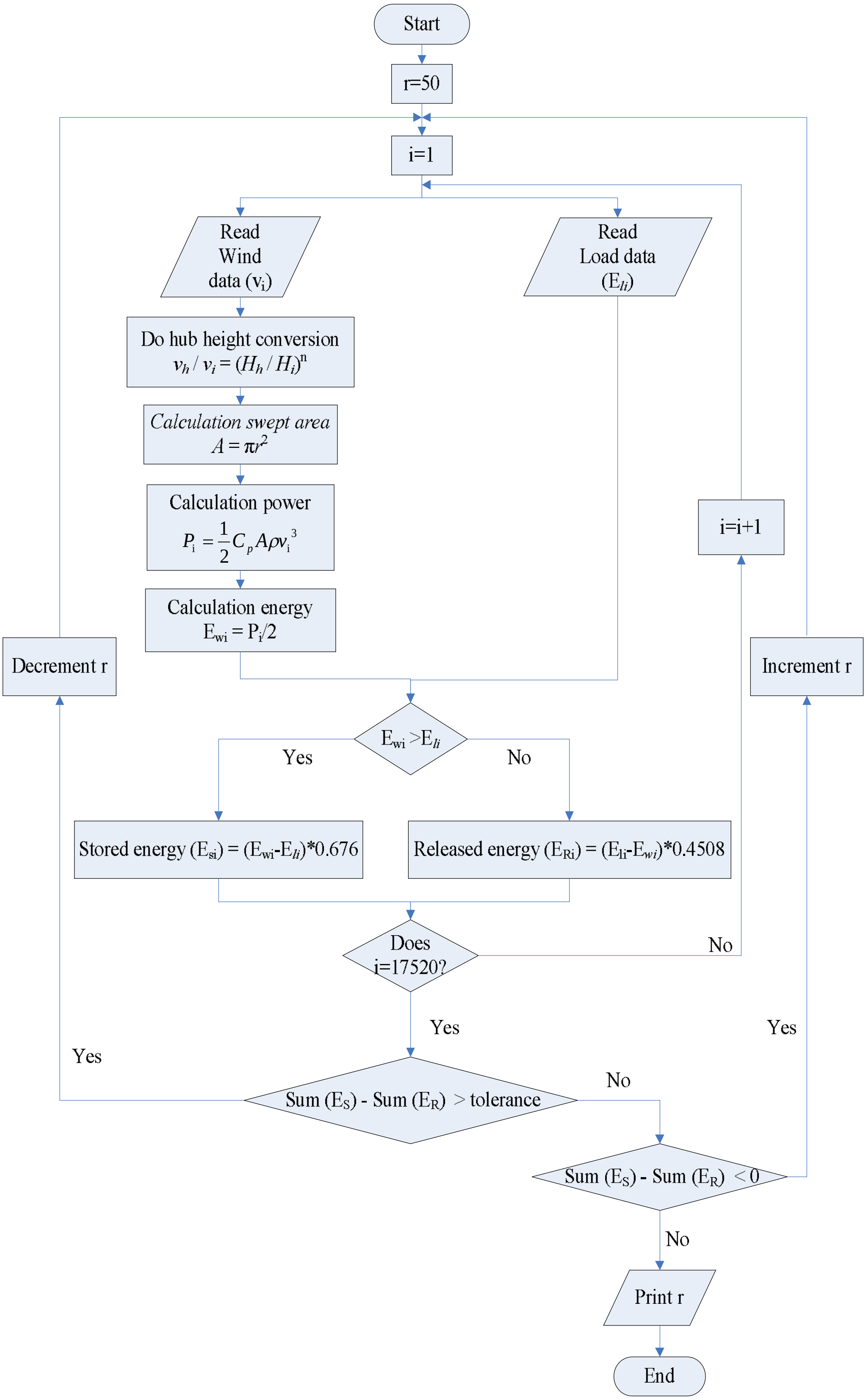

Fig. 4-4 Flow diagram of how to size the wind turbine

II) Description of the methodology

First, dealing with raw wind speed data

1) Without considering the wind blowing direction, converting the wind speed from knot into m s^{-1}.
2) Modifying the wind speed by the power law.
3) Keeping the wind speeds, when it is equal or greater than 3 m s^{-1}, and it is equal or less than 14 m s^{-1}; make the wind speeds be 14 m s^{-1}, when it is between 14 m s^{-1} and 25 m s^{-1}; and turn the wind speeds into zero, when it is less than 3 m s^{-1} or more than 25 m s^{-1}, according to the power curve.

This new wind speed data, which is obtained from the first step, is used to design the wind turbine size. The leakage of hydrogen from the compressed gas storage method was negligible in this case study.

Second, making the wind energy of the whole year 2006 equal to the demand energy

1) The power generated from wind is restrained by the wind power curve. Half hourly wind data in 2006 is calculated with the classical wind power conversion equation:

$$P = \frac{1}{2} C_p A \rho v^3 \qquad \text{Eq. 4-3}$$

Where, P is power, Cp is the power conversion coefficient; A is swept area of the turbine blades and ρ is the air density (1.239 kg m^{-3}) at standard conditions with temperature and pressure are 25 °C (298 K), and 1 bar. Betz's law shows that Cp cannot be higher than 0.593; in practice, it will only achieve about 0.5. The swept area, A, is normally defined as $A = \pi r^2$, where r is radius of the wind turbine rotor.

The wind energy has not been carried out yet, because the wind turbine size has not been determined. Fig. 4-5 shows half hourly wind speed in the University of Bath area in 2006 to give an overview of the wind profile.

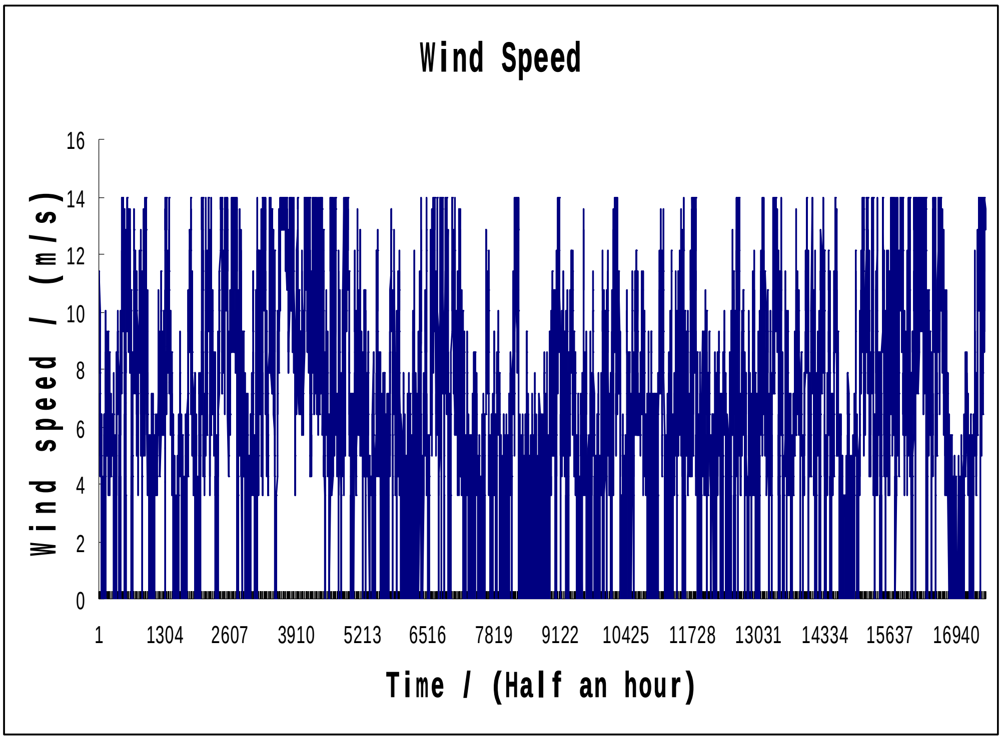

Fig. 4-5 Half hourly wind speed in the University of Bath area, 2006

2) To determine the wind turbine radius, half hourly electricity demand data for the University of Bath site, UK in 2006 is requested. Fig. 4-6 indicates the energy (kWh) consumed of every half an hour on campus in 2006.

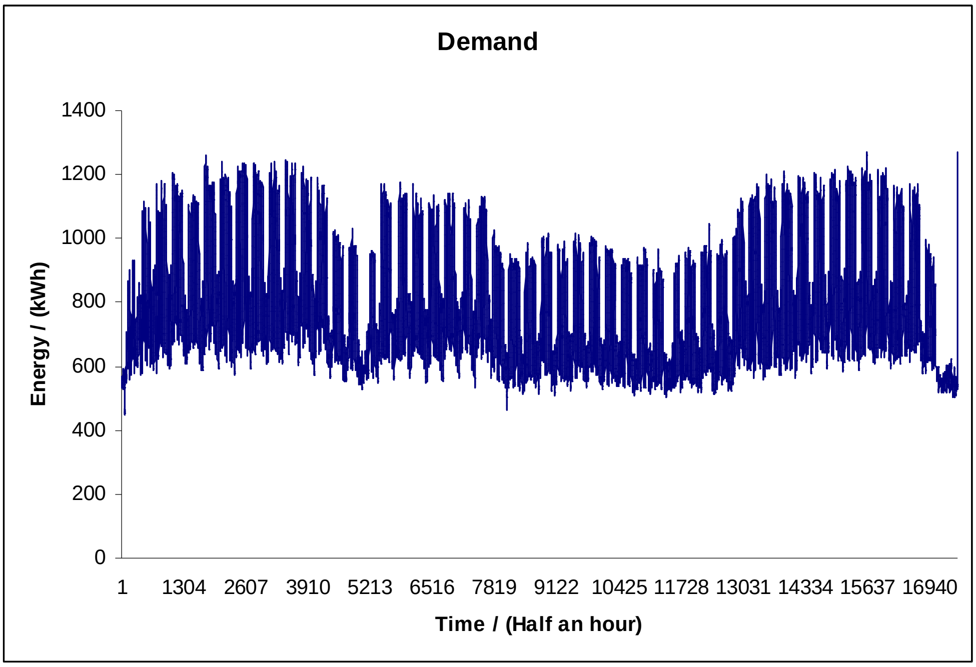

Fig. 4-6 Half hourly electricity demand for the University of Bath in 2006

To size the wind turbines, wind energy generated by the wind turbines is required to cover the demand energy. Wind energy can supply the load at different levels with different wind turbine and energy storage sizes.

Third, two extremities

1) The first assumption is that all the energy should be stored and released for supplying the load. As all energy goes via the energy storage in this calculation, it represents the maximum energy storage requirements. Wind turbines are only used for storing energy, and energy storage supplies the whole load. The efficiency of the whole system is 30.1 %, which implies only 30.1 % of the energy generated from the wind turbines can be used by the consumers. The consumers use 44907122 kWh (13651765 / 0.304) of electricity in 2006, so the wind turbine should generate more than 44907122 kWh of energy in the year.

2) Under another condition, assuming wind energy is always greater than load, and then the system mostly does not need the energy

storage. Depending on the load, the generated wind energy must be more than 13651765 kWh during the year 2006. In this situation, the peak load of the year is picked out to make sure the wind energy should always be plentiful to meet the load. In the year 2006, 1271.35 kWh at 13:20 on 22nd Nov is the peak load. Assuming the wind speed is quite low 4.2 m s^{-1} can be chosen based on real data, then from Eq. 4-3, the calculation should be expressed as

$$1271.35\ \text{kWh}/0.5\text{h} = (0.5*0.5*3.142*r^2*1.239*4.2^3)/1000\ \text{kW} \qquad \text{Eq. 4-4}$$

From this calculation, the maximum size of the wind turbine can be worked out. Therefore, the proper use of energy storage in this case study should give a total annual energy flow somewhere between these two figures.

Considering the whole year's half hourly data, the total wind energy, E (KWh), provided by wind turbines is given by:

$$E = 0.5\ (P_1 + P_2 + P_3 + \ldots. + P_{17520})\ \text{Wh} \qquad \text{Eq. 4-5}$$

Then, from the equation above and Eq. 4-3,

$$E = \frac{1}{4} C_p A \rho\ (v_1^3 + v_2^3 + v_3^3 + \ldots + v_{17520}^3)\ \text{Wh} \qquad \text{Eq. 4-6}$$

From Eq. 4-6 and the load energy, the wind turbine sizes can be worked out. An excel worksheet, which is in the Appendix, was used to size the wind turbines in this study.

Last, sizing the wind turbines

The extreme case would be satisfied by a single wind turbine with the blade radius of 95.6 m, if energy must go through the hydrogen storage, then come to the load; to the contrary, blade radius of 188 m wind turbine is enough to supply the load, for the case without hydrogen energy storage through Eq. 4-6 and half hourly wind and load data of the year 2006.

Between these two extreme conditions, there is an optimized methodology: when wind energy is greater than load, the excess generated power is stored at an efficiency of 67.6 % (AC to DC followed by water electrolysis and compressed hydrogen); when the generated wind power is lower than the load, energy is released at an efficiency of 45.08 % (fuel cell followed by DC to AC). Therefore, the power is used in two ways, first directly going to the load, and then the excess wind power goes through the hydrogen energy storage. The stored energy can be made equal to the released energy for the optimal wind turbine size, which is 70.2 m for the University of Bath network.

Fig. 4-7 shows the flow of energy left-over during the whole year 2006. This energy here is the difference between the exceed energy multiplied by the efficiency 67.6 %, and the short energy divided by 45.08 %, which means it can be used to the load end directly. The optimal wind turbine size-70.2 m, based on the result of the simulation, and other wind turbine sizes are discussed in Fig. 4-7 for illustration. The two extreme wind turbine sizes, 95.6 m and 188 m both show that there is too much energy left over the year; the 55 m wind turbine is too small to supply the load; and between them, the 72 m wind turbine is found to show the best energy balance. This situation means that combination of these two extreme shows the best result. The 70.2 m wind turbine is the optimized one in this case study, but 72 m wind turbine shows the priority for the energy storage size, which is discussed in Section 4.3.2.

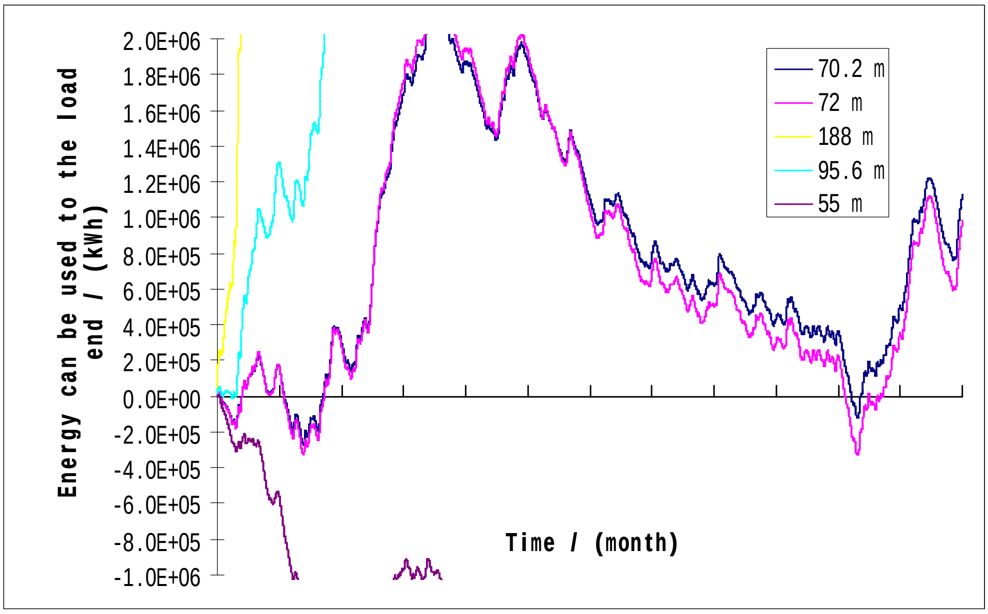

Fig. 4-7 Energy left in the cylinder during the year 2006

The technology of the wind turbine size has not mature enough; therefore, the large size of the wind turbine blade is limited by the strength and stiffness of the materials of it. Several smaller wind turbines can be used rather than these particular large blade sizes, as long as they can supply the same peak capacity. The relationship between the two radii should be:

$$r_1 = \sqrt{n} r_2 \qquad \text{Eq. 4-7}$$

Where, r_1 is radius of the single wind turbine rotor, r_2 is radius of one of the several smaller wind turbines, n is the number of the wind turbines.

Six 40 m bladed wind turbines can be used to supply the same peak capacity as a single 95.6 m bladed wind turbine, and twenty-two 40 m bladed wind turbines can be used as a single 188 m wind turbine from Eq. 4-7. For illustration purpose, the power curve of such an 80 m diameter (40 m bladed) wind turbine is shown in Fig. 4-8. This shows the rated power capacity of this wind turbine would be about 2.5 MW. Other wind turbine sizes have similar power conversion curves. Throughout the remainder of this thesis it is assumed that single wind turbines cases with variable blade sizes are used, without loss of generality.

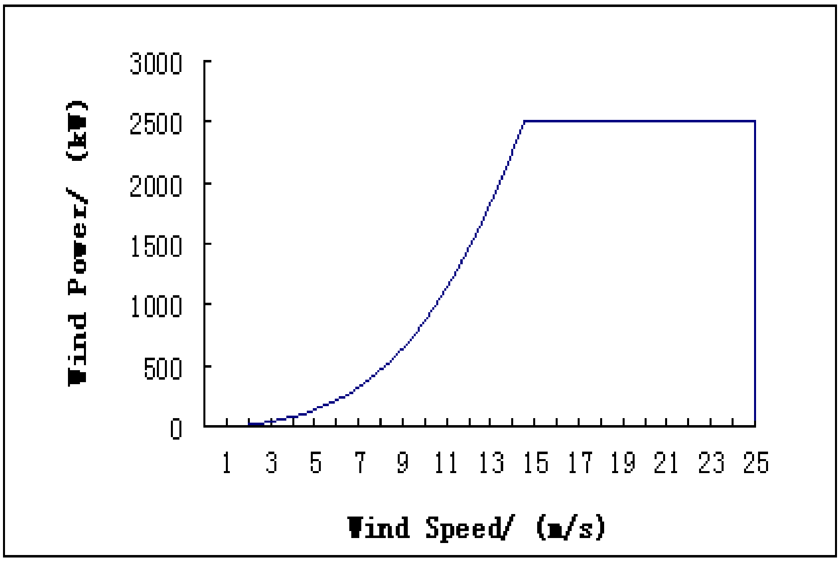

Fig. 4-8 80 m diameter wind turbine power curve

4.3.2 Sizing the energy storage

The different wind turbine sizes also bring different energy storage sizes; hydrogen energy storage is used as the simulated energy storage method in this section. To illustrate the optimized methodology, a Matlab programme is used to pick out the data of the windy day (18/03/2006), peak load day (22/11/2006), the max wind exceeding load day (30/12/2006), and the max wind less than load day (07/11/2006) as examples. The differences between the energy generated from the different wind turbines and the load on these days are presented in Fig. 4-9, Fig. 4-10, Fig. 4-11, and Fig. 4-12.

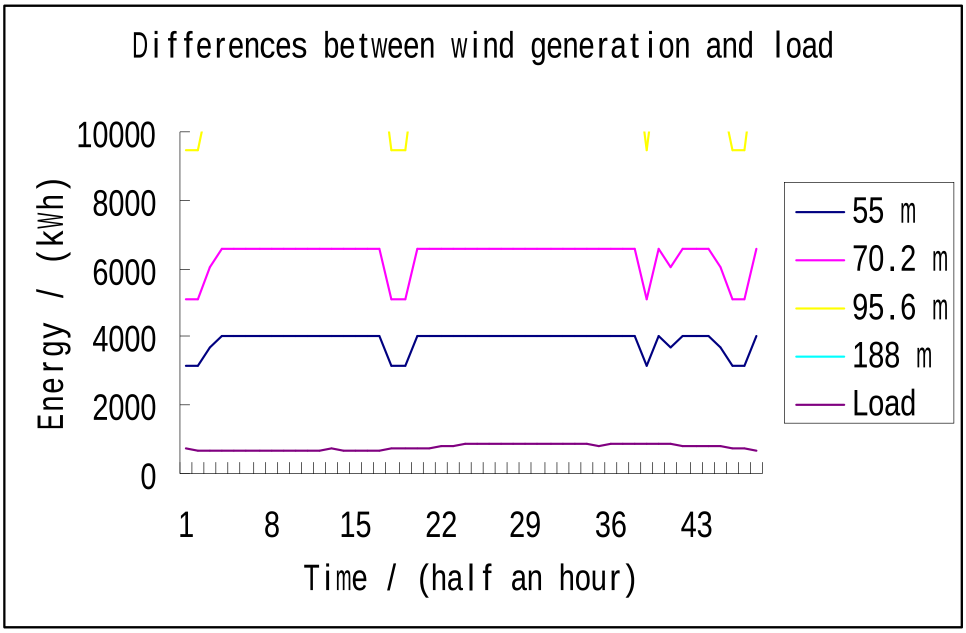

Fig. 4-9 Differences between load and generated energy on 18/03/2006

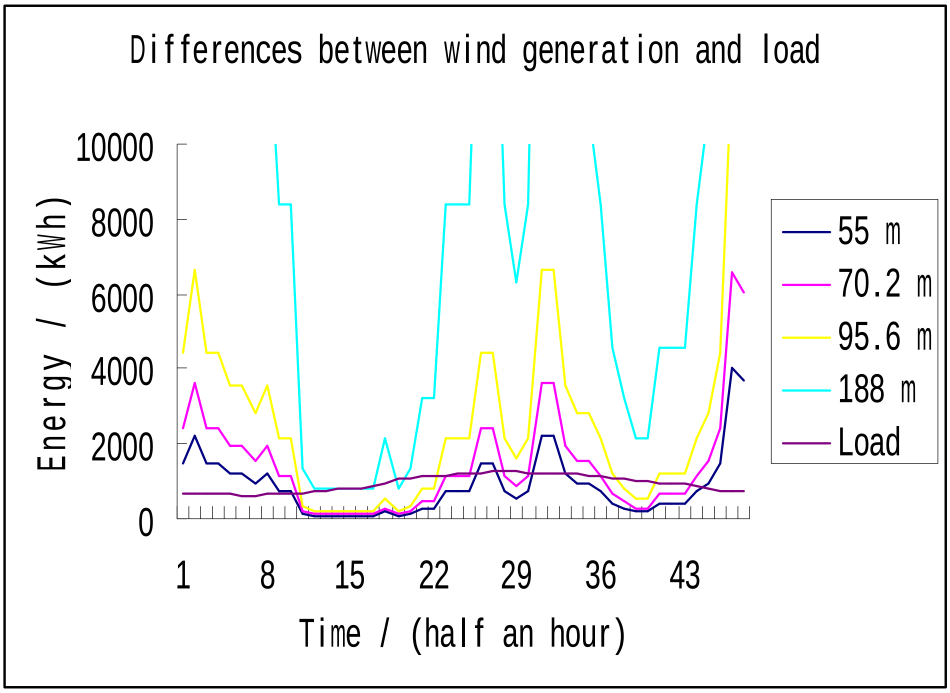

Fig. 4-10 Differences between load and generated energy on 22/11/2006

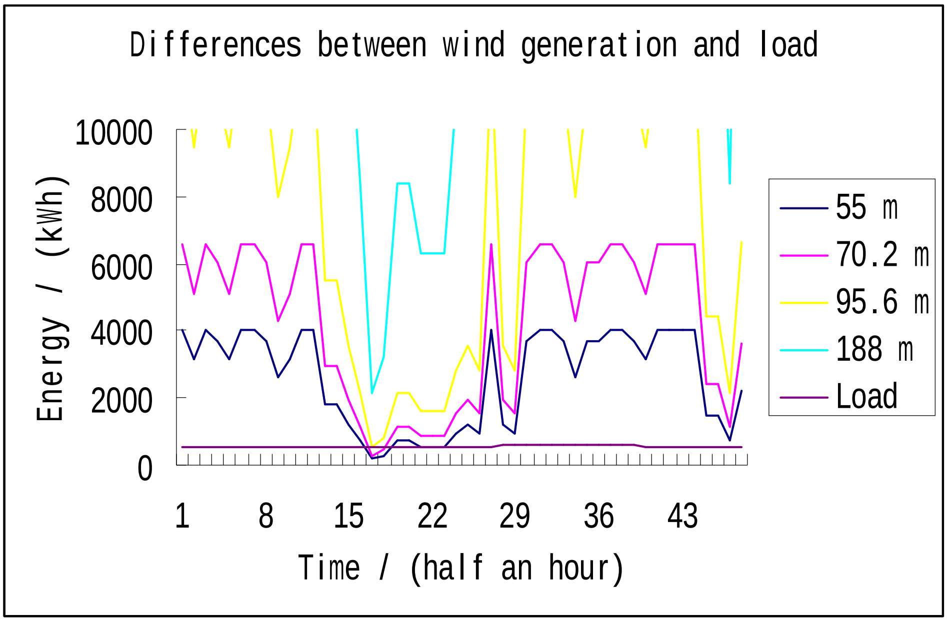

Fig. 4-11 Differences between load and generated energy on 30/12/2006

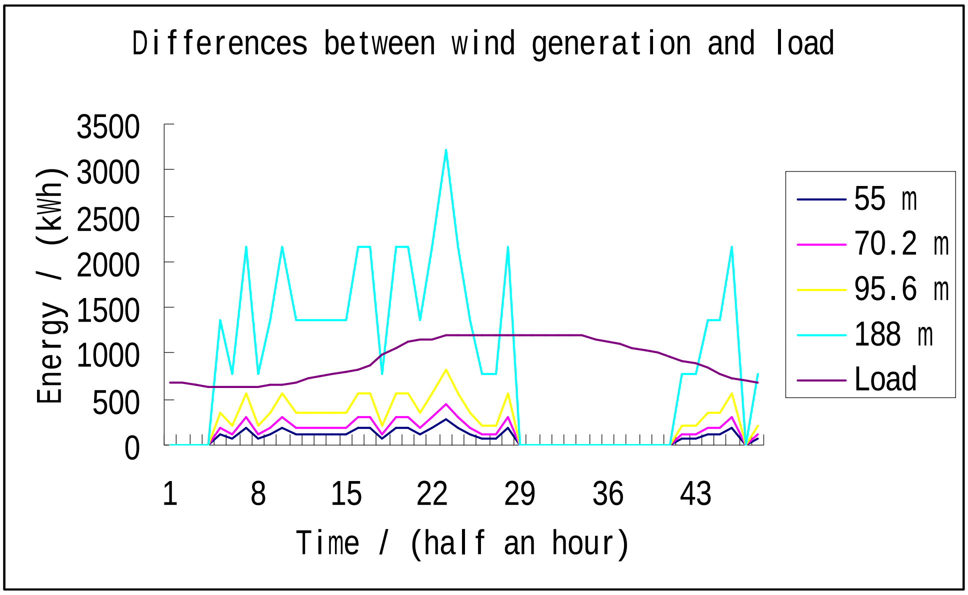

Fig. 4-12 Differences between load and generated energy on 07/11/2006

The last five figures show that too much wind is wasted with the 188 m and 95.6 m wind turbines in most situations; the 55 m wind turbine cannot supply the load completely; and the 70.2 m wind turbine is quite a good fit in this case of the University of Bath. A simulation is worked out to find out which wind turbine, 70.2 m or 72 m, brings a smallest energy storage size, and how big the energy storage capacity required.

