# Thermodynamic and Economic Analysis of Geothermal Energy Use in Hydrogen Production and Liquefaction

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# ABSTRACT

# THERMODYNAMIC AND ECONOMIC ANALYSIS OF GEOTHERMAL ENERGYUSE IN HYDROGEN PRODUCTION AND LIQUEFACTION

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Hydrogen, an alternative energy source, is subject of a lot of research work and some consider it as the energy of the future. If hydrogen is to become the energy of the future, it must be produced using renewable energy sources and the technical and economic problems on its production, storage, transportation, and use should be solved. There are various methods used in hydrogen production. These methods may require both electricity and heat inputs and renewable energies such as solar, wind, hydro and nuclear energy use are being investigated. Hydrogen can be stored and transported either as compressed gas or as a liquid occupying a small volume after being liquefied. Hydrogen liquefaction requires considerable energy consumption and involves advanced refrigeration techniques.

The subject of this thesis is the thermodynamic and economic investigation of geothermal energy use in hydrogen production and liquefaction. For this aim, various methods used in hydrogen production and liquefaction are examined, the methods most suitable for geothermal energy use are identified, and appropriate models for using geothermal energy are structured. These models are simulated in computer environment, thermodynamic and economic analyses are done, and these models are compared using thermodynamic and economic performance criteria. When structuring the models, alternatives such as direct use of geothermal heat and/or the use of produced electricity are considered. A binary geothermal cycle is selected for power production. Electrolysis and high-temperature electrolysis are used for hydrogen production and a precooled Linde-Hampson cycle is used for hydrogen liquefaction. Also, an absorption refrigeration system is incorporated into the models for precooling of hydrogen before liquefaction.

Seven models are developed and their thermodynamic and economic analyses are performed. The amount of hydrogen production and liquefaction per unit mass of geothermal water and the cost of producing and liquefying a unit mass of hydrogen are calculated for each model. The effects of geothermal water temperature on these performance parameters are studied. It appears that the amount of hydrogen production per unit mass of geothermal water increases and the cost of hydrogen production decreases as the geothermal temperature increases. An economic analysis indicates that the initial costs of the models involving hydrogen liquefaction are higher compared to the models not including liquefaction. The results of this thesis are compared to those involving wind, solar, and nuclear-based hydrogen production. The models developed in this study are applied to the geothermal resources in Turkey, and the potential amounts of hydrogen production are estimated.

The results of this thesis indicate that geothermal-based hydrogen production and liquefaction may take an important place in a future renewable-based hydrogen economy as it can be accomplished with the current systems and technology.

**Keywords:** Hydrogen, geothermal energy, hydrogen production, hydrogen liquefaction, hydrogen economy, hydrogen cost.

# ÖZET

# JEOTERMAL ENERJİNİN HİDROJEN ÜRETİMİ VE SIVILAŞTIRILMASINDA KULLANIMININ TERMODİNAMİK VE EKONOMİK ANALİZİ

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Hidrojen, bazılarınca geleceğin enerji kaynağı olarak görülen ve üzerinde çok sayıda araştırmanın yapıldığı alternatif bir enerji kaynağıdır. Hidrojenin geleceğin enerjisi olabilmesi için yenilenebilir enerji kaynakları kullanılarak üretilmesi, üretim, depolama, taşıma ve kullanımı gibi konulardaki teknik ve ekonomik problemlerin aşılması gerekmektedir. Hidrojen üretiminde kullanılan birçok yöntem vardır. Hem elektrik hem de ısı girdisi gerektirebilen bu metotlarda güneş, rüzgâr ve hidroelektrik gibi yenilenebilir enerji kaynaklarının yanı sıra nükleer enerjinin kullanımı da üzerinde çokça çalışılan konular arasındadır. Hidrojen sıkıştırılmış gaz olarak depolanabileceği ve taşınabileceği gibi sıvılaştırılarak sıvı fazında çok daha küçük bir hacimde muhafaza edilebilir. Hidrojen sıvılaştırması yüksek miktarda enerji tüketimi gerektiren ve ileri soğutma tekniklerinin kullanıldığı bir işlemdir.

Bu tezde, jeotermal enerjinin hidrojen üretimi ve sıvılaştırmasında kullanımının termodinamik ve ekonomik olarak araştırılması yapılmıştır. Bu amaçla hidrojenin farklı üretim ve sıvılaştırma teknikleri incelenerek jeotermal enerjinin kullanımına uygun metotlar tespit edilmiş ve jeotermal enerjinin kullanılabileceği uygun modeller oluşturulmuştur. Bu modeller, bilgisayar ortamında simüle edilerek modellerin termodinamik ve ekonomik analizleri gerçekleştirilmiş ve farklı modeller, termodinamik ve ekonomik performans kriterleri yardımıyla karşılaştırılmıştır. Modellerde hem jeotermal ısı hem de jeotermalden üretilen elektrik girdi olarak kullanılmıştır. Güç üretimi için çift akışkanlı jeotermal çevrim seçilmiştir. Hidrojen üretimi için elektroliz ve yüksek sıcaklıkta elektroliz metotları kullanılmıştır. Hidrojen sıvılaştırmasında ön soğutmalı Linde-Hampson çevrimi kullanılmış ve sıvılaştırma öncesi ön soğutma için absorpsiyonlu soğutma sistemi uygun modellere entegre edilmiştir.

Bu sistemlerle geliştirilen 7 modelin termodinamik ve ekonomik analizleri gerçekleştirilerek birim kg ile üretilebilecek ve sıvılaştırılabilecek hidrojen miktarları her bir model için hesaplanmış ve birim kg hidrojenin üretim ve sıvılaştırma maliyeti araştırılmıştır. Bu performans parametrelerinin jeotermal kaynak sıcaklığı ile değişimi incelenmiş ve birim kg başına üretilebilecek hidrojen miktarının jeotermal sıcaklıkla arttığı ve birim hidrojen maliyetinin azaldığı tespit edilmiştir. Toplam maliyet incelemesi sonucunda sıvılaştırma ünitesi olan modellerin toplam yatırım maliyetinin daha fazla olduğu ortaya çıkmıştır. Elde edilen sonuçların güneş, rüzgâr ve nükleer gibi diğer enerji kaynaklarının kullanımı ile ilgili literatürden elde edilen sonuçlarla karşılaştırması yapılmıştır. Jeotermal destekli hidrojen üretimi, diğer yenilenebilir kaynaklarla hidrojen üretimine benzer bir performans göstermektedir. Geliştirilen 7 modelin Türkiye'deki jeotermal kaynaklara uygulaması yapılarak, bu modeller yardımıyla Türkiye'deki jeotermal kaynaklardan elde edilebilecek hidrojen miktarları tahmini yapılmıştır. Bu çalışmada yapılan analizler ve elde edilen sonuçlar, jeotermal enerjiden hidrojen üretimi ve sıvılaştırmasının mevcut teknolojilerle gerçekleştirilebilecek uygun bir alternatif olduğunu ve muhtemel bir hidrojen ekonomisinde önemli bir yer tutabileceğini göstermektedir.

**Anahtar Kelimeler:** Hidrojen, jeotermal enerji, hidrojen üretimi, hidrojen sıvılaştırılması, hidrojen ekonomisi, hidrojen maliyeti.

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# CHAPTER 1

# INTRODUCTION AND LITERATURE SURVEY

## 1.1 Introduction

Geothermal energy is the thermal energy within the earth’s interior. Geothermal energy is used to generate electricity and for direct uses such as space heating and cooling, industrial processes, and greenhouse heating. High-temperature geothermal resources above 150°C are generally used for power generation. Moderate- (between 90°C and 150°C) and low-temperature (below 90°C) geothermal resources are best suited for direct uses such as space and process heating, cooling, aquaculture, and fish farming [1]. With the increasing scarcity of fossil fuels and increasing concerns over the environmental problems they cause, the use of renewable energy resources will likely increase and diversify. Geothermal energy appears to be a potential solution where it is available to some of the current energy and environmental problems, and a key resource for making society more sustainable [2].

Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy. Geothermal power plants tap certain high-temperature resources to generate electricity with minimal or no air emissions. The common types of geothermal power plants are dry steam, single- and double-flash, binary, and flash/binary cycles.

Hydrogen is considered by many to be a potential replacement for fossil fuels [3]. The total cost of producing hydrogen depends on production, liquefaction, storage, and distribution costs [4]. Sherif et al. [5] provides some key data on economics of hydrogen production.

Hydrogen, an alternative energy source, is subject of a lot of research work and some consider it as the energy of the future. If hydrogen is to become the energy of the future, it must be produced using renewable energy sources and the technical and economic problems on its production, storage, transportation, and use should be solved. There are various methods used in hydrogen production. These methods include: steam methane reforming (SMR), electrolysis, coal gasification, liquid reforming, nuclear high-temperature electrolysis, and high-temperature thermo-chemical water-splitting, photo-biological, and photo-electrochemical. The first three methods are currently used while the remaining ones are still being researched or developed. Electrolysis is the process of making a non-spontaneous process occurs by applying an external power supply to the application. These methods may require electricity and/or heat inputs [6].

There are several methods used to produce hydrogen. These methods include: steam methane reforming (SMR), electrolysis, coal gasification, liquid reforming, nuclear high-temperature electrolysis, high-temperature thermo-chemical water-splitting, photo-biological, and photo-electrochemical. The first three methods are currently used while the remaining ones are still being researched or developed. Electrolysis is a method of using an electric current to drive an otherwise non-spontaneous chemical reaction. Electrolysis is the passage of an electric current through an ionic substance that is either molten or dissolved in a suitable solvent, resulting in chemical reactions at the electrodes and separation of materials [7].

Currently, 80–85% of the world’s total hydrogen production is derived via steam methane reforming of natural gas. Most of the remaining hydrogen production is accomplished via coal gasification and water electrolysis (at a smaller scale). Worldwide, some 48% of hydrogen is currently produced from natural gas, 30% from oil, and 18% from coal. The remaining 4% is produced through water electrolysis [8]. Hydrogen production requires the investment of energy and capital. Conventionally produced hydrogen gas cost about twice that of natural gas or oil and about 3 times more than coal. At present only the space industry seems to be willing to pay the high cost of hydrogen energy. These industrial methods mainly consume fossil fuels as energy source and are considered to be energy intensive and not always environmental friendly. Over the past several years hydrogen production has become more efficient and less expensive, and this trend is expected to continue [9, 10].

With the increasing scarcity of fossil fuels and increasing concerns over the environmental problems they cause, the use of renewable energy resources will likely increase and diversify. Geothermal energy appears to be a potential solution where it is available to some of the current energy and environmental problems, and a key resource for making society more sustainable [11]. Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy. Geothermal power plants tap certain high-temperature resources to generate electricity with minimal or no air emissions. The common types of geothermal power plants are dry steam, single- and double-flash, binary, and flash/binary cycles [12].

Geothermal energy has a significant potential on hydrogen economy where it can contribute sustainable production of hydrogen by renewable energy sources. With the increasing scarcity of fossil fuels and increasing concerns over the environmental problems they cause, the use of renewable energy resources will likely increase and diversify. In this regard, the use of geothermal energy for hydrogen production and liquefaction can prove to be effective option in the future hydrogen structure.

A number of existing and planned demonstration projects are using or will use electrolysis, even though it is one of the more energy intensive processes for producing hydrogen. However, it provides a pathway for producing hydrogen from carbon free renewable energy. Hydrogen provides the connecting point between renewable electricity production and transportation, stationary and portable energy needs. When the electricity from solar photovoltaic, wind, geothermal, ocean and hydro technologies is used to produce and store hydrogen, the renewable source becomes more valuable and can meet a variety of needs [13].

Jonsson et al. [14] investigated the feasibility of using geothermal energy for hydrogen production and estimated that using geothermal energy could avoid 16% of the work consumption for electrolysis and 2% for liquefaction. Sigurvinssona et al. [15] investigated the use of geothermal heat in high-temperature electrolysis (HTE) process. This HTE process includes heat exchangers and an electrolyser based on solid oxide fuel cell (SOFC) technology working in inverse, producing oxygen and hydrogen instead of consuming them. Using features related to the heat exchangers and the electrolysers, a set of physical parameters were calculated by using a techno-economic optimization methodology.

Mansilla et al. [16] studied a techno-economic optimization of the upper heat exchanger network in the high temperature electrolysis process for producing hydrogen. Heat obtained by coupling the process either to a high-temperature reactor or to a geothermal source. Ingason et al. [17] investigated the most economical ways of producing hydrogen solely via electrolysis from water, using electricity from hydro and geothermal power. The mixed integer programming model presented here facilitates the search for optimal choices from the 23 potential power plants, 11 of which are based on geothermal sources, and 12 are hydropower stations. The potential of geothermal resources of the western United States for producing electricity is investigated. This electricity would be used for the production of hydrogen [18]. Balta et al. [19] analyzed high temperature electrolysis process where geothermal water is used as the heat source. Another study [20] discussed various options for geothermal-based hydrogen production systems and their technical, operational and efficiency aspects.

