Master of Science Thesis

Renewable Hydrogen Energy System For Households Application

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Acknowledgment

This Master of Science thesis was carried out at the International Master Programme in Environmental Science, Lund University (LUMES).

My thesis work was under the supervising of Professor Bertil Holmström from Chalmers University of Technology and Jan Johanson from EcomIteCH AB in Sweden. I particularly thank my supervisors for their lots of valuable suggestions and comments. The topic of renewable hydrogen energy system was a brand new subject to me and the thesis could not be finished without their guidance and support throughout the period of thesis work.

I also wish to express my gratitude to Professor Harald Sverdrup from LUMES for his valuable advice and encouragement to my thesis work.

Finally, I would like to thank my classmate Frank Grimm who provided me a lot of information and ideas on this topic.
Abstract

The purpose of this thesis is to define and assess a renewable hydrogen energy supply system for households use. The system combines solar energy, wind energy, hydrogen production, fuel cells and households energy supply. This solar/wind hydrogen energy system is a small scale system and especially suitable for a remote village application. The whole system is a zero-emission system without any pollution and only use renewable resources, solar/wind energy and water. The components of the system are available, but have not yet to be integrated in this way. This study concentrates on solar energy as problems of wind energy are of similar nature.

The technical and economical status and prospects of system components are discussed based on literature review and recent relevant projects all over the world. The main advantages and problems of this system are discussed from technical, economic and environmental aspects. The major obstacle to apply this system derives from the need for a high capital investment. The system is not economical feasible nowadays but has great cost reduction potentials. Intensive research and development are still needed to substantially improve the efficiency and reduce the cost of the system.

The possibility of applying this system into China are discussed and evaluated. The sizes of system components are calculated based on households from Chinese urban and rural areas. Tibet and Xinjiang Provinces are recommended as suitable regions for application of this system in China considering their special resources, economic and environmental conditions.
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1 Background

1.1 Objectives

There is a growing global demand for energy, but also for reduced strain on the environment. Considerable investments were made in alternative energy research worldwide recently. Growing demand for environment-friendly energy makes renewable energy development and production a sound investment for the future. The purpose of this thesis is to define and assess a new, renewable and sustainable energy supply system for households. The objectives are:

- To define an environmentally friendly stand-alone energy supply system for households, which only uses renewable resources — solar and wind energy;
- To assess the technical and economic status and prospects of the system components;
- To discuss the advantages and problems of this system from technical, economic and environmental points of view;
- To discuss the feasibility of applying this system into China.

1.2 Scope

The solar/wind hydrogen energy system proposed in the thesis is a small scale system and especially suitable for a remote village application. The components of the system are available, but have not yet to be integrated in this way. This study concentrates on solar energy only, as problems of wind energy are of similar nature. In calculations, it is assumed that wind and solar each supply 50% of the electricity needed if a hybrid system is adopted.

1.3 Methods and Outline

The thesis is based on a literature review and experiences from relevant projects all over the world. The solar/wind hydrogen energy system defined in this thesis is based on the study of Svein Olav Morner from his Ph.D. dissertation which is ‘Seasonal Storage of Solar Energy for Self-Sufficient Buildings with Focus on Hydrogen Systems’, Norwegian Institute of Technology.

The main considerations of designing and evaluating the system include:
- the system should be renewable, i.e. all the energy comes from renewable sources;
- the whole system should be emission-free;
- the noise and safety risk should be minimized;
- it should be able to contribute to local and global sustainability;
- the system should be technological and economic feasible in the near future, if not
System analyses approach is taken which include technical, economic and sustainability analyses of the solar/wind hydrogen energy system and preliminary feasibility study for its application.

The thesis is divided into seven different chapters. A renewable hydrogen energy system with solar and wind energy is defined (chapter 3) after a brief introduction to solar, wind energy and hydrogen storage (chapter 2). Then there are general analyses in chapter 4 and 5 about the solar/wind hydrogen energy system from technical and economic perspectives. A case study is taken in chapter 6 for a Chinese village and a residential building with specific figures about the capacity demand and cost estimation of the system. Tibet and Xinjiang provinces are recommended as the best sites to apply this system in China. Conclusions are drawn at last (chapter 7) to assess the obstacles and prospects of the system.
2 Introduction

2.1 Renewable Energy Resources

Meeting energy demands for 21st century is an enormous challenge for our society and environment. The 1973 energy crisis brought the world the fact that sooner or later we would be running out of fossil fuels. More immediate are increasingly exacerbating environmental problems being caused by fossil fuels, such as pollution, acid rain, global warming, ozone layer depletion and oil spills. The increasing concern about air pollution, global warming and energy crisis will inevitably result in a transition in energy section from fossil fuel-based mode to renewable and non-polluting mode. The environment must be safeguarded when meeting people’s need for lighting, power, heating and cooling.

Sustainable energy production is an important component of sustainable development. Basically there are two possible approaches to achieve sustainable energy production. One approach is to improve efficiency of energy production, which means improving the ratio between energy input and desired energy output. It ties in with the concept of eco-efficiency and is a key component of sustainable energy strategies. Another more radical approach is to find the substitutions. Rather than use fossil fuels, power generation should increasingly look towards renewable energy sources which do not consume limited resources and also cause much less pollution than the energy forms they replace. As the conversion of energy is one of the major sources of pollution today, renewable processes that convert energy from renewable sources can be a part of the solution to the pollution problem. Increasingly, renewable and sustainable sources of energy — solar power, wind power, biomass, geothermal resources, and hydroelectric power — are contributing to meeting global energy needs.

This thesis only studies on solar energy and wind energy with focus on solar energy. It is mainly because solar energy is the most abundant renewable energy and available almost everywhere on the earth. Solar power and wind power are environment-friendly alternatives to conventional power stations. Generating electricity with the photovoltaic cells is becoming more widespread with improved technology and reduced costs. The growth of PV market will depend chiefly on how production costs evolve. Technology advances are likely to bring further significant cost reductions in the future. Wind has been recognised for some times as one of the most promising renewable sources of energy, and considerable investment and continuous development have made wind technology productive, efficient and cost-effective. In grid connected mode wind power has proven itself to be cost effective at good windy sites. In many areas of the world, solar and wind resources complement each other: winter’s winds balancing summer’s sun. Solar and wind hybrids capitalize on each technology’s assets, enabling designers to reduce the size and cost of each component.

Solar and wind energy are totally renewable and clean. They are unlimited but very dilute and intermittent. The low intensity and wide distribution of renewable sources favor decentralized end-use. Therefore energy from renewable sources will often not require much further distribution since the resources are already distributed. The main
problem to utilize the solar and wind energy is the great variation in available power which occurs from season to season, day to day, hour to hour. This would not be a problem if the load was well correlated to the energy availability, but unfortunately this is not often the case. Efficient storage is essential for large scale exploitation of intermittent renewable sources.

Today most of solar/wind electricity systems use battery as storage medium. This type of storage is expensive and large per unit of stored energy, but has the advantage of high efficiency. Batteries can be used for short term storage, but in order to keep the solar/wind power system dependable, a relatively large number of batteries will generally be needed. This can result in high costs. Until now, one of the key factors constraining the usefulness of renewable power sources has been the inability of batteries to store enough electricity to meet user needs during extended periods of calm or cloudy days.

### 2.2 Hydrogen — the Flexible Storage for Renewable Energy

The introduction of hydrogen will help to overcome the storage difficulty of renewable energy. Hydrogen can be easily produced by electricity via electrolysis and reconverted to electricity by fuel cell power plants. Hydrogen can be produced at any location using local renewable energy sources, thus avoiding the need to transport fuel to end use sites. A renewable hydrogen system with electrolyzer, storage and fuel cell can be used to provide households with a reliable power supply.

Hydrogen is the suitable energy carrier to store solar and wind energy and transform them to most convenient energy form - electricity. The temporal discord between production and demand of solar/wind energy can be compensated for. Compared to battery storage, hydrogen storage has improved storage density, economies of scale, temperature response characteristics and lifetimes. If there is a need to store a large amount of energy for a long time, hydrogen storage system is today often cheaper and more compact than battery storage. So hydrogen is preferred as media in a long-term storage.

Hydrogen (H) is the lightest and most abundant element in the universe. On a molar basis, 2/3 of the oceans are H. Hydrogen is little polluting when burning and capable of conversion directly to electricity in fuel cells with no pollution. The benefits of hydrogen make it the ideal component of a renewable, sustainable energy system of the future. Furthermore, the utilization of hydrogen is not limited to power plants. Hydrogen as a flexible energy carrier can be used as a fuel for mobile applications like fuel cell powered vehicles. Unfortunately, the widespread use of hydrogen energy is not currently feasible because of economic and technological barriers.

Although hydrogen element is so abundant, molecular hydrogen (H$_2$) is very reactive and does not exist anywhere on earth (unless manufactured by chemical approaches). Almost all of the world's hydrogen production today comes from fossil fuels: 3/4 from natural gas, 1/4 from oil or coal. The problem with producing hydrogen from fossil fuel is that greenhouse gases are produced in the process. Hydrogen can also be made
from water by electrolysis, using any source of DC electricity. Only 1-4 % of hydrogen are currently produced from the electrolysis of water, which is presently a very expensive process. If electrical power is used to electrolyze water, you must consider the energy source for producing the electricity. If it is fossil fuel based or nuclear, then you still have a pollution problem.