In the hydrogen energy storage system, the amount of energy stored in the cylinder is the excess wind energy multiplied 0.676, if wind is greater than the load; the amount of stored energy which is released is the shortage energy multiplied by 0.4598, if wind is lower than load. One day later, the energy lest in the cylinder is the difference between stored energy and released energy, multiplied (1-0.00000033). Therefore, the energy left in the cylinder after a whole year is the difference between stored energy and released energy, multiplied $(1-0.00000033)^{365}$. The flow diagram of the simulation of how to determine dynamic energy left with the efficiency and energy loss under the hydrogen energy storage system in the year 2006 is shown in Fig. 4-13.

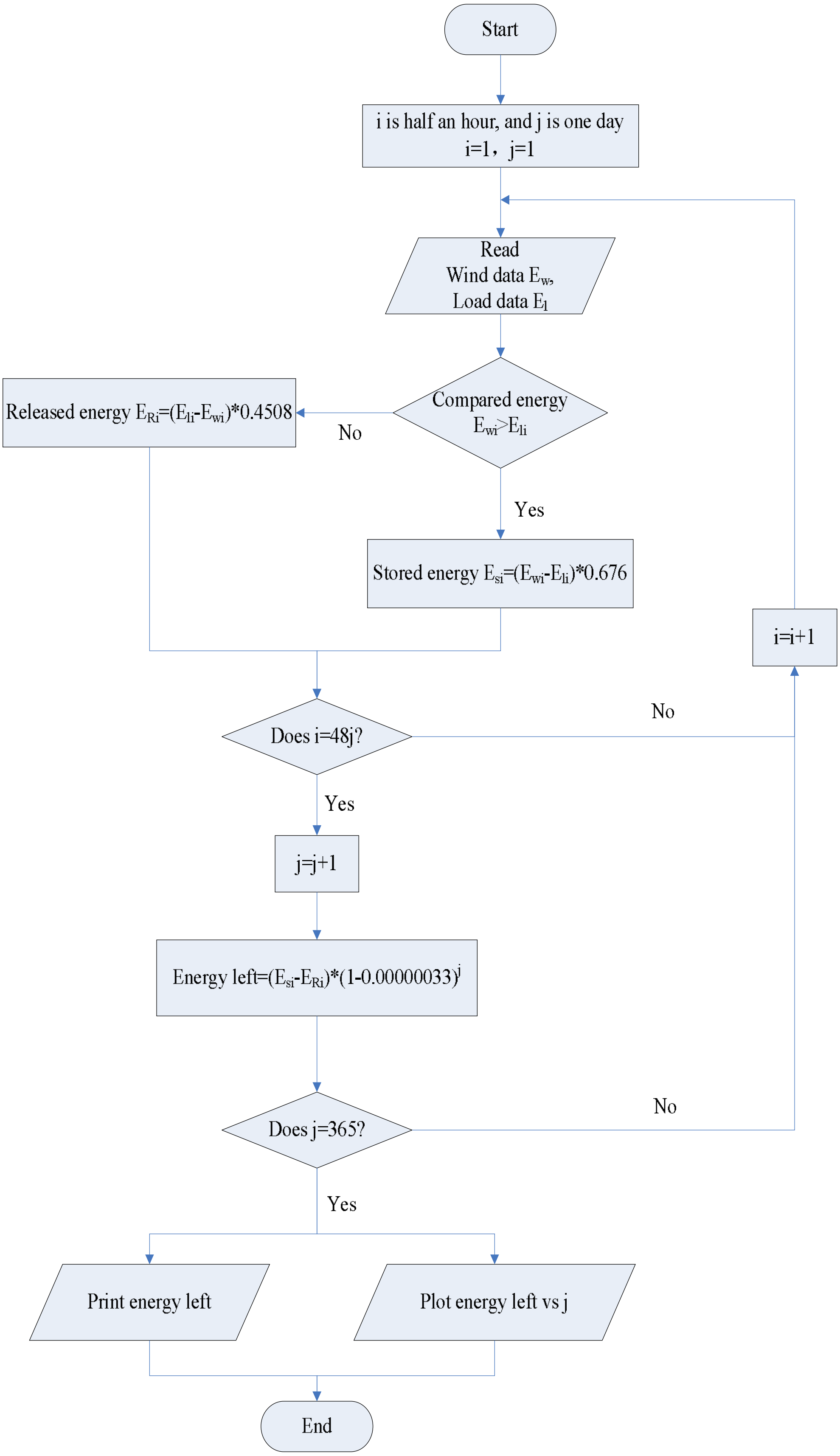

Fig. 4-13 Flow diagram of how to determine dynamic energy left with the efficiency and energy loss

Fig. 4-14 and Fig. 4-15 show the energy storage capacity required in the 70.2 m and 72 m wind turbine systems. Every point shows the storage size required in this system till that time. Final energy storage capacity is the sum of max energy storage and max energy recovery.

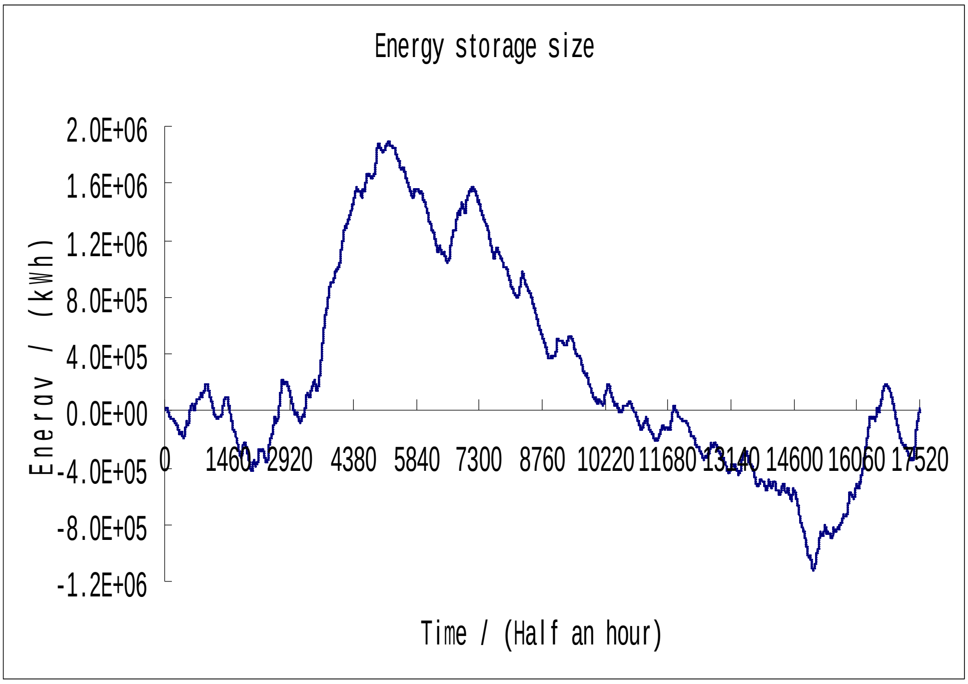

Fig. 4-14 Energy storage size required over time with a 70.2 m wind turbine

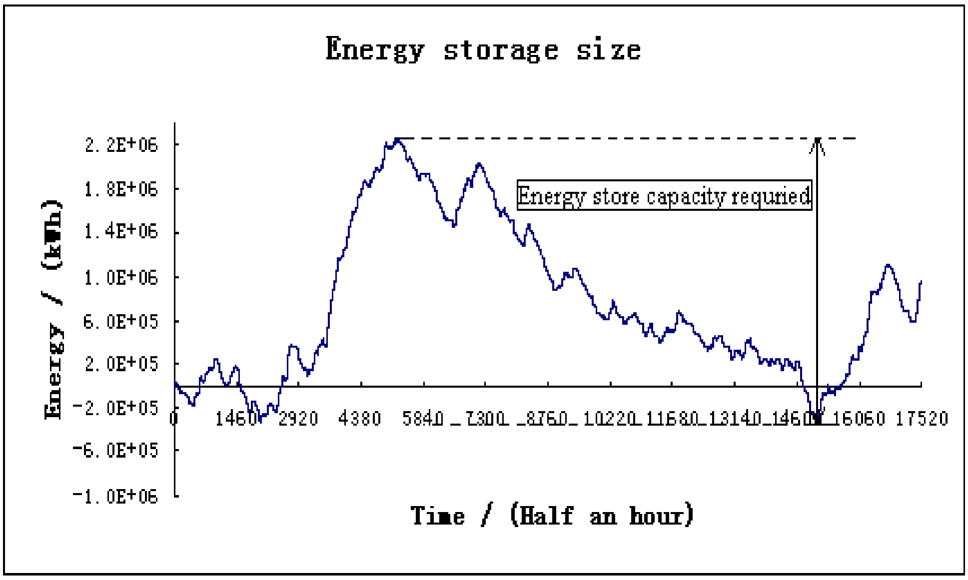

Fig. 4-15 Energy storage capacity required for the 72 m wind turbine

The results of the differences between the peak energy stored and the minimum energy stored during the period for a range of wind turbine sizes are shown in Fig. 4-16. This figure represents the energy recovery capacity for the case of 55 m is high, due to the assumption that the energy storage has to be pre-charged with about 7.97 GWh of energy to cope with the temporary mismatch between demand and the availability of wind power, and also the inefficiency of the energy storage system, which wastes power when carrying out temporal shifting. The pre-charge of the energy storage system represents an annual either import of hydrogen into the storage tanks, or power from the grid instead of hydrogen storage. Likewise, the interpretation of 97.18 GWh of energy recovery capacity for the case of 188 m is that the capacity is increased to store the excess energy, due to the fact that the wind turbines are sized based on the presumption that the hydrogen storage efficiency would apply to all the energy generated by wind turbines. In reality, there would be no practical reasons why the energy recovery capacity would have to be this large in both cases. It would be possible to have a recovery capacity closer to the minimum point on the curve as long as the import and export correct the generation and demand mismatches, occurred more often than once per year.

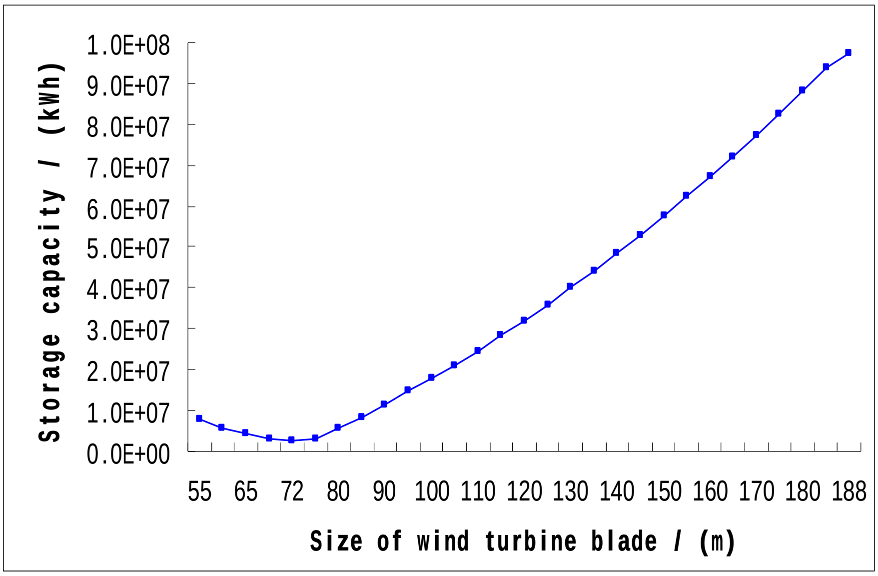

Fig. 4-16 Energy storage recovery capacity requirement for the PEMFC system

Fig. 4-16 also presents the optimal wind turbine size 70.2 m shows a small energy storage size near the lowest point; but the 72 m bladed turbine has the optimal energy storage capacity about 2.58 GWh with net import / export of zero energy from the grid. These energy recovery capacities are referenced to the load energy requirements. From the evaluations of wind turbine and storage sizes, the 72 m wind turbine is considered for further use.

The actual maximum amount of hydrogen left in the cylinder has to be adjusted by the efficiency of the fuel cells and DC to AC conversion stages (45.08 %). 1 kg of hydrogen can produce energy about 120 MJ = 33.3 kWh. Also, 1 kg of hydrogen occupies 100 L at a pressure of 150 bar, typical for this application. Taking these parameters into account, the optimal hydrogen storage capacity should be $(100 \times 2.58 \times 10^6) / (0.4508 \times 33.3)$ L capacity = 1.719×10^7 L = 17.19×10^3 m^3. This is a large volume, nominally a cube of 25.8 m on a side, but it must be recognised that the wind turbine sizes would be far larger than this.

Notice that, the wind turbine and hydrogen storage size of this optimal system are both lower than the two extremes, 14.91 GWh of the 95.6 m and 97.18 GWh of the 188 m wind turbine, as expected. The total energy recovered for the system with a 72m wind turbine and hydrogen storage system is amounted to be 9.15 GWh. Therefore, about 18.67 GWh of hydrogen energy needs to be produced by water electrolysis per year, as a result of the efficiency of regenerating electricity from the hydrogen (45.08 %).

From the data of the maximum wind exceeding load day (30/12/2006), the maximum excess wind energy hour is 03:00, and the excess wind energy multiplied 0.6208 is 3982.5 + 3981.0 = 7963.5 kWh. Therefore, the rated output of the water electrolyser should be higher than 7963.5 kW. There are many water electrolyser manufacturers, and parameters of the water electrolysers in different companies vary. The model FDQ-400/3.0 water electrolyser from Tianjin Mainland Hydrogen Equipment Co., Ltd is chosen. The output of this model is 6600 A × 274 V / 1000= 1808.4 kW, which means five components are required in this case. Based on half hourly wind and load data in 2006, the average output required for the University of Bath network is 7347758 kWh / 8760 h = 838.8 kW. Under this situation, one FDQ-200/3.0 water electrolyser is required, and the excess wind can be dumped.

From the data of the maximum wind less than load day (07/11/2006), the maximum energy shortage hour is 14:00, and the energy needed is 2460.2 + 2427.1 = 4887.3 kWh. Then hydrogen generated from water electrolysers and converted to electricity by fuel cells needs to be higher than 4887.3 kWh of energy. As BALLARD is a professional company that produces fuel cells, the ClearGen Multi-MW PowerBanks from BALLARD has been selected here. The information of the ClearGen Multi-MW PEMFC: rated power-1 MW; efficiency-46 %; output voltage-380-480 V; and output frequency-50-60 Hz. Fuel cells used in this system are PEMFCs, and the output can be 1 MW. Therefore, five power banks are needed to support the University of Bath network. Fig. 4-17 shows how the energy flows.

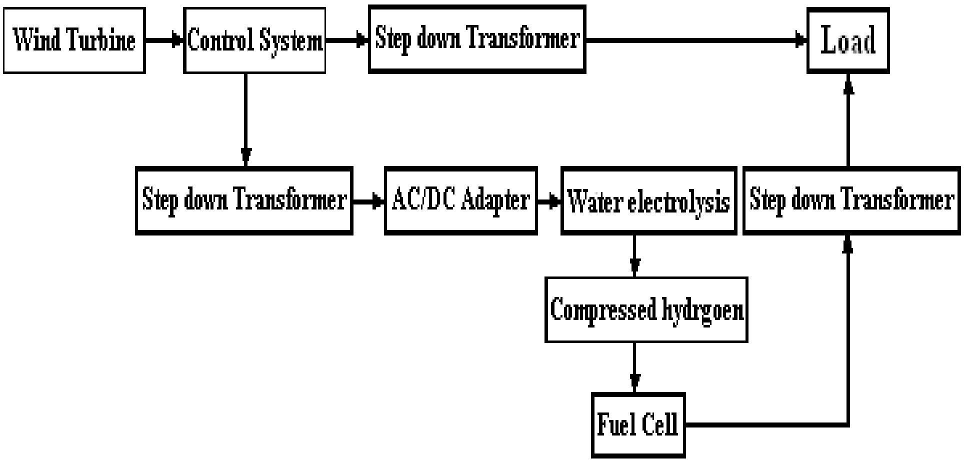

Fig. 4-17 Energy flow chart

The efficiency of the system is not too high, but the utilization of wind energy is quite high. The efficiency of the transformer is 98 %; it of an AC/DC adapter is also 98 %; the water electrolyser's efficiency is about 76 %; for stationary applications, the volume is not a huge problem, 150 bar pressure is employed for compressed gas, then the efficiency of the compressed gas is 91.5 %; and the efficiency of the ClearGen Multi-MW PEMFC is as low as 46 %. Therefore, the final efficiency of the whole system is only 98 % × 98 % × 76 % × 91.5 % × 46 % × 98 % = 30.1 %.

4.4 Summary

The new optimal methodology for the power system with wind energy, which identifies the optimal use of hydrogen energy storage in order to balance the energy generated by wind turbines and the demand, has been described. First, the wind speed at 10 m was translated to that at 100 m in this methodology. It was then modified with the cut-in, cut-off and rated speed constraints.

The wind energy factor is proportional to the square of wind turbine size. The excess energy generated is stored by considering the energy loss. In contrary, if the energy generated is less than the demand, the energy should be recovered. The balance point between the stored energy and recovered energy is found out by optimising the wind turbine size in this chapter. Finally, the energy storage size is decided by the largest stored energy during this year 2006.

The methodology is tested by using a case study based on half hourly wind and load data for the University of Bath, UK. The energy storage size is calculated by using the minimum of the integrated energy balance curve for a complete annual cycle of data. The maximum depth of storage capacity from this is also identified. Wind turbine size and energy storage size are interrelated and interact on each other. The results show that the electricity demands can be met entirely locally by the equivalent of a 72 m radius wind turbine in conjunction with a compressed hydrogen energy storage and recovery system with a 17.19×10^3 m^3 capacity. Double check the system, it shows that, the wind turbine of 72 m ensures that the micro-grid becomes self-sufficient with hydrogen storage for this case study. The large wind turbine technology has not been developed maturely enough, so a set of smaller wind turbines can be used instead.

Chapter 5 Comparison of hydrogen pipeline and electricity distribution

THIS chapter introduces a new energy transportation method—hydrogen pipelines. This and the traditional approach—distributing electricity are simulated for the chosen University of Bath network.

5.1 Introduction of the hydrogen pipeline

Hydrogen pipelines are an optional method to transport energy, instead of the traditional electricity distribution approach. Hydrogen pipelines work in a similar way to natural gas pipelines; however, natural gas pipelines cannot be used directly to deliver pure hydrogen, because of the physical properties of hydrogen [152]. Hydrogen molecule is very small, so they can easily diffuse, which means they could easily escape through normal natural gas pipelines. However, natural gas pipelines can still be used to transport hydrogen, after upgrading.

Nowadays, pipelines are already used for delivering large amounts of hydrogen commercially. The pipelines are currently operated at the pressure of 10-30 bar. Hydrogen flow rate is 310-8900 kg/h [153]. 1 kg of hydrogen can produce about 33.3 kWh of energy. In other words, hydrogen pipelines can distribute up to 3 $\times 10^5$ kWh of energy per hour.

The cost of hydrogen pipelines depends on the installed capital cost of the pipelines and the compression and storage costs at the central hydrogen store [154]. The initial capital cost is not only the cost of pipeline materials, but also the installation costs, rights of way and other costs. For small-diameter pipelines, the capital costs per meter are not as sensitive to pipeline diameters as they are to large-diameter pipelines; other costs, like installation and rights of way also play an important role [154].

There are already hydrogen pipelines in the UK, for instance in Wales, for production plants and heavy industry. For the distribution application, the relationship between capital cost and the pipeline diameter is shown in Fig. 5-1.

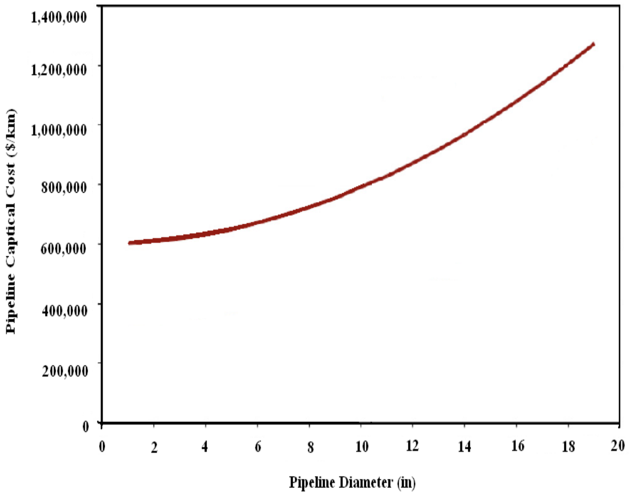

Fig. 5-1 Pipeline capital cost versus the pipe diameter for distribution [154]

From the figure above, the capital cost of pipelines is nearly flat when the diameter of pipelines is small; on the contrary, it changes much more when the diameter is getting larger. The capital cost of hydrogen pipelines does not only depend on the diameter, but is also based on the other aspects. The diameter is determined by the inlet and outlet pressures, pipeline length, and mass flow [155].

Table 5-1 below shows some information about the right of way (ROW) cost, capital costs depending on the diameter of the pipeline (d_{pipe}), pipeline inlet and outlet pressure, other costs and requirements for the pipeline.

Table 5-1 Information of the pipeline [156, 157]

Installation and ROW cost--rural	\$ 300,000 /km
Installation and ROW cost--urban	\$ 600,000 /km
Capital cost	$\$ 1869 (d_{pipe})^2$ /km
Maximum pipeline inlet pressure	70 bar
Pipeline outlet pressure	35 bar
Fixed operating cost	5 % of total capital
Compressor capital cost	$\$ 15,000 (\frac{\text{compressor size}}{10\text{ kw}})^{0.9}$
Compression energy requirement	0.7-1.0 kWh/kg

5.2 Case study—University of Bath

Particular parts of the University of Bath system were used as the case study in this research. Geographically, Eastwood House and the Estates Building from the north, 1 South and 5 South from the south, the Fresh Shop and 9 West from the west, 2 East and 8 East from the east, and the Library in the centre are picked out for the further research, shown in the map Fig. 5-2. Half hourly load data, in the form of kWhs consumed per half hour, for 1 South, 2 East, 8 East, the Estates Building, Eastwood House, and the Fresh Shop in the year 2009 was obtained from the Eastates Department, University of Bath. Also, monthly electricity consumption of all of these locations from 2006-2012 was used.