Kanoglu et al. [21] investigated the use of geothermal energy for hydrogen liquefaction. Three models were considered for the analysis including the use of geothermal power for liquefaction cycle, the use of absorption cooling system for precooling gas before liquefaction and a cogeneration option for which both geothermal electricity and geothermal heat for absorption system are used. The cogeneration option appeared to provide significant savings in the energy requirement in the liquefaction process.

Hydrogen can be stored and transported either as compressed gas or as a liquid occupying a small volume after being liquefied. Hydrogen liquefaction requires considerable energy consumption and involves advanced refrigeration techniques. Despite the existence of numerous investigations on the use of renewable energy sources for hydrogen production, reports on using geothermal energy sources for hydrogen production and liquefaction are limited as summarized above.

We propose the use of geothermal energy for hydrogen production and liquefaction, and investigate seven possible cases for accomplishing such a task. We provide thermodynamic procedure to evaluate the systems considered and define appropriate performance parameters. The effects of geothermal water temperature on system performance parameters are also studied.

## 1.2 Literature Survey

This section gives information about hydrogen and geothermal energy, hydrogen production methods are examined. A detailed literature survey is made of hydrogen production and liquefaction. The project constitutes the main subject of geothermal energy and hydrogen production and liquefaction of the details of which are necessary for the models are determined.

### 1.2.1 Hydrogen

Hydrogen is the chemical element with atomic number 1. It is represented by the symbol H. At standard temperature and pressure, hydrogen is a colorless, odorless, nonmetallic, tasteless, highly flammable diatomic gas with the molecular formula $H_2$. With an atomic mass of 1.00794 amu, hydrogen is the lightest element.

Hydrogen is the most abundant of the chemical elements, constituting roughly 75% of the universe's elemental mass [22]. Stars in the main sequence are mainly composed of hydrogen in its plasma state. Elemental hydrogen is relatively rare on Earth, and is industrially produced from hydrocarbons such as methane, after which most elemental hydrogen is used "captively" (meaning locally at the production site), with the largest markets about equally divided between fossil fuel upgrading (e.g., hydrocracking) and ammonia production (mostly for the fertilizer market). Hydrogen may be produced from water using the process of electrolysis, but this process is presently significantly more expensive commercially than hydrogen production from natural gas [23].

The most common naturally occurring isotope of hydrogen, known as protium, has a single proton and no neutrons. In ionic compounds it can take on either a positive charge (becoming a cation composed of a bare proton) or a negative charge (becoming an anion known as a hydride). Hydrogen can form compounds with most elements and is present in water and most organic compounds. It plays a particularly important role in acid-base chemistry, in which many reactions involve the exchange of protons between soluble molecules. As the only neutral atom for which the Schrödinger equation can be solved analytically, study of the energetic and bonding of the hydrogen atom has played a key role in the development of quantum mechanics [24].

The solubility and characteristics of hydrogen with various metals are very important in metallurgy (as many metals can suffer hydrogen embrittlement) and in developing safe ways to store it for use as a fuel. Hydrogen is highly soluble in many compounds composed of rare earth metals and transition metals and can be dissolved in both crystalline and amorphous metals. Hydrogen solubility in metals is influenced by local distortions or impurities in the metal crystal lattice.

Hydrogen is an odorless, colorless gas. With a molecular weight of 2.016 g/mol, hydrogen is the lightest element. Its density is about 14 times less than air (0.08376 $kg/m^3$ at Standard temperature and pressure). Hydrogen is liquid at temperatures below 20.3 K (at atmospheric pressure). Hydrogen has the highest energy content per unit mass of all fuels-its higher heating value is 141.9 MJ/kg, almost three times higher than that of gasoline. However, because of its low density, its heating value on volumetric basis is almost one third that of natural gas. It exists in three isotopes: protium, deuterium, and tritium. A standard hydrogen atom (protium) is the simplest of all the elements and consists of one proton and one electron. Molecular hydrogen ($H_2$) exists in two forms: ortho- and para-hydrogen. Both forms have identical chemical properties, but due to different spin orientations have somewhat different physical properties. At room temperature hydrogen consists of approximately 75% ortho- and 25% para-hydrogen. Because para-hydrogen is more stable at lower temperatures its concentration increases at lower temperatures, reaching virtually 100% at liquid hydrogen temperatures [25].

Table 1.1 Properties of hydrogen (at standard Temperature and Pressure) [26].

| **Properties** | **Unit** | **Value** |
|---|---|---|
| Molecular Weight | Kg/kmol | 2.016 |
| Density | kg/m$^3$ | 0.0838 |
| Higher heating value | MJ/kg | 141.9 |
|  | MJ/m$^3$ | 11.89 |
| Lower heating value | MJ/kg | 119.90 |
|  | MJ/m$^3$ | 10.05 |
| Boiling temperature | K | 20.3 |
| Density as liquid | kg/m$^3$ | 70.8 |
| Critical point |  |  |
| Temperature | K | 32.94 |
| Pressure | Bar | 12.84 |
| Density | kg/m$^3$ | 31.40 |
| Self-ignition temperature | K | 858 |
| Ignition limits in air | Vol. (%) | 4-75 |
| Stoichiometric mixture in air | Vol. (%) | 29.53 |
| Flame temperature in air | K | 2,318 |

| | | |
|---|---|---|
| Diffusion coefficient | $cm^2/s$ | 0.61 |
| Specific heat ($c_p$) | kJ/kg.K | 14.89 |

### 1.2.2 Hydrogen Energy

Since hydrogen is considered as an alternative energy long periods. But, when the producing the technical, practical and economic difficulties have prevented the spread. Although hydrogen is the most plentiful element in the universe, making up about three quarters of all matter, free hydrogen is scarce. The atmosphere contains trace amounts of it (0.07%), and it is usually found in small amounts mixed with natural gas in crustal reservoirs. A few wells, however, have been found to contain large amounts of hydrogen, such as some wells in Kansas that contain 40% hydrogen, 60% nitrogen, and trace amounts of hydrocarbons [27]. The Earth’s surface contains about 0.14% hydrogen (the tenth most abundant element), most of which resides in chemical combination with oxygen as water. Hydrogen, therefore, must be produced. Logical sources of hydrogen are hydrocarbon (fossil) fuels (CxHy) and water ($H_2O$).

Primary energy sources, including the physical state change in the secondary energies obtained by transforming the energy carrier is called. Electricity is the 20th century marked an energy carrier. Hydrogen may be a carrier of energy in the 21st century will mark another.

Hydrogen energy is considered as one of the next century's most important energy sources. This energy can be achieved water with high efficiency, without causing any bed effect on the environment can be converted into useful energy. As the demand for energy resources continues to increase non-electrical source, non-fossil sources, the fossil will be forced to switch to a synthetic sources. New energy sources to complement the shortcomings of its way to becoming an ideal energy sources, and this will serve as a bridge between the consumer and hydrogen energy systems to create and use these systems are possible.

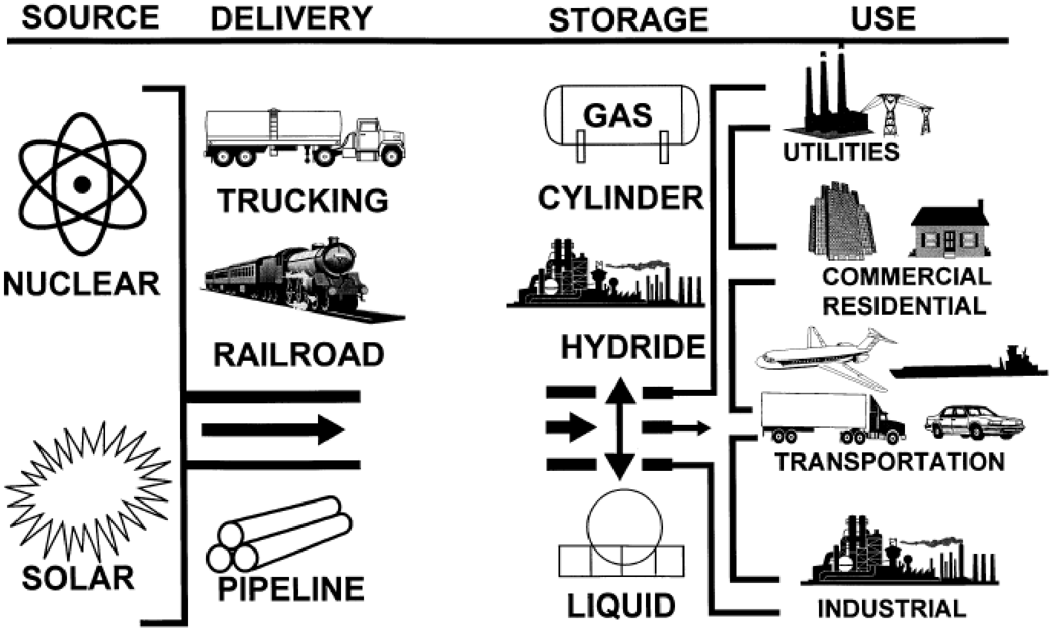


Figure 1.1 Hydrogen energy systems [28].

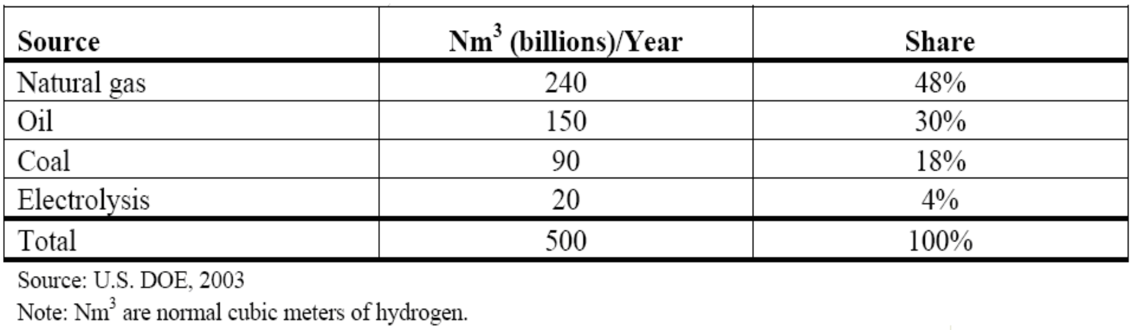
Hydrogen is expensive compared to other fuels in the long run despite the technological advances will play a major role in energy use. Depending on the size of the market area and the cost per kg of hydrogen is between 2.5 to 7 $/kg. However, this cost is relative; step-entering the hydrogen age is expected to decline rapidly [28].

### 1.2.3 Hydrogen Production Methods

Hydrogen is an energy carrier, not an energy source, it stores and delivers energy in a usable form, but it must be produced from compounds that contain it. Hydrogen can be produced using diverse, domestic resources including fossil fuels, such as coal (with carbon sequestration) and natural gas; nuclear; and biomass and other renewable energy technologies, such as wind, solar, geothermal, and hydroelectric power. Great potential for diversity of supply is an important reason why hydrogen is such a promising energy carrier.

Hydrogen can be produced using a variety of resources. This diversity of sources makes hydrogen a promising energy carrier and enables hydrogen production almost anywhere in the world. Researchers are developing a wide range of technologies to produce hydrogen economically from a variety of resources in environmentally friendly ways.

Table 1.2 Annual worldwide hydrogen production share by source[29].



| Source | $Nm^3$ (billions)/Year | Share |
|---|---|---|
| Natural gas | 240 | 48% |
| Oil | 150 | 30% |
| Coal | 90 | 18% |
| Electrolysis | 20 | 4% |
| Total | 500 | 100% |

Source: U.S. DOE, 2003
Note: $Nm^3$ are normal cubic meters of hydrogen.

Presently, hydrogen is mostly being produced from fossil fuels (natural gas, oil, and coal). However, except for the space program, hydrogen is not being used directly as a fuel or as an energy carrier. It is being used in refineries to upgrade crude oil (hydrotreating and hydrocracking), in the chemical industry to synthesize various chemical compounds (such as ammonia, methanol, etc.), and in metallurgical processes (as a reduction or protection gas). The total annual hydrogen production worldwide in 1996 was about 40 million tons (5.6 EJ) [29]. Less than 10% of that amount was supplied by industrial gas companies; the rest was produced at consumer-owned and operated plants (so-called captive production) such as refineries and at ammonia and methanol production facilities. Production of hydrogen as an energy carrier would require an increase in production rates by several orders of magnitude.