The advantages of using hydrogen as storage medium for renewable sources are obvious. Hydrogen made from renewable energy resources is an inexhaustible, environmentally friendly energy carrier. So is electricity made from renewable energy sources. As an energy carrier, hydrogen will help make renewable energy sources viable and practical. International interest in hydrogen as an energy carrier is high. Research, development and demonstration of hydrogen energy systems are in progress in many countries. The development of hydrogen energy carrier systems will be supported by the expected fast development of fuel cells for mobile applications in the near future.
3 Define A Renewable Hydrogen Energy System For Households

3.1 System Design for Households Energy Supply

3.1.1 Electricity Supply

The energy production and storage system studied in this thesis is to convert solar/wind energy to electricity and heat to meet the energy demands of households. The system is a stand-alone system with all the energy coming from sun and wind. Thus the system has to be located at some places with rich solar/wind resources. The loads of the system are the energy needs of households, which include electricity, heating and cooling. The energy needs for communication and transportation are not included. The system should be able to supply all the energy needs of households throughout the year in normal weather conditions. The reliability of the system will depend on sufficient hydrogen storage to meet the energy needs of households when there is no solar or wind energy available.

The renewable hydrogen energy system for households electricity supply is defined as: Solar/Wind energy — PV Cells/Wind turbines — Converter — Electrolyzer — Hydrogen storage — Fuel cells — (Power conditioner) — Households.

The renewable hydrogen energy system consists of the following major components:
- Photovoltaics/Wind turbines producing electricity
- Electrolyzer producing hydrogen
- Hydrogen Storage
- Fuel Cells producing electricity from hydrogen

Here is how the solar/wind hydrogen system works: Photovoltaics and wind turbines convert solar and wind energy into direct current electricity which is utilized by the electrolyzer to separate water into its two constituents: hydrogen and oxygen. The oxygen is released into the air and the hydrogen is stored in compressed gas form. The stored hydrogen can be efficiently converted back into electricity on demand using fuel cells. Power conditioning includes DC to AC inversion and current and voltage controls. It is optional and will not be needed if the household equipment can use 24V DC electricity. The only byproduct of this process is pure water. There is no need for hydrogen transport in this system. This clean and efficient stand-alone power supply system can provide consistent dependable electricity for households.

The system defined above is especially for a village or a building, considering that it is more cost-effective to supply energy to many households together than only to one household. The possible solutions for the power supply of a village and a residential building are illustrated in figure 3.1 and 3.2 (wind turbines are not showed here).

Specific weather condition is important for choosing a solar, wind or hybrid system, i.e. utilizing wind energy in windy areas and solar energy in sunny areas. Stand-alone
power systems, however, seldom use wind energy exclusively. A hybrid system which combine solar and wind energy will increase the system capacity and efficiency if the wind resource is abundant at the application site. The pattern of the wind varies from place to place. The wind generator will supply energy during all seasons but the energy collected during winter and nights is especially valuable. The best combination will be wind turbines on a location that have the largest energy output in winter. The storage capacity and solar area needed in a stand-alone system can thus be reduced.

Figure 3.1 Solar hydrogen energy system for a village

Figure 3.2 Solar hydrogen energy system for a residential building
3.1.2 Thermal Energy Supply

Thermal energy supply is another important consideration for households. Space heating is especially difficult for a solar system because heating is needed during wintertime when there is less solar energy available. There are two different systems considering that if the thermal energy is utilized in the solar/wind hydrogen systems.

One is the all-electrical system which will supply all the loads with electricity. This system needs large components due to the exclusive use of high grade energy-electricity. For all-electrical systems, it is crucial to find an efficient solution to meet the heating and cooling demand of households. Firstly, heating and cooling represent a relatively large portion of energy demand of households, which will influence the total energy loads substantially. Secondly, it is necessary to find a more energy-saving way to supply the heating and cooling to households as the renewable hydrogen energy system is an environmentally friendly system itself.

Heat pump seems to represent a promising solution to the heating and cooling demand of households, especially for the stand-alone system in a remote area. It is more energy efficient and cost-effective compared with other traditional residential heating and cooling systems. By definition, a heat pump is a machine which moves heat. In the winter, a heat pump draws heat from the outdoor air and circulates it through ducts into the house. During the summer, it reverses the process and draws heat from interior air and releases it outdoors. So the heat pump can serve both as air conditioner and heater. The drawback of the heat pump is that it is preferred to be installed in areas where winter temperatures do not get too low if without backup system.

Generally speaking, heat pumps with higher efficiency are more expensive than traditional counterparts. However, because they utilize less electricity, they are actually more cost-effective in the long run. Heat pump could also be used for water heating. Heat pump water heaters are an energy-efficient way to heat water with electricity, typically providing the same amount of hot water at one-half to one-third the energy used in electric resistance water heaters (Pacific Northwest National Laboratory, 1995).

Another system is electrical and thermal system. The electrical and thermal system is competitive, especially when the electrical system can not supply enough electricity to cover the whole load. There are two possible sources to get thermal energy from the solar/wind hydrogen system. One is from solar thermal collectors which will take up some space from photovoltaic panels. Flat plate collectors are the most common thermal collectors for small scale systems. The most common way of storing solar thermal energy is to heat water. The advantage of this storage method is that the storage media is cheap and the technology is well known. Water also has a high thermal capacity. The advantage of using solar thermal collector is that the efficiency of solar collector is 5 to 8 times higher than PV cells and solar collector is much cheaper than PV cells (S. Morner, 1995). Another source is from fuel cells waste heat. It is possible to use the heat produced from fuel cells to provide hot water for households. It will increase the system efficiency but the complexity and costs of whole system will also increase.
The combination of solar thermal collector and fuel cells “waste” heat could be used for water and space heating. The advantage of using thermal energy for households heating is that it will reduce the loads of renewable hydrogen system, and consequently the sizes and costs of components. There are different possible configurations for thermal energy system, including using heat pump, solar heat, fuel cells waste heat or combining them together in different ways. The different approaches for thermal energy supply is illustrated in figure 3.3.

![Figure 3.3 Thermal Energy Supply of the Solar/Wind Hydrogen System for Households](image)

Which approach is better for the renewable energy system depends on the specific conditions of applications, especially the weather conditions. For example, in a cold area where heating is the major consideration and solar energy is well available during wintertime, it would be a better choice to adopt a solar thermal system together with fuel cells waste heat. For a relatively warmer area where space heating and cooling are both needed, and it is not sunny enough during wintertime, a heat pump will be a obvious better choice, which is supplied by the energy stored in hydrogen from the solar energy of wintertime as well as summertime, or together from wind energy.

### 3.2 Introduction to Main System Components

#### 3.2.1 Primary Electricity Production

**3.2.1.1 Photovoltaics**

Photovoltaics are solid state semiconductor devices that convert light directly into direct current electricity. When the sunlight strikes the cells, a flow of electrons is generated proportional to the intensity of the sunlight and the area of the cell. The power produced by a photovoltaic system is the product of incident solar radiation (S), the PV system’s energy conversion efficiency (η) and the area of solar panel (A): \( P = S \times \eta \times A \). Economic consideration has always been crucial in choosing a solar system, i.e. to choose the cheapest way to produce electricity with full considerations of the efficiency, cost and stability of the system.
Each solar cell produces approximately one-half volt. Single PV cells are connected electrically to form PV modules, which are the building blocks of PV systems. Although individual PV cells produce only small amounts of electricity, PV modules are manufactured with varying electrical outputs ranging from a few watts to more than 100 watts of direct current (DC) electricity. The modules can be connected into PV arrays for powering a wide variety of electrical equipment. The photovoltaic panels are usually mounted on the roof of the house, preferably on a south-facing slope. This modularity is an advantage of the photovoltaic system.

Two primary types of PV technologies available commercially are crystalline silicon and thin film. In crystalline-silicon technologies, individual PV cells are cut from large single crystals or from ingots of crystalline silicon. In thin-film PV technologies, the PV material is deposited on glass or thin metal that mechanically supports the cell or module. Thin film PV are inherently cheaper to produce than crystalline silicon but are not as efficient.

3.2.1.2 Wind Turbines

Wind turbines are already supplying economically competitive electricity throughout the world. Wind turbine hardware and management experience are available in the marketplace. Today’s best machines can convert about 40% of the wind’s energy to mechanical energy. The overall efficiency of conversion to electricity is about 35% (US Department of Energy, 1996). A wind turbine has an expected useful life of around twenty years. Wind power plants have shown themselves to be reliable and durable.

Wind speed is basic to a wind turbine’s productivity. The power in the wind in watts is

\[ P = \frac{1}{2} \rho A V^3 \]

where \( \rho \) is the air density, \( A \) the area intercepting the wind, and \( V \) the wind’s velocity. Air density varies with temperature and elevation. Warm air is less dense than cold air and packs less energy. Power in the wind is a cubic function of speed. Even a small increase in wind speed can substantially boost the power in the wind. So it is very important to find the windiest sites for wind power production. Wind speed also varies with height above the ground. And because wind speed increases with height above ground, designers must trade off increased output power on tall towers against the increased cost of taller towers.