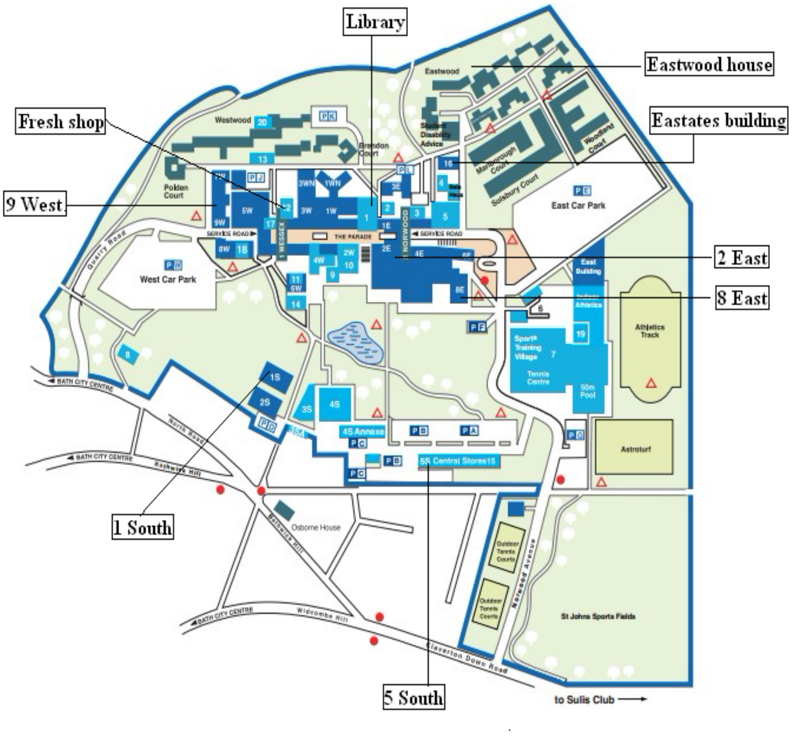

Fig. 5-2 Campus flat map of the University of Bath

From monthly electricity consumption data in 2009, the total energy consumed in 1 South, 5 South, the Fresh Shop, 9 West, 2 East, 8 East, Eastwood House, the Estates Building, and the Library was 118.9 MWh, 59.1 MWh, 211.9 MWh, 577.1 MWh, 270.7 MWh, 130.6 MWh, 598.6 MWh, 33.6 MWh, and 994.9 MWh, respectively. The Library consumed the most energy among these, which is sensible, because most of the university's computers and studying areas are in the Library, and the students all study hard there.

In this case study, a system with shared hydrogen to electricity conversion equipment, which was PEMFC here, and a distributed PEMFCs system were compared to find out the most suitable energy storage method for the chosen University of Bath network. According to the amount of energy consumed in each building, it was determined that the best location for the main generator should be near the largest demand, which is the Library here. Therefore, the influence of the Library on energy distribution can be ignored.

Half hourly load data of the Estates Building, 1 South, 2 East, and the Fresh Shop in 2009 was used for this research, and also monthly load data of the other four buildings, 5 South, 9 West, 8 East, and Eastwood House in 2009. The distances between these buildings (1 South, 5 South, the Fresh Shop, 9 West, 2 East, 8 East, Eastwood House, and the Estates Building) and the Library are about 300 m, 500 m, 200 m, 300 m, 100 m, 200 m, 500 m, and 300 m, respectively. The information for these buildings is listed clearly in Table 5-2.

Table 5-2 Information for the buildings used for this case study

Building Name	**Energy consumed in 2009 (MWh)**	**Distance with Library (m)**
1 South	118.9	300
5 South	59.1	500
Fresh Shop	211.9	200
9 West	577.1	300
2 East	270.7	100
8 East	130.6	200
Eastwood House	598.6	500
Estates Building	33.6	300

The total energy consumed in these 8 buildings during the year 2009 was 2000.5 MWh. If all the wind energy needs to be stored as hydrogen energy first, then used to supply the load using PEMFCs, which means the average power of the PEMFC is 2000.5 MWh / 8760 h = 228.8 kW. Using the same principle, the average power for the PEMFCs in each building (1 South, 5 South, the Fresh Shop, 9 West, 2 East, 8 East, Eastwood House, and the Estates Building) should be 13.6 kW, 6.8 kW, 24.2 kW, 65.9 kW, 31 kW, 15 kW, 68.4 kW, and 3.9 kW, respectively. The peak power of these buildings from the half hourly load data (the Estates Building, 1 South, 2 East, and the Fresh Shop) is 11 kWh / (1/2) = 22 kW, 17.9 kWh / (1/2) = 35.8 kW, 41.5 kWh / (1/2) = 83 kW, and 33 kWh / (1/2) = 66 kW, respectively. This shows that the peak power required for the PEMFCs is much greater than the average power of the PEMFCs. The peak power of the four buildings is in-all about 2.7 times more than their corresponding average generated power. Assuming that the relationship is similar for the other PEMFCs, the rated power is 2.7 times of the average power. Therefore, the rated power required of these PEMFCs (1 South, 5 South, the Fresh Shop, 9 West, 2 East, 8 East, Eastwood House, and the Estates Building) can be estimated to be 35.8 kW, 18.36 kW, 66 kW, 177.9 kW, 83 kW, 83.7 kW, 40.5 kW, and 22 kW. The total rated power of these PEMFCs for the whole system is 527.3 kW.

Two methods are compared here for supplying the consumers, one is the traditional method, a shared PEMFC to distribute the electricity to each building; the other method is to transport hydrogen gas, and then several PEMFCs can be used to convert hydrogen energy to electricity at each building.

5.3 A shared PEMFC for the chosen network

Half hourly wind and load data of the 4 buildings (1 South, 2 East, Fresh Shop and Estates Building) in 2009 is used in this chapter. PEMFCs manufactured by BALLARD are chosen as the shared hydrogen to electricity conversion equipment for the chosen University of Bath network. There are many advantages of using BALLARD’s PEMFCs for this distributed generation application, including: zero carbon emissions; high efficiency; good dynamic response; robust and reliable operation.

There are two kinds of PEMFCs that are designed for distributed generation applications by BALLARD: the ClearGen multi-MW series, and the FCgen-1300 series. The efficiency of a ClearGen multi-500 kW PEMFC is around 46 % and the life cycle is up to 20 years. It can output 370-480V AC directly. The efficiency of the FCgen-1300 PEMFC is up to 64 %, and the life cycle is 20000 hours, depending on the duty cycle. The rated output power is between 2–11 kW and the output voltage is 17.5–77.6 V DC.

Half hourly load data of the above four buildings in 2009 has been put together as the whole load data for the chosen University of Bath network. The ClearGen multi-500 kW PEMFC was chosen as a high power rating will be needed; therefore, the total efficiency of the shared PEMFC system is 98 % (AC/DC) × 98 % (transformer) × 76 % (water electrolysis) × 91.5 % (compressed hydrogen) × 46 % (PEMFC) × 98 % (transformer) = 30.1 %. The algorithm in Chapter 4 was used to work out the optimal wind turbine size as 15.6 m for the shared PEMFC method for the chosen University of Bath network. The total energy to be stored in the whole year for 2009 was 0.217 GWh, and the storage size was 71.9 × 10^3 kWh. Fig. 5-3 shows the dynamic hydrogen energy left in the compressed hydrogen cylinder of the shared PEMFC system for the chosen University of Bath network in 2009.

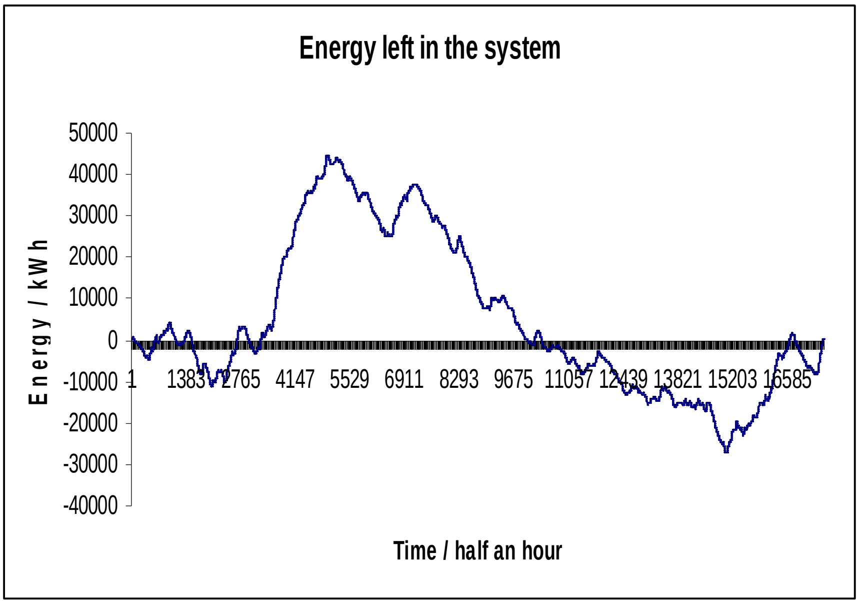

Fig. 5-3 Energy left in the shared PEMFC system for the chosen network

To obtain the rated power of the PEMFC, the largest difference between load and wind should be found, which in this case, was 77.9 kWh at 14:50 on 3rd March, and 09:20 on 12th May, 2009. Then, the peak power was 77.9 kWh / (1/2) = 155.8 kW. Therefore, the ClearGen multi-500 kW PEMFC was confirmed as the shared PEMFC here because of this power requirement. The capital cost of the ClearGen multi-500 kW PEMFC is $ 2250/kW. The calculations of the capital costs of the ClearGen multi-500 kW PEMFC PowerBank for the chosen University of Bath network in this case study are shown below:

The average capital cost is 217394.2575 kWh / 8760 h = 25 kW

$$25 \text{ kW} \times 2250 \text{ \$/kW} = \$\ 56250 \qquad \text{Eq. 5-1}$$

The maximum capital cost is $155.8 \text{ kW} \times 2250 \text{ \$/kW} = \$\ 3.5 \times 10^5$ Eq. 5-2

5.4 Distributed PEMFCs for sub-networks

For the sub-network, the FCgen-1300 series PEMFCs was chosen as the rated power requirement was likely to be smaller. Then the total efficiency of the sub network is 98 % (AC/DC) × 98 % (transformer) × 76 % (water electrolysis) × 91.5 % (compressed hydrogen) × 64 % (PEMFC) × 98 % (DC/AC) × 98 % (transformer) = 41 %. In this case, all the wind energy should be changed to hydrogen energy, stored in the main cylinder, and then the hydrogen gas is delivered by pipelines to the buildings. Therefore, the algorithm of the capital and others costs for the distributed PEMFCs system is different than that of the shared PEMFC system.

The total energy consumed by the four buildings is 118.9 MWh + 270.7 MWh + 211.9 MWh + 33.6 MWh = 635.1 MWh in 2009. Then wind turbines need to generate at least 635.1 MWh / 41 % = 1.549 GWh of wind energy. Here a 17.8 m wind turbine was designed, using the algorithm in Chapter 4, for the method of using several PEMFCs in this chosen University of Bath network. All the wind energy should be stored in this case, and the energy storage size is 241.5 kWh.

Fig. 5-4 shows dynamic hydrogen energy left in the cylinder in the distributed PEMFCs system for the chosen University of Bath network in 2009. From comparing the two figures, Fig. 5-3 is much smoother than Fig. 5-4, but the range of the energy in Fig. 5-3 is much larger than it in Fig. 5-4, which means the distributed PEMFCs system does not need such big hydrogen storage tanks, as the shared PEMFC system does. From this analysis, the average capital cost and the maximum capital cost of the distributed PEMFCs system was calculated.

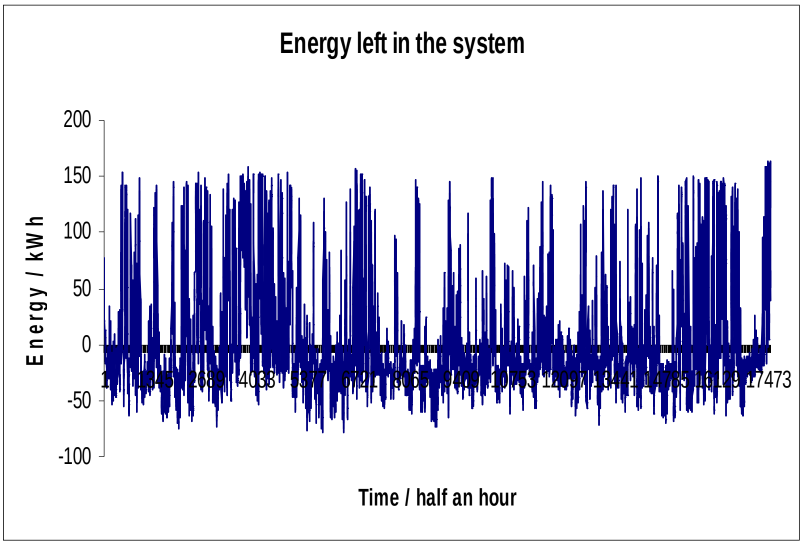

Fig. 5-4 Energy left in the distributed PEMFCs system for the chosen network

5.4.1 Average capital cost for the chosen network

The average capital cost of the FCgen-1300 PEMFC for the chosen network is:

$$635100\ \text{kWh} / 8760\ \text{h} = 72.5\ \text{kW}$$

$$72.5\ \text{kW} \times 2250\ \$/\text{kW} = \$\ 1.63 \times 10^{5} \qquad \text{Eq. 5-3}$$

1 South consumed 118914.9 kWh of electricity in 2009, which was 19 % of the total consumed electricity by the chosen network. Therefore, 19 % of the wind energy goes through the controller into 1 South’s FCgen-1300 series PEMFC. 0.27 GWh, 0.212 GWh, and 0.032 GWh of electricity are used for the other three

buildings, 2 East, the Fresh Shop, and the Estates Building, so the percentages of these of the total are 43 %, 33 %, and 5 %, respectively.

Therefore, the output power of these FCgen-1300 PEMFCs for 1 South, 2 East, the Fresh Shop, and the Estates Building can be set as 13.775 kW (two FCgen-1300 series PEMFCs with rated power of 7 kW), 31.175 kW (three FCgen-1300 series PEMFCs with rated power of 10.5 kW), 23.925 kW (three FCgen-1300 series PEMFCs with rated power of 8 kW), and 3.625 kW (one FCgen-1300 series PEMFC with rated power of 4 kW); and the average capital costs of these FCgen-1300 PEMFCs are 14 kW × 2250 \$/kW = \$ 31500, 31.5 kW × 2250 \$/kW = \$ 70875, 24 kW × 2250 \$/kW = \$ 54000 and 4 kW × 2250 \$/kW = \$ 9000. Then the average capital cost of the distributed FCgen-1300 PEMFCs for the whole chosen network is \$ 31500 + \$ 70875 + \$ 54000 + \$ 9000 = \$ 1.65×10^5.

5.4.2 Maximum capital cost for the chosen network

Case of 1 South

The peak load in 1 South is 17.89844 kWh at 11:50 on 20th January 2009; therefore, the rated power of the PEMFC is 17.89844 kWh / (1/2 h) = 35.8 kW. The rated output power of the FCgen-1300 series is between 2–11 kW, so four FCgen-1300 series PEMFCs with rated power of 9 kW are needed for 1 South. The maximum capital cost of the FCgen-1300 PEMFC for 1 South is 36 kW × 2250 \$/kW = \$ 81000.

Case of 2 East

The peak load in 2 East is 41.5 kWh at 09:20 and 11:20 on 08th July 2009; therefore, the rated power of the PEMFC is 41.5 kWh / (1/2 h) = 83 kW. Then, seven PEMFCs with rated power of 11 kW, and one PEMFC with rated power of 6 kW are required here. The maximum capital cost of the FCgen-1300 PEMFC for 2 East is 83 kW × 2250 \$/kW = \$ 1.87×10^5.

Case of the Fresh Shop

The peak load in the Fresh Shop is 33 kWh at 11:20 on 24th April 2009; therefore, the rated power of the PEMFC is 33 kWh / (1/2 h) = 66 kW. Then, six PEMFCs with rated power of 11 kW are used here. The maximum capital cost of the FCgen-1300 PEMFC for Fresh Shop is 66 kW × 2250 \$/kW = \$ 1.49×10^5.

Case of the Estates Building

The peak load in the Estates Building is 11 kWh at 14:20 on 1st July 2009; therefore, the rated power of the PEMFC is 11kWh / (1/2 h) = 22 kW. Then, two PEMFCs with rated power of 11 kW are used here. The maximum capital cost of the FCgen-1300 PEMFC for the Estates Building is 22 kW × 2250 \$/kW = \$ 49500.

Then the maximum capital cost of the distributed FCgen-1300 PEMFCs for the whole chosen network is \$ 81000 + \$ 186750 + \$ 148500 + \$ 49500 = \$ 4.66×10^5.

5.5 Results and discussion

From the calculations in this chapter, the comparison results of the shared PEMFC and the distributed PEMFCs for the chosen network are listed in Table 5-3. BALLARD’s FCgen-1300 fuel cell is a low cost, liquid cooled PEMFC specifically designed for the stationary applications.

Table 5-3 Comparisons of the two methods for the chosen network

	Shared PEMFC	**Distributed PEMFCs**
Mode	ClearGen multi-500 kW	FCgen-1300
Round-trip efficiency	30.1 %	41 %
Average capital cost (\$)	56250	165375
Max capital cost (\$)	3.5×10^5	4.66×10^5

Wind turbine size (m)	15.6	17.8
Storage size (kWh)	71.9×10^3	241.5

The original natural gas pipelines can be upgraded for hydrogen transportation in the distributed PEMFCs system. The average cost of the distributed PEMFCs system is nearly three times higher than the shared PEMFC system, and the maximum capital cost of the distributed PEMFCs system is only a bit higher than the shared PEMFC system, but the hydrogen storage size of distributed PEMFCs system is much smaller than the shared PEMFC system, which means compared to the capital cost of the hydrogen storage tanks for the shared PEMFC system, the capital cost of the hydrogen storage tanks for the distributed PEMFCs system is extremely low. Therefore, it is hard to tell which one is more economic at this stage-the traditional electricity distribution method or the hydrogen pipeline method. Further work could be done on this area.

5.6 Summary

Energy storage is definitely a solution to improve the utilization of wind energy. As an alternative to the traditional method of electricity distribution, hydrogen gas can be delivered like natural gas with upgraded pipelines to local PEMFCs. Half hourly data for four buildings in the University of Bath in 2009 were used for simulations to verify the feasibility of hydrogen transportation. Comparisons of these two methods for finding out the most economic method have been worked out in this chapter for the chosen University of Bath system.

The traditional method uses a big ClearGen multi-500 kW PEMFC, which is located in the centre and shared by four buildings; the new approach introduced here is that a set of smaller FCgen-1300 series PEMFCs be used in each building. The results show that both of these have different advantages and disadvantages.

The maximum capital cost of the shared PEMFC system for the chosen network is \$ 3.5×10^5, which is much lower than the figure of \$ 4.66×10^5 for the distributed PEMFCs system. However, the round-trip efficiency of the shared

PEMFC system is only 30.1 %, much lower than that of the distributed PEMFCs system, which is 41 %; and the hydrogen energy storage size required for the shared PEMFC system is 71.9×10^3 kWh, which is hugely bigger than 241.5 kWh for the distributed PEMFCs system. Therefore, it is still hard to tell which one is the optimal approach for the chosen University of Bath network so far.

Chapter 6 Comparison of hydrogen with batteries & flywheels approaches

THIS chapter firstly compares three different energy storage approaches, flywheel, NaS battery, and hydrogen energy storage based on efficiency, costs, energy loss, life cycle, payback time and revenue. After that, it discusses the strength and weaknesses of H_2-ICEs and H_2-CCGTs, and then attempts to show that the hydrogen energy storage method can be developed by introducing H_2-ICEs and H_2-CCGTs instead of PEMFCs.

6.1 Introduction

In order for wind energy to be generally used for regular consumers, energy storage methods have been considered as solutions to smooth variations in wind power production to follow the scheduling plans. There are many potential energy storage methods, such as batteries, flywheels and hydrogen storage, which have been studied and reported in the literature. Energy storage can only be used to store excess energy generated and the stored energy is released when wind is weak; but also can be used to store energy generated at off-peak times and the electricity is then discharged at peak time.

In comparison with other energy storage systems, the H_2 alternative offers great flexibility in sizing because of the modularity of electrolysers, fuel cells and storage tanks [3]. Hydrogen energy storage is a good candidate in the University of Bath network. Compared to other energy storage units, it is chosen here as it has low environmental impact and it is suitable for large-scale network, long-term storage. Although the whole system has very low efficiency, it can hold energy for several months with little loss. Hydrogen can be released by a combustion engine or a fuel cell. Fuel cells are a relatively new technology. They have higher efficiency than internal combustion engines, but are more expensive.

Flywheels will lose the stored energy in a few hours, which is not suitable for the DG application. NaS batteries are a new technology, and have a longer life cycle than the traditional batteries. Unfortunately, they are still available in only quite small capacities and are very expensive.

From the literature review, the hydrogen storage method can be modified by introducing H_2-ICEs or H_2-CCGTs instead of PEMFCs. Pure hydrogen is required as the fuel of PEMFCs, but not an issue in this case, because pure hydrogen can be got from the first stage of the process - water electrolysers. The requirements of the fuel for the H_2-ICEs and H_2-CCGTs are not that high. Air can be used as the oxidizer instead of oxygen. However, nitrogen oxide (NO_x) will contribute to the air pollution during its operation.

6.2 Practical cost comparisons of the three systems

Cost is a vital consideration for a real system. The comparative average costs of wind energy with NaS batteries, with flywheels and with hydrogen energy storage are displayed in Table 6-1. The total cost can be determined by a lot of factors. In this system, many kinds of costs for setting up, running, fixing, replacement, revenue, etc, are taken into account. The capital cost in the table below is the set-up fee and it is in US dollars per kilowatt of the energy storage size; the annual O&M cost stands for the operation and maintenance costs every year, and it is in US dollars per kilowatt of the whole energy stored in the year.

Table 6-1 The costs of the three methods for the DG application [5-11][158, 159]

	NaS battery	**Flywheel**	**Hydrogen Electrolyser / PEMFC**
Capital cost ($/kW)	1150-2250	550-850	400+1500+2250
Annual O&M	20 $/kW-yr	20-30 $/kW-yr	0.038 $/kWh

6.2.1 NaS battery as the energy storage in the University of Bath

The efficiency of converting the electricity from a transformer, AC to DC, DC to AC, and a transformer is 98 %, in each case. Therefore, the efficiency of the whole NaS battery energy storage system is 0.98 × 0.98 × 0.98 × 0.98 × 0.7 (NaS battery) = 0.6456 (64.56 %).

From the sizing algorithm used in Chapter 4, a large single wind turbine, whose radius is about 58.4 m, is the optimal wind turbine size for the case of using NaS batteries as the energy storage method in the University of Bath network. In this case, the total energy generated in the year 2006 is 16.77 GWh. 8.24 GWh of energy needed to be stored, and 8.22 GWh of the stored energy needed to be released in the whole year 2006. Furthermore, the energy store size should be 2.7 GWh.

If under the situation when the wind energy is completely used, without dumping, the maximum capacity of the NaS battery should cover the point at which the most stored wind energy is required, which is 4047.7 kWh / 0.5 h = 8095.4 kW at 2:50 on the 20th Dec, 2006. The calculations of the capital cost, and annual operation and maintenance costs are given below:

Average Capital Cost is 8.24 GWh / 8760 h = 941.2 kW

$$941.2 \text{ kW} \times 1700 \text{ \$/kW} = \$\ 1.6 \times 10^{6} \qquad \text{Eq. 6-1}$$

Maximum Capital Cost is

$$8095.4 \text{ kW} \times 1700 \text{ \$/kW} = \$\ 1.3 \times 10^{7} \qquad \text{Eq. 6-2}$$

Annual fixed O&M cost is 8.22 GWh / 8760 h = 939.05 kW

$$939.05 \text{ kW} \times 20 \text{ \$/kW} = \$\ 18781 = \$\ 1.8 \times 10^{4} \qquad \text{Eq. 6-3}$$

6.2.2 Flywheel as the energy storage in the University of Bath

In the case of using flywheels as the energy storage approach in the University of Bath network, the efficiency of the whole system is quite high—multiply the efficiencies of the AC to DC, DC to AC, and the transformer—about 0.98 × 0.98 × 0.98 × 0.98 × 0.95 (flywheel) = 0.8941 (89.41 %). Using the same algorithm given in Chapter 4, a 54.1 m wind turbine is chosen in this system. Two 40 m wind turbines are required in this case. The total energy generated in this case in the year 2006 is 14.39 GWh. 6.56 GWh of energy should be stored for supporting a stand-alone system, and 6.54 GWh of the stored energy needed to be released in the whole year is in the University of Bath network. Moreover, the energy store size is about 2.17 GWh.

If under the situation when the wind energy is completely used, without dumping, the maximum capacity of the flywheel should cover the point at which the most stored wind energy is required, which in this case, is 3401 kWh / 0.5 h = 6802 kW. Here are the cost calculations for the flywheel energy system:

Average Capital Cost is 6.56 GWh / 8760 h = 749.1 kW

$$749.1 \text{ kW} \times 700 \text{ \$/kW} = \$\ 524370 = \$\ 5.24 \times 10^5 \qquad \text{Eq. 6-4}$$

Maximum Capital Cost is

$$6802.208 \text{ kW} \times 700 \text{ \$/kW} = \$\ 4761545.6 = \$\ 4.76 \times 10^6 \qquad \text{Eq. 6-5}$$

Annual O&M cost is 6.54 GWh / 8760 h = 747.29 kW

$$726.18 \text{ kW} \times 25 \text{ \$/kW} = \$\ 18682.25 = \$\ 1.87 \times 10^4 \qquad \text{Eq. 6-6}$$

6.2.3 Hydrogen as the energy storage in the University of Bath

From Chapter 4, a large single 72 m wind turbine is the optimal size for the case of hydrogen as the energy storage in the University of Bath. One 45 m wind turbine and two 40 m wind turbines are required in the hydrogen energy storage system. The total energy generated in the year 2006 is 25.5 GWh. The total load used in the University is 13651765 kWh. Because the efficiency of the whole system is 30.1 %, the energy that should be stored in the whole year is 10.1 GWh, and 9.15 GWh of the stored energy needs to be released in the whole year. The energy storage size is about 2.58 GWh.