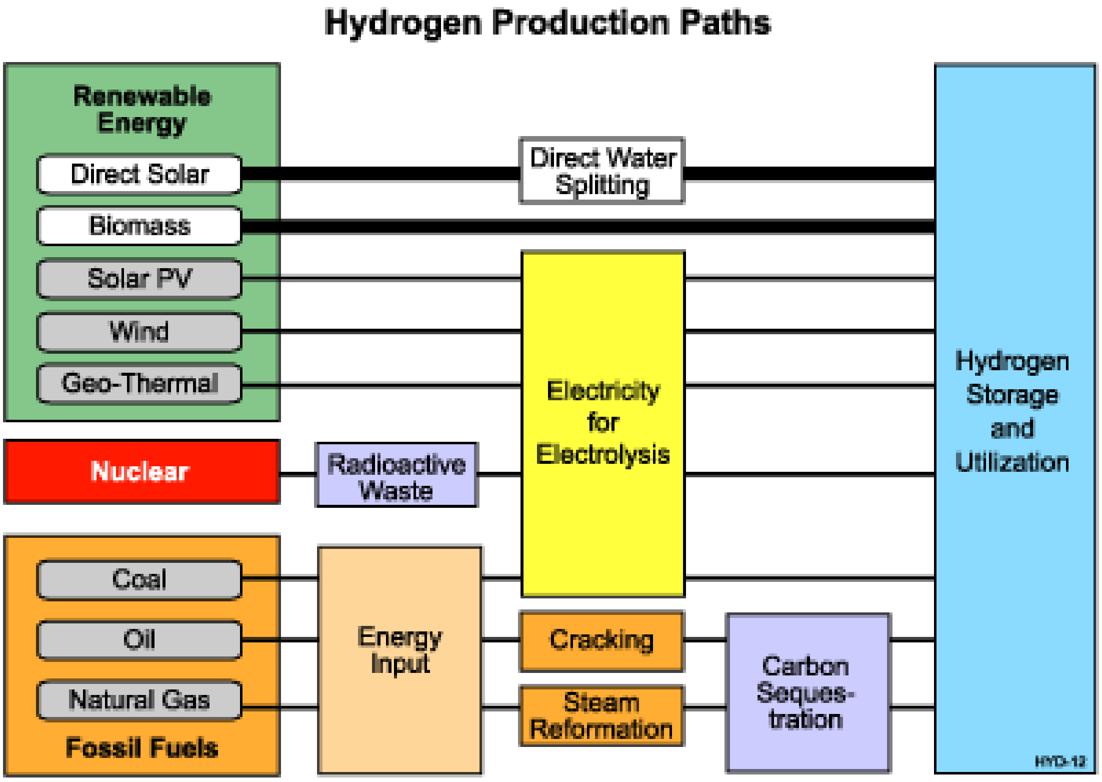


Figure 1.2 Hydrogen production paths [29].

### 1.2.4 Energy Required for Production of Hydrogen from Ensured

A certain amount of hydrogen during the production and use of energy are needed. Fossil fuel energy input provided that the existing systems are required. This continued deterioration of the natural balance and increasing amounts of waste is released into the atmosphere. In other words, the use of hydrogen energy in this way will not be any contribution of the prevention of environmental disaster. Therefore, current hydrogen production systems should be changed with environmental systems. It is not possible to complete the change of energy systems from today to tomorrow. Because of high cost and economic reason, it is not meaningful. Transition period should be gradual. In this process, all energy sources should be used to obtain hydrogen. Environmental emissions of hydrogen production can be reduced using by renewable source instead of fossil fuels [31].

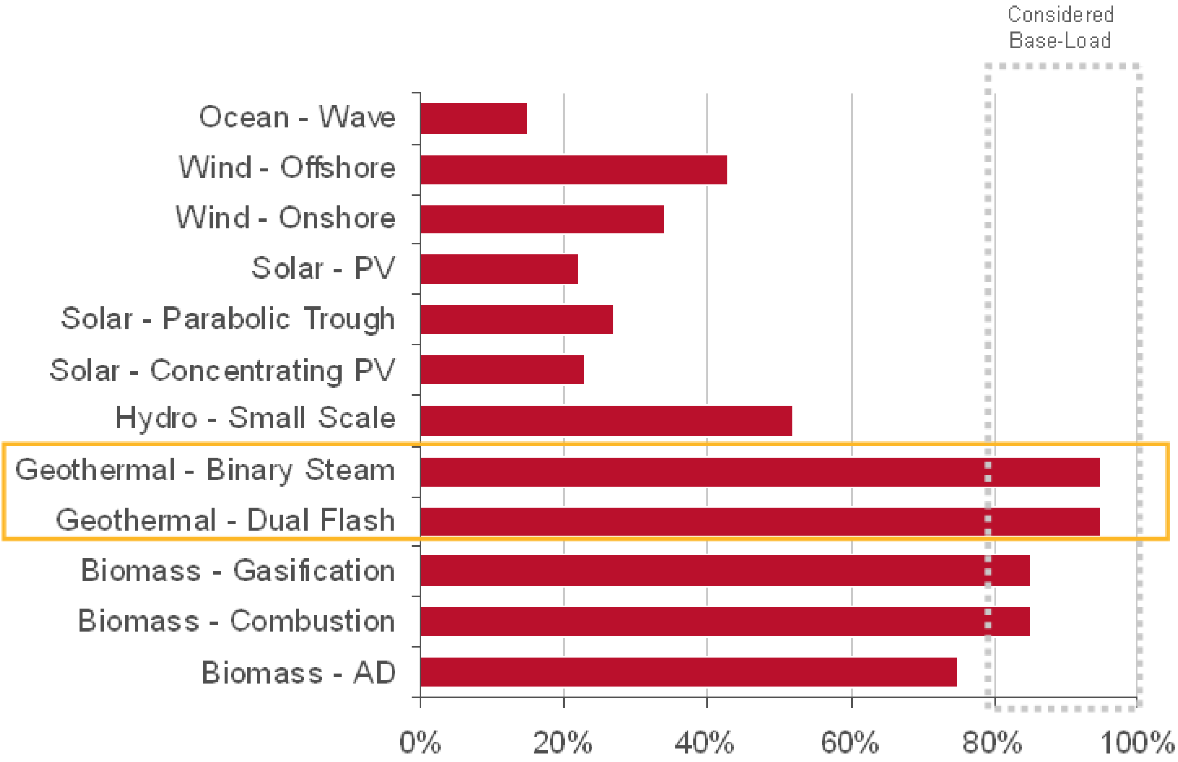


Figure 1.3 Average net capacity factors (%) for selected renewable in the world [32].

A hydrogen economy, renewable energy sources must be used for hydrogen production. The potential of renewable energy is seen around the world in the Figure 1.3.

### 1.2.5 Hydrogen Production Options and Methods

#### 1.2.5.1 Hydrogen Production Using By Solar Energy

The most important property of renewable energy sources is not harmful for environment. So far all studied systems up to the here the best example of this solar-hydrogen energy systems. Renewable energy sources are expected to provide a large part of the world's energy needs in the near future. These resources of solar-hydrogen hybrid system are the most efficient systems in these studies. The natural gas steam production to produce hydrogen system is currently most economical method of hydrogen production systems the most economical and relatively the cost of production is 6 $/GJ. But the next time, the natural gas will be run out off in a system of this kind, considering of the high emission rates despite low levels of cost, it is not the desired method and appears very efficient [33].

Electric power generation process of solar energy was applied in various fields. However, storage of solar energy is a problem in the process appears. Solar energy is converted to clean and safe manner to electrical energy via solar panels were made of silicon semi-conductor systems. This electrical energy storage of hydrogen is performed by electrolysis process. Useful form of energy conversion of solar energy can be divided into two parts, as thermal and photonics. Thermal process, solar energy is firstly converted into heat or utilized in this heat energy or energy is converted to mechanical or electrical energy with different energy conversion systems. Another option is stored this energy by various ways. The photons are absorbed directly by an absorbing material in photonic process. These photon absorbers substances are converted directly (such as photovoltaic cells) electrical energy or to split water into the hydrogen and oxygen some part of this photon energy.

### 1.2.5.2 Hydrogen Production Using By Wind Energy

Electricity produced from wind turbines, converted to hydrogen using by electrolysis process. Wind-hydrogen hybrid system consists of the following sections (Figure 1.4):

- The wind turbine,
- The power control and settings,
- Electrolyser,
- Hydrogen storage,
- Fuel cells.

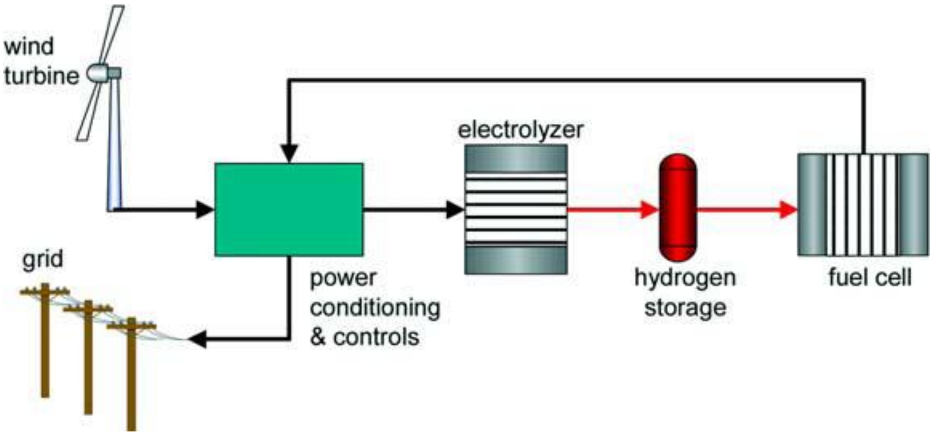


Figure 1.4 Schematic diagram of integrated wind-hydrogen utility energy system [34].

### 1.2.5.3 Hydrogen Production Using by Natural Gas (Methane) Steam Reformation

Today, hydrogen production is obtained approximately 95% by steam methane conversion (steam methane reforming). Hydrogen production of steam reformation process is the most common, economical and efficient process for hydrocarbons (usually natural gas). This method has involves simply three main steps.

- Synthesis gas production,
- Water-gas replacement,
- Gas refinement.

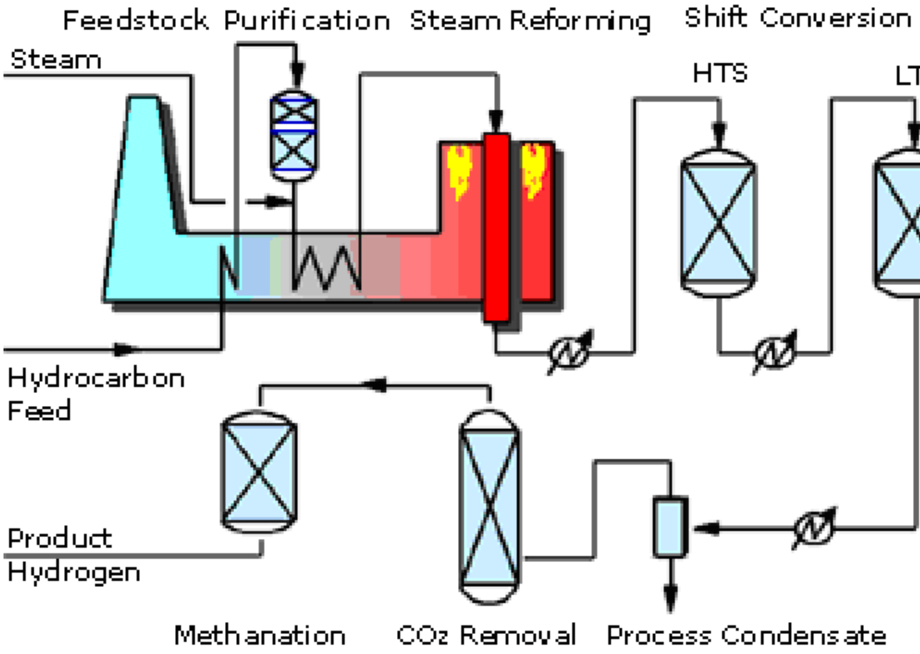


Figure 1.5 Steam reformation of natural gas [35].

### 1.2.5.4 Natural Gas Thermal Fragmentation Using by Hydrogen Production

Thermal separation of natural gas is a method used to obtain different products for many years. Methane air flame temperature is at 1400°C to remove. Because this method generates by-product (black carbon) is the economic as well suited.

### 1.2.5.5 Coal Gasification using by Hydrogen Production

When is coal gasification process, pulverized coal oxidation is suffers broken down quickly under atmospheric pressure with oxygen and steam (Figure 1.6). Coal gasification process has become very complex due to the necessity of carrying large amounts of solid fuel and ash in particular process. In general, coal is a cheaper fuel, but the function of coal gasification is not a cheap method for hydrogen production. Hydrogen production cost range is approximately from 12 to 14 \$/GJ in coal gasification process [36].