The distribution of the wind energy collected is somewhat influenced by the choice of the wind turbine. If the wind blows evenly and with a low velocity, a wind turbine that can convert the wind energy at low wind speeds, should be chosen. If in another case the wind will have periods with no or little wind but in short periods the wind will blow hard, a wind turbine that will have a higher rated wind speed might be a better choice.

One of the advantages of wind plants is modularity, which offers substantial cost savings over traditional, large power stations. Wind plant’s minimum economic size is small compared to that of conventional generation technologies. The unit cost per kilowatt of capacity is relatively insensitive to plant size.
3.2.2 Hydrogen Production and Handling

3.2.2.1 Electrolyzer and DC/DC Converter

The electrolyzer decomposes water into hydrogen and oxygen. An electrolyzer cell is a sandwich of two electrodes on the outside, with the electrolyte in the middle, fixed in a porous material. Applying a direct current between the two electrodes decomposes the water into hydrogen (cathode) and oxygen (anode). The necessary exchange of charge occurs through the flow of ions. In order to keep the produced gases isolated, the two reaction areas are separated by an ion conducting separator diaphragm. The production of gases can be increased by connecting more cells in parallel.

The efficiency of electrolysis is about 60% nowadays. Some of the loss is due to electrical resistance in the circuit. Modern advanced electrolyzers are optimized for high efficient results at low operation voltages, while on the other hand photovoltaic generators normally operate with a high system voltage. The mismatch between PV-array and electrolyzer may reduce the overall efficiency of the system dramatically without the use of DC/DC converter. Another problem with many electrolyzers is the degradation of the electrodes and for the bipolar electrolyzer a growing distance between the electrodes due to swelling of the frame that will cause an increased resistance and thereby higher voltage over the cells. The increased voltage may over time cause a mismatch between the PV-cell and electrolyzer curves. Thus it is convenient to use a DC-DC-converter to transform the voltage levels. The converter also adds control possibilities.

DC/DC converter has a varying input voltage from the PV-array or wind turbine and a voltage output that fits the electrolyzer. Compared with direct coupling, this gives an improved overall efficiency and additionally allows magnitudes variance of photovoltaics, wind turbines or electrolysis without unnecessary losses. It gives a better use of the energy from the PV-array and wind turbine, but increases the complexity and cost of the system.

3.2.2.2 Alternative Hydrogen Production Approaches

Hydrogen can also be obtained from water by a variety of other methods that are not currently feasible for large-scale production, but are the targets of research and development activities. These include photoconversion, which uses biological organisms or synthetic material to split water, and photoelectrochemical processes, which use semiconductors to generate an electric charge to cause the water-splitting activity. These methods use solar energy to take electrons from water and use these electrons to produce hydrogen, which does not go through the separate electric generation step required by electrolysis. They are in the early research and development stages, but have strong potential for being cost-effective production systems.
Photoconversion couples a light-absorbing system with a water-splitting catalyst - a substance to initiate or speed up a chemical reaction. Many recent research activities in photoconversion are focusing on artificial photosynthesis for energy production, which mimic the function of the natural photosynthetic system. There are also some other methods to produce hydrogen from solar energy such as concentrated solar thermal energy. These non-electrolysis methods are not considered in this study as they are not technically stable enough for practical applications. Some significant technical improvements are still needed for applying those new approaches into renewable hydrogen energy systems.

3.2.2.3 Hydrogen Storage

Storing hydrogen can be done in three major approaches: in compressed form, liquid form and by chemical bonding. Research into future storage technologies focuses on solid-state storage using gas-on-solid adsorption in materials such as high surface-area carbon, or absorption in the interstices of a metal hydride.

Compression of hydrogen is carried out in the same way as for natural gas. Almost all common natural gas compressors can be easily modified to be suitable for hydrogen. Compressed gas is stored at 140 to 170 bar and currently requires large, heavy containers. Common materials for storage canisters are mild steel, aluminum, and composites. Because of the logarithmic relationship between pressure and work required for compression, the increased energy required for a higher filling pressure is not that great. Thus the compression from 0.1 to 30 MPa needs only 10% more energy than the compression from 0.1 to 20 MPa (W Zittel et al., 1996). So the choice of the highest pressure level is primarily dependent on the maximum permitted pressure that the storage tank can withstand.

Liquid hydrogen is 845 times the density of the gas but at -253 degrees C. It requires almost thirty percent of its energy to cool and compress it enough to liquefy it. Solid-state systems chemically or physically bind hydrogen to a solid material. Metal and liquid hydrides and adsorbed carbon compounds are the principal methods of bonding hydrogen chemically. The hydrogen attaches to the surface of the solid and is released by changing temperature and pressure levels.

3.2.3 Secondary Electricity Production – Fuel Cells

Fuel cells produce electricity through an electrochemical reaction between hydrogen and oxygen. Oxygen is taken from air. The basic fuel cell structure consists of an electrolyte within a support matrix sandwiched between two electrodes (the anode and the cathode). The energy stored in hydrogen is converted directly into low-voltage, DC electricity. The difference between a battery and a fuel cell is that the fuel cell does not have any internal storage of chemical energy, but the energy is supplied from a separate source. Fuel cells can essentially be a continuous source of electrical power.

One of the most attractive characteristics of fuel cells is its high efficiency, with hydrogen to electricity conversion at up to 70% efficiency. Furthermore, it has the ability to cogenerate, i.e. to produce hot water and low-temperature steam at the same
time as it generates electricity. Thermal energy produced in the generation process can be recaptured and used to heat air or water for households use.

A single cell has no practical value due to its low voltage (0.5-1.0 V). For any practical application a stack of cells connected in series is required. The number of cells in stack is determined by the required voltage. Many of the advantages of fuel cell power systems are attribute to their modularity. Fuel cell power plants can achieve high efficiency independent of plant scale. Thus, fuel cell power plants can be configured in a wide range of electrical output, ranging from watts to megawatts. The modular nature of fuel cells allows capacity to be added wherever it’s needed.

In addition to its relatively constant efficiency over a wide range of operating conditions, a fuel cell system also has a very fast reactive power response. Moreover, fuel cells systems have a good part load behaviour, are easy to operate, require short construction times due to a high level of modularity, and should need low maintenance since no rotating parts are needed. The high reliability of a fuel cell system will largely result from the modularity of the stacks and stack components, but should also be attributable to their lack of highly stressed moving parts operating under extreme conditions and to their ease of maintenance.

There are five types of fuel cells available nowadays, classified by the type of electrolyte. The different fuel cells and their operating characteristics are shown in table 3.1.

**Table 3.1 Classification of fuel cells**

<table>
<thead>
<tr>
<th>Fuel Cells</th>
<th>Temperature</th>
<th>Efficiency</th>
<th>Electrolyte</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline Fuel Cell</td>
<td>60-90°C</td>
<td>50-60%</td>
<td>35-50% KOH</td>
</tr>
<tr>
<td>Polymer Electrolyte Fuel Cell</td>
<td>50-80°C</td>
<td>50-60%</td>
<td>Polymer Membrane</td>
</tr>
<tr>
<td>Phosphoric Acid Fuel Cell</td>
<td>160-220°C</td>
<td>40-50%</td>
<td>Phosphoric Acid</td>
</tr>
<tr>
<td>Molten Carbonate Fuel Cell</td>
<td>620-660°C</td>
<td>60-65%</td>
<td>Molten Carbonate</td>
</tr>
<tr>
<td>Solid Oxide Fuel Cell</td>
<td>800-1000°C</td>
<td>55-65%</td>
<td>ZrO₂ / Y₂O₃</td>
</tr>
</tbody>
</table>
4 Technical and Economical Analyses of Components

4.1 Photovoltaics Systems

Photovoltaic systems basically can be divided into concentrating and non-concentrating systems. Concentrating systems use a lens to concentrate sunlight into small, high-efficiency cells. The greater light intensity means that more power is generated by the cell, so a given amount of power can be produced using a smaller quantity of semiconductor material. This approach minimizes the amount of expensive semiconductor material used, but does require the use of a tracking system. Photovoltaic arrays can be mounted on a tracking system that allows the array to follow the sun as it moves across the sky. Tracking systems make more efficient use of available sunlight. Since concentrating systems can use direct sunlight only, they must track the sun precisely and do not work under cloudy conditions. They are, therefore, especially suited to mostly cloudless locations and must be constantly aligned to the sun.

Modern two-axis trackers are quite reliable and require little maintenance, but they are also relatively expensive. Because of this added complexity and the requirement for accurate tracking, photovoltaic concentrator modules are generally used only in large scale systems. A substantial initial investment is required to purchase such large systems, so concentrators have not yet made significant headway in the commercial marketplace. The efficiency and cost comparisons of concentrating system and flat plate system in 1995 and prospect for 2005 are shown in the table 4.1.

The simplest and most frequently used design in the 100kWe output range consists of non-concentrating, fixed structures. Crystalline silicon flat plate collectors are the most developed and prevalent type in use today. Although making PV cells and modules requires advanced technology, they are very simple to use. Once installed, a PV array generally requires no maintenance other than an occasional cleaning due to having no moving or wearing parts.