If under the situation when the wind energy is completely used, without dumping, the maximum capacity of the hydrogen energy storage should cover the point at which the most stored wind energy is required, which in this case, is 6415.1 kWh / 0.5 h = 12830.2 kW. Besides, this amount of hydrogen does not need to be converted back to electricity, but can be used in the form of hydrogen for other applications, like medicine. A compressed hydrogen energy storage and recovery system with a 17190 m^3 capacity is enough for this case. The capital costs are calculated as below:

Average Capital Cost is 10130880.1 kWh / 8760 h = 1156.5 kW

$$1156.5 \text{ kW} \times 4150 \text{ \$/kW} = \$\ 4799446.62 = \$\ 4.8 \times 10^6 \qquad \text{Eq. 6-7}$$

Maximum Capital Cost is

$$12830.16 \text{ kW} \times (400+1500) \text{ \$/kW} + 1156.5 \text{ kW} \times 2250 \text{ \$/kW} = \$\ 26979429 = \$\ 2.7 \times 10^{7} \qquad \text{Eq. 6-8}$$

Only water electrolysis and compressed hydrogen gas parts, the capital cost is

$$1156.5 \text{ kW} \times (400+1500) \text{ \$/kW} = \$\ 2197350 = \$\ 2.2 \times 10^{6} \qquad \text{Eq. 6-9}$$

The Average Capital Cost of the PEM fuel cell only is

$$1156.5 \text{ kW} \times 2250 \text{ \$/kW} = \$\ 2602125 = \$\ 2.6 \times 10^{6} \qquad \text{Eq. 6-10}$$

Annual fixed O&M cost is

$$9149229.67 \text{ kWh} \times 0.038 \text{ \$/kWh} = \$\ 3.5 \times 10^{5} \qquad \text{Eq. 6-11}$$

These capital costs, the annual operation and maintenance costs for the NaS batteries, flywheels and Hydrogen energy storage for the University of Bath network are listed for comparison in Fig. 6-1. The hydrogen energy storage method has the highest capital cost and annual O&M cost. PEMFC makes the total capital cost of the hydrogen storage method quite high, nearly 10 times that of the flywheel storage method. The calculations above show that there are significant differences in the wind energy generated from the three systems with the different energy storage methods, but the energy storage size differences for the three systems are not too much. Without the fuel cells component, the capital cost of the hydrogen storage method and it of the NaS batteries are similar.

The costs comparison shows that the flywheel has the lowest capital cost among the storage methods. The hydrogen storage method can be made more commercial by using other hydrogen to electricity conversion equipment instead of the PEMFCs.

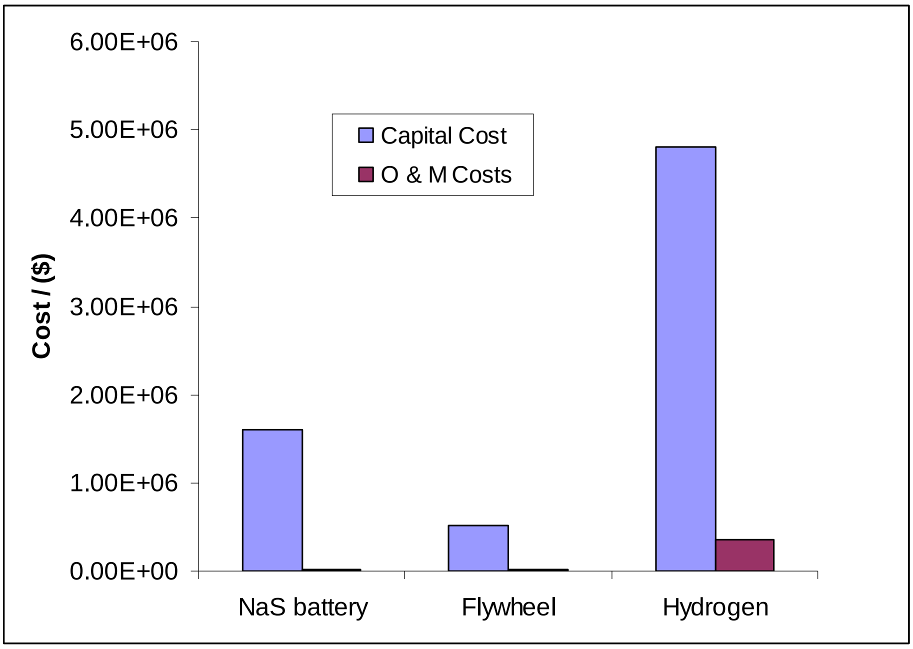

Fig. 6-1 Compared costs of three methods for the University of Bath network

6.3 Practical energy loss comparison of the three systems

From the overview above, the efficiency of the flywheel system is quite high, about 89.41 %, but the best flywheel self-discharges energy very quickly, around 20 % per day, and about 0.1 % per hour friction energy loss so far; the efficiency of the real NaS battery system is about 64.56 %, and the energy loss is 0.5 % per day. A hydrogen storage system with the components chosen in Chapter 3 has the lowest efficiency of 30.1 %, but the system self-discharges energy very slow about 0.000033 % every day. Fig. 6-2 shows the comparison of the energy losses with the initial efficiencies of Flywheel, NaS battery, and hydrogen storage systems.

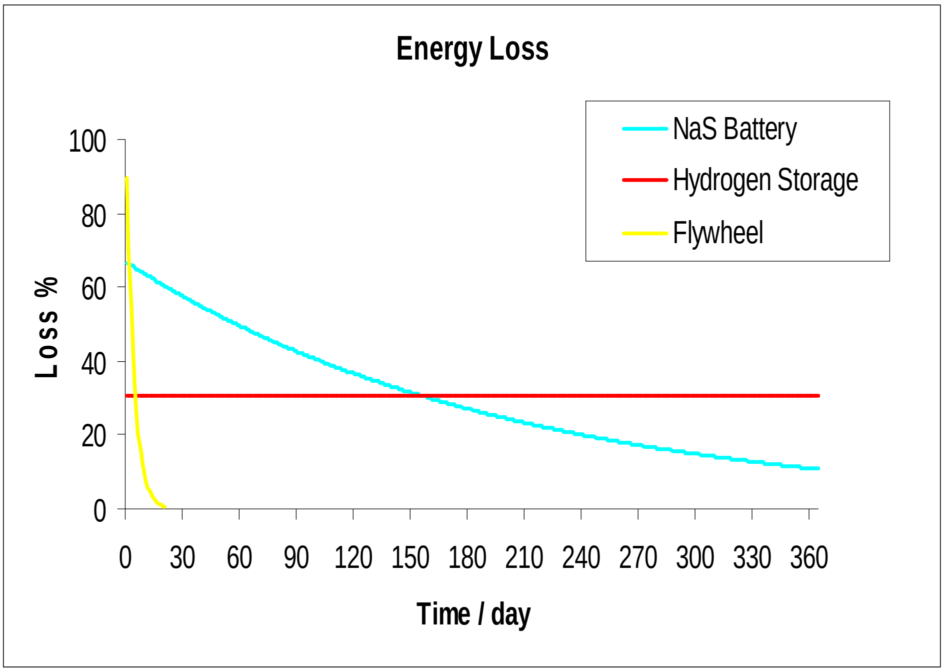

Fig. 6-2 Energy losses of NaS, Flywheel and Hydrogen storage

After comparing costs in Fig. 6-1 and energy losses in Fig. 6-2, the flywheel energy storage system has the price advantage; however, the energy loss dynamics show that flywheels self-discharge very quickly and can lose all the energy in few days, not suitable for long-term storage. For the stand alone power system, long-term storage is necessary. Hydrogen storage system is more expensive than NaS battery system, but the energy loss is much lower than NaS battery system. The interesting result of the loss dynamics is that hydrogen and NaS battery curves cross at about 150 days. It is not clear which is more economics from this study. Other dynamic demonstrations are worked on to find out the better energy storage way for this University of Bath system.

6.4 Practical life cycle comparison of the three systems

An equipment completes a process of discharge and starts to charge; this process is called a cycle. Life cycle represents the number of completing charge-discharge operations a storage system can perform before it becomes unusable. Matlab dynamic simulations are carried out, in order to find the number of cycles and the energy flow of hydrogen energy storage and NaS battery systems for the University of Bath network.

In the case of hydrogen energy storage system, if the wind energy is greater than the load, hydrogen is storage; if not, the stored hydrogen energy is released. Since energy released happens after stored, a cycle is formed. The flow diagram Fig. 6-3 shows how to determine the number of cycles of hydrogen energy storage and NaS battery in the systems.

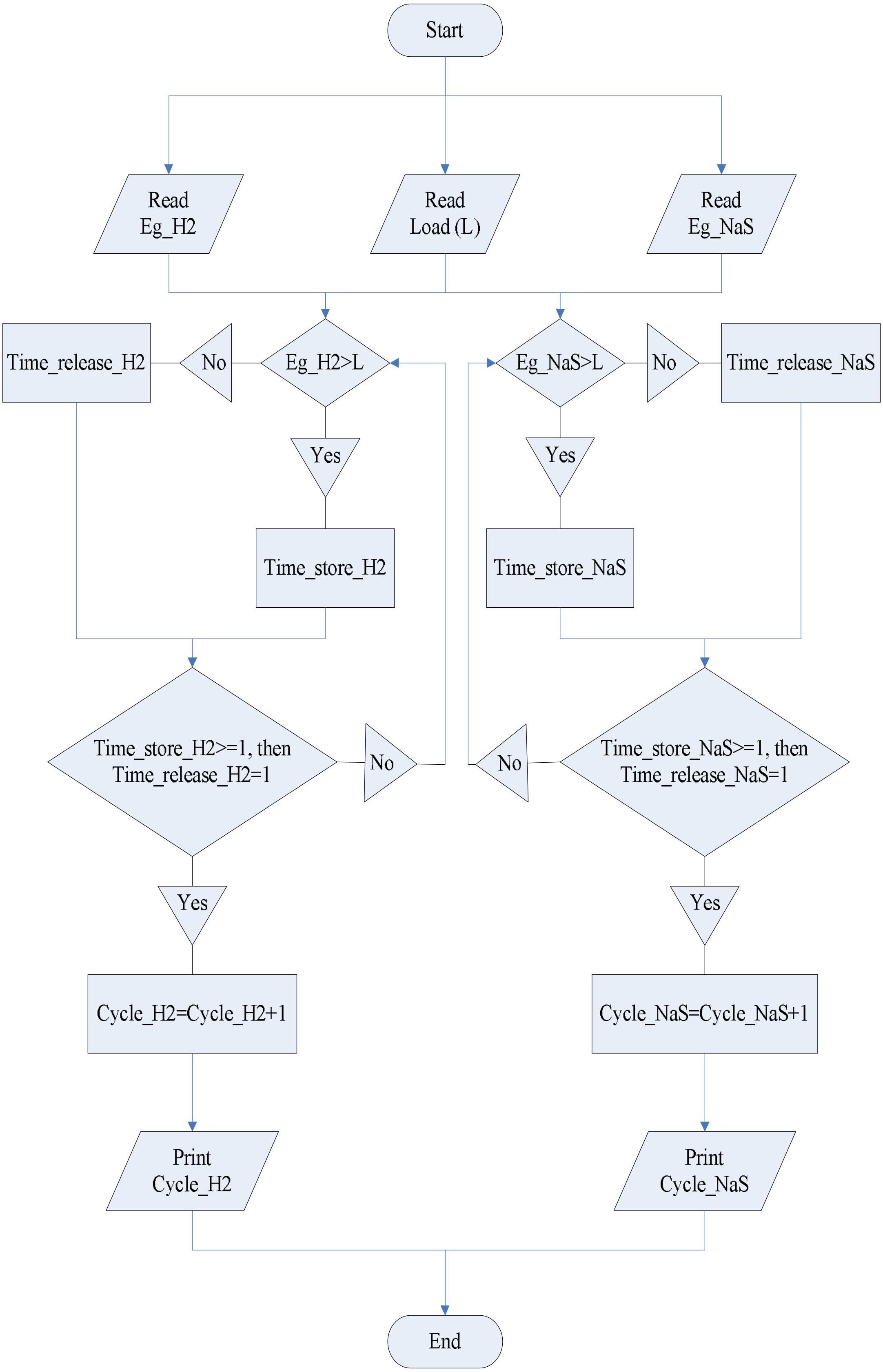

Fig. 6-3 Flow diagram of cycle times of hydrogen energy storage and NaS battery

The other result of the Matlab shows the energy store times, release times, and the number of cycles of the hydrogen storage and NaS battery systems, which are listed in Table 6-2. The Matlab programme is shown in the Appendix.

Table 6-2 Number of cycles of hydrogen storage and NaS battery systems

	Store times	**Release times**	**Cycle times**
Hydrogen storage	8373	9147	1259
NaS battery	6421	11099	1199

The life cycle of a commercial NaS battery is around 15 years, nearly 6500 cycles for 65 %，4500 cycles for 90 %, and 2500 cycles for 100 % DOD cycles [160]. Flywheels have a long life cycle, about 20 years at the 90 % depth of discharge (DOD). N. Lu et al from the Pacific Northwest National Laboratory US, carried out research on the relationship between life cycle and depth of discharge, shown in Fig. 6-4 [161].

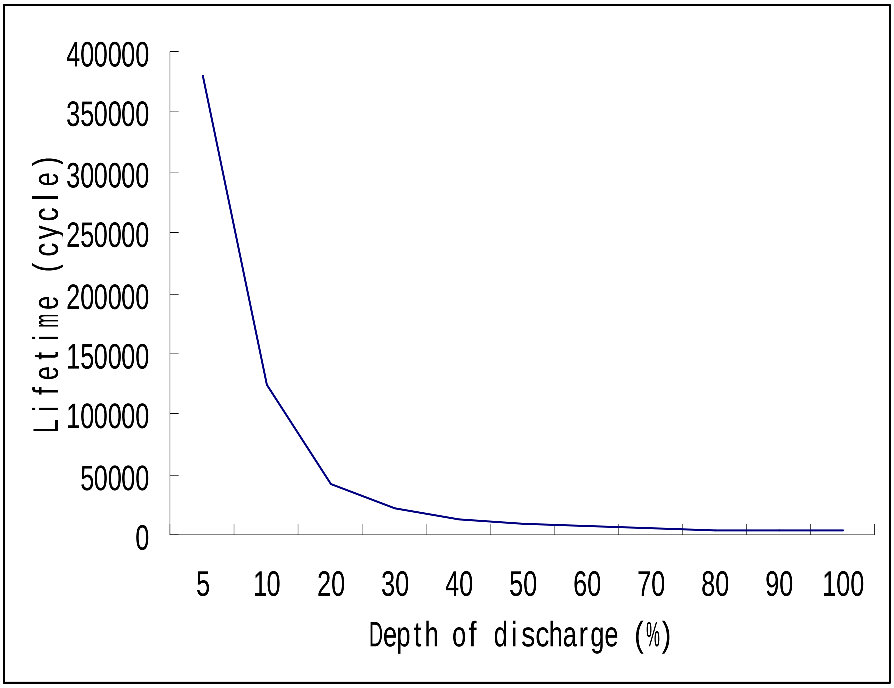

Fig. 6-4 NaS battery life cycle with respect to the depth of discharge

From Table 6-2, hydrogen energy storage method has similar store and release times, whereas NaS battery has much more release times than store times. Therefore, the depth of discharge of NaS battery should be deeper than hydrogen storage. The number of cycles of NaS battery is 1199 for the whole year 2006, and the average depth of discharge is about 50 %. Then the cycle time of NaS battery is about 7000 cycles, which equals to 6 years.

The initial hydrogen storage system has three parts: water electrolysers, compressed hydrogen cylinder, and fuel cells. The electrolysers' life is about 20 years; the life of hydrogen storage cylinder is 20 years [162]; the life of PEMFCs is quite short usually, only around 6 years, but the ClearGen multi-MW series PEMFC from BALLARD designed for distributed generation is commercially available now, and with corrective maintenance, the product can last 20 years.

The hydrogen energy storage system cannot be used commercially because of the high cost and low efficiency of fuel cells. It can be improved by using internal combustion engines or CCGTs instead of fuel cells.

6.5 Practical dynamic energy flow comparison of the two systems

The simulation result of dynamic energy flow for hydrogen energy storage and NaS battery systems over approximately one month is shown in Fig. 6-5 and Fig. 6-6. They show similar results with slightly lower peaks and troughs differences.

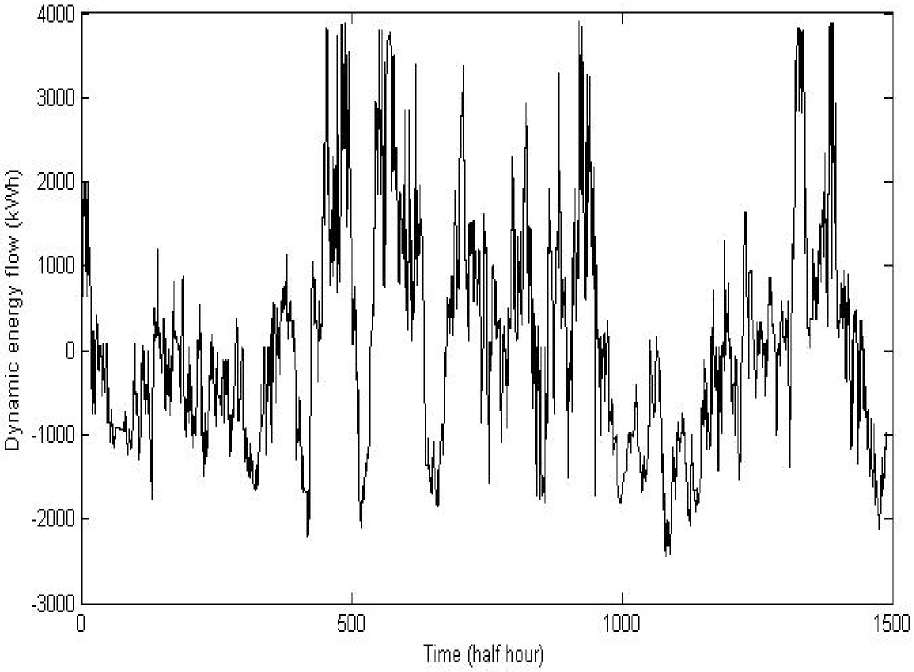

Fig. 6-5 Dynamic energy flow of Hydrogen storage method in January 2006

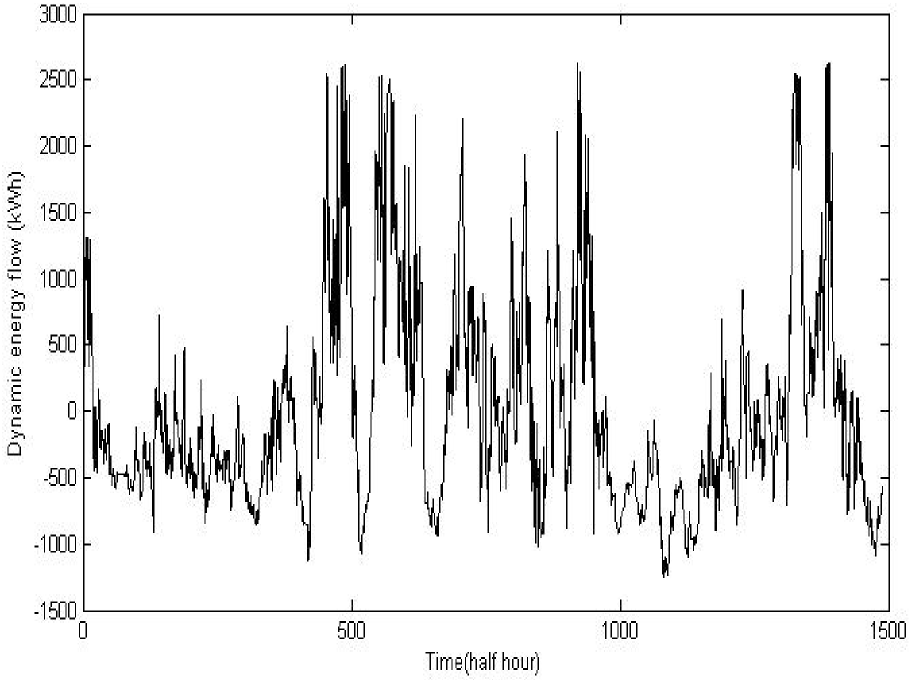

Fig. 6-6 Dynamic energy flow of NaS battery method in January 2006

6.6 Payback time comparison of the two systems

Payback time (payback period) is a general approach to measure the length of time the stuff required to pay for itself in investment areas, often with respect to energy efficiency technologies, capital cost, maintenance, and other fees. Payback time is usually expressed in years. It can be easily calculated as below [163]:

Payback Time = Cost of Project / Estimated Annual Net Cash Flow Eq. 6-12

Undoubtedly, shorter payback time is more desirable than the longer payback time. Payback time as an analysis method is widely used, because it is easy to be calculated and understood. However, it still has many drawbacks to limit its use. For example, it does not consider the risk, time value of money or other issues.

From the comparison results of the capital cost, system efficiency, life cycle, and other aspects between the NaS battery system and the hydrogen storage system for the University of Bath network are listed clearly in Table 6-3. The payback time of the two systems are worked out for the further comparison. These results were obtained that based on half hourly wind and load data for the University of Bath in 2006. In the table below, A, B, C stands for the three parts of hydrogen energy storage: water electrolyser, compressed hydrogen gas, and PEMFCs, respectively. The energy generated in the table below means the total wind energy generated in the whole year 2006; the load is the total electricity consumed by the University of Bath in 2006; and the energy left is calculated from 00:20 on 1st Jan, 2006 till 12:50 on 31st Jan, 2006. The left energy here is not in the form of electricity, which can be used directly to the consumers. In the NaS battery system, the left energy is the energy which has not been stored into NaS battery; and in the hydrogen energy storage system, the left energy is the hydrogen energy.

Table 6-3 Comparisons between systems with NaS battery and hydrogen storage

	NaS battery	**Hydrogen storage (A/B/C)**
Life cycle (years)	6	20 / 20 / 6
System efficiency	64.56 %	30.1 %
Energy loss (/day)	0.5 %	0.000033 %
Wind turbine size (m)	58.4	72
Energy generated (kWh)	16768398.97	25487714.7
Load (kWh)	13651765	13651765
Energy left (MWh)	18.6	981.7
Capital costs ($)	1.6×10^6	4.8×10^6
O&M cost ($)	1.8×10^4	3.5×10^5

The E.ON Company supplies the energy to the University of Bath, and the price of electricity from E.ON is about £ 0.143 / kWh. Assuming all the energy consumed in the University of Bath is electricity, then it cost about 13651765 kWh × £ 0.143 / kWh = £ 1.95×10^6 in 2006. The average exchange rate of British pounds to US dollars is 1.8 in 2006, so the total cost in US dollar is £ $1.95 \times 10^6 \times 1.8$ = \$ 3.5×10^6.

6.6.1 Payback time of the NaS battery system

Because the energy left in the NaS battery system is the energy which has not been stored into the NaS battery, the actually electricity left should be 18.6×10^3 kWh × 70 % = 13×10^3 kWh. Therefore, the Estimated Annual Net Cash Flow of the NaS battery system for the University of Bath network in 2006 is $(13 \times 10^3 + 13.7 \times 10^6)$ kWh × 0.143 £/kWh = £ 1.95×10^6= \$ $(1.95 \times 10^6 \times 1.8)$ = \$ 3.5×10^6.

One 45 m wind turbine and one 40 m wind turbine were chosen for the NaS battery system. The wind turbine generally costs about \$ 1.3 million per MW. The capital cost of the wind turbines for the NaS battery system for the University of Bath network is (3 + 2) MW × 1.3×10^6 \$/MW = \$ 6.5×10^6.

The capital cost of the NaS battery is \$ 1.6×10^6 and the annual O&M cost is \$ 1.8×10^4. The life cycle of a NaS battery in the University of Bath network is 6 years. Therefore, the costs of the NaS battery for the University of Bath network is \$ 1.6×10^6 + 6 × \$ 1.8×10^4 = \$ 1.71×10^6. The cost of the project with the NaS battery system is \$ 6.5×10^6 + \$ 1.71×10^6 = \$ 8.21×10^6.