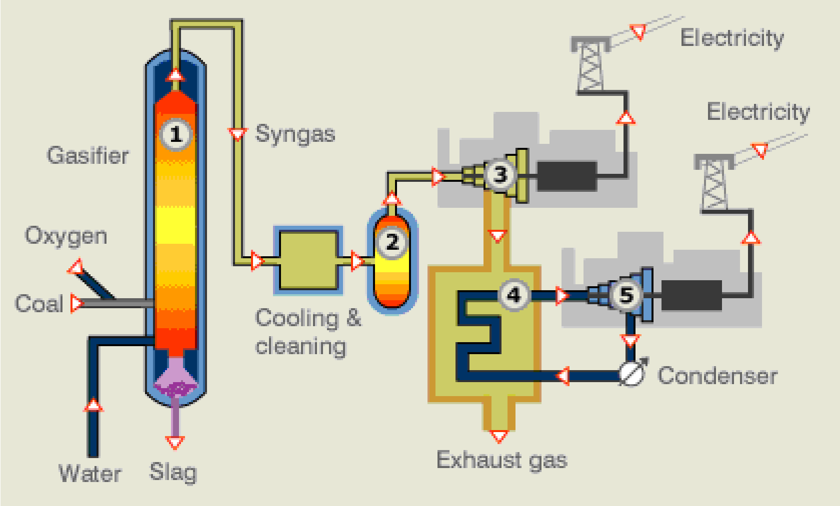


Figure 1.6 Hydrogen production using by coal gasification.

### 1.2.5.6 Biomass Process Using by Hydrogen Production

Hydrogen can be produce with pirolisis biomass/gasification in the biomass process. Biomass is processed under high temperature and low pressure in the reactor. At the end of operation hydrogen, methane, $CO_2$, CO and nitrogen are obtained. Gas flows are found at high temperature due to increased hydrogen content and relatively high-purity hydrogen can be obtained at the end of this process.

### 1.2.5.7 Direct Thermal Decomposition of Water (Thermoli) Using by Hydrogen Production

Water can be divided into thermally above the 2000K temperature. This decomposition can be shown by the following equation.

$$H_2O \rightarrow a\, H_2O + b\, OH + c\, H + d\, O + e\, H_2 + f\, O_2$$

Part of the decomposition process is only occurs 1% at 2000K, 8.5% at 2500K and 34% at 3000K. Product of the gas mixture is quite high temperatures. The biggest problem of this process transaction to perform the necessary of reaction materials can't be stand for this temperature.

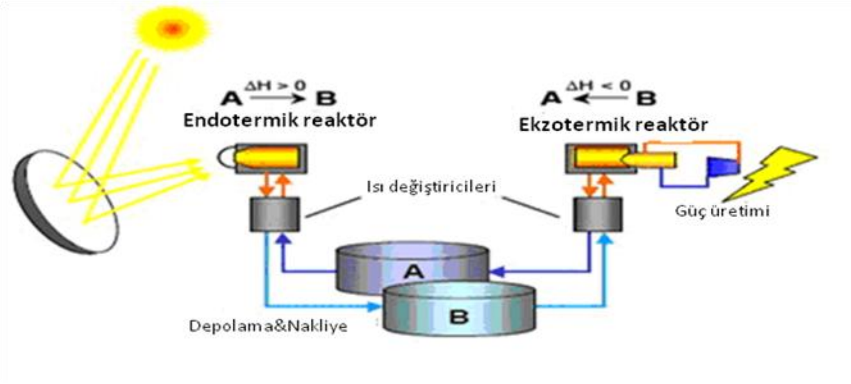


Figure1.7 Thermolysis process [37].

### 1.2.5.8 Thermochemical Cycles Using by Hydrogen Production

Thermochemical production of hydrogen allows to chemical water fragmentation at lower temperatures for necessary of Thermolysis process temperatures (Figure 1.8). For hydrogen production from thermochemical cycles were many found since the middle of 1960. But today one of them, only 20-30 is available for hydrogen production.

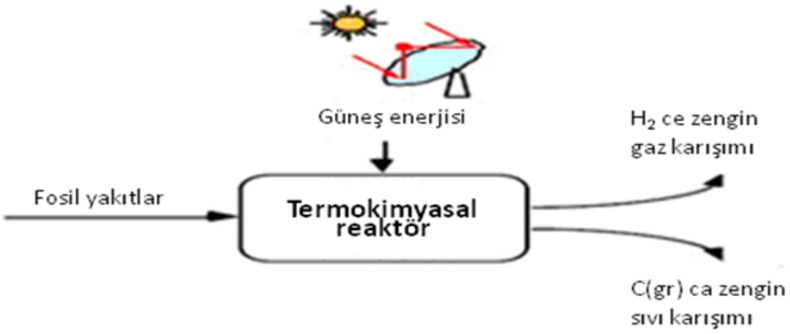


Figure 1.8 Hydrogen production using by thermochemical process [38].

### 1.2.5.9 Partial Oxidation Using by Hydrogen Production

In general, partial oxidation performed in three steps. The first step is synthesis gas, the second step of water gas exchange and gas purification is the third step (Figure 1.9). Partial oxidation of hydrocarbons is used to the make heavier form than naphtha oil. In general, partial oxidation has low efficiency from steam reformation and which about 50%. Hydrogen cost range is approximately 10 $/GJ.

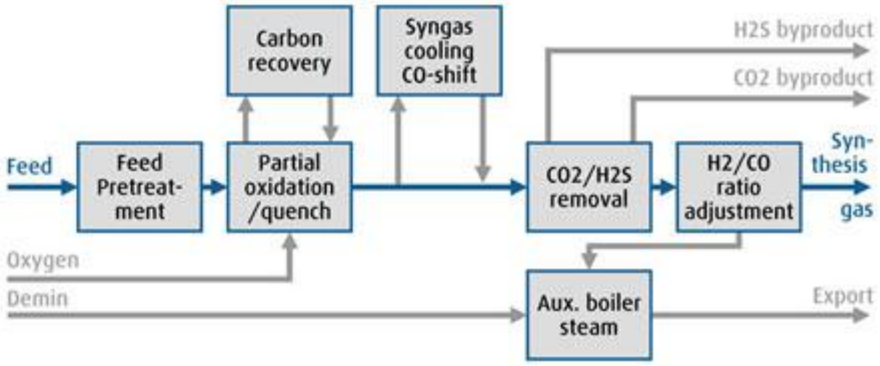


Figure 1.9 Partial oxidation for hydrogen production [39].

## 1.3 Hydrogen Production Use in by Electrolysis

### 1.3.1 Alkaline Water Electrolysis

Electrolysis is the process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyzer. Electrolyzers can be small, appliance-size equipment and well-suited for small scale distributed hydrogen production. Research is also under way to examine larger scale electrolysis that could be tied directly to renewable or other non-greenhouse gas emitting electricity production. Hydrogen production at a wind farm generating electricity is an example of this.

Hydrogen produced via electrolysis can result in zero greenhouse gas emissions, depending on the source of the electricity used. The source of the required electricity including its cost and efficiency, as well as emissions resulting from electricity generation must be considered when evaluating the benefits of hydrogen production via electrolysis. In many regions of the country, today's power grid is not ideal for providing the electricity required for electrolysis because of the greenhouse gases released and the amount of energy required to generate electricity. Hydrogen production via electrolysis is being pursued for renewable (wind, solar and geothermal) options. These pathways result in virtually zero GHG emissions and criteria pollutants [40].

Chemical equation shown below:

$H_2O \rightarrow H_2+1/2O_2$

Liquid water formation of Gibbs function at 25 °C and 1 atm pressure in thermophysical tables 237,180 kJ/kmol are provided. This value is the minimum work necessary for the expression of electrolysis at the same time. While this value is 13.166 kJ for 1 kg water and this value is 117,650 kJ for 1 kg hydrogen. In other words, this value is 32.7 kWh for 1 kg hydrogen. If the water is at 25°C in the steam form, minimum work is 113,387 kJ for the production of 1 kg hydrogen which will be 31.5 kWh.

There are three methods used to produce hydrogen in the electrolysis process: alkaline water electrolysis, solid polymer electrolysis and high-temperature steam electrolysis [41]. Alkaline water electrolysis is the most common method (Figure 1.10). Electrolyte solution is used as the electrolyte, approximately at 80°C and at a rate of 25-35% KOH.

$2H_2O + 2e^- \Rightarrow H_2 + 2OH^-$ at the cathode

$2OH^- \Rightarrow \frac{1}{2}O_2 + 2OH^- + 2e^-$ at the anode

Amount of electricity consumed for water electrolysis is about 50 kWh/kg hydrogen. Alkaline electrolyzes are continuing to decrease of electricity consumption is about 43 kWh by using an advanced alkaline electrolyzes. In addition to research is done to further reduce power consumption by using an inorganic membrane [42].

For electrolysis of water is ideally sufficient 1.23 volts under the normal pressure and temperature. Higher voltages used in the process of electrolysis for the reaction is slow and other reasons. Hydrogen production rate is proportional to the actual current intensity; high current densities are preferred for economic reasons. Therefore, applied voltage per cell for decomposition of water usually is about 2 volts in practice.

Developing advanced electrolysis a few techniques are listed below:

- Advanced alkaline electrolysis has efficiency up to 90%.
- Solid polymer electrolysis as the proton conduction uses an ion exchange element in the electrolytic process. This type of electrolyser can be work very high currents (2 A/cm²).

- High-temperature steam electrolysis operates between 700-1000 °C as the oxygen ion conductive ceramic electrolyte uses in this process.

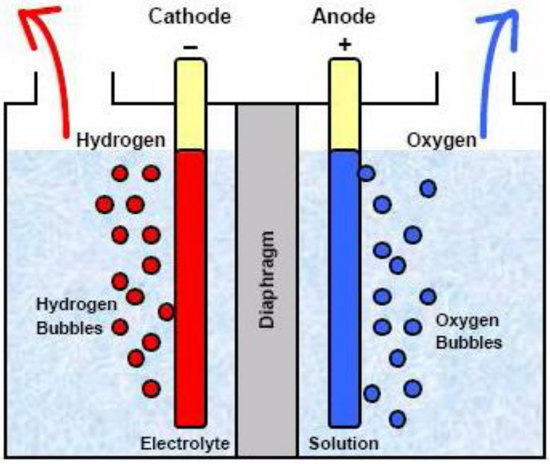


Figure 1.10 Alkaline water electrolysis [42].

### 1.3.2 High Temperature Steam Electrolysis

The most important advantage of this method, the required energy for decomposition of water taken from the, outside to reduce the energy required for electrolysis. High-temperature electrolysis of steam to heat 850-1000°C with the help of heat source and electricity consumption can be reduce approximately 30% according to the normal electrolysis process in this way (Figure 1.11). The biggest advantage of this system, total energy needs is the low, according to the normal methods of electrolysis.

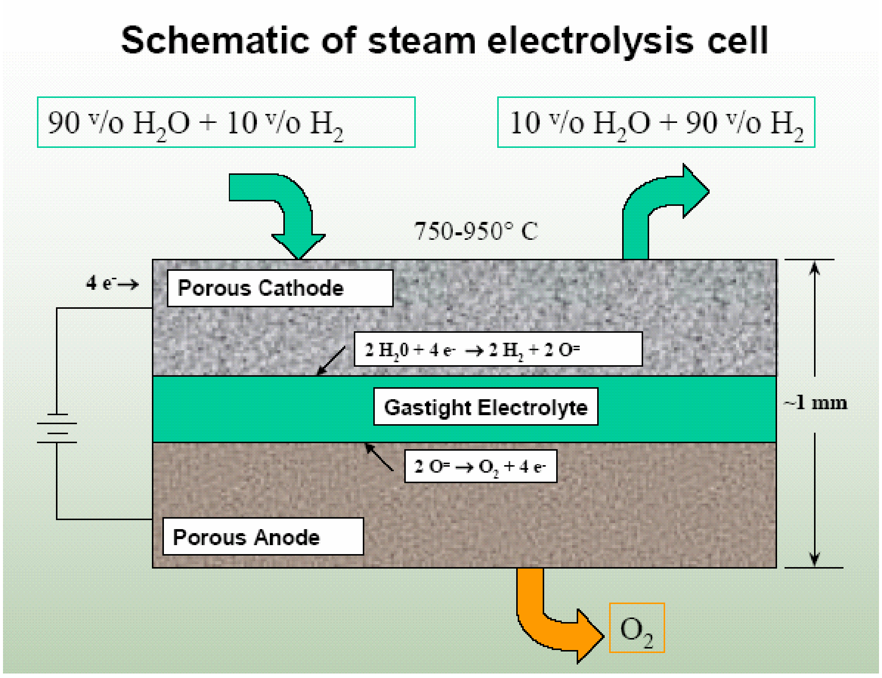


Figure 1.11 The basic principle of high-temperature steam electrolysis [43].

## 1.4 Geothermal Energy Using by Hydrogen Production

Geothermal is domestic energy resource with cost, reliability and environmental advantages over the conventional energy sources. Geothermal energy contributes both to energy supply, with the electrical power generation and direct heat uses, and to reduce energy demand, with savings in electricity and natural gas through use of geothermal heat pumps to heat and cool buildings. Only a small fraction of our geothermal resources are in use today.

Geothermal energy is renewable heat energy from deep into the earth. The word Geothermal comes from the Greek words geo (earth) and therme (heat). Geothermal energy is heat within the earth.