According to the technology and economical status and prospect, the crystalline silicon flat plate system is generally more suitable PV system for the small scale solar hydrogen system aiming at households application than other systems. It is not cost effective to introduce complex and expensive tracking and concentrating systems in a small scale solar hydrogen system, especially for a remote village application.

The quoted price in 1995 for the cost of large-scale PV is $4 per peak watt. Smaller systems will be more expensive on a per-watt basis. Projections through 2004 indicate a steady decline to an average module manufacturing cost of $1.25 per peak watt by 2004 (National Center for Photovoltaics, 1999). Each watt of PV array will generally produce between 2 and 6 watt-hours of energy per day depending on the season and location. According to the calculations of Department of Energy of U.S., PV-produced dc electricity costs $0.14 to $0.36/kWh in 1995, and that $0.06 to $0.09/kWh is achievable in 10 years (National Center for Photovoltaics, 1999). This
cost generally limits the current application of PV to areas which are not served by an existing utility grid.

Table 4.1 Photovoltaic Efficiencies And Costs (DOE Information Bridge, 1996)

<table>
<thead>
<tr>
<th>PV Systems</th>
<th>Present Day</th>
<th>Ten Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Plate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module efficiency</td>
<td>12%</td>
<td>15%</td>
</tr>
<tr>
<td>Module cost</td>
<td>$400/m²</td>
<td>$250/m²</td>
</tr>
<tr>
<td>Balance-of-system cost</td>
<td>$100/m²</td>
<td>$75/m²</td>
</tr>
<tr>
<td>Operation and maintenance cost/year</td>
<td>$3/m²</td>
<td>$2/m²</td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Concentrators</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module efficiency</td>
<td>18%</td>
<td>21%</td>
</tr>
<tr>
<td>Concentrator module cost</td>
<td>$600/m²</td>
<td>$400/m²</td>
</tr>
<tr>
<td>Balance-of-system cost</td>
<td>$100/m²</td>
<td>$90/m²</td>
</tr>
<tr>
<td>Tracking cost</td>
<td>$100/m²</td>
<td>$75/m²</td>
</tr>
<tr>
<td>Operation and maintenance cost/year</td>
<td>$3.75/m²</td>
<td>$2.50/m²</td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

4.2 Electrolyzers

Two major types of electrolyzer are Alkaline Electrolyzer and Proton Exchange Membrane Electrolyzers. Alkaline water electrolyzers have been in use commercially for sometime. Both unipolar and bipolar designs are available. Electrolyzer Corporation of Toronto, Canada, the world’s largest producer of commercial electrolyzer systems, estimated that the cost of its unipolar alkaline system would be about $400/kW, with a range of $250/kW to $600/kW (DOE Information Bridge, 1995). PEM electrolyzers exhibit higher efficiency while operating at significantly higher current densities when compared to the advanced alkaline electrolyzers. PEM electrolyzers are commercially available and becoming the focus of manufactures and researches recently.

A key point that must be made is that world wide interest in PEM fuel cells, the reverse of PEM electrolyzers, is extremely high. The technology base being established for PEM fuel cell will clearly accelerate PEM electrolyzer development. Thus the PEM electrolyzer seems to be more promising in the future. In principle, PEM electrolyzers should be less costly and more user friendly for the home environment than the alkaline electrolyzers. These benefits are offset by the need for potentially expensive catalysts and fragile membranes.

Some have argued that PEM electrolyzers should cost even less than PEM fuel cells, because the electrolysis operation is inherently less complex than the fuel cell process.
wherein the reactive gases must be introduced over a large area in proper ratios. The goal of U.S. Department of Energy is to achieve a cost of $300/kW for stationary fuel cells (DOE Information Bridge, 1995). The appropriate comparison for electrolyzers is $300/kW; if stationary fuel cells could be built for $300/kW, then industry should be able to build electrolyzers for less than $300/kW.

The efficiency and operating & maintenance cost status and prospects of electrolyzer are shown in Table 4.2. Operating efficiencies lie in the 50-60% range for the smaller electrolyzers and around 65-70% for the larger plants.

**Table 4.2 Electrolyzer Efficiency and Cost (DOE Information Bridge, 1996)**

<table>
<thead>
<tr>
<th>Electrolyzer</th>
<th>Present Day</th>
<th>Ten Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>60%</td>
<td>70%</td>
</tr>
<tr>
<td>Operating &amp; Maintenance cost as percent of initial cost</td>
<td>10%</td>
<td>7.5%</td>
</tr>
<tr>
<td>Lifetime (years)</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

**4.3 Hydrogen Storage**

The advantages of liquid and solid hydrogen storage systems are not attractive for the renewable hydrogen system because volume density and weight are not critical factors for stationary applications. Normally it is not difficult to get enough space to install the hydrogen storage system in a village or a building. Storage efficiency and system costs are the major considerations in these applications instead.

The advantage of liquid hydrogen is its high volume density. However, it is difficult to store and the insulated tank required may be large and bulky. Cryogenic liquid hydrogen requires significant energy consumption for the liquefaction process, and it is expensive. Up to 40% of the energy content in the hydrogen can be lost (D Hart, 1998). Solid-state storage system is safer than physical storage systems due to low loading pressure, and could potentially store more hydrogen per unit volume. But it is also more expensive and heavier. Gaseous storage is the best way to store hydrogen in the small energy system for household applications, which is simpler, cheaper and more reliable.

There are two different approaches to store hydrogen gas. One system is to run the PEM electrolyzer at high pressure so the gaseous hydrogen is already compressed for storage. The other system is to operate the cell at low pressure and then pressurize the hydrogen and oxygen for storage using a compressor.

The advantage of the high pressure system is that it does not require additional energy input to store the hydrogen. A drawback of this system is that the high pressures can produce a large amount of hydrogen crossover due to higher gas solubility. In addition to a loss in work, this mixture of hydrogen with oxygen represents a safety hazard because it is an explosive mixture. Another requirement is a system of injecting liquid water at high pressure. The pump used to inject the water represents an energy
consuming device. Another drawback to the high pressure system is that it is less efficient than operating at low pressure. As the pressure of the cell increases, the potential needed to electrolyze the water increases.

Another system is to run the electrolyzer at ambient pressure and use a compressor to store the hydrogen. The drawback of this system is that the compressor is an energy consuming device with moving parts. However, this system does not have high hydrogen crossover problems or the increased inefficiency due to high pressure. Another advantage of the low pressure system is that there are fewer high pressure components. For the low pressure system, the storage tank is the only high pressure component. So the low pressure system is favored over the high pressure system for hydrogen storage.

4.4 Fuel cell systems

4.4.1 Alkaline fuel cells

A major disadvantage of AFCs is that alkaline electrolytes do not reject CO₂. AFCs are highly sensitive to poisoning by both carbon monoxide and carbon dioxide. The consequence of this property is that AFCs are currently restricted to specialized applications where pure H₂ and O₂ are utilized. AFC is being phased out in the U.S. where its only use has been in space vehicles (J.H. Hirschenhofer et al., 1998). The AFC is not considered for this renewable hydrogen system due to the challenge to economically remove CO₂ from air. It will increase the cost and complexity of the system. Another reason is that the projected lifetime of AFC (15,000h) is short comparing with PEMFC (>40,000h) and PAFC (40,000 h) (J.H. Hirschenhofer et al., 1998).

4.4.2 Polymer Electrolyte Fuel cells

Polymer electrolyte fuel cells (PEFC), also known as proton exchange membrane fuel cell (PEMFC), are very attractive as a power source for various transportation and stationary applications. PEMFC deliver high power density, which offers low weight, cost, and volume. The immobilized electrolyte membrane simplifies sealing in the production process, reduces corrosion, and provides for longer cell and stack life. The only liquid in this fuel cell is water, thus corrosion problems are minimal. Water management in the membrane is critical for efficient performance. The PEMFC system is seen as the system of choice for vehicular power applications, but is also being developed for smaller scale stationary power.

Another valuable characteristic of PEMFC is that the reactions in the fuel cell are reversible. When an electric power-supply is connected to the both electrodes and water is injected in the fuel cell, the cell will produce oxygen gas and hydrogen gas. So the fuel cell could also be designed to operate in reverse as an electrolyzer, then electricity can be used to convert the water back into hydrogen and oxygen. This dual-function system is known as a reversible or unitized regenerative fuel cell and commercially
available now. Proton Energy Systems Inc. recently announced their new product- Proton Exchange Membrane Unitized Regenerative Fuel Cell Energy Storage System. The performance of this system is better than that of separate fuel cells and electrolyzers. It is a promising development direction for efficiency improvement and cost reduction of hydrogen energy system.

The major challenge for applications of PEMFC is economic, namely significantly reducing the costs of proton-conducting membrane and the platinum-catalyzed electrodes. There has been an accelerated interest in PEMFC within the last few years, which has led to improvements in both cost and performance.

4.4.3. Phosphoric Acid Fuel Cells

Phosphoric acid fuel cells (PAFC) are the most mature fuel cells in terms of technological advancement and readiness for commercialization. State-of-the-art PAFC power plants range from 25 KW to 4.6 MW, and the nominal economic targets of a 40,000 hours lifetime and a stack cost of less than $400/kW have been achieved for the fuel cell stacks (J.H. Hirschenhofer et al., 1998). The rejected heat from the cell is high enough in temperature to heat water or air in a system operating at atmospheric pressure. Phosphoric acid fuel cells generate electricity at more than 40% efficiency, and nearly 85% if steam this fuel cell produces is used for cogeneration (U.S. Department of Defense, 1999).