From the calculations above, the payback time of the NaS battery system for the University of Bath network can be calculated as:

$$\text{Payback Time} = (\$\ 8.21 \times 10^6) / \$\ 3517366.27\ /\text{year} = 2.33\ \text{years} \qquad \text{Eq. 6-13}$$

The result shows the NaS battery system for the University of Bath network can pay itself back after 2 years, but the NaS battery needs to be changed every 6 years. If constructing a 20 years project, the cost of project is \$ $1.6 \times 10^6 \times 20 / 6 + 20 \times$ \$ 1.8×10^4 = \$ 5.69×10^6. The total cost of the project is \$ 6.5×10^6 + \$ 5.69×10^6 = \$ 12.19×10^6. Then the payback time of the 20 years project in the case of NaS battery for the University of Bath network is:

$$\text{Payback Time} = \$12.19 \times 10^6 / \$\ 3517366.27\ /\text{year} = 3.5\ \text{years} \qquad \text{Eq. 6-14}$$

Over the 20 year project, the total net benefit of the NaS battery system is

$$\$\ 3517366.27 \times (20 - 3.5) = \$\ 5.8 \times 10^7 \qquad \text{Eq. 6-15}$$

6.6.2 Payback time of the hydrogen storage system with PEMFC

The energy left in the hydrogen storage system is hydrogen energy, so the Estimated Annual Net Cash Flow of the hydrogen storage system for the University of Bath network in 2006 is 9.82×10^5 kWh of hydrogen energy and the cost of the total electricity consumed. Hydrogen gas can be used for other applications, so the hydrogen energy left in the cylinder does not need to be changed to the electricity by PEMFCs. 1 kg of hydrogen can produce energy about 120 MJ = 33.3 kWh. Therefore, 9.82×10^5 kWh of energy left is about

9.82×10^5 kWh / 33.3 kWh / kg = 29.5×10^3 kg of hydrogen. The commercial price of 1 kg of hydrogen is approximate \$ 10, and then the net cash flow of the energy left in the hydrogen storage system is 29.5×10^3 kg × 10 \$ / kg = \$ 29.5×10^4. At last, the Estimated Annual Net Cash Flow of the hydrogen storage system for the University of Bath network in 2006 is \$ 3.5×10^6 + \$ 29.5×10^4 = \$ 3.8×10^6.

The Estimated Annual Net Cash Flow is even higher, if the value of pure oxygen is under consideration as well. The energy goes through water electrolysers, converting into the form of stored hydrogen and stored oxygen, which can be released as the fuels for PEMFCs. Oxygen can be used for other applications, because air can be used replacing the oxygen in PEMFCs. The 25.5 GWh of wind energy was generated in the year 2006, and then about 25.5 GWh × 98 % × 98 % × 76 % × 91.5 % = 17 GWh of energy was stored. Therefore, 17 GWh / 33.3 kWh / kg = 0.51×10^6 kg of hydrogen was stored in 2006. From the chemical reaction equation below, 2 mol of water can produce 2 mol of hydrogen and 1 mol of oxygen, which means 36 kg water can generate 4 kg of hydrogen and 32 kg oxygen.

$$2\ H_2O = 2\ H_2 + O_2 \qquad \text{Eq. 6-16}$$

In the University of Bath network in 2006, 0.51×10^6 kg × 32/4 = 4.08×10^6 kg of oxygen can be produced. For the medical application, the price of 40 L of pure oxygen with cylinder is about RMB 25, and for the industry application, the price of it is RMB 15. Taking away the cost of the cylinder, assuming the price of 40 L of pure oxygen is RMB 5 only. The density of oxygen is 1.43 g/L, and then the price of 1 kg oxygen is about RMB 80, which equals to RMB 80 / 8 (exchange rate in 2006) = \$ 10. Therefore, the additional income of oxygen is about 4.08×10^6 kg × \$ 10 = \$ 4.1×10^7. Eliminating the costs of transport, labour, and other fees, assumes that only 1/3 of the benefit left. The Estimated Annual Net Cash Flow of the hydrogen storage system for the University of Bath network in 2006, with taking into account the additional benefit of oxygen is \$ 3.5×10^6 + \$ 0.29×10^6 + \$ 4.1×10^7 / 3 = \$ 1.7×10^7.

One 45 m wind turbine and two 40 m wind turbines are required for the hydrogen storage system. The wind turbine costs estimated at \$ 1.3 million per MW. The capital cost of the wind turbines for the hydrogen storage system for the University of Bath network is (3 + 2 + 2) MW × 1.3×10^6 \$ / MW = \$ 9.1×10^6.

The capital costs of the water electrolyser and compressed hydrogen cylinder are \$ 2.2×10^6, The capital costs of the PEMFC are \$ 2.6×10^6, and the annual O&M cost is \$ 3.5×10^5, and the life cycle of a hydrogen storage system in the University of Bath network is 20/20/6 years (water electrolyser/compressed hydrogen cylinder/PEM fuel cell). Therefore, the first hydrogen storage system for the University of Bath network can be a 20 years project, with changing the PEMFCs.

The cost of the hydrogen energy storage for the University of Bath network is \$ $2.2 \times 10^6 + 20 / 6 \times$ \$ $2.6 \times 10^6 + 20 \times$ \$ $3.5 \times 10^5 =$ \$ 17.8×10^6. The cost of the project is \$ $9.1 \times 10^6 +$ \$ $17.8 \times 10^6 =$ \$ 26.9×10^6.

From the calculations above, the payback time of the system with the first set of hydrogen energy storage for the University of Bath network is the same with the payback time of the 20 years project with the hydrogen energy storage system for the University of Bath network, and the payback time without the additional benefit of oxygen can be calculated:

$$\text{Payback Time} = (\$\ 26.9 \times 10^6) / \$\ 3.8 \times 10^6\ /\text{year} = 7\ \text{years} \qquad \text{Eq. 6-17}$$

The payback time with the additional benefit of oxygen is

$$\text{Payback Time} = (\$\ 26.9 \times 10^6) / \$\ 1.7 \times 10^7\ /\text{year} = 1.5\ \text{years} \qquad \text{Eq. 6-18}$$

Over the 20 year project, the total net benefit of the hydrogen energy storage system without the additional benefit of oxygen is

$$\$\ 3.8 \times 10^{6} \times (20 - 7) = \$\ 4.95 \times 10^{7} \qquad \text{Eq. 6-19}$$

The total net benefit of the hydrogen energy storage system considering the additional benefit of oxygen is

$$\$\ 1.7 \times 10^{7} \times (20 - 1.5) = \$\ 3.23 \times 10^{8} \qquad \text{Eq. 6-20}$$

6.6.3 Comparison of the payback time of the two systems

From the results given in Section 6.6.1 and Section 6.6.2, the comparison of the payback time of the NaS battery system and that of the hydrogen energy storage system are listed clearly in Fig. 6-7. In this figure, the first set of NaS battery can last 6 years, and the first set of hydrogen energy storage can be used for 20 years.

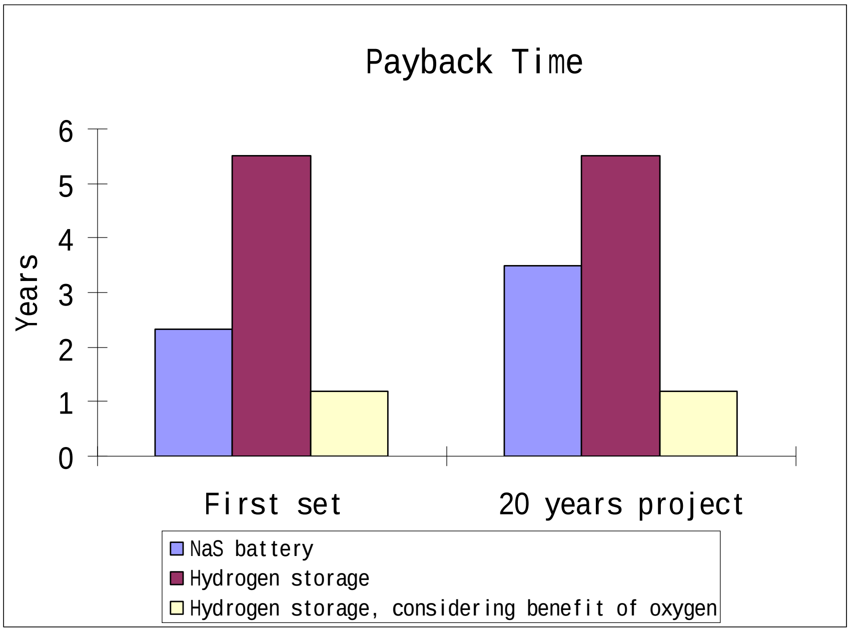

Fig. 6-7 Payback time of the NaS battery and hydrogen energy storage systems

From the comparison figure above, the NaS battery and hydrogen energy storage systems are both economic for the University of Bath network. The NaS battery system shows the priority than the hydrogen energy storage system not only in the case of first set, but also in the case of 20 years project, if without considering the additional benefit of oxygen. However, the life cycle of the NaS battery for the University of Bath network is much shorter than that of the hydrogen energy storage. If the hydrogen energy storage system takes into account the additional benefit of oxygen, the results change a lot. The hydrogen energy storage system considering the additional benefit of oxygen has much shorter payback time than the NaS battery system.

Fig. 6-7 also indicates that the investment of wind turbines takes a large proportion of the total cost in both cases for the University of Bath network. Lower the price of the wind turbines is the essential work in the future.

Fig. 6-8 shows the return on investment of the 20 years project. Fig. 6-7 and Fig. 6-8 show that the system of NaS battery not only has shorter payback time, but also has more net benefit back after 20 years than the hydrogen energy storage system, if without considering the additional benefit of oxygen; to the contrary, the hydrogen energy storage system has much shorter payback time, and much greater return on investment than the NaS battery system, if take into account the benefit of oxygen.

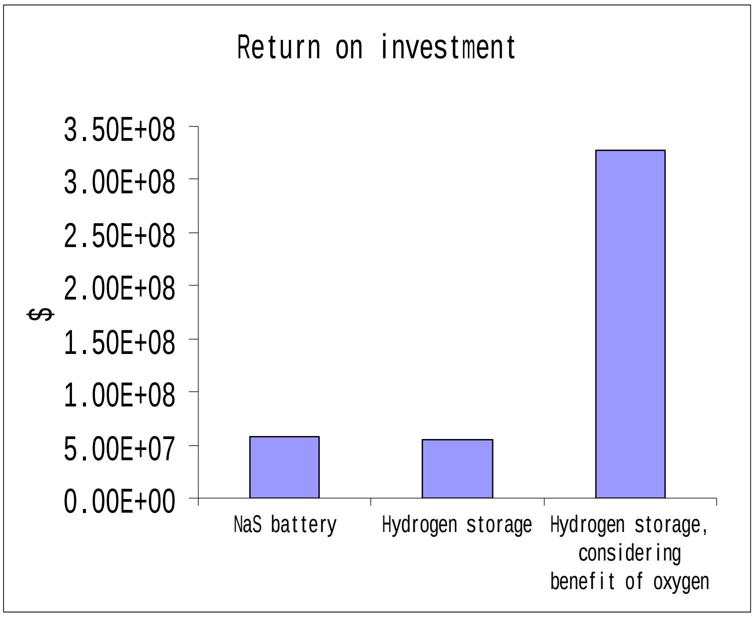

Fig. 6-8 Return on investment of the NaS battery and hydrogen energy storage systems

6.7 Energy storage with wind power in the University of Bath

6.7.1 CO_2 emission

CO_2 emissions from the traditional fossil fuels are causing increased concern, which has led to the rapid development of renewable energy. From half hourly load data for the University of Bath, the system consumed about 13651765 kWh of electricity, which is equal to 1.56 MW of power on average. Table 6-4 shows the CO_2 emissions per kWh of electricity consumed from 1990 to 2007 for the UK electrical power systems, and from it, 0.56 kg of CO_2 per kWh electricity consumed for the year 2006.

The output rates of CO_2 emissions are so widely varied, because the CO_2 emissions are different for various generation types over this period. Taking the CO_2 emissions data for 1999 in the United States as an example; 0.95 kg of CO_2 is produced when per kWh of electricity is consumed, if the electricity is generated from coal; 0.893 kg of CO_2 is produced per kWh of electricity is consumed, which is generated from petroleum; 0.599 kg of CO_2 is produced per kWh of electricity is consumed, which is generated from gas; and about 0.625 kg of CO_2 is produced per kWh of electricity is consumed, which is generated from other fuels [164].

In other words, if clean energy such as wind power is used to support the whole University of Bath network, it could reduce at least 7.64×10^6 kg of CO_2 emissions in the year 2006. The density of the CO_2 is 1.98 kg/m^3 under the normal condition, which means approximate 3.9×10^6 m^3 of CO_2 was released in the air in 2006 from the University of Bath, if the traditional fuels were used only to support the University of Bath network.

Table 6-4 Output rates for CO_2 emissions [165]

UK Grid Electricity Year	**CO_2 (kg kWh^{-1})**
1990	0.77
1991	0.75
1992	0.70
1993	0.62
1994	0.61
1995	0.58
1996	0.56
1997	0.52
1998	0.53
1999	0.49
2000	0.52
2001	0.54
2002	0.52
2003	0.53
2004	0.54
2005	0.53
2006	0.56
2007	0.54

6.7.2 Utilization of the wind energy

Low utilization of wind energy is one reason why wind energy cannot be used widely today. Increasing the wind turbine size can reduce the usable proportion of energy. However, introducing hydrogen storage in the system can greatly improve the utilization of renewable energy and allow smaller wind turbines to be used in isolated power systems. The utilization of wind energy generated by a range of wind turbine sizes with the hydrogen energy storage, and without the energy storage in the University of Bath network is calculated below.

For example, the 55 m wind turbine size is chosen for this system; the total energy generated by it is 14.87 GWh, and the energy left after the year 2006 is

-7.76 GWh. The load of the whole year is 13651765 kWh. Therefore, the utilization of wind energy with the 55 m wind turbine and hydrogen storage is (13651765 - 7.76 × 10^6) kWh / 1.49 × 10^7 kWh × 100 % = 39.6 %, but the energy left is less than zero, which means the wind turbine is too small to support the whole network. The utilization of wind energy in the system without the energy storage is worked out as: when wind is greater than the load, the value equals to the value of the load multiplied the energy loss (step-up and transformers), 98 % × 98 % = 96.04 %. If wind is less than the load, the value is 0. Added up the values of the used wind energy is 4.5 GWh, and then, the utilization of wind energy in the system without the energy storage is (4.5 GWh / 14.9 GWh) × 100 % = 30.2 %.

The similar calculations for the other wind turbine sizes are worked out. Take the 188 m wind turbine size as the other example. The total energy generated by it is 173.8 GWh, and the energy left after the year 2006 is 97.2 GWh. Then the utilization of wind in the system with 188 m wind turbine and hydrogen storage is (13651765 + 97.2) GWh / 173.8 GWh × 100 % = 63.78 %.

The utilization of wind energy in this system without the energy storage is calculated as the 55 m wind turbine system. The value of the wind energy used in this system is 11.3 GWh, so the utilization of wind energy here is (11.3 GWh / 173.8 GWh) × 100 % = 6.5 %. The same calculation method is used for the other wind turbine sizes in the University of Bath system, and the results are listed in Table 6-5.

From Table 6-5, it is obviously the utilization of wind energy of the system with hydrogen energy storage is much greater than it of the system without the energy storage. Therefore, the energy storage is very important for the renewable energy system. From the table above, the wind turbine is larger; the utilization of wind energy is lower without the energy storage, and the utilization is only about 16 % on average, whereas the utilization of wind energy of the system with energy storage is quite smooth and high, around 60 %.

Table 6-5 Utilization of wind energy in different wind turbine sizes

Wind turbine size	**Total energy generated (GWh)**	**Usage without energy storage**	**Usage with hydrogen storage**
55 m	14.9	30.2 %	39.6 %
65 m	20.8	27.1 %	52.5 %
70.2 m	24.2	25.4 %	56.4 %
72 m	25.5	24.9 %	57.4 %
85 m	35.5	20.9 %	61.9 %
95 m	44.4	18.2 %	63.5 %
105 m	54.2	16 %	64.2 %
115 m	65	14.2 %	64.5 %
125 m	76.8	12.5 %	64.6 %
135 m	89.6	11.2 %	64.5 %
145 m	103.4	9.96 %	64.4 %
155 m	118.1	8.8 %	64.3 %
165 m	133.9	8 %	64.1 %
175 m	150.6	7.3 %	64 %
188 m	173.8	6.5 %	63.8 %

The optimal wind turbine sizes for the NaS battery and hydrogen storage energy storage systems are 58.4 m and 72 m, respectively. The utilization of wind energy of a 58.4 m wind turbine system with NaS batteries, and it of a 72 m wind turbine system with the hydrogen energy storage are worked out and listed in Table 6-6. Table 6-5 shows that the utilization of wind energy with NaS battery system is much higher than that of the hydrogen energy storage system.

Table 6-6 Wind penetration of the optimal wind turbine systems

Wind turbine size	**Total energy generated (GWh)**	**Usage without energy storage**	**Usage with energy storage**
58.4 m (NaS)	16.8	29.1 %	81.5 %
72 m (H_2)	25.5	24.9 %	57.4 %

6.8 Development of hydrogen storage system with H_2-ICEs and H_2-CCGTs

6.8.1 Introduction of H_2-ICEs

The principle of H_2-ICEs is similar to the traditional internal combustion engines, but H_2-ICEs are 20 % to 25 % more efficient than that of gasoline ICEs [16, 136]. The efficiency can be improved by increasing either the compression ratio or the specific heat ratio. Both the ratios of H_2-ICEs are higher than them of the traditional ICEs, due to hydrogen's lower self-ignition temperature and leaner air-fuel ratio [16]. Then the efficiency of the H_2-ICEs is about 40-55 % [166], and in General Motors (GM) European well-to-wheel (WTW) study, a full load efficiency of 27-52 % is obtained for this technology. The theoretical thermodynamic efficiency of an engine is limited by the compression ratio of the engine and the specific heat ratio of the fuel.

The maintenance of H_2-ICEs is very similar to it of the gasoline ICEs, but the capital cost of H_2-ICEs is nearly 1.5 times as much as that of traditional gasoline ICEs [136]. The capital cost of gasoline ICEs is about US$ 700 per kW [167, 168], compared to that of H_2-ICEs which is US$ 1050 per kW. The O&M cost of H_2-ICEs is US$ 0.0182 per kWh [131], which is about US$ 160 per kW-yr.

6.8.2 Introduction of H_2-CCGTs

The combined cycle is well known as that a gas turbine generator generates electricity and heat, and then the wasted heat is used to make steam to generate additional electricity via a steam turbine. Therefore, the efficiency of a CCGT is higher than that of either plant on its own, around 55-60 % [169]. The hydrogen-power efficiency goal of H_2-CCGTs is exceeding 70 % and with low nitric oxide metabolite emissions by 2020 [125].

The capital cost is relatively low as well, less than half of a conventional coal fired plant. A typical industrial size CCGT is about a 400 MW gas turbine with a 200 MW steam turbine, making 600 MW in total [170]. The life cycle of CCGTs is about 30 years [171]. Gas turbine technology is still under development, and the capital cost of coal fuelled CCGTs in 2005 would be about US$ 370 per kW [172]. The O&M cost of it is US$ 0.00436 per kWh, about US$ 40 per kW-yr [144].

6.8.3 Comparison of the systems with PEMFCs, SOFCs, H_2-ICEs and H_2-CCGTs

The efficiencies of PEMFCs, H_2-ICEs, and H_2-CCGTs are similar, 46 %, 40-45 %, and 55-60 %, respectively. But the costs of H_2-ICEs and H_2-CCGTs are much lower than that of PEMFCs.

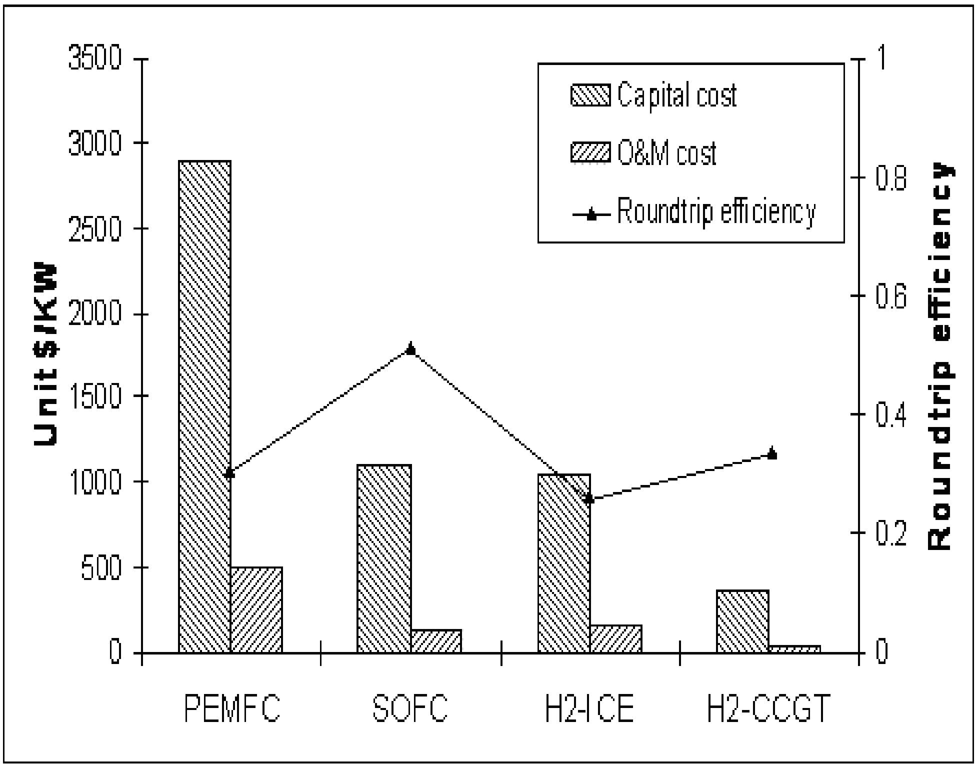

Fig. 6-9 Cost and efficiency comparisons of the four devices

The cost and efficiency comparisons of the four different kinds of hydrogen-electricity conversion devices are shown in Fig. 6-9. The cost unit is

US$ per kW, and the round-trip efficiency is for the whole system from wind turbine to the consumers. The round-trip efficiencies are 30.1 %, 45.8 %, 37.6 %, and 27.8 % for the hydrogen energy storage systems with PEMFCs, SOFCs, H_2-CCGTs, and H_2-ICEs, respectively.

Using the method described in Chapter 4, for the hydrogen energy hydrogen energy storage system with PEMFCs, a wind turbine radius of 72 m is needed with a storage size of 2.58 GWh; 10130880.1 kWh of energy should be stored during the year 2006 and the stored energy which needs to be released in the whole year is 9.15 GWh. If SOFCs are used in this system, the optimal wind turbine size would be 63.5 m, and the storage size would be 2.43 GWh; 7.57 GWh of energy needs to be stored and 7.53 GWh of stored energy should be released. With the H_2-CCGTs, a wind turbine radius of 66.6 m, and a storage size of 2.80 GWh, 8.72 GWh of energy needs to be stored and 8.7 GWh of stored energy should be released. Similarly, for H_2-ICEs, these become 71.8 m, 3.45 GWh, 10.8 GWh, and 10.8 GWh. Fig. 6-10 shows the hydrogen energy left in the cylinders in the systems with four kinds of hydrogen to electricity conversion devices: PEMFCs, SOFCs, H_2-CCGTs, and H_2-ICEs.

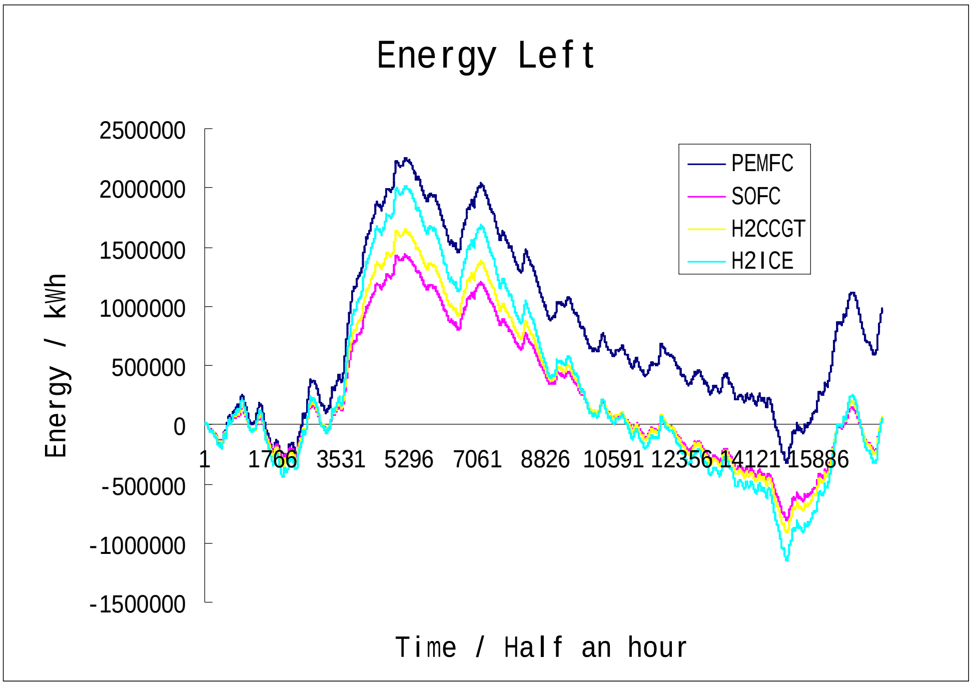

Fig. 6-10 The energy left in the system with the four devices

The capital cost and O&M cost of the hydrogen energy system with SOFCs are worked out:

The capital cost is 7567834.2 kWh / 8760 h = 863.9 kW

$$863.9 \text{ kW} \times (1100 + 400 + 1500) \text{ \$/kW} = \$\ 2591700 = \$\ 2.59 \times 10^6 \qquad \text{Eq. 6-21}$$

Annual fixed O&M cost is

$$7525712.6 \text{ kWh} \times 0.0156 \text{ \$/kWh} = \$\ 117401.12 = \$\ 1.17 \times 10^5 \qquad \text{Eq. 6-22}$$

The capital cost and O&M cost of the hydrogen energy storage system with H_2-CCGTs are:

The capital cost is 8715650.55 kWh / 8760 h = 994.9 kW

$$994.9 \text{ kW} \times (370 + 400 + 1500) \text{ \$/kW} = \$\ 2258423 = \$\ 2.26 \times 10^6 \qquad \text{Eq. 6-23}$$

Annual fixed O&M cost is

$$8.7 \times 10^6 \text{ kWh} \times 0.00436 \text{ \$/kWh} = \$\ 3.8 \times 10^5 \qquad \text{Eq. 6-24}$$

The capital cost and O&M cost of the hydrogen energy system with H_2-ICEs are:

The capital cost is 10.8×10^6 kWh / 8760 h = 1233.98 kW

$$1233.98 \text{ kW} \times (1050 + 400 + 1500) \text{ \$/kW} = \$\ 3640241 = \$\ 3.6 \times 10^6 \qquad \text{Eq. 6-25}$$

Annual fixed O&M cost is

$$10.8 \times 10^6 \text{ kWh} \times 0.0182 \text{ \$/kWh} = \$\ 196758.59 = \$\ 1.97 \times 10^5 \qquad \text{Eq. 6-26}$$

The comparative results of the capital and maintenance costs, efficiencies, and wind turbine sizes required of the systems with the four kinds of hydrogen to electricity conversion devices are listed clearly in Table 6-7.