Geothermal energy provides an affordable, clean method of generating electricity and providing thermal energy. Geothermal power plants tap certain high-temperature resources (above 90°C) to generate electricity with minimal or no air emissions. Heat pumps and ‘direct-use’ applications, which rely on more common low-temperature resources (typically from as low as 35°C up to 150°C) are used throughout the country as an energy and dollar saving alternative to traditional furnaces and boilers. Two challenges for geothermal energy are that resources are difficult to locate and tend to be found in rural areas. The fact that they are found in remote areas constrains generation and direct use development. It is difficult to transmit heat energy or electricity to the population centers where people will use it. [44].

Geothermal energy can be used directly in temperatures ranging from about 35 to 150°C to heat buildings, greenhouses, aquaculture facilities and to provide industrial process heat. Indirectly, high-temperature geothermal steam can be used to drive a turbine and create electricity or in heat pumps [45]. Green and Gerald [46] stated that new low-temperature electric generation technology may greatly expand the geothermal resources that can be developed economically today.

Our country's existing geothermal potential can be use of 6.3% of the geothermal potential. The modern geothermal energy power plants have very low $CO_2$, $NO_x$, $SO_x$ emissions levels, it makes attractive to use this resource in the production of electrical energy. Today, continuing geothermal electricity production approximately 22 countries has approximately 8000 MW electricity capacity [47].

Temperatures of geothermal energy resources;

- Low temperature (below 90°C)
- The average temperature (between 90-150°C)
- High temperature (above 150°C) as classified.

Geothermal power plants use the earth’s heat in the form of underground steam or hot water to spin a turbine and generate electricity. Wells hundreds to thousands of feet deep are used to deliver the hot fluid to the power plant on the surface, where the heat is converted to electrical energy. Nearly all the water is returned to the reservoir through injection wells to be reheated. Currently, geothermal electricity production is limited to certain western states where the hottest resources are closer to the surface. Advances in drilling and energy conversion technologies could make it possible to expand the use of geothermal power plants to other states.

Depending on the geothermal fluid is extracted from underground to produce electricity as is used in different cycles. The three types of commercial geothermal power plants are dry steam plants that use resources of pure steam, flash steam and binary cycle plants that tap reservoirs of hot water (Figure 1.12-14) [48].

Dry steam power plants, draw from underground resources of steam. The steam is piped directly from underground wells to the power plant, where it is directed into a turbine/generator unit. There are only two known underground resources of steam in the

United States: The Geysers in northern California and Yellowstone National Park in Wyoming, where there's a well-known geyser called Old Faithful. Since Yellowstone is protected from development, the only dry steam plants in the country are at The Geysers [49].

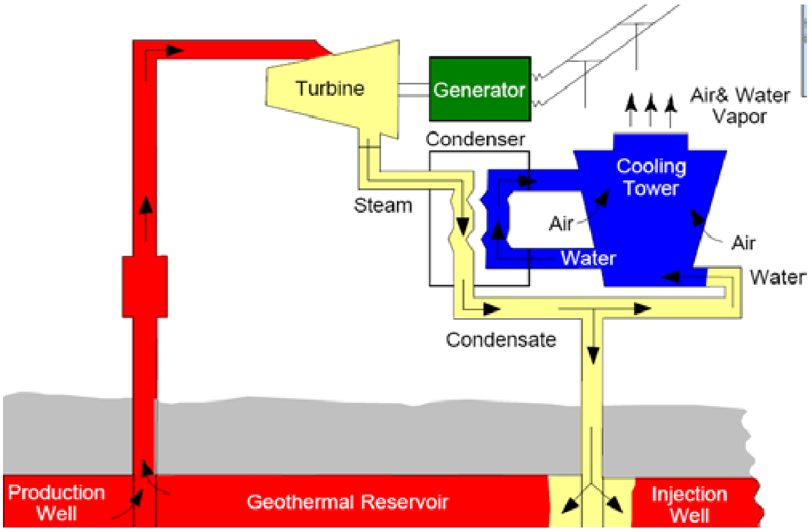


Figure 1.12 Schematic of the dry steam power plant [49].

Flash steam power plants are the most common. They use geothermal reservoirs of water with temperatures greater than 182°C. This very hot water flows up through wells in the ground under its own pressure. As it flows upward, the pressure decreases and some of the hot water boils into steam. The steam is then separated from the water and used to power a turbine/generator. Any leftover water and condensed steam are injected back into the reservoir, making this a sustainable resource [50].

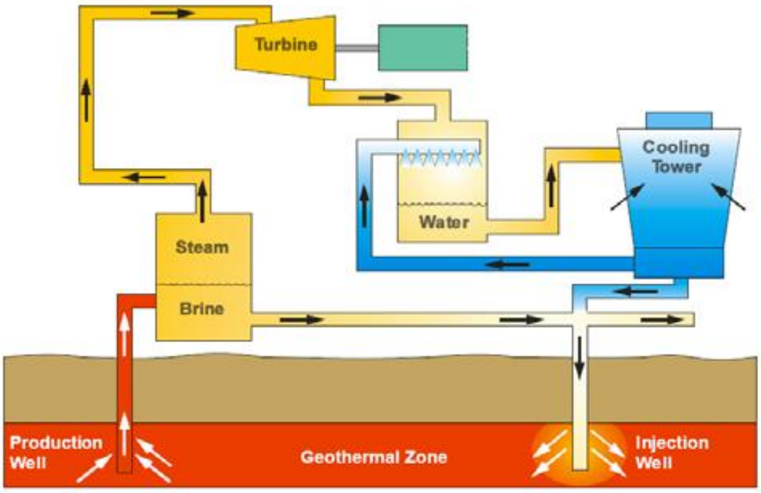


Figure 1.13 Schematic of the flash steam power plant [50].

Binary cycle power plants operate on water at lower temperatures of about 90-180°C. These plants use the heat from the hot water to boil a working fluid, usually an organic compound with a low boiling point. The working fluid is vaporized in a heat exchanger and used to turn a turbine. The water is then injected back into the ground to be reheated. The water and the working fluid are kept separated during the whole process, so there are little or no air emissions [51].

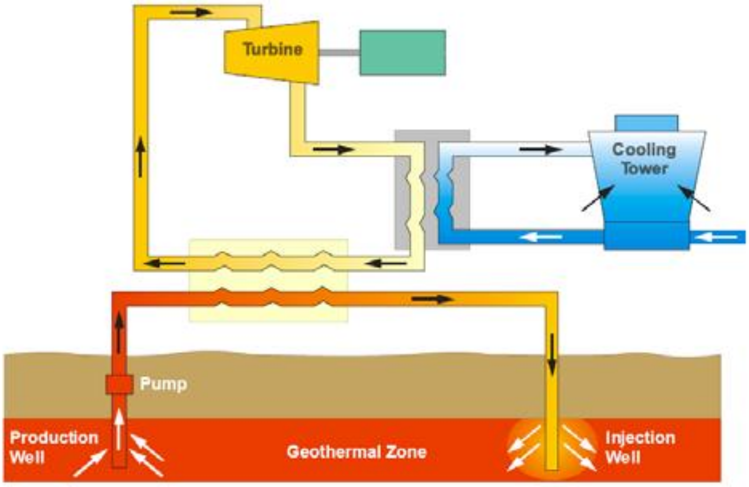


Figure 1.14 Schematic of the binary cycle power plant [51].

These some of geothermal power plants have ranged from 10-20% thermal efficiencies according to water temperatures. This efficiency is lower than use binary fluid power plants. Eco-friendly of this geothermal energy will be made hydrogen production, storage and liquefaction from these plants to be obtained from the thermal energy or electricity.

Geothermal energy is an important option in hydrogen production with renewable energy sources. In countries with abundant geothermal energy resources such as in Island Iceland, geothermal energy using by hydrogen production is an important method of energy production. Nowadays, various methods have been used for hydrogen production.

Recent research has been carried out by Landsvirkjun, Iceland’s national power company on deep drilling in Iceland shows the possibility of extracting 500-600°C of steam at a depth of 4-5 km for various applications, ranging from power production to hydrogen production [52]. In countries with abundant geothermal sources, certainly geothermal-based hydrogen production may become a major potential. Although only approximately 200-250°C of thermal input in the hydrogen production process coupled with a geothermal source is possible today, this may change within the next decades (Figure 1.15) [52].

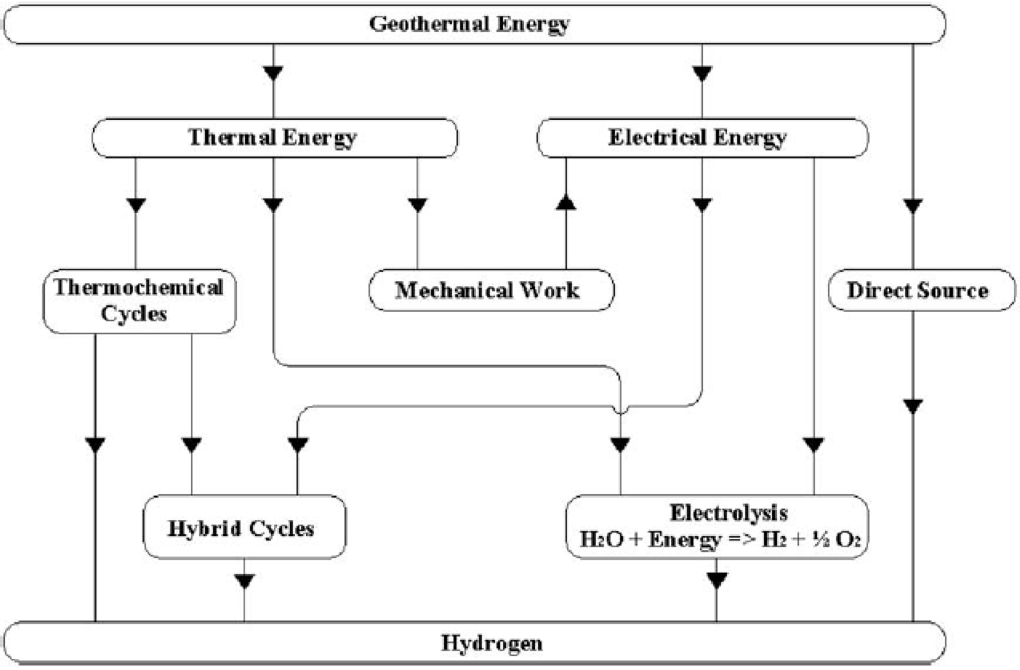


Figure 1.15 Production pathways of geothermal-based hydrogen production[52].

Hydrogen can be produced from geothermal energy using four potential methods, as shown in Fig. 1.15. Some studies on the origin of these methods have been made, while each method is described in the following subsections. These production methods are still on the developmental stage and may appear to be potential methods for hydrogen production in hydrogen economy.

*(a) Direct production of hydrogen from the steam*

In many regions of the earth, geothermal steam is generally vented to the atmosphere through hydrogen. Hydrogen is released to the atmosphere in technically recoverable concentrations and quantities. The utilization of this hydrogen directly requires cleaning of the gas (Fig. 1.16).

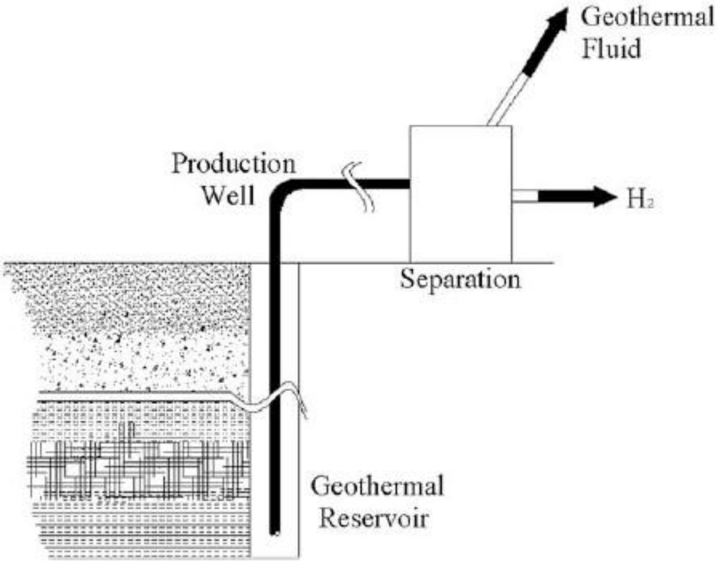


Figure 1.16 A simplified sketch of the direct production of hydrogen[52].

*(b) Hydrogen production using thermal energy*

Geothermal energy may be valorized in two different ways, in the form of electricity or in the form of heat. This heat and electricity can be used to produce hydrogen by hybrid cycles or electrolysis which is described in the below sections. Thermal hydrogen production needs to deliver heat at high temperatures such as 500-950°C.

*(c) Hydrogen production through electrolysis*

In this method, the geothermal heat is first converted to mechanical work through a geothermally driven power plant to produce electricity. Typically, geothermal power is converted into electricity through turbines operating on the flash steam or the binary Rankine cycle. The electricity is then used in an electrolysis process to split water into hydrogen and oxygen.