The most recent intended application of the PAFC system is for on-site integrated energy systems to provide electrical and heat (space heating, hot water) energy for apartment buildings, shopping centers, hospitals, hotels, etc. Phosphoric acid technology does not lend itself well to small-scale applications due to the support systems required to manage liquid acids at such high operating temperatures, the use of more expensive metal catalysts such as platinum, and greater maintenance requirements.

4.4.4 Molten Carbonate Fuel Cells

The MCFC uses non-noble metal electrodes and has an electrolyte of molten alkali metal carbonates in a porous ceramic tile. The higher operating temperature of MCFCs provides the opportunity for achieving higher overall system efficiencies and greater flexibility in the use of available fuels. A number of technical problems such as corrosion and reliability still have to be solved. It is expected that commercialization will take 5-10 years (European Commission, 1998).

4.4.5 Solid Oxide Fuel Cells

Solid oxide technology operates at even higher temperatures than MCFCs. Due to these extremely high operating temperatures, design and operation issues are very challenging. The high temperature of the SOFC places stringent requirements on its materials. The development of suitable materials and the fabrication of ceramic structures are presently the key technical challenges facing SOFCs.
Noticeable development activities for SOFC is being carried out worldwide recently. The U.S. Department of Energy (DOE) started a cooperation project recently toward a dramatic reduction in the cost of fuel cells. The cost-reduction goal is to bring fuel cell power plant costs down to a range of $400 to $600 per kilowatt – or roughly half the projected costs of today's technology (DOE News, 1999). The new projects will focus on the ceramic-based SOFC, with both electrodes and electrolyte manufactured from ceramic materials. DOE has set a goal of achieving 40,000-hour life expectancies for stacks in power plants. Shell and Siemens are also starting a cooperation project to foster the technical and commercial development of SOFC.

4.4.6 Analyses and Conclusions

Fuel cells represent a promising clean and efficient energy conversion technology, but they are not yet capable of competing with established technologies. All kinds of fuel cells are facing the same cost problem which is the major obstacle for its widespread applications. A large research, development and demonstration effort is still needed to solve technical and reliability problems and to bring the costs of fuel cells down to acceptable levels.

Today the interests in the research and application of fuel cell technology are mainly focusing on transport field. The society has more interests in mobile applications of fuel cells because it is an effective solution to the air pollution coming from transportation, which is widely concerned. The prices of fuel cells are projected to decrease substantially with rapidly increasing production and commercial applications. However, the fuel cell itself is more suitable for stationary applications from technological point of view. The choices of fuel cells could be more flexible in stationary applications without strict volume and weight limitations. It also gives the possibility to choose relatively cheaper fuel cells for the renewable hydrogen energy system to increase its economic feasibility.

Low-temperature fuel cells (PAFC and PEFC) require noble metal electrocatalysts to achieve practical reaction rates at the anode and cathode. With high-temperature fuel cells (MCFC, SOFC), the requirements for catalysis are relaxed, and the number of potential fuels expands. However, MCFC and SOFC systems are not in so advanced a stage of development as the PAFC and PEMFC.

PAFC and PEMFC are possible choices nowadays for this renewable hydrogen system. PEMFC is more promising to expect considerable cost reduction and performance improvements in the near future as it is the main focus of extensive researches for transport applications. PEMFC are also ideal for low temperature cogeneration of heat and electricity for households.
5 System Analyses

5.1 Technical Analyses

The renewable hydrogen energy system needs virtually no basic engineering breakthrough. All components of the system exist and only need gradual development. A demonstration project is possible to be built today.

The design, optimization, and integration procedure of the renewable hydrogen energy system is very complex because of the number of required systems, components and functions. Many possible design options and trade-offs exist that ultimately affect system costs, efficiency, complexity and reliability. Although a detailed discussion of the system optimization and integration is not within the scope of this thesis, a few of the most common system optimization areas are examined.

The most energy efficient approach to supply electricity to households is to use the solar-electricity directly as much as possible when the solar energy is available during daytime. The supply system (figure 5.1) which combines the electricity from photovoltaic cells and fuel cells will improve the system efficiency during daytime when solar energy is available.

![Diagram of the supply system](image)

**Figure 5.1** Supply system with electricity coming from photovoltaics and fuel cells

The working principles for the system are (during daytime):

1. When there is no loads demand, all the electricity from photovoltaic cells will go to hydrogen storage.
2. When there is a loads demand, there are two different conditions.
   2.1 If solar electricity > loads demand, then solar electricity – loads demand = hydrogen storage;
   2.2 If solar electricity < loads demand, then loads demand – solar electricity = fuel cell output.

There is a difference when this system is used for 100 households instead of one household. If the system is used to supply energy to one household, then it is obviously that it is the most efficient way to supply electricity to household directly...
from photovoltaics during sunny daytime. If this system is used for one village with a number of households, the complexity of the control system will increase. Power conditioning is also needed for each household, which will increase the system costs. There is a balance between energy efficiency and cost efficiency. The cost effectiveness of the system will depend on the balance between the saved energy and increased costs due to increased control systems and power conditioning. The comparison of these systems should be analyzed in a future study.

The weather condition is critical to design and apply this solar/wind hydrogen energy system. The system is restricted to the areas where solar or wind energy are abundant year around. Well located systems will eliminate the need to use seasonal storage. The electrolyzer must be able to deliver sufficient hydrogen to cover the expected average fuel cell consumption, plus enough reserve capacity to handle surge loads. The oxygen produced in this system could also be considered valuable if there is such a local demand for pure oxygen. The storage tanks must store hydrogen both to accommodate intermittent production and irregular load profiles. Even with electrolyzer surge factor of 1.5 for residential units, at least 3 days of storage are required. At bad locations where available solar and wind energy is not enough during wintertime, the seasonal storage is necessary and a much larger tank is needed.

The efficiency of a fuel cell is higher at part load than at full load. So fuel cells can be operated very efficiently with small loads. This advantage is very suitable for households application as the loads fluctuate from time to time and the design capacity has to be large enough to cover predictable maximum load.

Broadly speaking, the renewable hydrogen energy system could be applied for remote communities in industrialized countries or in developing countries. Each has its own particular requirements and design constraints. For example, system reliability, quality of power and competitiveness can be more important than cost of power for communities in industrialized countries. For communities in developing countries simplicity of maintenance is a prime consideration. The system should be designed such that maintenance is required only at infrequent intervals. It is not difficult to achieve from the experience of different renewable electricity systems running all over the world.

5.2 Economic Analyses

The costs of the system include the installation cost as well as operation and maintenance costs. The initial investment of the renewable hydrogen system is extremely high but the operating and maintenance cost is low. All these costs have been decreasing with constant striving for cost-effectiveness, thereby lowering the cost of energy. As the success of the installation depends heavily on qualified operation, maintenance and repair (OMR) staff, a training programme will be needed. The cost of these may have to be included in the installation costs.
The efficiency and capital investment of solar hydrogen system are shown in figure 5.1, and system efficiency = 10%× 60 %×60 % ×90% = 3.2 %. The efficiency of the system excluding PV-cells is 32%.

![Diagram]

**Figure 5.2 Efficiency and Capital Investment Analysis of Solar Hydrogen System**

The power conditioner is not necessary if the facilities of households could use DC electricity. The efficiency of dc to ac conversion is over 90%, and the projected capital cost of power conditioner is about $75 per kilowatt (Leo et al., 1993). Other efficiencies and costs estimations of figure 5.1 come from chapter 3 and 4 of this thesis.

So the efficiency of the system is still low and the investment is very high. The bottleneck of system efficiency is the efficiency of photovoltaic cells. Despite continuous decrease in the price of components, the cost of electricity from the solar hydrogen system still remains much greater than that of power from traditional power plants. Intensive research in improvement of system efficiency and cost reduction is still needed before the commercial applications of the system. Overriding aim is to optimize system design and reduce the cost that produce electricity at the lowest possible price per kWh.

The renewable hydrogen system will become more competitive if social or external costs are considered, such as pollution and human health. Not all costs of conventional generation are reflected in the price of electricity. Environmental impacts from conventional sources (for example, air pollution from fossil-fueled plants and radiation exposure from nuclear plants) exact costs from society at large. Environmental and safety regulations internalize some of these costs by increasing the cost of generation. However well-intentioned, regulation has failed to internalize all the social costs of conventional generation. This is particularly true for the costs of pollutant emissions that meet air quality standards. Even though these emissions meet society’s accepted limits, they still exact a social or environmental cost, for example through additional sickness and death. Capital investment for renewable hydrogen systems is currently expected to be very expensive per unit of energy, but the system is emission free. Production costs and “external” environmental costs must also be factored into any economic comparison of these systems.

Apparently the renewable hydrogen energy systems are not economically competitive nowadays compared with traditional energy systems based on fossil fuel. But the system will become more and more attractive in the future. It is because the fossil fuel prices will increase with the depletion of the limited non-renewable resources, and the prices of the renewable hydrogen energy systems will decrease rapidly with the
process of mass production. The change pattern is shown in Figure 5.2. When will the renewable hydrogen energy system become competitive depends on the speeds of fossil fuel depletion and the mass production of renewable hydrogen systems.