Table 6-7 Comparative information of the hydrogen storage systems with PEMFCs, SOFCs, H_2-CCGTs, and H_2-ICEs

	PEMFC	**SOFC**	**H_2-CCGT**	**H_2-ICE**
Round-trip efficiency	30.1 %	45.8 %	37.6 %	27.8 %
Wind turbine size (m)	72	63.5	66.6	71.8
Capital cost ($)	4.8×10^6	2.59×10^6	2.26×10^6	3.6×10^6
O&M cost ($)	3.5×10^5	1.17×10^5	3.8×10^5	1.97×10^5

6.8.4 Developing the system with H_2-CCGTs replacing PEMFCs

The results in Table 6-7 show that H_2-CCGTs have much lower capital costs than the others, but the highest O&M cost. The efficiencies of H_2-CCGTs and SOFCs are higher than the other two. Also, the wind turbine size required for the systems with H_2-CCGTs and SOFCs are similar as well. However, the operation temperature of SOFCs is quite high, about 600-1000 ºC, and its durability is low due to the corrosive materials and high temperature. Based on that, H_2-CCGT is chosen for improving the properties of the hydrogen energy storage system by replacing the ClearGen multi-MW series PEMFC, The comparative information of the whole systems with H_2-CCGTs and PEMFCs for the University of Bath network is shown in Table 6-8.

Table 6-8 Comparative information of the systems with H_2-CCGTs and PEMFCs

	PEMFC	**H_2-CCGT**
Round-trip efficiency	30.1 %	37.6 %
Wind turbine size (m)	72	66.6
Generated energy (GWh)	25.5	21.8
Energy to stored (GWh)	10.1	8.72
Energy to released (GWh)	9.15	8.7

Energy left-over (MWh)	981.7	14
Storage size (GWh)	2.58	2.8
Life cycle (years)	20	30
Capital cost ($)	4.8×10^6	2.26×10^6
O&M cost ($)	3.5×10^5	3.8×10^5

6.8.5 Payback time of the system with H_2-CCGT

To equal the large wind turbine size of 66.6 m, three 40 m wind turbines could be used for the hydrogen energy storage system using H_2-CCGT for the University of Bath network in 2006. Therefore, the wind energy generated in 2006 is 22.9 GWh; energy which needs to be stored in the whole year is 9.38 GWh; the total stored energy which should be released to supply the load is 8.46 GWh; and the energy left in the cylinder is 0.919 GWh.

The capital cost and O&M cost of the hydrogen energy storage system with H_2-CCGTs are worked out:

The capital cost is 9.38 GWh / 8760 h = 1070.4 kW

$$1070.4 \text{ kW} \times (370 + 400 + 1500) \text{ \$/kW} = \$ 2429808 = \$ 2.4 \times 10^6 \qquad \text{Eq. 6-27}$$

Annual fixed O&M cost is

$$8.46 \text{ GWh} \times 0.00436 \text{ \$/kWh} = \$ 36873.15 = \$ 3.69 \times 10^5 \qquad \text{Eq. 6-28}$$

The total cost of the hydrogen energy storage system with H_2-CCGTs for a 20 years project is

$$\$ 2.4 \times 10^6 \times 20 / 30 + 20 \times \$ 3.69 \times 10^5 = \$ 8.98 \times 10^6 \qquad \text{Eq. 6-29}$$

The cost of the 20 years project is

$$\$ 7.8 \times 10^6 + \$ 8.98 \times 10^6 = \$ 16.78 \times 10^6 \qquad \text{Eq. 6-30}$$

0.919 GWh of energy left is about 0.919 GWh / 33.3 kWh / kg = 27608 kg of hydrogen. Therefore, the Estimated Annual Net Cash Flow of the system without considering the additional benefit of oxygen is \$ 3.51×10^6 + \$ 0.276×10^6 = \$ 3.79×10^6. The payback time can be calculated:

$$\text{Payback Time} = (\$16.78 \times 10^6) / \$ 3.79 \times 10^6 /\text{year} = 4.4 \text{ years} \qquad \text{Eq. 6-31}$$

Over the 20 year project, the total net benefit of the hydrogen energy storage system with H_2-CCGT is

$$\$ 3.79 \times 10^6 \times (20 - 4.4) = \$ 5.9 \times 10^7 \qquad \text{Eq. 6-32}$$

If consider the additional benefit of oxygen, 22.9 GWh of wind energy was generated in this case in 2006, and then about 22.9 GWh × 98 % × 98 % × 76 % × 91.5 % = 15.3 GWh of energy was stored. Therefore, 15.3 GWh / 33.3 kWh / kg = 46 kg of hydrogen was stored in 2006, which means 46 kg × 32/4 = 368 kg of oxygen can be produced. The Estimated Annual Net Cash Flow of the hydrogen energy storage system for the University of Bath network in 2006, taking into account the additional benefit of oxygen is \$ 3.51×10^6 + \$ 0.276×10^6 + \$ $36.8 \times 10^6 / 3$ = \$ 16.06×10^6. The payback time is

$$\text{Payback Time} = (\$ 16.78 \times 10^6) / \$ 16.06 \times 10^6 /\text{year} = 1 \text{ year} \qquad \text{Eq. 6-33}$$

The total net benefit of the hydrogen energy storage system with H_2-CCGT is

$$\$ 16.06 \times 10^6 \times (20 - 1) = \$ 3.05 \times 10^8 \qquad \text{Eq. 6-34}$$

Then the comparative results of the NaS battery system and the hydrogen energy storage systems with H_2-CCGTs and with PEMFCs are clearly shown in Fig. 6-11 and Fig. 6-12. In the two figures, “without” means without considering the additional benefit of oxygen; and “with” stands for taking into account the additional benefit of oxygen. From Fig. 6-11, the hydrogen energy storage system with H_2-CCGTs has shorter payback time than the hydrogen energy storage system with PEMFCs, whether consider the additional benefit of oxygen or not. The hydrogen energy storage systems have shorter payback time than the NaS battery system, if considering the additional benefit of oxygen.

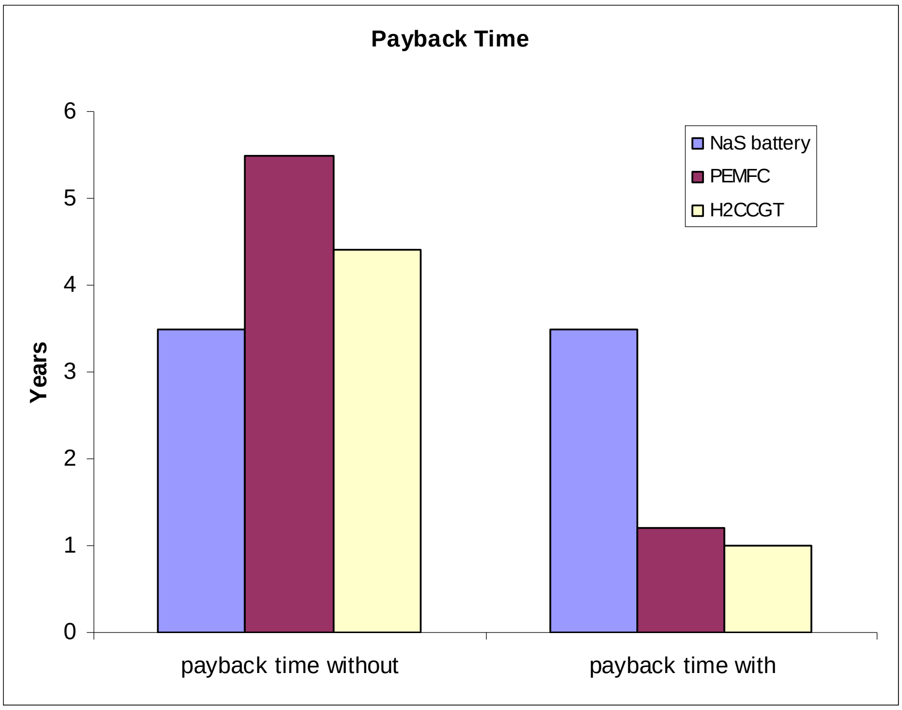

Fig. 6-11 Payback time of the NaS battery, PEMFC and H_2-CCGT systems

Fig. 6-12 shows that the hydrogen energy storage system with H_2-CCGTs has greater return on investment than the hydrogen energy storage system with PEMFCs and the NaS battery system, if without considering the additional benefit of oxygen; but if take into account the additional benefit of oxygen, the hydrogen energy storage system with H_2-CCGTs has less return on investment than the hydrogen energy storage system with PEMFCs, but much higher than it of the NaS battery system.

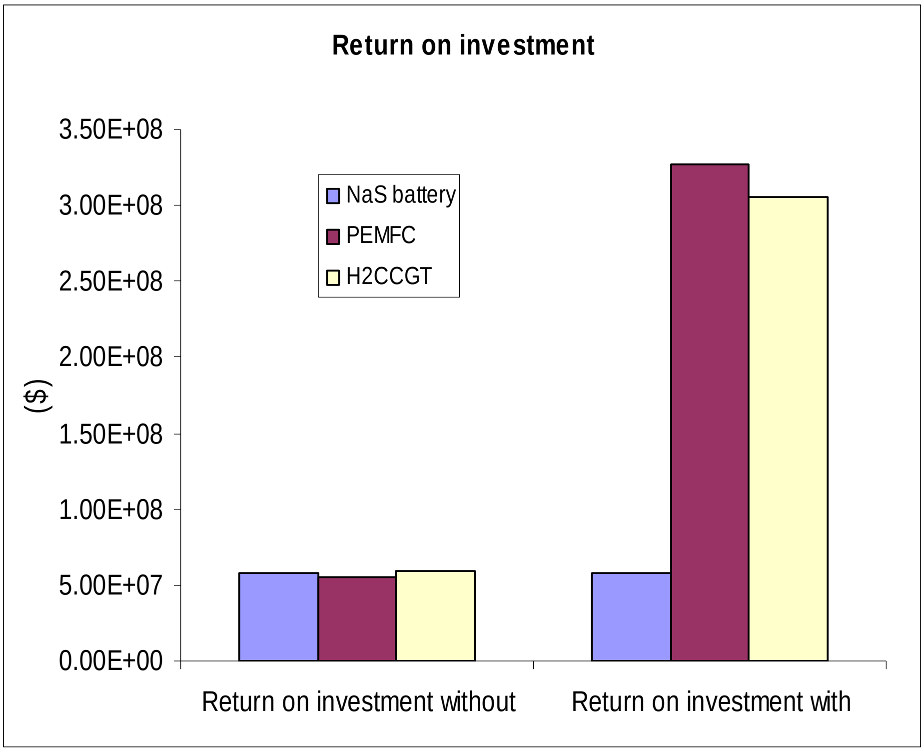

Fig. 6-12 Return on investment of the NaS battery, PEMFC and H_2-CCGT systems

The two figures above show that the wind turbine sizes is the essential factor contributing to the return on investment. From the comparisons of the payback time and return on investment between the hydrogen energy storage systems with PEMFCs and H_2-CCGTs, the hydrogen energy storage hydrogen energy storage system with PEMFCs is more economic than the hydrogen energy storage system with H_2-CCGTs. H_2-CCGTs are more efficient, and cheaper than PEMFCs, so why the results display differently. The reason is that for the hydrogen energy storage system with PEMFCs, the wind turbine chosen is not the optimal one 70.2 m, but 72 m with smallest energy storage size instead. The large single wind turbine sizes of 70.2 m and 72 m both require one 45 m wind turbine and two 40 m wind turbines, so the wind energy generated is the same, but the energy left in the hydrogen energy storage system with PEMFCs is much greater than the hydrogen energy storage system with H_2-CCGTs, which means that the additional benefit of hydrogen and oxygen of the hydrogen energy storage system with PEMFCs is much greater than it of the hydrogen energy storage system with H_2-CCGTs. Therefore, the hydrogen energy storage hydrogen energy storage system with H_2-CCGTs is integrated into the wind power system in the next chapter for the University of Bath network.

6.9 Summary

The comparison of various types of batteries shows that NaS has higher energy and power density, higher efficiency and longer cycle time than the other traditional batteries. In the case of the University of Bath network, NaS batteries, flywheels and Hydrogen energy storage are further compared to find the most suitable energy storage solution for this application. In doing this, a comparison among energy storage technologies, i.e. flywheels, NaS batteries and hydrogen energy storage, are conducted in terms of energy loss, efficiency, cost and life cycle. Due to the high energy loss and self-discharge rate of flywheels, NaS battery and hydrogen energy storage are considered to be better methods for the long-term energy storage purpose. NaS battery has a lower capital cost and annual O&M cost than hydrogen energy storage; however, the energy loss of hydrogen is much slower than NaS battery. The results show that hydrogen storage has a lower energy loss and longer life cycle, which make it suitable for long-term storage compared with the other technologies described here.

The energy storage systems were compared from the efficiency and life cycle as well. The capital cost and annual O&M cost for the NaS battery energy storage system are $ 1.6×10^6, and $ 1.8×10^4 respectively; efficiency is 64.56 % and the life cycle is around 6 years. The capital cost for the hydrogen energy storage system is $ 4.8×10^6 and annual cost is $ 3.5×10^5; efficiency is quite low about 30.1 %; and the life cycle is 20 years, because the life cycle of water electrolyser is 20 years, of storage cylinder is 20 years, and of the ClearGen multi-MW series PEMFC from BALLARD is 20 years as well. The energy left in NaS battery and hydrogen energy storage systems meet at around 150 days. From these comparisons, it is still hard to tell which one is the best energy storage method here yet.

Therefore, the further comparison of payback time and return on investment are worked out to get the optimal method for the University of Bath network. No matter the payback time for the first set project, or that for the 20 years project, the NaS battery system can get pay itself back in shorter time than the hydrogen energy storage system, if not consider the additional benefit of oxygen. Over the 20 year project, the payback time of the NaS battery system is 3.5 years, and that of the hydrogen energy storage system is 7 years. Besides, after 20 years, the return on investment of the NaS battery system is much higher than that of the hydrogen energy storage system for the University of Bath network as well.

If considering the additional benefit of oxygen, the results are hugely changed. The payback time of the hydrogen energy storage system is only 1.5 years, and the return on investment over the 20 year project is $ 3.23×10^8. Therefore, the hydrogen energy storage system is more economic than the NaS battery system for the University of Bath network, with selling the oxygen for the other applications, and using air in PEMFCs instead.

Generally speaking, after introducing the energy storage, CO_2 emissions can be reduced by 7.6×10^6 kg and the utilization of wind energy is improved significantly by introducing the energy storage. The utilization of wind energy in the system without the energy storage is only about 16 % on average, whereas the utilization of wind energy in the system with energy storage (taking the hydrogen energy storage method as an example) is quite smooth and high, around 60 %. From utilization of wind energy comparison, NaS battery with a 58.4 m wind turbine system is better than hydrogen energy storage with a 72 m wind turbine system. The utilization of wind energy is much higher, about 81.5 %.

Meanwhile, it should be noted that the drawbacks of the hydrogen storage system still exist, including high cost and low efficiency. However, they can be improved by introducing H_2-ICEs or H_2-CCGTs instead of PEMFCs. In the next few years, H_2-ICEs are expected to instead fuel cells, for its much lower cost. Scientists found out that compared with the quite low efficiency of traditional ICEs, the efficiency of H_2- ICEs is quite higher than the traditional ICEs.

The comparisons between SOFCs, PEMFCs, H_2-ICEs, and H_2-CCGTs are worked out to find the optimal method as the hydrogen to electricity conversion equipment for the University of Bath network. The results show that the best approach among them for the University of Bath network is H_2-CCGT, because the system with H_2-CCGT has higher efficiency and lower cost, and it does not need the high operation temperature like SOFC. Over the 20 year project, the system with H_2-CCGT has much greater return on investment than the other systems, although its payback time is a bit longer than that of the system with SOFC.

Chapter 7 Realistic hydrogen energy storage system with wind turbines for the University of Bath

THIS chapter begins by discussing each component's characteristics, and then studies how the components fit in to the proposed system at Bath. Finally, a realistic hydrogen energy storage system is designed for the University of Bath in this chapter.

7.1 Introduction

From the former studies, many technologies can be used as energy storage methods for the University of Bath network. Hydrogen energy storage is chosen in this research, because it is a new technology, and many researchers are still working on this area.

From the calculations in Chapter 6, with the same wind turbine sizes, it can be deduced that the hydrogen energy storage system with H_2-CCGTs could be much more economic than the others. Therefore, H_2-CCGTs should be chosen to develop the hydrogen energy storage system.

For integrating H_2-CCGTs to wind power system for the University of Bath network, the algorithm in Chapter 4 is used to determine the optimal wind turbine size and energy storage size. Although components from many manufacturers could be used for this system in this chapter, the author chose the particular components suggested just giving an example about how the components fit in to the whole system.

After that, an overview of the whole system, from wind energy to the load, is described. Finally, the characteristics of the whole system are worked out to find the feasibility of the hydrogen energy storage for the University of Bath network.

7.2 Integrated H_2-CCGTs to wind power system based on the University of Bath network

Fig. 7-1 is obtained by using the algorithm of how to size the wind turbine in Chapter 4. It shows that the wind turbine size of 68.3 m requires the smallest energy storage size for the hydrogen energy storage system with H_2-CCGTs in the University of Bath network. The energy storage size is 2.41 kWh.

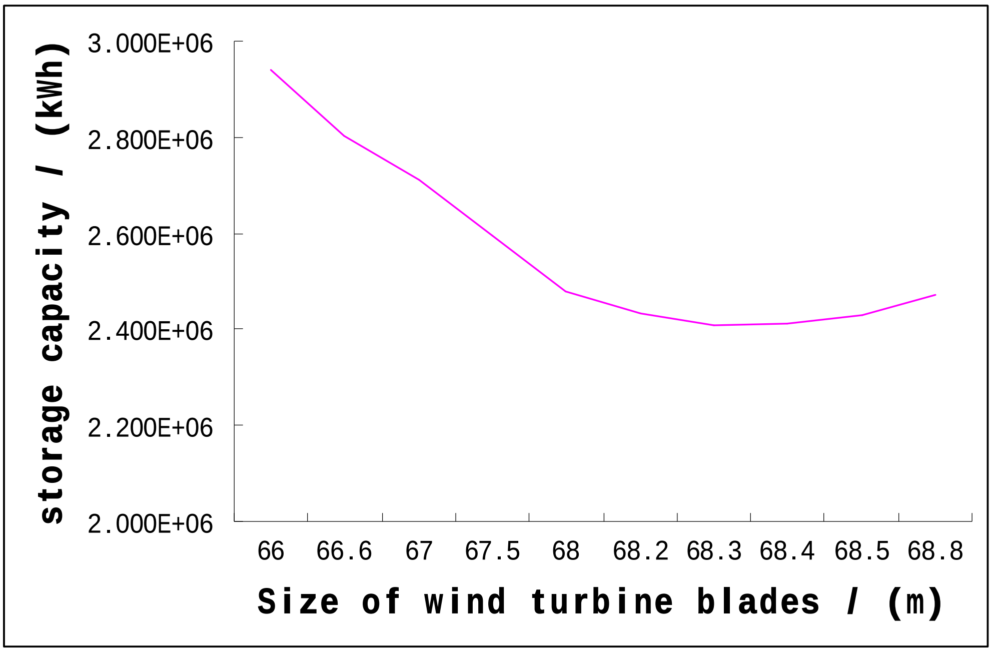

Fig. 7-1 Energy storage recovery capacity requirement for the H_2-CCGT system

From the algorithm of how to determine the energy storage size in Chapter 4, the dynamic energy left is shown in Fig. 7-2. This figure indicates the dynamic energy left for the case when the wind turbine size is 68.3 m in the hydrogen energy storage system using H_2-CCGT for the University of Bath network.

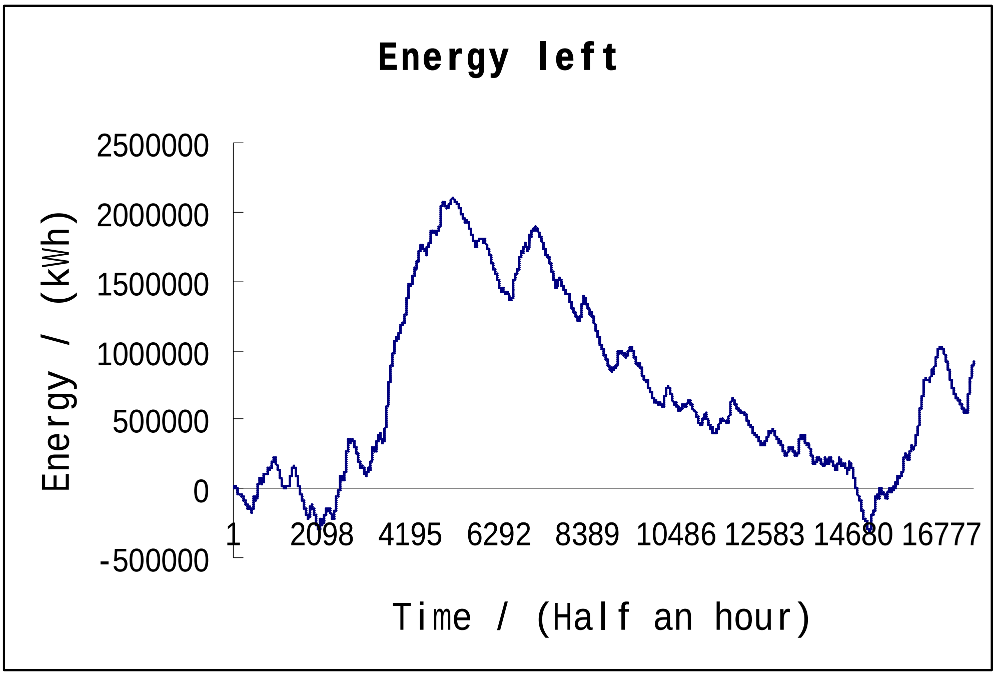

Fig. 7-2 The energy left in the H_2-CCGT system

Three 40 m wind turbines are required in this case. Therefore, the wind energy generated in 2006 is 22.9 GWh; the energy which needs to be stored in the whole year is 9.38 GWh; the total stored energy which should be released to supply the load is 8.46 GWh; and the energy left in the cylinder is 0.919 GWh.

7.3 The system with H_2-CCGT design for the University of Bath network

The SGT-100 gas turbine from Siemens has a gross power output of 5.4 MW. The efficiency is 31 %, and the frequency is 50 Hz or 60 Hz. The SST-050 steam turbine has an output of 0.75 MW for combined cycle applications, and the frequency can be 50 Hz or 60 Hz. The combined cycle gas turbine is more efficient, its efficiency can reach 58.9 % and the power output can be up to 6 MW. The life cycle is longer than 200000 h [173], which means the life cycle is longer than 23 years, if the CCGT is non-stop. A typical large combined power plant is shown in Fig. 7-3. The capital cost of the H_2-CCGT with a Siemens series gas turbine is about 497 $/kW, and the O&M cost is 0.00416 $/kWh [174].