## 1.5 Hydrogen Liquefaction

Hydrogen as a fuel cannot become economically viable until its costs become comparable to those of fossil fuels. The cost of liquid hydrogen depends on several processes such as production, liquefaction, storage, and distribution. The by-products of liquefaction may be included in the cost of liquid hydrogen. There mainly are two byproducts; deuterium and liquefaction energy. Distillation of liquid hydrogen offers an attractive means of obtaining deuterium which is a fuel for fusion reactors. Although the maximum amount of energy recoverable from liquefaction is only about 10 percent of the combustion energy as noted by Parrish and Voth [53], it represents a significant amount of energy in large vaporizing facilities.

Firstly, hydrogen liquefaction method before the storing and transporting hydrogen is the good way after the super-insulated stored in warehouses. Liquefied hydrogen density is increased by about 600 times. Advanced cooling systems used to hydrogen liquefaction process is in non-traditional. For the liquefaction of a gas, we consider the precooled Linde-Hampson cycle because it is a well-known and relatively simple system used for hydrogen liquefaction (Fig. 2.7). Hydrogen is obtained approximately -253°C as a liquid [54].

Studies dealing with liquid hydrogen are numerous; however, very few of these studies address the economics of liquefaction. Sarangi [55] observed that low liquefaction temperatures mean a larger refrigeration cost, while low density means a larger volume, and hence a greater investment in containers and structural members. Justi [56] noted that the heat of transformation from ortho- to para-hydrogen will give rise to an evaporation of about 70 percent of the existing liquid hydrogen. One of the mechanisms used to reduce boil-off losses during storage is forcing the hydrogen to reach fast equilibrium using catalysts [57]. Parrish and Voth [53] discussed issues related to cost and availability of hydrogen, while Block et al. [58] in their detailed study on the storage of hydrogen in solid, liquid, and gaseous forms included some economic figures pertaining to storing hydrogen in those forms.

Even more energy is needed to compact hydrogen by liquefaction. Theoretically, only about 14.2 MJ/kgLH$_2$ have to be removed to cool hydrogen gas from 298 K (25 °C) to 20.3 K and to condense the gas at 20.3 K and atmospheric pressure [59].

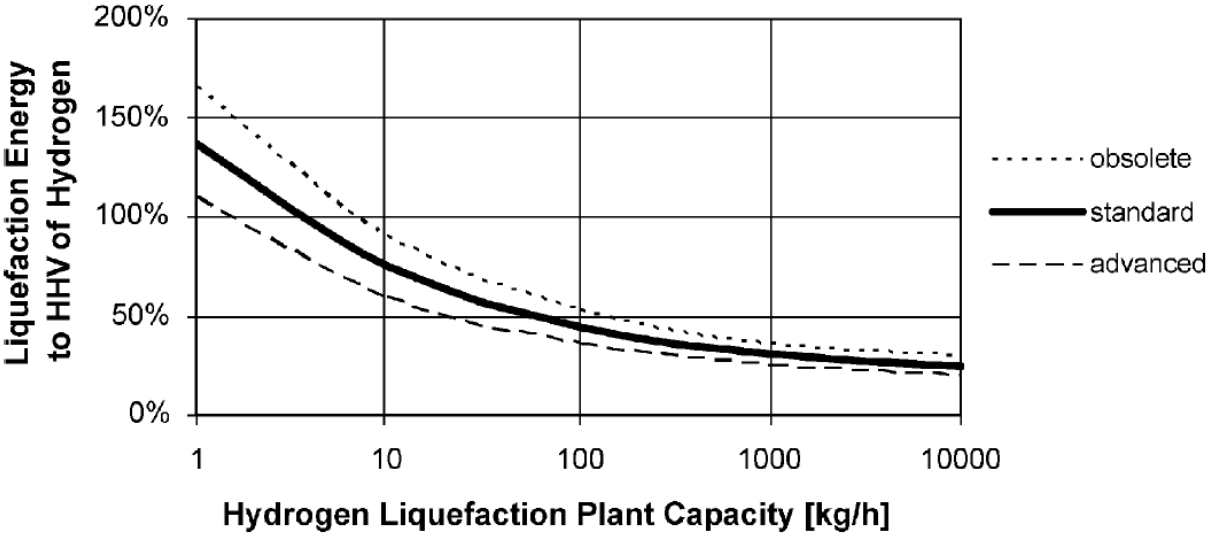


Figure 1.17 Liquefaction energy relative to the HHV of hydrogen versus plant capacity[62].

However, at such low temperatures, no heat sinks exist for cooling and condensing hydrogen. Generally, a three-stage propane refrigeration system is used for cooling hydrogen gas from ambient temperature to about 170 K, followed by multistage nitrogen expansion to obtain 77 K, and a multistage helium compression–expansion to complete the liquefaction of hydrogen at 20.3 K and atmospheric pressure [60]. The energy consumed by these three stages is much higher than the exergetic limit mentioned above. Therefore, published data of representative hydrogen liquefaction plants are used for reference.

The medium size liquefaction plant of Linde Gas AG at Ingolstadt in Germany produces 182 kg/h of $LH_2$ [16] at a specific energy consumption of about 54 MJ/kg$LH_2$ [59]. Advanced larger plants in the United States require 36 MJ/kg$LH_2$ to liquefy hydrogen [59]. In a Japanese feasibility study [61] of a hydrogen liquefaction plant of 300 metric tons $LH_2$ per day or 12,500 kg $LH_2$/h, the best case power consumption is given at 105.2 MW. This corresponds to 30.3 MJ/kg$LH_2$ for a plant about six times larger than any existing facility. The use a helium-neon mixture for the low-temperature cycle has been suggested to reduce the energy consumption to, perhaps, 25.2 MJ/kg$LH_2$ (=7 kWh/kg$LH_2$) for a plant producing 7200 kg$LH_2$ per hour, or 173 metric tons $LH_2$ per day [14]. However, experimental results are not yet available.

Large liquefaction plants are more efficient than small facilities. The variation of energy consumption with capacity for existing hydrogen liquefaction plants [62] is reflected in Figure 1.17. More electrical energy is consumed for the liquefaction of hydrogen in small plants than in large facilities.

# CHAPTER 2

# BACKGROUND AND METHODOLOGY

## 2.1 Geothermal Energy Use in Hydrogen Production and Liquefaction Models

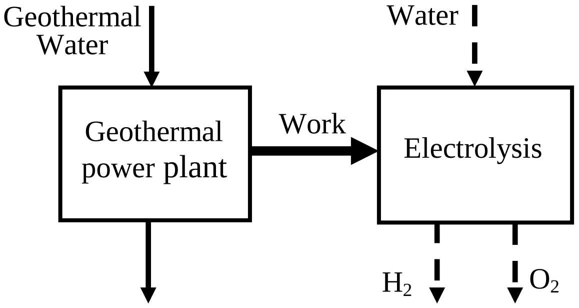
Hydrogen, an alternative energy source, is subject of a lot of research work and some consider it as the energy of the future. If hydrogen is to become the energy of the future, it must be produced using renewable energy sources and the technical and economic problems on its production, storage, transportation, and use should be solved. There are various methods used in hydrogen production. These methods may require both electricity and heat inputs and renewable energies such as solar, wind, hydro and nuclear energy use are being investigated. Hydrogen can be stored and transported either as compressed gas or as a liquid occupying a small volume after being liquefied. Hydrogen liquefaction requires considerable energy consumption and involves advanced refrigeration techniques. Although there are a large number of studies in using solar, wind and nuclear energies for hydrogen production there are a very limited number of studies on using geothermal energy.

In this study, the models that can be used in hydrogen production and liquefaction by geothermal energy are investigated and thermodynamic analysis of these models is performed. When structuring the models, alternatives such as direct use of geothermal heat and/or the use of produced electricity are considered. Hydrogen production methods suitable for the use of geothermal energy such as electrolysis and high temperature electrolysis are evaluated. In hydrogen liquefaction, the use of geothermal electricity in liquefaction cycle and the use of geothermal heat in absorption refrigeration process for precooling of hydrogen are examined.

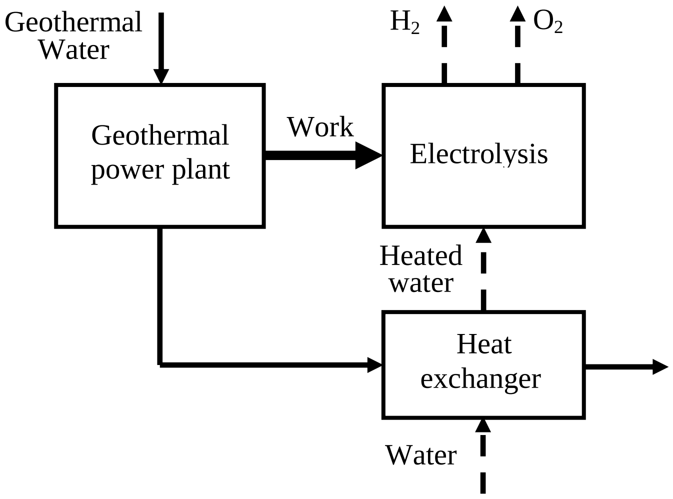
## 2.2 System Descriptions

Seven cases are developed for the use of geothermal energy for hydrogen production and liquefaction (Fig. 2.1): Case 1: Using geothermal work output as the work input for an electrolysis process (Fig. 2a). Case 2: Using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water (Fig. 2b). Case 3: Using geothermal heat to preheat water in a high-temperature electrolysis process (Fig. 2c). Case 4: Using geothermal output work as the input for a liquefaction cycle (Fig. 2d). Case 5: Using geothermal heat in an absorption refrigeration process to precool the gas before the gas is liquefied in a liquefaction cycle (Fig. 2e). Case 6: Using part of the geothermal heat for absorption refrigeration to precool the gas and part of the geothermal heat to produce work and use it in a liquefaction cycle (Fig. 2f). Case 7: Using part of geothermal work for electrolysis and the remaining part for liquefaction (Fig. 2g).

These cases are studied thermodynamically, and particularly reversible operation of the models is considered. The effect of geothermal water temperature on the amount of hydrogen production and liquefaction per unit mass of geothermal water is investigated for the representative seven cases. The results show that as the temperature of geothermal water increases the amount of hydrogen production and liquefaction increases.



(a)



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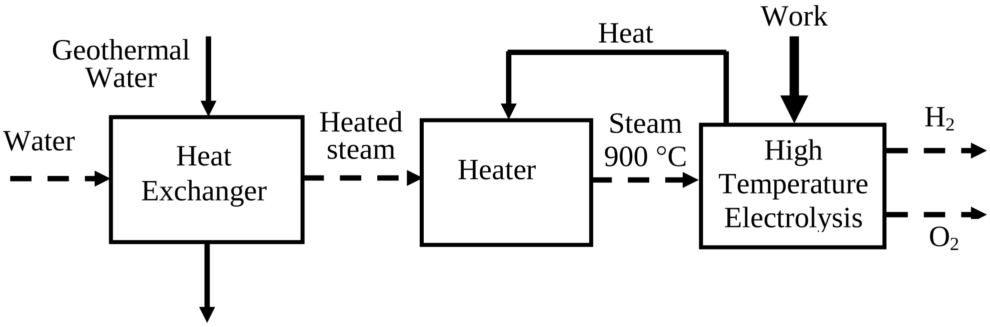
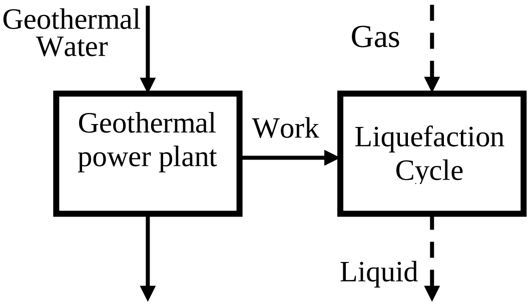
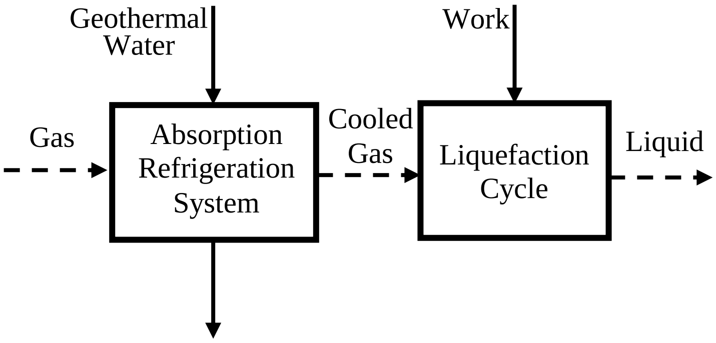

Geothermal Water
Water
Heat Exchanger
Heated steam
Heater
Heat
Steam 900 °C
Work
High Temperature Electrolysis
H2
O2