![Graph showing the comparison of prices between fossil fuel based systems and renewable hydrogen systems over time.](image)

Figure 5.3  Prospect Of System Costs Comparing With Fossil Fuel Based Energy Systems

To stimulate the development and mass production of the renewable hydrogen systems, some strategies have to be made from both the industries and governments. On the one hand, the energy industries should find some niche markets for the commercialization of the renewable systems, such as power supply to the remote communities. On the other hand, the government should improve the environmental regulations to favor the environment-friendly technologies. It is crucial for the governments to increase the green taxes to better the economic competitiveness of the renewable energy system.

5.3 Environmental Analyses

The environmental advantages of the renewable hydrogen energy system are obvious. At first, the whole system is a zero-emission system during its energy production process. The second is that the energy production only use renewable resources, solar/wind and water. So the system is a sustainable energy production system.

In this context it should be noted that the benefits of the solar/wind hydrogen energy system must be considered over its entire life cycle. For example, although there is no emissions at all during power generation process, there is still energy consumption, material use, and pollution during the manufacture and construction processes of photovoltaics, electrolyzers, and fuel cells. There is also a lower capability for the recycling of used materials. The overall energy and pollution balance of the renewable hydrogen system depends on the service life of the system. The service life of PV systems and electrolysers is 20-25 years, lifetime of wind turbines is 20 years, and fuel cells have relatively shorter lifetime which is around 5 years. The long service life of the solar/wind hydrogen energy systems makes the overall energy and pollution balance clearly positive. All in all, few power-generation technologies have as little impact on the environment as renewable hydrogen energy systems.
The whole system operates very quietly except wind turbines, which may be noisy. Some consideration of noise should be given when siting wind turbines close to houses. For the hydrogen system which is close to the households, special attention must be paid to safety. Hydrogen is often considered to be a dangerous gas. Handled the right way, hydrogen should not be more dangerous than other energy carriers like methane and petroleum. Since hydrogen can neither be seen nor smelled, a safety precaution should be considered. Hydrogen leak detectors are commercially available to assure the safety of the system in case of hydrogen leakage.

However there will still be more or less some psychological barrier for the application of the system concerning the safety of hydrogen. Actually hydrogen is much safer than most people think it is. So some kinds of education programme might be needed to relieve the fear of people toward hydrogen. People will build up their confidence on the safety characteristic of hydrogen once they get familiar with the hydrogen technology and its wide applications all over the world. Thus a number of demonstration projects all over the world are important to disseminate the message that hydrogen is capable of storing energy to meet households needs and it is safe.

Utilizing solar and wind energy with hydrogen will have strong environmental effect, to promote the concept of using renewable and clean resources and protect the environment. Although the provision of electricity and environmental protection are the most obvious benefits of the system, it is worthwhile assessing some other social-economic effects. The improvements in quality of life that can result from the deployment of a renewable hydrogen energy system can not be underestimated.

5.4 Sustainability Analyses

The world primary energy consumption is projected to grow at an annual rate of 2.6% during 1993-2010 to provide for a GDP growth of 2.9% (Bharat Petroleum, 1993). Prediction for the future growth of the photovoltaic industry vary enormously depending on the source. The most optimistic scenario estimates that renewable energy sources will expand to account for 10% of the world’s total energy consumption by the year 2010, and the solar power will increase its standing within the group of renewable energy sources to 10% (equivalent to 1% of global energy consumption). This would signify an annual growth rate of more than 52% for solar power. With the most conservative scenario, solar energy production by the year 2010 should reach around 800 MW, which would still mean an average growth rate of over 15% per year (F Figge et al., 1998).

Despite surprisingly fast growth rates in the last few years, photovoltaic production across the globe is still extremely low at 0.004%, or around 400 MW compared with total energy capacity of 10 million MW worldwide (F Figge et al., 1998). Solar energy is only of interest for niche applications where it offers clear advantages over other technologies, such as providing power for houses in remote locations. One major obstacle to solar/wind energy utilization has been the lack of efficient and cost-effective storage methods. The hydrogen storage system is a promising solution to the problem with its clean, efficient and reliable energy storage. It is superior to the
traditional battery storage especially when large-scale or long-term energy storage is needed. The hydrogen storage system can play an important role in stimulating and accelerating the development of solar and wind energy utilization in a larger scale.

In the areas which are connected to the grid, it is certainly not worthwhile to use the renewable hydrogen system nowadays. It is an environmentally friendly system but too costly. However in the remote areas where has no connection to utility grid, the renewable hydrogen system is an attractive solution. Two billion people, one-third of the world's population currently does not have electricity. Throughout the world there are hundreds of thousands of villages, remote communities, and islands which do not have power or are supplied on an individual basis by small gas or diesel generator sets, small wind turbines and photovoltaic systems. In many places, due to remoteness and cost, it is unlikely that a main grid connection will ever be established. The infrastructure for distributing electricity through grid is costly in areas where are far away from existing grid or population density is low. It also demands a large amount of copper consumption, which will exert a pressure on the limited copper resource.

At present, the most common way to supply electricity to remote loads is with a diesel engine driving a generator set. Diesel generating sets have a low capital cost and high operating cost. The high costs are due primarily to the cost of purchasing the diesel fuel and delivering it to where it is needed. Operation and maintenance of the diesel generators may also contribute to high cost at remote sites. Besides the high operating costs and consumption of fossil fuel, the diesel systems also cause severe pollution. These problems generate a powerful incentive to find more sustainable alternatives.

The barrier of the applications of hydrogen system is its high costs in its early development stage. Economically this system can not compete with traditional energy systems in most situations. But it is especially attractive for remote communities which are not connected to utility grid. For remote areas, the value of solar/wind energy is extremely high because of the difficulty and expense of bringing in fuel or building a power line. The renewable hydrogen system can supply energy with locally available renewable sources. Other benefits such as reduced emissions and social value of the electricity, may be more difficult to evaluate in an economic framework, but should be included in the assessment. Compared with its alternative, diesel-electric systems based on fossil fuel, the renewable hydrogen energy system is a more sustainable solution to remote energy supply. The costs of the system will reduce substantially when mass production is achieved. The small scale household applications will help to establish the niche markets for the hydrogen system and accelerate its mass production process.

This system contributes even more value in developing countries. Many developing nations are scrambling to expand their power systems to meet the demand for rural electrification. Rural households in the developing world typically require only a small amount of electricity — generally just enough to power a few electric lights and a television or radio for three to four hours in the evening. In most cases, the revenue from such small energy usage does not cover the actual costs of generating and distributing electricity from a conventional power plant. Extending utility service from the cities to remote villages is a seldom affordable luxury. Thus renewable
hydrogen systems, even though they generate little power in comparison to central power plants, can meet the modest needs of Third World villages. Low per capita consumption magnifies the system's benefits because so little electricity is needed to raise the quality of life. Consequently, developing countries are turning to wind and solar energy as a cost-effective way to meet the electrical needs of rural areas.

The rural markets in developing countries include village electrification, power for medical centers and schools, communications. It is in these regions that renewable hydrogen systems could make the greatest contribution to development aspirations and to global environmental goals. The developing world markets from this perspective would be a key to the large-scale production that will bring down costs. In addition, the system offer basic electrification (village power) and may reduce urbanization through enhancing the quality of life of rural populations. To open major markets in developing countries should be a focus for international funds from the United Nations or World Bank.

As humankind enters the new millennium with ever-increasing energy requirements, renewable hydrogen technology will make a significant contribution to the sustainability of global civilization.
6 Feasibility Of Applying The System To Chinese Households

6.1 Why Is This System Suitable For Chinese Households?

Energy shortages and severe environmental pollution caused by the burning of fossil fuels (particularly coal) are core problems which constraint the development of China's economy. China suffers from persistent, severe shortages of electricity. Today over 100 million Chinese people have no electricity, which comes to about 20 million households (U.S. Embassy, 1997). Growing energy demands are likely to triple coal consumption and CO₂ emissions by 2025 (World Resource Institute, 1995). Traditional fuels provide 80 percent of the energy used in rural households in China (World Resource Institute, 1995). Traditional fuels include fuelwood, charcoal, bagasse, and animal and vegetable wastes. Fuelwood is being consumed at an unsustainable rate, and there are shortages. The unsustainable rural energy consumption pattern cause exacerbating rural air pollution in China.

China hopes to meet rural energy needs by investing in renewable sources of energy (wind, solar, hydro, or biomass). China has a rich renewable energy resource base. The solar resource is abundant in China with average insolation of $5.9 \times 10^6$ kJ/m² year round. More than 2/3 of the area of China has insolation time of above 2,000 hours (Wu, 1997). There is more abundant solar energy in the western parts, especially in Tibet and Xinjiang provinces. The wind resource in China is enormous, with exploitable wind resources being estimated at around 250 GW by the Ministry of Electric Power (Golden State Group Corp., 1999). The wind resource is concentrated in the north and west regions of China and along the coast. The distribution of wind resources complements the distribution of coal and water power resources so the prospects for wind power utilization are excellent.