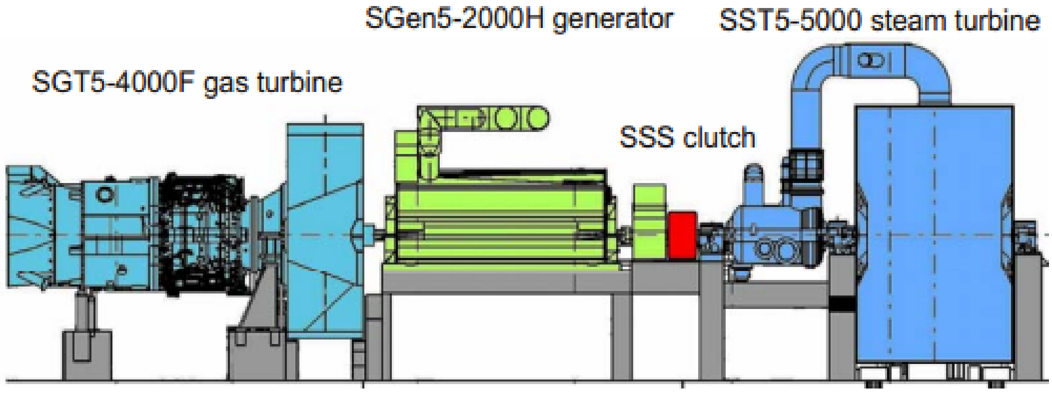

Fig. 7-3 Combined cycle gas turbine from Siemens

The SGT-100 gas turbine and SST-050 steam turbine from Siemens are chosen here for further calculations. Half hourly wind and load data for the University of Bath in 2006 is used to verify its feasibility. The efficiency of the whole system with the H_2-CCGT including a SGT-100 gas turbine and a SST-050 steam turbine is 98 % × 98 % × 76 % × 91.5 % × 58.9 % × 98 % = 38.6 %.

7.3.1 Sizing the main components of the system with H_2-CCGT

The sizes of wind turbines, water electrolysers, hydrogen cylinder, and H_2-CCGTs can be worked out by using the same algorithm as in Chapter 4. A large 66.2 m wind turbine is required to supply the load. The stored energy could be 8.57 GWh in the whole year 2006, and 8.54 GWh of the stored energy should be released. The energy storage size is 2.75 GWh. And the system with the 67.9 m wind turbine has the smallest energy storage size of 2.36 GWh, which is shown in Fig. 7-4. The total energy stored for this situation is 9.22 GWh, and 8.3 GWh of stored energy needs to be released to supply the University of Bath network.

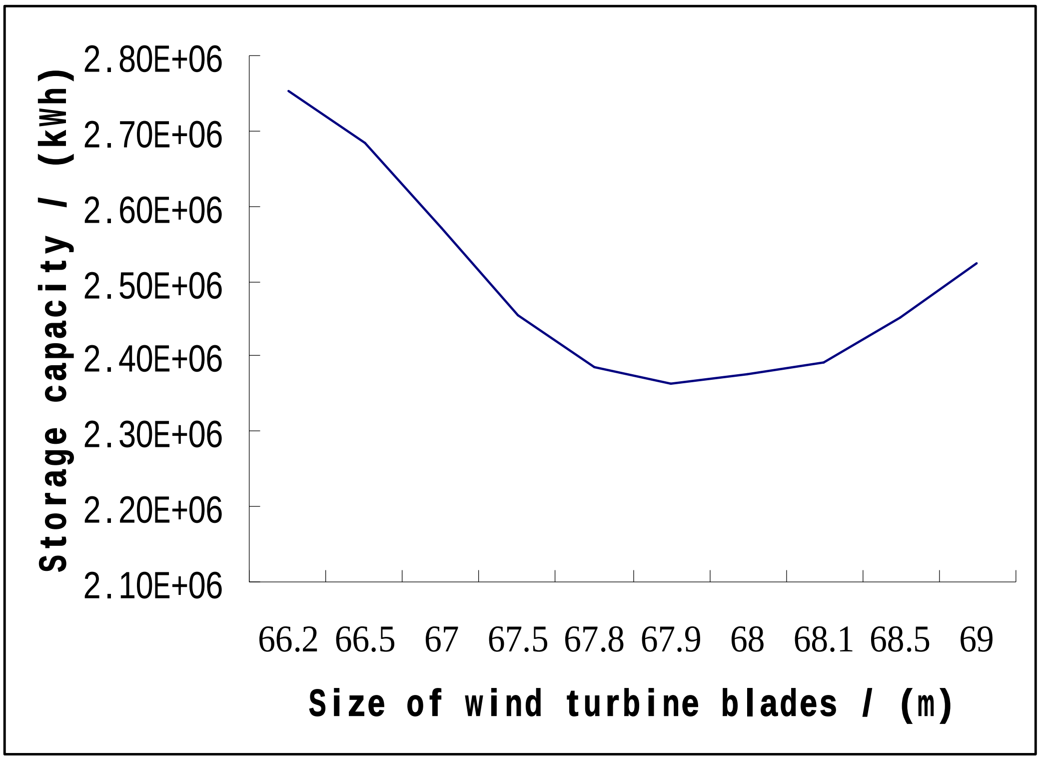

Fig. 7-4 Energy storage recovery capacity requirement for the real H_2-CCGT system

I) Wind turbine

There are many wind turbine manufacturers in the world, like Vestas from Denmark, Sinovel from China, GE Energy from US, Siemens from Germany, and so on. After studying the technology of the wind turbines and market availability, the parameter of wind turbines from Vestas were chosen for further research in this study. Whether the wind turbine is 66.2 m or 67.9 m, the realistic system with H_2-CCGT needs three Vestas V 80-2.0 MW (40 m) wind turbines. Therefore, the realistic large wind turbine size in this system is $((40 \times 40) \times 3)^{1/2} = 69.3$ m. Then the total wind energy generated in 2006 was 23611978.2 kWh; the energy stored during the year was 9.78 GWh; and 8.11 GWh of the stored energy needed to be released to supply the University of Bath network in 2006. The energy storage size is 2.57 GWh, and the energy left in the cylinder in 2006 is 1.67 GWh.

II) Water electrolysis

Water electrolysis is a mature technology, so there are lots of producers, especially nowadays in China. Also, Tianjin Mainland Hydrogen Equipment Co., Ltd is a professional manufacturer of hydrogen generator and gas purification equipment in China. The products from this company are used in this research. From the data of the max wind exceeding load day (30/12/2006), the max excess energy hour is 03:00, and the excess energy is 3944.1 + 3942.6 = 7886.7 kWh. Therefore, the rated output of the water electrolysers should be higher than 7886.7 kW. Then five FDQ-400/3.0 water electrolysers are required from Tianjin Mainland Hydrogen Equipment Co., Ltd. The efficiency of the FDQ-400/3.0 water electrolysers is about 76 %.

III) Compressed hydrogen cylinder

The actual maximum amount of hydrogen in the cylinder has to be adjusted for the efficiency of the H_2-CCGT and DC to AC conversion stages (58.9 % × 98 % = 57.722 %). 1 kg of hydrogen can produce about 120 MJ = 33.3 kWh of energy. Also, 1 kg of hydrogen occupies 100 L at a pressure of 150 bar, typical for this application. Taking these facts into account, the optimum hydrogen storage capacity would have to be (100 × 2.57 × 10^6) / (0.57722 × 33.3) L capacity = 13.37 × 10^6 L = 13.37 × 10^3 m^3. Therefore, the volume that equals to a cube 23.73 m on each side is required. The pressure is 150 bar, and the efficiency of compressed hydrogen is 91.5 %.

IV) H_2-CCGT

13651765 kWh of electricity was consumed totally in the University of Bath in 2006. Therefore, the University of Bath network is about a 13651765 kWh / 8670 h = 1558.4 kW ~ 2 MW micro-grid. The capacity of the whole system should be a 5 MW network. The technology of the H_2-CCGT is not mature enough, and there are not many manufacturers. Siemens has the most mature products. The smallest capacity of the H_2-CCGT from Siemens is the combined cycle with a SGT-100 gas turbine and a SST-050 steam turbine. The rated output of the H_2-CCGT is around 6 MW, and the efficiency of the combined cycle is 58.9 %.

7.3.2 The realistic system

From the discussion above, a system including three Vestas V 80-2.0 MW (40 m) wind turbines, five FDQ-400/3.0 water electrolysers, a cube of about 23.73 m on a side hydrogen storage tank, a SGT-100 gas turbine and a SST-050 steam turbine, is indicated. All the devices are commercially available and their details are listed below:

1) The technical information of the V 90-3.0 MW wind turbine from Vestas: rated power-3.0 MW; cut in wind speed-3.5 m/s; rated wind speed-15 m/s; cut-out wind speed-25 m/s; re-cut in wind speed-20 m/s; rotor diameter-90 m; swept area-6362 m^2; hub heights-65, 80, 105 m; frequency-50/60 Hz; and output voltage-1000 V.

The technical information of the V 80-2.0 MW wind turbine from Vestas: rated power-2.0 MW; cut in wind speed-4 m/s; rated wind speed-16 m/s; cut out wind speed-25 m/s; re-cut in wind speed-20 m/s; rotor diameter-80 m; swept area-5027 m^2; hub heights-65, 80, 105 m; frequency-50/60 Hz; and output voltage-1000 V.

2) The facts of the FDQ-400/3.0 water electrolyser: hydrogen capacity-400 Nm^3/h; Oxygen capacity-200 Nm^3/h; hydrogen purity>=99.9 %; working pressure-3 MPa (30 bar); current-6600 A; voltage-274 V; working temperature-90 °C; electrolyte-potassium hydroxide (KOH) 30 %; feed water-400 kg/h; and number of cells-274 piece.

3) The work pressure of the compressed hydrogen cylinder is 150 bar, the leakage rate is 0.000024 %, and the efficiency is 91.5 %.

4) The technical information of the SGT-100 & SST-050 from Siemens: SGT-100 has a gross power output of 5.4 MW, and SST-050 steam turbine has an output of 0.75 MW, so the combined power output-6 MW; frequency is 50 Hz or 60 Hz; efficiency of the SGT-100 is 31 %, the combined efficiency-58.9 %; life cycle>200000 h (23 years); voltage-1100 V; operational pressure-101 bar.

The technical and economic parameters of the main components of the designed H_2-CCGT system are concluded for clarity in Table 7-1, which can be easily used for further calculations.

Table 7-1 Parameters of the four components of the designed H_2-CCGT system

	Wind turbine	**Water electrolysis**	**Cylinder**	**H_2-CCGT**
Mode	V 80-2.0 MW	FDQ-400/3.0	---	SGT-100 & SST-050
Manufacturer	Vestas	Tianjin Mainland Hydrogen Equipment	---	Siemens
Output (MW)	2.0	1.8	---	6.0
Number	3	5	1	1 / 1
Efficiency	---	76 %	91.5 %	59.8 %
Voltage (V)	1000	274	---	1100
Frequency (Hz)	50/60	DC	---	50/60
Pressure (bar)	---	30	150	101
Life cycle (yrs)	20	20	20	23
Capital cost ($/kW)	1300	400	1500	497
O&M cost ($/kWh)	0.0089	0.012	0.01	0.00416

Through analysing the main parts of the system, the 1000 V power from wind turbines needs a transformer before being connected to the University of Bath network; one more transformer is required to take the voltage down to 274 V, before the electricity goes through the water electrolysers; an AC/DC adapter is needed, because DC is needed for water electrolysers; the voltage from H_2-CCGT is 1100 V, so there should be another transformer, before the electricity is supplied to the University of Bath network. Therefore, besides the four main components, three transformers and an inverter are required for this realistic proposed system.

7.3.3 Energy flow diagram of the realistic system

Given the components chosen, Fig 7-5 shows the energy flow in the realistic system for the University of Bath network. The blue arrow is the way energy goes from the wind turbine to the University of Bath directly, and the green arrow shows the energy from wind turbine that goes through hydrogen energy storage system, including; water electrolysis, compressed gas, and H_2-CCGT, this then serves the University of Bath network.

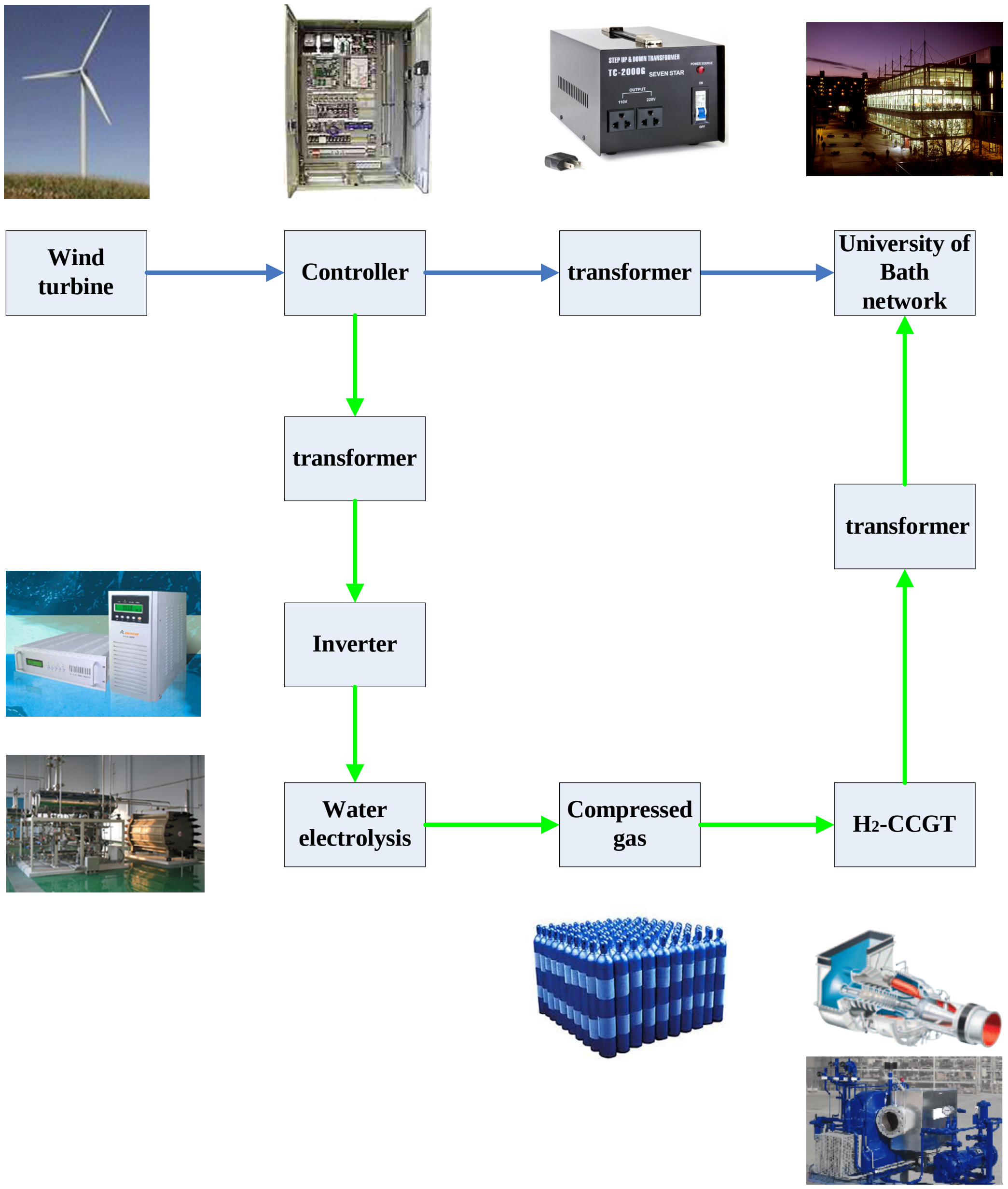

Fig. 7-5 Energy flow diagram of the realistic system

7.4 Verifying this system using data of the University of Bath

The dynamic energy flow in the system with the four main components is shown in Fig. 7-6, and the energy left during 2006 is shown in Fig. 7-7. The figure also shows the wind turbine size of 69.3 m is too large for the University of Bath network with the system with H_2-CCGT. Therefore the hydrogen energy storage method does not play a very important role here, but contributes to the revenue.

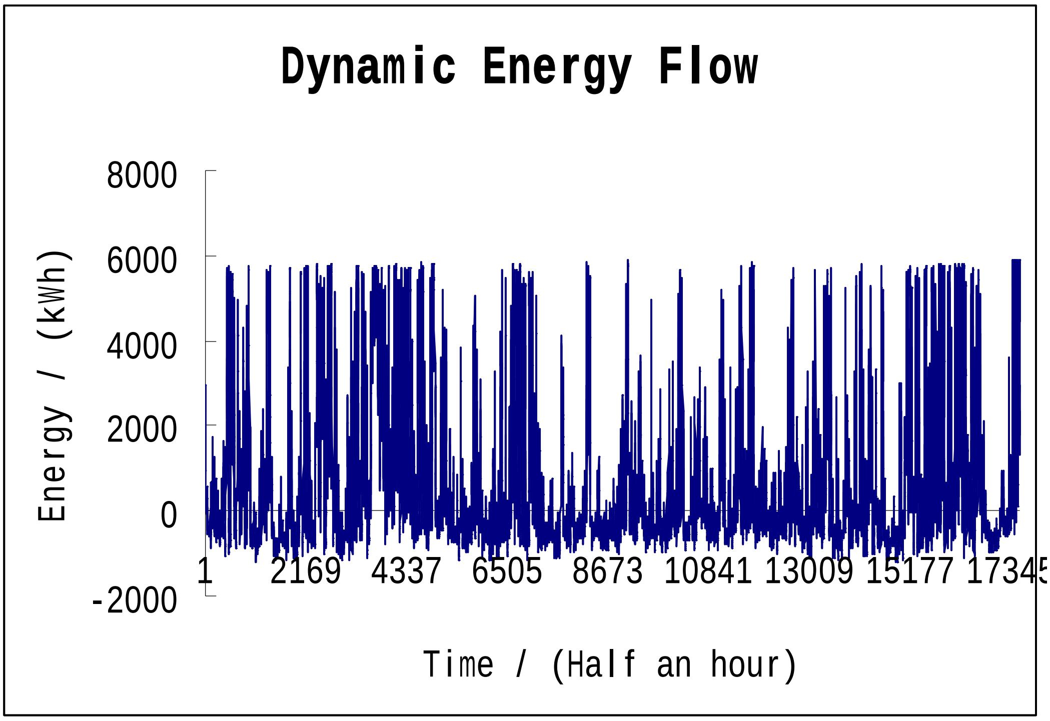

Fig. 7-6 Dynamic energy flow in the real H_2-CCGT system

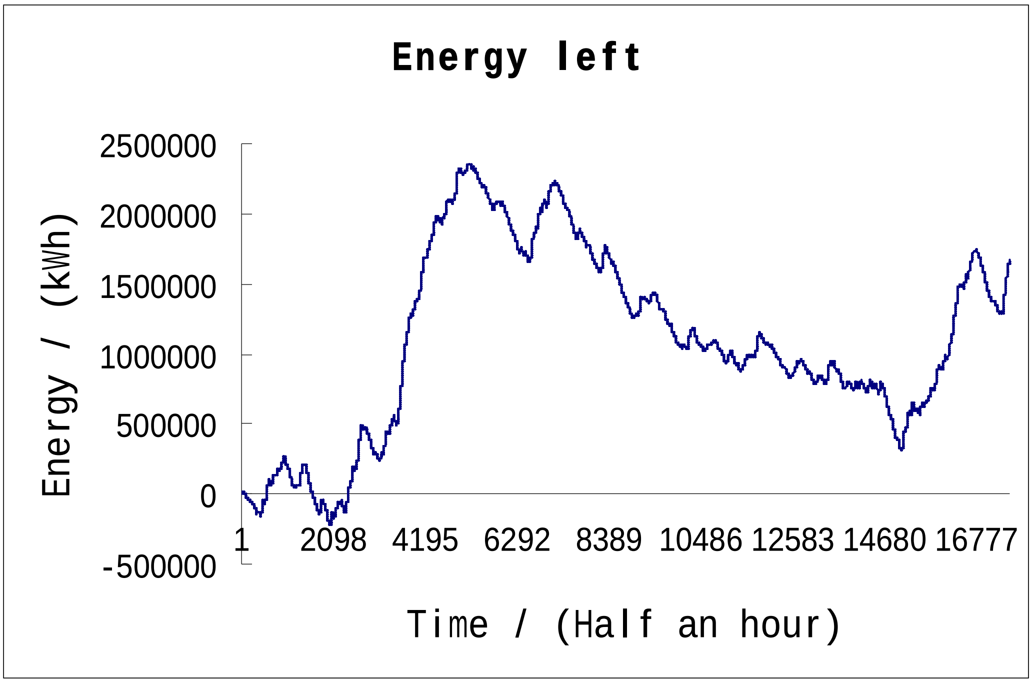

Fig. 7-7 The energy left in the real H_2-CCGT system

7.5 Capital cost and O&M cost of the designed system with H_2-CCGT

The capital cost of the system with H_2-CCGT for the University of Bath network in 2006 is the total capital costs of the main four components. The capital cost of the three V 80-2.0 MW (40 m) wind turbines is (3×2) MW $\times 1.3 \times 10^6$ \$ / MW = \$ 7.8×10^6; the capital cost of the five FDQ-400/3.0 water electrolysers is 5 × 6600 A × 274 V / 1000 × 400 \$/kW = \$ 3616800 = \$ 3.6×10^6; the capital cost of the compressed hydrogen cylinder is 9.78 GWh / 8760 h × 1500 \$/kW = \$ 1674600.8 = \$ 1.67×10^6; and the capital cost of the H_2-CCGT is 6000 kW × 497 \$/kW = \$ 2982000 = \$ 2.98×10^6. Therefore, the total capital cost of the H_2-CCGT system is

$$\$\ 7.8 \times 10^6 + \$\ 3.6 \times 10^6 + \$\ 1.67 \times 10^6 + \$\ 2.98 \times 10^6 = \$\ 16.05 \times 10^6 \quad \text{Eq. 7-1}$$

The annual O&M cost of the V 80-2.0 MW (40 m) wind turbine is 78 \$/kW/yr / 8760 h= 0.0089 \$/kWh; then for the University of Bath network in 2006, the annual O&M cost of the three V 80-2.0 MW (40 m) wind turbines is 23.6 GWh

× 0.0089 \$/kWh = \$ 2.1 × 10^5; the annual O&M cost of the five FDQ-400/3.0 water electrolysers is 9.78 GWh / 76 % × 0.012 \$/kWh = \$ 1.5 × 10^5; the annual O&M cost of the compressed hydrogen cylinder is 9.78 GWh × 0.01 \$/kWh = \$ 9.78 × 10^4; and the annual O&M cost of the H_2-CCGT is 8.11 × 10^6 kWh × 0.00416 \$/kWh = \$ 3.38 × 10^4. Add up these figures, and then the total annual O&M cost of the system with H_2-CCGT is

$$\$\ 2.1 \times 10^5 + \$\ 1.5 \times 10^5 + \$\ 9.78 \times 10^4 + \$\ 3.38 \times 10^4 = \$\ 4.9 \times 10^5$$

Assuming all the energy consumed in the University of Bath network is electricity, then it costs about 13651765 kWh × £ 0.143 / kWh × 1.8 = \$ 3.51 × 10^6 in 2006. In this case, the additional benefit of oxygen is not taken into account.

The energy left in the hydrogen energy storage system is hydrogen energy, so the Estimated Annual Net Cash Flow of the system for the University of Bath network in 2006 is the value of 1.67 × 10^6 kWh of hydrogen energy and the cost of the total electricity consumed. According the calculations before, the net cash flow of the energy left in the system is 1.67 × 10^6 kWh / 33.3 kWh / kg × 10 \$ / kg = \$ 5 × 10^5. At last, the Estimated Annual Net Cash Flow of the designed system with H_2-CCGT for the University of Bath network in 2006 is \$ 3.51 × 10^6 + \$ 5 × 10^5 = \$ 4.01 × 10^6.

The capital cost of the designed H_2-CCGT system is \$ 16.05 × 10^6 and the annual O&M cost is \$ 496109.8; the cycle lives of the V 80-2.0 MW (40 m) wind turbines, the FDQ-400/3.0 water electrolysers, and the compressed hydrogen cylinder for the University of Bath network all can be up to 20 years, and the cycle lives of the hydrogen-fuelled SGT-100 gas turbine and SST-050 steam turbine from Siemens are longer than 200000 h. Therefore, the first set of designed H_2-CCGT system for the University of Bath network can be a 20 years project as well. The total 20 years' O&M cost of the H_2-CCGT system is

$$20 \times (\$\ 2.1 + \$\ 1.5 + \$\ 0.98) \times 10^5 + 20 / 23 \times \$\ 0.34 \times 10^5 = \$\ 9.28 \times 10^6 \qquad \text{Eq. 7-2}$$

The 20 years project costs of the designed system with H_2-CCGT for the University of Bath network are the capital cost and the 20 years' O&M cost, which equal to $ 16.05 × 10^6 + $ 9.28 × 10^6 = $ 25.3 × 10^6.

The payback time of the designed system with H_2-CCGT for the University of Bath network can be calculated:

$$\text{Payback Time} = (\$25.3 \times 10^6) / \$\ 4.01 \times 10^6\ /\text{year} = 6.3 \text{ years} \qquad \text{Eq. 7-3}$$

Over the 20 year project, the total net benefit of the designed system with H_2-CCGT for the University of Bath network is

$$\$\ 4.01 \times 10^6 \times (20 - 6.3) = \$\ 5.5 \times 10^7 \qquad \text{Eq. 7-4}$$

The characteristics of the 20 years project with the whole designed system with H_2-CCGT for the University of Bath network, which are worked out in Section 7.4.2 and this section, are shown in Table 7-2. The results show that the designed system with H_2-CCGT is suitable for the 5 MW micro-grids. Although the capital cost and O&M cost are huge, the revenue is rich and generous.