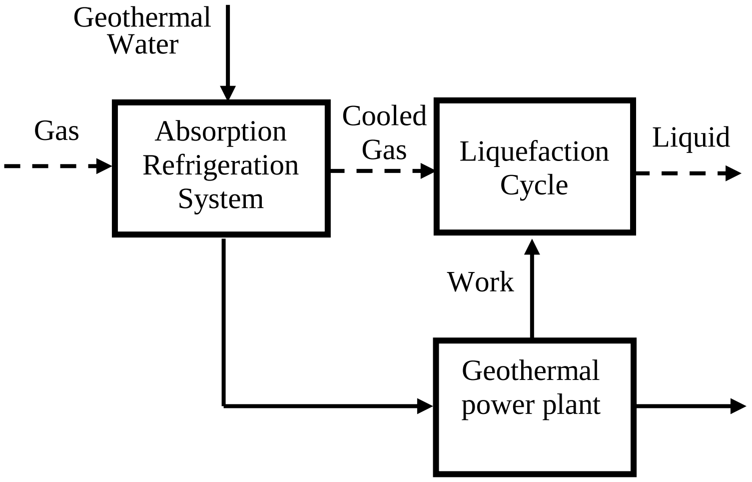
(c)


Geothermal Water
Geothermal power plant
Work
Gas
Liquefaction Cycle
Liquid

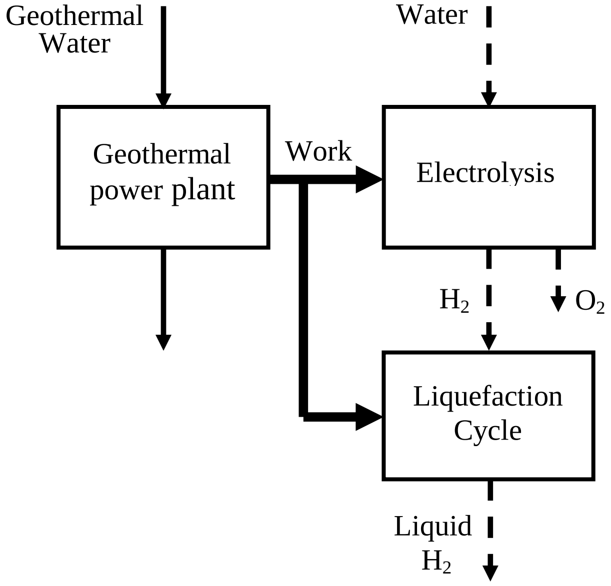
(d)


Geothermal Water
Gas
Absorption Refrigeration System
Cooled Gas
Work
Liquefaction Cycle
Liquid

(e)



(f)



(g)

Figure 2.1 Seven cases are considered in the hydrogen production and liquefaction: (a) using geothermal work output work as the input for an electrolysis process. (b) using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water. (c) using geothermal heat to preheat water in a high-temperature electrolysis process. (d) using geothermal output work as the input for a liquefaction cycle. (e) using geothermal heat in an absorption refrigeration process to precool the gas before the gas is liquefied in a liquefaction cycle. (f) using part of the geothermal heat for absorption refrigeration to precool the gas and part of the geothermal heat to produce work and use it in a liquefaction cycle (g) using part of geothermal work for electrolysis and the remaining part for liquefaction.

## 2.3 Geothermal Power Plant Selection

Depending on the geothermal fluid is extracted from underground to produce electricity as is used in different cycles. The three types of commercial geothermal power plants are dry steam plants that use resources of pure steam, flash steam and binary cycle plants that tap reservoirs of hot water [48]. In this study we selected a binary cycle. A binary cycle is the economic choice for hydrothermal sources with temperature below approximately 150 °C. A binary cycle uses a secondary heat transfer fluid instead of steam in the power generation equipment.

The major thermodynamic disadvantage of the binary cycles is the high-temperature difference between the geothermal brine at the wellhead and operating temperature of secondary fluid. The reason for this high-temperature is that in the conventional binary installations all the secondary fluid operates in the heat exchanger. Binary units are in general more efficient, but also more capital intensive [63].

A secondary fluid is chosen with desired thermodynamic characteristic, so that the flashing chambers may operate at temperatures well below 100°C (something which impractical in steam flashing units because of air leakage in the flashing chambers). At low operating temperatures, the proper selection of the organic working fluid can help keep the condenser pressure above 1 atm in order to avoid inward leakage of non-condensable gasses, whereas this is not always possible to achieve in the direct-flashing type of plants for resource temperatures below 150°C. Since such low-temperature geothermal sites are abundant, binary-fluid geothermal plants have more applications possibilities and, hence, merit in-depth examination [63].

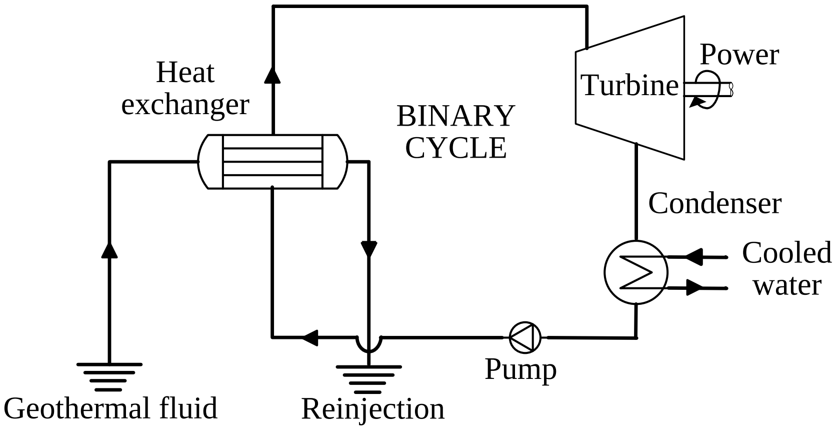


Figure 2.2 Binary geothermal power plant.

The cycle shown in figure 2.2, uses isobutene as the binary heat transfer fluid. This cycle is representative of units with capacities of approximately 20 MW. Many small modular units with capacities of 1 or 2 megawatts use pentane as the binary fluid. Heat from geothermal brine vaporizes the binary fluid in the brine heat exchanger. The spent brine is returned to the resource in injection wells, and the binary fluid vapor drives a turbine generator. The turbine exhaust vapor is delivered to an air-cooled condenser, where the vapor is condensed liquid binary fluid drains to an accumulator vessel before being pumped back to the brine heat exchanger to repeat the cycle. The turbine for binary fluid vapor is smaller and less expensive than a geothermal steam turbine of similar capacity. However, the higher cost of the auxiliary equipment for a binary plant eliminates the cost advantage [64].

Binary geothermal plants have been in service for less than 10 years. The inevitable resources decline has yet to significantly affect these facilities. When it occurs, a likely first response will be to modify the composition of the binary fluid to reestablish a match between the new resource conditions and existing power generation equipment.

### 2.3.1 System Description and Formulation

For the ideal and non-ideal (e.g., reversible and irreversible) operations of the seven cases considered, we consider a binary geothermal power plant with isobutane as the working fluid as shown in Fig. 2.3. This is usually the choice of cycle for liquid-dominated geothermal resources at this temperature level. In this cycle, isobutane is heated and vaporized in the heat exchanger by geothermal water. Then, it flows through the turbine, is condensed and pumped back to the heat exchanger, completing the binary cycle. The heat exchanger and condenser pressures are taken to be 3000 kPa and 400 kPa, respectively while the temperature at the turbine inlet (i.e., heat exchanger exit) is taken to be 190°C, which is 10°C lower than the geothermal water temperature at the heat exchanger inlet (200°C). Also, isentropic efficiencies of the turbine and pump are taken to be 80% and 70%, respectively. The present assumptions and values taken for the analysis of the binary power plant closely correspond to those encountered in actual power plants using similar geothermal resources [65].

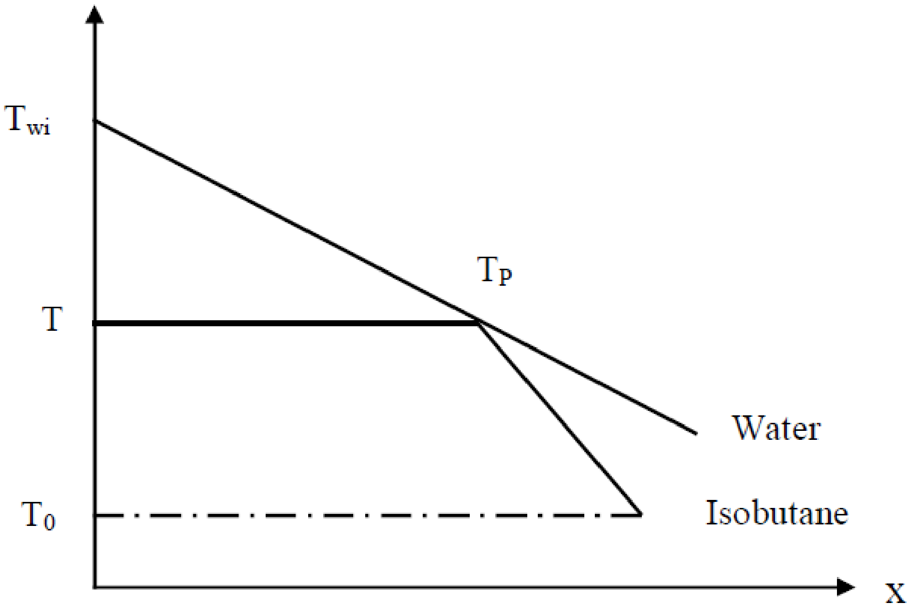


Figure 2.3 Heat exchanger diagram of the conventional binary power plant.

For this purpose, available power for conventional binary cycle is calculated from,

$$\dot{W}_{geo} = \dot{m}[h_{iso} - h_0 - T_0(s_{iso} - s_0)] \qquad (1)$$

Where, $\dot{m}$ is the mass flow rate of the secondary fluid (isobutene), h is the specific enthalpy, and s is the specific entropy of the secondary fluid before entering the turbine, T is the temperature and subscript zero refers to conditions in the condenser.

The maximum specific (ideal) work that can be obtained by a geothermal binary power plant utilizing a resource at temperature $T_s$ in an environment at $T_0$ is given by

$$w_{\text{rev,geo}} = c(T_s - T_0) - T_0 c \ln\left(\frac{T_s}{T_0}\right) \qquad (2)$$

The temperature diagram is shown in figure 2.3 for heat exchanger. The geothermal water evaporates the secondary fluid in the heat exchanger and is then reinjected into the ground at lower temperature. The secondary fluid comes out of the heat exchanger as a dry, saturated vapor and undergoes a closed Rankine cycle. The operation of the heat exchanger is depicted in figure 2.3. In the operation of binary geothermal power plant (Fig. 2.2), a pinch-point will occur at the start of vaporization of the working fluid in the heat exchanger. The energy balance relations for the heat exchanger can be written as,

$$\dot{m}_{\text{geo}} c_{\text{geo}} \left[ T_{\text{geo,in}} - (T_{\text{vap}} + \Delta T_{\text{pp}}) \right] = \dot{m}_{\text{iso}} (h_{\text{iso,out}} - h_{\text{iso},f}) \tag{3}$$

$$\dot{m}_{\text{geo}} c_{\text{geo}} \left[ (T_{\text{vap}} + \Delta T_{\text{pp}}) - T_{\text{geo,out}} \right] = \dot{m}_{\text{iso}} (h_{\text{iso},f} - h_{\text{iso,in}}) \tag{4}$$

where $\dot{m}_{\text{geo}}$ and $\dot{m}_{\text{iso}}$ are the mass flow rates of geothermal water and isobutane, respectively, $c_{\text{geo}}$ is the specific heat of geothermal water, $T_{\text{vap}}$ is vaporization temperature of isobutane at the heat exchanger pressure, $\Delta T_{\text{pp}}$ is the pinch-point temperature difference, $h_{\text{iso},f}$ is the specific enthalpy of isobutane at the start of vaporization, and $h_{\text{iso,in}}$ and $h_{\text{iso,out}}$ are the specific enthalpies of isobutane at the inlet and outlet of the heat exchanger, respectively. The pinch-point temperature difference is assumed to be 6°C. Equations 3 and 4 uniquely set the mass flow rates of isobutane and the geothermal water temperature at the heat exchanger exit [66].

So, we can be obtained actual or non-ideal work output of geothermal power plant. $w_{\text{out,geo}}$ is the net actual work (non-ideal) output from the geothermal power plant per unit mass of geothermal water and is calculated as,

$$w_{\text{out,geo}} = w_{\text{turbine,out}} - w_{\text{pump,in}} - w_{\text{parasitic}} \tag{5}$$

Where, $w_{\text{turbine,out}}$ is the actual work output from the turbine, $w_{\text{pump,in}}$ is the work input to the pump and $w_{\text{parasitic}}$ is the parasitic work used in the plant for various internal and auxiliary uses. The parasitic work is mainly comprised of fan work consumption in the air-cooled condenser. It is assumed that about 20% of net work output ($w_{\text{turbine,out}}$ - $w_{\text{pump,in}}$) is used satisfy the parasitic work requirements [66]. The term $w_{\text{in,nitrogen}}$ is the work consumed per unit mass of nitrogen liquefaction for use in the liquefaction cycle.