Renewable energy utilization will bring China great commercial and social benefit, and play an important role in the improvement of environment. China has wind energy farms and photovoltaic factories, but investment in renewables is only a small fraction of the total energy investment. The development and utilization of renewable energy will depend on the sustainable development strategies of Chinese government in a large extent, i.e. if it will continue to reinforce environmental regulations and green taxes.

The renewable hydrogen energy system is a promising candidate for remote community power supply in China. The disadvantages of the system for households, which are the limited energy production capacity and high cost, would be mitigated in Chinese households applications. At first, the energy demand of a Chinese household is very low compared to a western household. China is the third largest energy consumer in the world. However, on a per capita basis, China's energy use is low. So it is easier to cover the total energy demand of a Chinese household by hydrogen energy system than of a western household. Consequently, it makes the system possible to supply energy to a Chinese village. The cost of the energy system will be
shared among households, which will increase the cost-effectiveness. What makes the stand-alone hydrogen energy system more cost-effective is that many rural areas in China has no electricity available and connection to national utility grid is impractical in the near future. So the most cost-effective application of the system is to supply a Chinese village in the remote areas.

To promote the use of renewable hydrogen energy system, it is necessary to build a demonstration village and deliver solar/wind electric energy to rural households and educate visitors about the benefits of renewable energy. Introducing renewable energy to the countryside in China faces the same challenges as elsewhere in the world, i.e., those who need it most are those who can least afford it. Effective international cooperation is crucial to set up demonstration systems to remote and rural areas to improve the living conditions of the local people and help the development of the local economy. For the households in remote areas where connection to national utility grid is impossible or impractical, it is possible to get the subsidies from Chinese government. There is also some possibilities to get funding from international aids aiming at China's sustainable development. The funding from Chinese government and international society are increasing with the exacerbating problems of resources depletion and pollution in China.

6.2 System Design For Chinese Households Applications

6.2.1 Define The Energy Needs Of Chinese Households

The energy needs of Chinese households vary with the sizes and living quality of households. The energy needs of typical Chinese households are assumed in table 6.1 for analyses. The energy needs of urban households are divided into low consumption pattern and high consumption pattern according to different living quality. The data are based on summer condition, with electric fan and air-conditioner and without space heating.

Table 6.1 Energy Needs Of Chinese Households In Rural And Urban Areas

<table>
<thead>
<tr>
<th>Household Energy Needs</th>
<th>Rural (low)</th>
<th>Urban (low)</th>
<th>Urban (high)</th>
<th>Using Hours Per Day</th>
<th>Consumption (kWh/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting</td>
<td>250W</td>
<td>250W</td>
<td>250W</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>TV</td>
<td>80W</td>
<td>80W</td>
<td>80W</td>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>300W</td>
<td>300W</td>
<td>300W</td>
<td>1/3</td>
<td>0.1</td>
</tr>
<tr>
<td>Electrical fan</td>
<td>75W</td>
<td>75W</td>
<td>75W</td>
<td>2</td>
<td>0.15</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>200W</td>
<td>200W</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Electrical hair drier</td>
<td></td>
<td>400W</td>
<td></td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>Air-conditioner</td>
<td></td>
<td>1000W</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Electrical cooker</td>
<td></td>
<td>1000W</td>
<td></td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Audio &amp; Video</td>
<td></td>
<td>200W</td>
<td></td>
<td>1</td>
<td>0.2</td>
</tr>
<tr>
<td>Total Power Need</td>
<td>705W</td>
<td>905W</td>
<td>3505W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Energy Need</td>
<td>1.65</td>
<td>2.65</td>
<td>6.45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
All figures of power needs of households equipment come from Chinese national design standards (Chen, 1993) and the corresponding using hours are estimated according to normal condition of Chinese households. Taking a Chinese village with 100 households and an urban residential building with 40 households as examples, the energy needs of the village and the building are calculated below.

Electricity consumption of the village = 1.65×100 = 165 kWh/Day
Taking 4 kWh/Day as the energy consumption of an average urban household, the electricity consumption of the building = 4×40 = 160 kWh/Day

For simplification, assuming 0.5 as the peak load demand coefficient for one household as well as for the village with 100 households and the building with 40 households, taking 0.8 kW for one rural household and 2 kW for one urban household as the total power need, then
the power need of each rural household = 0.8×0.5=0.4 kW;
the power need of the village = 0.4×100×0.5=20 kW;
the power need of each urban household = 2×0.5=1 kW;
the power need of the building = 1×40×0.5=20 kW.

So the power need of a urban residential building with 40 households is the same as the need of a rural village with 100 households.

6.2.2 Calculations Of Components Capacities

The symbols using in the calculations are introduced below:
E = electricity consumption of the village per day;
E_{EL} = the electricity needed for electrolyzing;
\eta_{EL} = the hydrogen-to-electricity energy conversion efficiency;
\eta_{FC} = the hydrogen-to-electricity energy conversion efficiency of fuel cells;
\eta_{PC} = the efficiency of power conditioning;
\eta_{EL} = the efficiency of electrolyzer;
\eta_{PV} = the efficiency of PV;
\eta_{DC} = the efficiency of DC-DC converter;
P_{FC} = the power capacity of fuel cells;
P_{EL} = the power capacity of the electrolyzer;
P_{PV} = the power capacity of photovoltaics;
C_{EL} = the energy output capacity of the electrolyzer;
h = hydrogen energy density;
s = hydrogen production surge factor,

a. Fuel Cell Capacity

According to the estimation and calculation of energy needs, a medium size fuel cell of 25 kW will be able to cover the energy needs of a village with 100 households or a residential building with 40 households. A fuel cell of 30kW will be suitable considering the improving living quality and increasing energy consumption in China.
So \( P_{FC} = 30 \text{ kW} \), and assuming \( \eta_{PC} = 90\% \), then
the capacity of power output for households = \( P_{FC} \eta_{PC} = 30 \times 0.9 = 27 \text{ kW} \);
The average running time of the fuel cell at full load = \( 165/27 = 6.1 \text{ hours/Day} \).

b. Hydrogen Demand

In order to calculate the mass of hydrogen, \( m \), needed per day, we must estimate \( E \), and know \( h \) and \( \eta \). The relation is
\[
m = E/(\eta \times h) = E/(\eta_{FC} \times \eta_{PC} \times h)
\]
Introducing \( E = 165 \text{ kWh} = 594 \text{ MJ} \), \( h = 140 \text{ MJ/kg} \), \( \eta_{PC} = 90\% \), and assuming \( \eta_{FC} = 60\% \), we get \( m = 7.9 \text{ kg} \).

c. Hydrogen Storage Capacity

Hydrogen production surge factor, \( s \), has to be chosen, considering the weather condition, load fluctuation, components efficiency and storage leakage.
Assuming \( s = 1.5 \), the hydrogen production capacity = \( m \times s = 7.9 \times 1.5 = 12 \text{ kg/Day} \).

The hydrogen tank should have the capacity of at least 30 kg for the hydrogen storage. It will cover the hydrogen demand of the system for a period of 3-4 days. The energy supply will be more reliable with bigger hydrogen storage tank in the system. For the hybrid system with wind turbines, the hydrogen tank could be smaller as wind energy will reduce the fluctuation of energy production of the system.

d. Electrolyzer Capacity

Assuming \( \eta_{EL} = 60\% \), then
\[
P_{EL} = [P_{FC} / (\eta_{EL} \eta_{PC})] \times s = [30 \text{ kW} / (0.6 \times 0.6)] \times 1.5 = 125 \text{ kW}
\]
\[
C_{EL} = [E / (\eta_{FC} \eta_{PC})] \times s = [165 \text{ kWh} / (0.9 \times 0.6)] \times 1.5 = 458.3 \text{ kWh/Day}
\]
\[
E_{EL} = C_{EL} / \eta_{EL} = 458.3/0.6 = 764 \text{ kWh/Day}
\]
The running time of electrolyzer at full load = 6.1 hours/Day.

e. Area Needed For Photovoltaics

Assuming \( \eta_{PV} = 10\% \), \( \eta_{DC} = 90\% \), then
the solar energy needed = \( E_{EL} / (\eta_{PV} \eta_{DC}) = 764/(0.1 \times 0.9) = 8489 \text{ kWh/Day} \);
\[
P_{PV} = P_{EL} / \eta_{DC} = 125/0.9 = 139 \text{ kW}.
\]
The average solar insolation of China =
\[
(5.9 \times 10^6 \text{ kJ/m}^2/\text{Year}) / (3600 \text{ kJ/kWh})(365\text{Days/Year}) = 4.5 \text{ kWh/m}^2/\text{Day}
\]
Assuming the solar insolation is 5 kWh/m\(^2\)/Day for the village,
the area needed for photovoltaic panels = 8489/5 = 1698 m\(^2\).
For the village with 100 households, the area needed for photovoltaic panels per household = 1698 / 100 = 17 m\(^2\).
Table 6.2 Calculation Results For A Village In Rural Areas