Table 7-2 Characteristics of the whole designed H_2-CCGT system over the 20 year project

	Designed H_2-CCGT system	**Source**
Round-trip efficiency	38.6 %	---
Wind turbine size (m)	69.3	---
Capital cost ($)	16.05 × 10^6	Eq. 7-1
O&M cost ($)	9.28 × 10^6	Eq. 7-2
Payback time (years)	6.3	Eq. 7-3
Return on investment ($)	5.5 × 10^7	Eq. 7-4

7.6 Summary

During this case study, the whole realistic proposed system contains: three Vestas V 80-2.0 MW wind turbines, which can be used to generate wind energy, instead of a single 69.3 m wind turbine; five FDQ-400/3.0 water electrolysers from Tianjin Mainland Hydrogen Equipment Co., Ltd, to split the water into hydrogen and oxygen; a hydrogen cylinder with 5888 m^3, used to store the excess wind energy; and a H_2-CCGT including a SGT-100 gas turbine and a SST-050 steam turbine from Siemens could be chosen to convert hydrogen energy to electricity, when the wind energy is not sufficient. These components from the current commercial market are used to design the system with H_2-CCGT for the University of Bath network. Actually there are several other manufacturers of components that could be used instead of these particular parts; they are just available realistic examples. Besides these components, three transformers, one AC/DC adaptor, and one control system are required for the whole system.

The round-trip efficiency of the designed H_2-CCGT system is 38.6 %, and a large single size of 69.3 m wind turbine is required. Over the 20 year project, the designed H_2-CCGT system can pay itself back after six years and 4 months. Also, the revenue of the whole system after 20 years is $\$ 5.5 \times 10^7$. The feasibility of the designed system with H_2-CCGT was verified by the results for the University of Bath network.

Chapter 8 Conclusions & Future work

THIS chapter draws some conclusions for the thesis based on the main work presented. It is followed by discussions about potential future work.

8.1 Conclusions

The thesis has given an account of, and the reasons for, widespread use of energy storage in renewable energy systems. Power system imbalance can cause problems with safe operation, or exceed the capacity of power transmission systems. Therefore, increasing penetration of renewable power generation within existed power systems makes it necessary to carry out research into the applications of energy storage systems to solve the problem created by intermittency of the variable renewable generation resources.

Energy storage is one of the most effective methods that can be employed by power system engineers to enhance the penetration of renewable energy within power systems. This thesis has investigated different energy storage methods, especially flywheels, NaS batteries, and hydrogen energy storage. Furthermore, different hydrogen storage methods and kinds of hydrogen to electricity conversion equipment were studied during this research.

The purpose of the study was to determine which energy storage approach was the optimal method to integrate renewable energy into a typical 5 MW micro-grid. In this research, the University of Bath network was used as a case study. In this investigation, the traditional electricity distribution method and hydrogen pipeline approach are compared. Half hourly wind and load data for the University of Bath in 2006 was used to design the wind turbine and the energy store sizes. The feasibility of the energy storage system that was finally designed was verified using this data.

In recent years, there has been an increasing amount of literature published on different energy storage methods being introduced into wind power systems, including: PHS; CAES; BES; FES; SMES; SCES; and HES. After a comparison of each method, Flywheels, NaS batteries and hydrogen energy storage were chosen for further comparisons based on their relative merits.

Various hydrogen production sources were investigated. The water electrolysis method has been chosen for this study because it is a well-developed method with a high efficiency of 75 %. Different hydrogen storage methods were carefully compared as well. The compressed gas approach has been chosen as a better solution due to its relatively higher efficiency, easier operation and lower leakage rate, compared with the other hydrogen energy storage methods. Many kinds of hydrogen to electricity conversion equipment have been considered. The mature technology, PEMFC was initially chosen for this research to form an initial system and then used to verify the feasibility of the hydrogen energy storage method for the University of Bath network.

A new wind power design methodology was developed to work out the size of the initial hydrogen energy storage system. Half hourly wind data observed by the Met Office, UK, and half hourly load data from the University of Bath, UK, were used in the new algorithm. The excess energy generated was stored taking consideration of energy losses. Conversely, if the energy generated was less than the load, the energy should be recovered from the stored energy. The results showed that electricity demand can be met for the test system entirely by the equivalent of a single 72 m radius wind turbine in conjunction with a compressed hydrogen energy storage and recovery system with a 17190 m^3 capacity. Since the technology is not at a sufficiently mature stage of development to manufacture this size wind turbine, a set of several smaller wind turbines, e.g. 40 m radius, could be used in practice.

The calculations show that using the hydrogen energy storage to provide “off-grid” renewable energy smooth certainly seems practical when using this optimal methodology. The models of the wind turbine, water electrolysis, compressed hydrogen cylinder, and PEMFC have been initially chosen to make sure of the efficiencies and other technical parameters for the calculations and comparisons. Besides these, three transformers, one AC/DC adaptor, and one control system are required for the hydrogen energy storage system. A general system structure is worked out for calculating the energy flow.

The most obvious finding to emerge from this study was that energy storage is a desirable approach to improve the penetration of wind energy. As an alternative to the traditional method of electricity distribution, hydrogen gas can be delivered like natural gas with appropriate upgraded pipelines. The feasibility of hydrogen transportation was demonstrated using half hourly demand data for four of the buildings in the University of Bath, picked out by their locations.

The traditional approach for delivering the energy indicates a big ClearGen multi-500 kW PEMFC located in the centre and shared by the four buildings; the new approach introduced in this study was that each building has its own FCgen-1300 series PEMFC. A comparison of the two results reveals that for the chosen network, the capital cost of the shared PEMFC system is lower than the distributed PEMFCs system. However, the round-trip efficiency of the shared PEMFC system is lower than the distributed PEMFCs system; and the hydrogen storage size of the shared PEMFC system is much larger than the distributed PEMFCs system. Therefore, it is hard to tell which one is the optimal approach for the chosen network.

The comparisons of flywheels, NaS batteries, and hydrogen energy storage were conducted in terms of energy loss, efficiency, cost, and life cycle. Analyzing the results, it can be seen that flywheels were not suitable for the University of Bath network, due to their high energy loss and self-discharge rate; NaS batteries and hydrogen energy storage were considered to be promising approaches for long-term energy storage purposes.

Further comparisons show that NaS batteries have a lower capital cost and annual O&M cost than hydrogen energy storage. However, the energy loss rate of hydrogen energy is slower than NaS batteries. The results also show that hydrogen storage has a longer life cycle, which makes it useful for long-term storage when compared with the other energy storage technologies. From the comparisons of energy losses and efficiencies, the best energy storage method cannot be concluded yet, because the energy left in the two systems meet at around 150 days.

Therefore, the payback time and the return on investment were investigated in order to find the optimal energy storage technologies for the University of Bath network. For this study, hydrogen and oxygen were produced from the water electrolysis, and could be used for the step of hydrogen to electricity conversion, like PEMFCs. However, air could be used instead of oxygen, which can be sold for other applications, in the step of hydrogen to electricity conversion. Then the return on investment can be compared between the two, considering the additional benefit with and without oxygen.

In the case for the system without the additional benefit of oxygen, regardless of whether the payback time is for the first set of devices project, or for the 20 year project, the NaS battery system has shorter payback time than the hydrogen energy storage system. Moreover, after 20 years, the return on investment of the NaS battery system is much higher than it is for the hydrogen energy storage system for the University of Bath network.

In the case for the system including the additional benefit of oxygen, the results are quite different. The payback time of the hydrogen energy storage system is much shorter and the return on investment over the 20 year project is greatly increased. Therefore, the hydrogen energy storage system is more economical than the NaS battery system for the University of Bath network, for this case when selling the oxygen and using air instead for the stage of hydrogen to electricity conversion.

Generally speaking, when integrating energy storage into the power system, CO_2 emissions can be significantly reduced and the penetration of the wind energy can be improved.

Hydrogen energy storage has not been used on a widespread basis, due to the high cost and low efficiency of the PEMFC. This PhD project has studied hydrogen energy storage by introducing SOFCs, H_2-ICEs or H_2-CCGTs instead of the PEMFCs. The investigation results of some hydrogen to electricity conversion devices, which could be used in the hydrogen energy storage system for the University of Bath network, have been presented. This initial study was carried out using typical data for SOFCs, PEMFCs, H_2-ICEs, and H_2-CCGTs for comparisons.

The results indicate that the best approach for the University of Bath network is H_2-CCGT, because of its higher efficiency and lower cost. Also, it does not need the high operation temperature as SOFC does. The system with H_2-CCGT has much greater return on investment than the other systems, although its payback time is not as short as SOFC.

Therefore, the H_2-CCGT was chosen for the final system design. For the University of Bath network, after full analysis, the system with H_2-CCGT includes: three Vestas V 80-2.0 MW wind turbines; five FDQ-400/3.0 water electrolysers from Tianjin Mainland Hydrogen Equipment Co., Ltd; one compressed hydrogen cylinder with 5888 m^3; and one Siemens H_2-CCGT consisting of a SGT-100 gas turbine and a SST-050 steam turbine was designed for the University of Bath network.

Half hourly wind and load data for the University of Bath in 2006 was used again to verify the feasibility of the designed system with H_2-CCGT. The calculations show that the round-trip efficiency of the designed system with H_2-CCGT is 38.6 %. A wind turbine equivalent to a large single 69.3 m is required. It has been shown that over the 20 year project, the designed system with H_2-CCGT can pay itself back after six years and four months. Moreover, the revenue of the whole system after 20 years without considering the additional benefit of oxygen is $\$ 5.5 \times 10^7$. Large wind turbines (much larger than the load) make energy storage pointless, but contribute a lot to revenue, if considering the additional benefit of selling on the hydrogen and oxygen.

This study has found that generally the hydrogen energy storage system is an attractive and effective solution for the University of Bath network. The hydrogen energy storage system with H_2-CCGT is economical and suitable for a 5 MW micro-grid. From this research, NaS battery system and hydrogen energy storage system are both feasible for a system size of this size. However, from the simulation results shown in Section 6.4, a NaS battery system is more suitable for networks that switch between storing energy and releasing energy less frequently. This can reduce the number of cycles of the NaS batteries, in order to extend the life cycle, which makes the NaS battery system more economic; on the contrary, a hydrogen energy storage system is better for the larger networks. This is because the energy in the hydrogen energy storage system can be stored over several months, allowing it to be moved to less windy months.

From this research, the algorithms in Chapter 4 – describing how to size the wind turbine and how to size the energy storage – can be scaled in any size of network with wind generation. The result can be obtained by inputting the local wind speed and load data to the new methodology that has been developed. The hydrogen pipeline is more economic when used in large-scale networks. The algorithm in Chapter 6 – describing how to determine the cycle times – could be used for any electro-chemical devices in any scale of electrical network, given the depth of discharge against life cycle relationship. Therefore, these new methodologies developed in this PhD work could be adapted in any scale off-grid network with wind generation.

8.2 Future work

Finally, a number of important limitations need to be considered. First, this research is based on an isolated micro-grid network. Second, the study considers the energy storage method only, without other solutions. Third, Chapter 5 of this thesis describes the novel idea of distributing the energy using hydrogen pipelines, but only a simplified comparison of energy transport is given. Fourth, in this research renewable energy was limited to only wind energy.

Based on the work presented in this thesis, it is recommended that further research to be undertaken is in the following areas:

1) A large scale power system could be investigated to check the feasibility of the energy storage method. A backup system of the off-grid network should be designed simultaneously.

   Grid-connected renewable generation will significantly affect power transmission and generation systems. Integrating energy storage into the grid-connected renewable generation can be further researched.

2) NaS battery, flywheel, and hydrogen energy storage can be combined for new energy storage approaches to be used in an off-grid or grid-connected network. Simulations can be carried out to allocate the sizes of these energy storage methods, in order to find the most economical method.

3) Curtailing the output of the wind turbine is currently a common method used to protect the turbines in high wind, or to stay within power constraints nowadays. Comparison of curtailing the wind turbine output and the use of energy storage approaches can be studied to find out which method is more economic and effective. Combining curtailing wind turbine output with energy storage is expected to perform well in these further investigations.

4) In Chapter five, this work has only done a brief study of which energy transport method is better for the University of Bath network--the traditional electricity distribution method or the hydrogen pipeline approach. A more in-depth study is needed to determine which energy transport method is suitable for a wider range of other power systems.

5) In nature, the sun normally comes out on the less windy days and hides away on the windy days. Therefore, PV can usefully be introduced in this system, combined with the wind energy to reduce the intermittent behaviour of the combined renewable energy generation.

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Appendix

Appendix 1. The Matlab code of the dynamic energy flow, and cycle time

Appendix 2. The worksheet of the algorithms

Appendix 1. The matlab code of the dynamic energy flow, and cycle time

```
Eg_H2=[

];

Eg_NaS=[

];

Ld=[

];

format long;
disp('Calculation begins!')
% days in one year
%D_in_Y=365;
D_in_Y=17520;
%time span in on day
%T_in_D=48;
T_in_D=1;


Eg_H2_365=zeros(D_in_Y,1);
Eg_NaS_365=zeros(D_in_Y,1);
Ld_365=zeros(D_in_Y,1);


j_begin=1;
j_end=T_in_D;


% Eg_H2_365(1)=Eg_H2(1);
% Eg_NaS_365(1)=Eg_NaS(1);
% Ld_365(1)=Ld(1);

%--------variables for H2---
Time_store_H2=0;
Time_release_H2=0;
store_H2=false;
release_H2=false;
cycle_H2=0;

E_surplus_H2=zeros(D_in_Y,1);
Total_E_surplus_H2=0;
Daily_surplus_H2=zeros(D_in_Y,1);
loss_rate_H2=1-power((1-0.00000033),1/47);
loss_rate_NaS=1-power((1-0.005),1/47);
```

```
%--------variables for NaS---
Time_store_NaS=0;
Time_release_NaS=0;
store_NaS=false;
release_NaS=false;
cycle_NaS=0;

E_surplus_NaS=zeros(D_in_Y,1);
Total_E_surplus_NaS=0;
Daily_surplus_NaS=zeros(D_in_Y,1);

% for i=1:1:(D_in_Y-1)
%         for j=j_begin:1:j_end
%               Eg_H2_365(i+1)=Eg_H2_365(i)+Eg_H2(j);
%               Eg_NaS_365(i+1)= Eg_NaS_365(i)+Eg_NaS(j);
%               Ld_365(i+1)=Ld_365(i)+Ld(j);
%         end
%         j_begin=j_end+1;
%         j_end=j_begin+T_in_D-1;
% end


Eg_H2_365=Eg_H2;
Eg_NaS_365=Eg_NaS;
Ld_365=Ld;

for i=1:1:D_in_Y

      %-------------------to calculate the surplus of H2 storage
      if Eg_H2_365(i)>=Ld_365(i)
            E_surplus_H2(i)=(Eg_H2_365(i)-Ld_365(i))*0.6204;

Total_E_surplus_H2=Total_E_surplus_H2*(1-loss_rate_H2)+E_surplus_H2(i);

            Time_store_H2=Time_store_H2+1;
            store_H2=true;

Daily_surplus_H2(i)=Daily_surplus_H2(i)+E_surplus_H2(i)*(1-loss_rate_H2);

      else
            E_surplus_H2(i)=(Eg_H2_365(i)-Ld_365(i))/0.49;

Total_E_surplus_H2=Total_E_surplus_H2*(1-loss_rate_H2)+E_surplus_H2(i)
  ;

            Time_release_H2=Time_release_H2+1;
            release_H2=true;
```

```
Daily_surplus_H2(i)=Daily_surplus_H2(i)+E_surplus_H2(i)*(1-loss_rate_H2);
    end

    if(store_H2 && release_H2)
        cycle_H2=cycle_H2+1;
        store_H2=false;
        release_H2=false;
    end
    %----------------end of H2 storage


    %-------------------to calculate the surplus of NaS storage
    if Eg_NaS_365(i)>=Ld_365(i)
        E_surplus_NaS(i)=(Eg_NaS_365(i)-Ld_365(i))*0.67228;

Total_E_surplus_NaS=Total_E_surplus_NaS*(1-loss_rate_NaS)+E_surplus_NaS(i);

        Time_store_NaS=Time_store_NaS+1;
        store_NaS=true;


Daily_surplus_NaS(i)=Daily_surplus_NaS(i)+E_surplus_NaS(i)*(1-loss_rate_NaS);
    else
        E_surplus_NaS(i)=(Eg_NaS_365(i)-Ld_365(i))/0.9604;

Total_E_surplus_NaS=Total_E_surplus_NaS*(1-loss_rate_NaS)+E_surplus_NaS(i);

        Time_release_NaS=Time_release_NaS+1;
        release_NaS=true;


Daily_surplus_NaS(i)=Daily_surplus_NaS(i)+E_surplus_NaS(i)*(1-loss_rate_NaS);
    end

    if(store_NaS && release_NaS)
        cycle_NaS=cycle_NaS+1;
        store_NaS=false;
        release_NaS=false;
    end
    %----------------end of NaS storage

end

disp('---------------------------------------');
disp('--------Results for H2 storage:--------');
```

```
disp('Time to store (H2):');
disp(Time_store_H2);

disp('Time to release (H2):');
disp(Time_release_H2);

disp('Cycle time (H2):');
disp(cycle_H2);
disp('---------------------------------------');


disp('--------Results for NaS storage:-------');
disp('Time to store (NaS):');
disp(Time_store_NaS);

disp('Time to release (NaS):');
disp(Time_release_NaS);

disp('Cycle time (NaS):');
disp(cycle_NaS);
disp('---------------------------------------');


temp_H2=Daily_surplus_H2(1:1488,:);
plot(temp_H2,'black');
hold on;

% temp_NaS=Daily_surplus_NaS(1:1488,:);
% plot(temp_NaS,'black');
% plot(Daily_surplus_NaS,'black');
```

Appendix 2. The worksheet of the algorithms

		wind spee	IF(wind s	wind energy	stored energy			release ene	energy left	power(kw)	load(kwh)	difference
0020Z	2006-1-1	5.658884	7.865849	1227.6916	427.16724	1.239	row	0	427.16724	1079.2	539.6	688.09155
0050Z	2006-1-1	6.687772	9.296003	2026.4751	926.0319	44907122	load	0	1353.1991	1069.6	534.8	1491.6751
0120Z	2006-1-1	6.173328	8.580926	1593.8775	656.45102	0.5	Cp	0	2009.6502	1072.9	536.45	1057.4275
0150Z	2006-1-1	6.173328	8.580926	1593.8775	655.86126	3.142	pi	0	2665.5114	1074.8	537.4	1056.4775
0220Z	2006-1-1	7.71666	10.72616	3113.0421	1602.342	72	radius	0	4267.8534	1063.9	531.95	2581.0921
0250Z	2006-1-1	8.231104	11.44123	3778.0801	2012.9627	2522.6238	factor	0	6280.816	1071.1	535.55	3242.5301
0320Z	2006-1-1	7.71666	10.72616	3113.0421	1597.2824	25487715	generated	0	7878.0985	1080.2	540.1	2572.9421
0350Z	2006-1-1	8.231104	11.44123	3778.0801	2008.8033	10130880	stored	0	9886.9018	1084.5	542.25	3235.8301
0420Z	2006-1-1	8.231104	11.44123	3778.0801	2008.9585	9149229.7	recovrd	0	11895.86	1084	542	3236.0801
0450Z	2006-1-1	7.202216	10.01108	2531.0185	1231.2441	1.39	hub adjust	0	13127.104	1095.4	547.7	1983.3185
0520Z	2006-1-1	6.173328	8.580926	1593.8775	649.87054	0.2101649	load factor	0	13776.975	1094.1	547.05	1046.8275
0550Z	2006-1-1	7.71666	10.72616	3113.0421	1592.2229	2580234.1	store size	0	15369.198	1096.5	548.25	2564.7921
0620Z	2006-1-1	8.231104	11.44123	3778.0801	1999.6155	-5903499.7	pure stored	0	17368.813	1114.1	557.05	3221.0301
0650Z	2006-1-1	7.202216	10.01108	2531.0185	1224.198	7347757.6	wind in	0	18593.011	1118.1	559.05	1971.9685
0720Z	2006-1-1	6.687772	9.296003	2026.4751	908.40118	18671897	electricity ou	0	19501.413	1126.4	563.2	1463.2751
0750Z	2006-1-1	7.202216	10.01108	2531.0185	1220.1939	0.6208		0	20721.607	1131	565.5	1965.5185
0820Z	2006-1-1	6.687772	9.296003	2026.4751	906.10422	0.49		0	21627.711	1133.8	566.9	1459.5751
0850Z	2006-1-1	6.173328	8.580926	1593.8775	642.26574	0.304	efficiency	0	22269.976	1118.6	559.3	1034.5775
0920Z	2006-1-1	4.629996	6.435694	672.41709	71.340528			0	22341.317	1115	557.5	114.91709
0950Z	2006-1-1	4.115552	5.720617	472.26001	0			165.18365	22176.133	1106.4	553.2	-80.939988
1020Z	2006-1-1	3.086664	4.290463	199.23469	0			743.50063	21432.633	1127.1	563.55	-364.31531
1050Z	2006-1-1	5.14444	7.150772	922.38284	224.47062			0	21657.103	1121.6	560.8	361.58284
1120Z	2006-1-1	5.14444	7.150772	922.38284	222.08054			0	21879.184	1129.3	564.65	357.73284
1150Z	2006-1-1	4.115552	5.720617	472.26001	0			197.73467	21681.449	1138.3	569.15	-96.889988
1220Z	2006-1-1	3.601108	5.00554	316.37731	0			510.86263	21170.587	1133.4	566.7	-250.32269
1250Z	2006-1-1	3.086664	4.290463	199.23469	0			751.45981	20419.127	1134.9	567.45	-368.21531
1320Z	2006-1-1	4.629996	6.435694	672.41709	63.735728			0	20482.863	1139.5	569.75	102.66709
1350Z	2006-1-1	5.14444	7.150772	922.38284	216.40022			0	20699.263	1147.6	573.8	348.58284
1420Z	2006-1-1	5.658884	7.865849	1227.6916	409.66068			0	21108.923	1135.6	567.8	659.89155
1450Z	2006-1-1	5.658884	7.865849	1227.6916	407.05332			0	21515.977	1144	572	655.69155
1520Z	2006-1-1	5.14444	7.150772	922.38284	218.13846			0	21734.115	1142	571	351.38284
1550Z	2006-1-1	4.115552	5.720617	472.26001	0			206.3061	21527.809	1146.7	573.35	-101.08999
1620Z	2006-1-1	4.115552	5.720617	472.26001	0			230.48977	21297.319	1170.4	585.2	-112.93999
1650Z	2006-1-1	4.629996	6.435694	672.41709	49.550448			0	21346.87	1185.2	592.6	79.817087
1720Z	2006-1-1	4.629996	6.435694	672.41709	51.350768			0	21398.221	1179.4	589.7	82.717087
1750Z	2006-1-1	4.629996	6.435694	672.41709	51.319728			0	21449.54	1179.5	589.75	82.667087
1820Z	2006-1-1	4.629996	6.435694	672.41709	54.920368			0	21504.461	1167.9	583.95	88.467087
1850Z	2006-1-1	4.115552	5.720617	472.26001	0			223.04079	21281.42	1163.1	581.55	-109.28999
1920Z	2006-1-1	3.601108	5.00554	316.37731	0			535.76059	20745.659	1157.8	578.9	-262.52269
1950Z	2006-1-1	4.115552	5.720617	472.26001	0			207.63263	20538.027	1148	574	-101.73999
2020Z	2006-1-1	4.629996	6.435694	672.41709	66.622448			0	20604.649	1130.2	565.1	107.31709
2050Z	2006-1-1	4.115552	5.720617	472.26001	0			193.85712	20410.792	1134.5	567.25	-94.989988
2120Z	2006-1-1	3.601108	5.00554	316.37731	0			503.82181	19906.97	1126.5	563.25	-246.87269
2150Z	2006-1-1	3.601108	5.00554	316.37731	0			493.20957	19413.761	1116.1	558.05	-241.67269
2220Z	2006-1-1	3.601108	5.00554	316.37731	0			479.02589	18934.735	1102.2	551.1	-234.72269
2250Z	2006-1-1	4.629996	6.435694	672.41709	75.903408			0	19010.638	1100.3	550.15	122.26709
2320Z	2006-1-1	4.115552	5.720617	472.26001	0			145.18365	18865.454	1086.8	543.4	-71.139988
2350Z	2006-1-1	4.629996	6.435694	672.41709	85.277488			0	18950.732	1070.1	535.05	137.36709
0020Z	2006-1-2	4.115552	5.720617	472.26001	0			111.71426	18839.018	1054	527	-54.739988
0050Z	2006-1-2	2.57222	3.575386	115.29785	0			853.88193	17985.136	1067.4	533.7	-418.40215
0120Z	2006-1-2	3.601108	5.00554	316.37731	0			442.59732	17542.538	1066.5	533.25	-216.87269
0150Z	2006-1-2	2.57222	3.575386	115.29785	0			847.04519	16695.493	1060.7	530.35	-415.05215
0220Z	2006-1-2	2.57222	3.575386	115.29785	0			849.59622	15845.897	1063.2	531.6	-416.30215
0250Z	2006-1-2	2.57222	3.575386	115.29785	0			856.22887	14989.668	1069.7	534.85	-419.55215
0320Z	2006-1-2	2.057776	0	0	0			1086.7347	13902.933	1065	532.5	-532.5

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