<table>
<thead>
<tr>
<th>Number Of Households</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity need (kWh/Day)</td>
<td>165</td>
</tr>
<tr>
<td>Fuel cell capacity (kW)</td>
<td>30</td>
</tr>
<tr>
<td>( \text{H}_2 ) Consumption (kg/day)</td>
<td>7.9</td>
</tr>
<tr>
<td>Surge Factor</td>
<td>1.5</td>
</tr>
<tr>
<td>( \text{H}_2 ) Production capacity (kg/day)</td>
<td>12</td>
</tr>
<tr>
<td>Electrolyzer capacity (kW)</td>
<td>125</td>
</tr>
<tr>
<td>Electricity needed to electrolyze water (kWh)</td>
<td>764</td>
</tr>
<tr>
<td>Photovoltaics capacity (kW)</td>
<td>139</td>
</tr>
<tr>
<td>Area needed for PV Cells (m(^2))</td>
<td>1700</td>
</tr>
<tr>
<td>The area needed for PV Cells per household (m(^2))</td>
<td>17</td>
</tr>
</tbody>
</table>

In the case of the solar hydrogen system for a village, it is not a problem to have 17m\(^2\) to build photovoltaic panels on each household’s roof. However, it is difficult for a building to get 1700 m\(^2\) to erect photovoltaic panels on roof. It is better to have a hybrid system with wind turbines to cover the energy demand of the building. The area needed for photovoltaic panels in a hybrid system will be 1700/2 = 850 m\(^2\), assuming that the ratio of wind and solar energy available is 1:1. Area need in this size is possible to meet for a building.

f. Water and Space Heating

The thermal energy demands of Chinese households are mostly for bathing and space heating. There is no hot tap water system in Chinese households. The energy need of hot water for bathing and space heating is possible to cover by thermal system from solar thermal collectors and fuel cells ‘waste’ heat.

Although the village with 100 households is taken as an example, it is not difficult to change the components to the ones with bigger capacity to supply a larger village with more than 100 households. The modularity of solar/wind hydrogen technology makes the energy system very flexible for applications in villages. It can be easily copied to another village with different energy demand without much system modification.

6.2.3 The Installation Costs Of Solar Hydrogen Energy System

The installation cost of solar hydrogen energy system is expected to reduce considerably with the development of components technology. The status and prospects of the installation costs are estimated in table 6.3 and 6.4. It is assumed that in five years the efficiency of photovoltaics could increase from 10% to 15%, with cost reduction from $500/m\(^2\) to $325/m\(^2\); the efficiency of electrolyzer could increase from 60% to 70%, with cost reduction from $400/kW to $300/kW; the cost of fuel cells could reduce from $1000/kW to $500/kW (chapter 4).
### Table 6.3 Status of installation costs

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>Cost/Size</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaics</td>
<td>1700 m²</td>
<td>$500/m²</td>
<td>$850 000</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>30 kW</td>
<td>$1000/kW</td>
<td>$30 000</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>125 kW</td>
<td>$400/kW</td>
<td>$50 000</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>30 kg</td>
<td>$600/kg</td>
<td>$18 000</td>
</tr>
<tr>
<td>Total Cost</td>
<td></td>
<td></td>
<td>&gt; $948 000</td>
</tr>
</tbody>
</table>

### Table 6.4 Prospects of installation costs (in 5 years)

<table>
<thead>
<tr>
<th></th>
<th>Size</th>
<th>Cost/Size</th>
<th>Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photovoltaics</td>
<td>1450 m²</td>
<td>$325/m²</td>
<td>$472 000</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>30 kW</td>
<td>$500/kW</td>
<td>$15 000</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>110 kW</td>
<td>$300/kW</td>
<td>$33 000</td>
</tr>
<tr>
<td>Hydrogen storage</td>
<td>30 kg</td>
<td>$500/kg</td>
<td>$15 000</td>
</tr>
<tr>
<td>Total Cost</td>
<td></td>
<td></td>
<td>&gt; $535 000</td>
</tr>
</tbody>
</table>

### 6.3 Suggested Regions for Application -- Tibet And Xinjiang

As the renewable hydrogen energy system is new and costly, it is important to choose a suitable region carefully for its application in China. Tibet is one of the most suitable regions to apply the system in China considering its special resources, economic and environmental conditions.

a. Resources Consideration

Tibet has very little fossil fuel resources but has very abundant solar and wind resources with superior quality. Tibet also has rich geothermal energy but it is far from enough to solve the problem of energy shortage in Tibet. Tibet is so sunny that its insolation time is about 3,100 to 3,400 hours per year, 9 hours per day in average. The western areas of Tibet are very windy with wind speed over 4 m/s for more than 8 hours per day and more than 200 days per year (China News Center, 1998).

b. Economic Consideration

The living quality of Tibetan is very low. Severe energy shortage has always been a handicap to the economic development of Tibet. The utility infrastructure in Tibet is very poor and many areas are still not grid-connected, which will improve the cost-effectiveness of the system. The economic benefit from developing renewable energy system is obvious. International society also has the interest to help improve the economic situation of Tibet for a long time. It is relatively easy to attract capital and investment from Chinese government and international sources.
c. Environmental Consideration

Tibet is the last region in China which is still not polluted. It is the cleanest region in China with the lowest population density. To preserve the special ecology of Tibet is a contribution to the whole world. Renewable hydrogen energy system will certainly benefit the natural environment of Tibet. Tibetans have a strong worship to the nature and environment, which is the reflection of Tibetan traditional culture. Tibet has the most advanced environmental measurement equipment in China. Utilizing renewable energy will coincide with the feeling of Tibetan and consequently get the support from local people and municipalities.

Tibet already started to solve its energy problems by exploring renewable resources. Tibet is taking the lead in solar energy utilization in China. There are already 6 off-grid counties in Tibet have built photovoltaic systems. Tibet has also built more than 700 wind turbines with power supply over 100 KW (China News Center, 1998).

Xinjiang province has a similar environmental situation with Tibet. It has better wind resource but a bit less solar resource compared with Tibet. Wind speeds greater than 6 m/s occur more than 2000 hours annually in eastern part of Xinjiang. The solar insolation time in Xinjiang is about 2500-3000 hours per year. The total solar energy in Xinjiang is about 542.10-646.35 J/cm² per year, only less than Tibet in China (XinJiang Environmental Protection Bureau, 1999).

Tibet has the richest solar energy resource in China and photovoltaics are already a cost-effective solution in many areas of Tibet compared to other alternatives, such as utility grid, fossil fuels, biomass. But will the photovoltaics systems with hydrogen storage still be an attractive solution? Will it just be a luxury for poor Tibetan? This new and costly system will certainly face more difficulties but there are also some reasons making it promising to introduce the system to Tibet.

At first we can see from table 6.3 that the cost of hydrogen storage system including electrolyzer, hydrogen storage and fuel cells is $ 98,000, which is only 12% of the cost of photovoltaics. So the additional cost from hydrogen storage system is not so much compared with photovoltaics itself according to the calculation of the village case. And the hydrogen storage will increase the capacity and reliability of traditional photovoltaics systems in a large scale. So hydrogen storage could be a cost-effective solution to further exploring the solar energy utilization in Tibet. Secondly the transport and utility infrastructure is very poor in Tibet and it is very difficult to make a major progress in the near future due to the costs and tough geographical characteristics. Furthermore, there is also a strong political will from Chinese government to protect the environment of Tibet as it is the cleanest region in China. So there are economic, political and environmental incentives to invest more money on the solar energy utilization of Tibet. Battery storage systems are not yet capable to supply sufficient and reliable electricity to meet increasing energy demands of Tibet. The hydrogen storage is the only way to explore Tibet's solar energy resource in a larger scale and it will be a reasonable approach to accelerate the progress of Tibetan rural electrification in the near future.
In conclusion, solar/wind hydrogen energy systems will be an attractive alternative to supply energy to remote areas in Tibet and Xinjiang province. The application of this system will help improve living quality and environmental protection at the same time in this region. Firstly, demonstration projects are necessary to identify the feasibility of the system in this region. Solar Energy Research And Demonstration Center of Tibet is active in promoting solar electric energy to achieve sustainable development of Tibet. It could be a base for implementing the project and international cooperation in renewable hydrogen technology. Once some demonstration projects are carried out successfully, more interests and efforts will be attracted from outside, including Chinese government and international organizations. With the support of rapidly developing hydrogen technology all over the world, we could vision that the energy supply of Tibet and Xinjiang provinces will be based on hydrogen storage systems with energy coming from renewable sources in the future.
7 Conclusions

The solar/wind hydrogen energy system can provide villages and small buildings a reliable, safe, and environment-friendly way to meet all their energy needs. The system is very costly nowadays but is a promising candidate for the remote or stand-alone power systems in the near future. It is especially suitable for remote villages in developing countries.

Utilizing solar and wind energy with hydrogen will have strong environmental effect, to promote the concept of using renewable and clean resources and protect the environment. The major obstacle to apply this system derives from the need for a high capital investment. The system is not economic feasible nowadays but has great cost reduction potentials. Intensive research and development are still needed to substantially improve the efficiency and reduce the cost of the system. Integrated efforts have to be made from research organizations, industry, NGOs, government agencies, and international development agencies.
8 References


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Xinjiang Environmental Protection Bureau Information Centre, 1999, Xinjiang Environmental Protection, http://www.xjwpbst.net.cn/xjepb/xjepb.htm