The present assumptions and values taken for the analysis of the binary power plant closely correspond to those encountered in actual power plants using similar geothermal resources.

### 2.4 Water Electrolysis Systems

We used in this project three types of electrolysis systems. These are simple alkaline water electrolysis (25°C and 1 atm), low temperature water electrolysis (between the 20-85°C water electrolysis) and high temperature steam electrolysis(steam temperature under 800°C). Electrolysis process is a thermochemical process. During the thermodynamic analysis of electrolysis, the molecular state of  enthalpy and entropy properties are used in this process [67].

Separations of water hydrogen gas and oxygen ions are achieved with the water electrolysis, the passage of current between the electrodes and with electrolyte solution high ionic conductivity fluid [68].

$$H_2O_{(liquid)} + \text{Electrical Energy} \rightarrow H_{2(g)} + \tfrac{1}{2}\, O_{2(g)} \qquad (6)$$

For the realization of this reaction is necessary minimum current must be applied to electrodes.

The electrode reactions are:

$$H_2O_{(liquid)} + 2e^- \rightarrow H_{2(g)} + 2OH^-{}_{(aq)} \text{ at the cathode} \qquad (7)$$

$$2OH^-{}_{(aq)} \rightarrow 1/2O_2 + H_2O_{(liquid)} + 2e^- \text{ at the anode} \qquad (8)$$

The first and second laws of thermodynamics can be applied to this process as follows:

$$1^{st}\text{ law: } Q_H - Q_L = \Delta H_R \qquad (9)$$

$$2^{nd}\text{ law: } \Delta S_R \geq \frac{Q_H}{T_L} - \frac{Q_L}{T_H} \qquad (10)$$

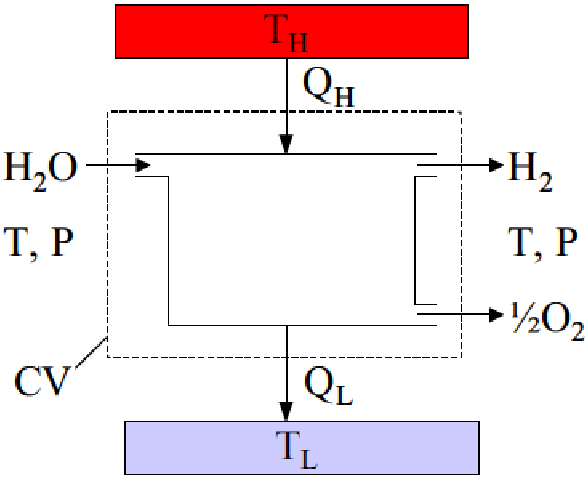


Figure 2.4 Schematic of a generic thermal water-splitting process operating between temperatures $T_H$ and $T_L$.

Where, $\Delta H_R$ is the enthalpy of reaction and $\Delta S_R$ is the entropy change of the reaction. $Q_H$ is high-temperature heat addition in J/mol; $Q_L$ is low-temperature heat rejection in J/mol. The overall thermal-to-hydrogen efficiency of thermal water splitting processes can be defined in terms of the net enthalpy increase of the reaction products over the reactants (can also be thought of as the energy content or heating value of the produced hydrogen), divided by the (costly) high-temperature heat added to the system:

$$\eta_H = \frac{\Delta H_R}{Q_H} \tag{11}$$

Combining the first and second law equations for the reversible case and substituting into the efficiency definition yields:

$$\eta_{H,\max} = \frac{1 - T_L / T_H}{1 - T_L \Delta S_R / \Delta H_R} \tag{12}$$

Note that the water splitting process defined in Fig. 2.4 is simply the reverse of the combustion reaction of hydrogen with oxygen. Therefore the enthalpy of reaction for the water splitting process is the opposite of the enthalpy of combustion, which by definition is equal to the “heating value” of the hydrogen. Since for our process, we have assumed that the water enters the control volume in the liquid phase,

$$\Delta H_R = HHV \tag{13}$$

Where, *HHV* is the “high heating value” of hydrogen. If we further assume that T and P represent standard conditions, and that $T_L = T_o$.

$$\Delta H_R = -T_L \Delta S_R = -\Delta G^0{}_{f,H2O} \tag{14}$$

Such that the efficiency expression can be rewritten as:

$$\eta_{H,\max} = \left(1 - \frac{T_L}{T_H}\right)\left(\frac{HHV}{-\Delta G^0{}_{f,H2O}}\right) \tag{15}$$

The high heating value of the hydrogen and the standard-state Gibbs energy of formation for water are fixed quantities such that the second factor on the right-hand side is a constant. This efficiency limit was also derived for the sulfur-iodine thermochemical process based on an exergy analysis [69].

Comparing Eqn. (15) to Eqn. (11), the high-temperature heat requirement for the process can be stated as:

$$Q_H \geq \frac{T_H}{T_H - T_L}\left(-\Delta G^0{}_{f,H2O}\right) \tag{16}$$

This result was derived for thermochemical cycles by Abraham and Schreiner [70], and applied to solar thermal dissociation of water by Fletcher and Moen [71], who noted that the maximum efficiencies of all thermochemical processes can be related to the efficiencies of Carnot engines operating between the same upper and lower temperatures. It is necessary only to add, conceptually, a reversible fuel cell which converts the hydrogen and oxygen to liquid water at the lower temperature, performing an amount of electrical work given by the Gibbs free energy of the reaction.

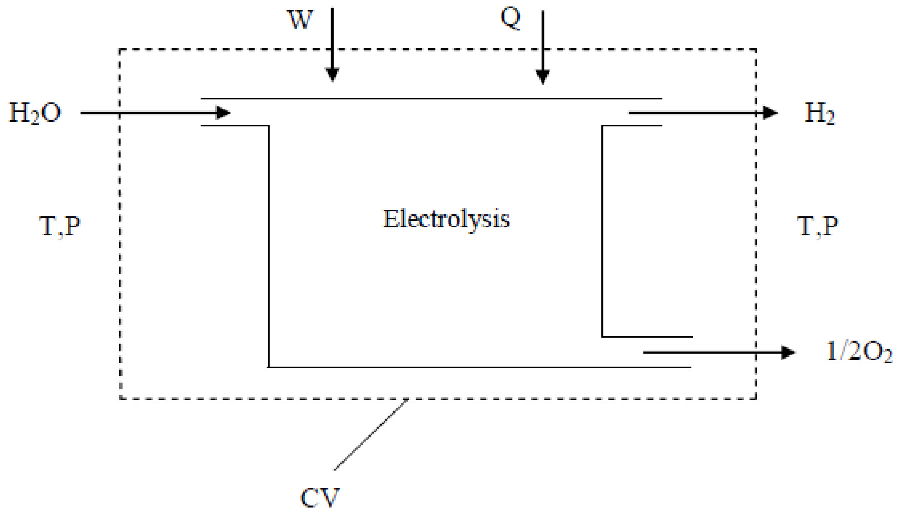


Figure 2.5 Schematic of a water electrolysis process operating temperature at T.

Focusing now on electrolysis, consider a control volume surrounding an isothermal electrolysis process, as shown in Fig. 2.5. In this case both work and heat interactions cross the control volume boundary. The first law for this process is given by:

$$Q - W = \Delta H_R \tag{17}$$

For reversible operation,

$$Q_{rev} = T\Delta S_R \tag{18}$$

Such that,

$$W_{rev} = \Delta H_R - T\Delta S_R = \Delta G_R \tag{19}$$

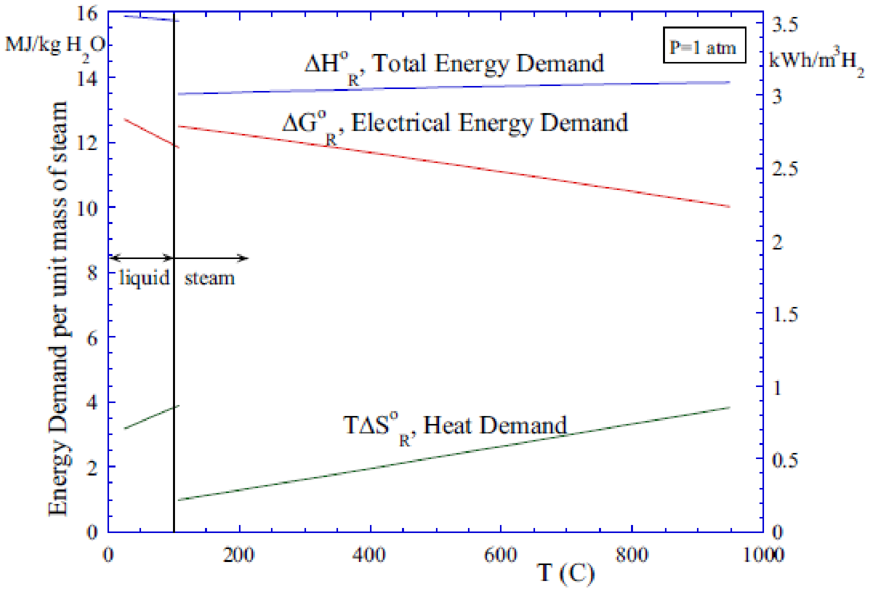


Figure 2.6 Standard-state energy requirements for electrolysis as a function of temperature [72].

The thermodynamic properties appearing in Eqn. (19) are plotted in Fig. 2.6 as a function of temperature for the $H_2$-$H_2O$ system from 0 to 1000°C at standard pressure. This figure is often cited as a motivation for high-temperature electrolysis versus low temperature electrolysis. It shows that the Gibbs free energy change, $\Delta G_R$, for the reacting system decreases with increasing temperature, while the product of temperature and the entropy change, $T\Delta S_R$, increases. Therefore, for reversible operation, the electrical work requirement decreases with temperature, and a larger fraction of the total energy required for electrolysis, $\Delta H_R$, can be supplied in the form of heat.

This section addresses the theoretical voltage required for water electrolysis at a temperature of $T$(K) and constant pressure of 1 atm. Energy is produced when hydrogen and oxygen react together to produce water as above. The thermoneutral potential $V_{tn}$(T) is given by $V_{tn}(T) = \Delta H(T)/2F$, where $\Delta H(T)$ is the standard enthalpy of the reaction at T.

Standard thermodynamic parameters such as $\Delta H$ ($T$), $\Delta G$ ($T$), and $\Delta S$ ($T$) are functions of temperature. Therefore, the standard thermodynamic parameters at different temperatures can be calculated according to Kirchhoff's equation, entropy equation and the relation between $\Delta G$ and Nernst potential ($E$). These equations are given by [73]:

$$\Delta H(T) = \Delta H^0{}_{298.15} + \int_{298.15}^{T} \Delta C_P dT \qquad (20)$$

$$\Delta S(T) = S^0{}_{298.15} + \int_{298.15}^{T} \frac{\Delta C_P}{T} dT \tag{21}$$

$$E(T) = -\frac{\Delta G(T)}{nF} \tag{22}$$

The Nernst potential at temperature T from Eq. (22) is considered to be under the standard pressure conditions for reactants and products. Where, E is Nernst potential (V), n is number of electrons transferred (n=2), F is Faraday constant (C $mol^{-1}$) and $\Delta C_P$ is heat capacity change of the reaction (J $mol^{-1}$ $K^{-1}$).

The values of $\Delta H$ $(T)$, $\Delta S$ $(T)$ and $\Delta G$ $(T)$ are represented by the following equations:

$$\Delta H(T) = -H_{H_2O(l)}(T) + H_{H_2}(T) + 1/2 H_{O_2}(T) \tag{23}$$

$$\Delta S(T) = -S_{H_2O(l)}(T) + S_{H_2}(T) + 1/2 S_{O_2}(T) \tag{24}$$

$$\Delta G(T) = -G_{H_2O(l)}(T) + G_{H_2}(T) + 1/2 G_{O_2}(T) \tag{25}$$

According to these equations, we obtain the minimum work required for an electrolysis process (in kJ/kg) is expressed as,

$$w_{rev,electrolysis} = \frac{\Delta G_{electrolysis,H_2O}}{M_{H_2}} \tag{26}$$

Where, $\Delta G_{electrolysis,H2O}$ is the same as $\Delta G(T)$ and is also change in the Gibbs function (in kJ/ kmol) and $M_{H2}$ is the molar mass of hydrogen (in kg/kmol).

For irreversible operation using the electrolysis efficiency, we can find the actual electrolysis work.

$$w_{\text{actual,electrolysis}} = \frac{w_{\text{rev,electrolysis}}}{\eta_{electrolysis}} \tag{27}$$

We used an electrolysis efficiency of 78% for alkaline electrolysis at room temperature and 82% at 85°C. The electrolysis efficiency is taken 94% for high-temperature steam electrolysis [52].

The mass of hydrogen produced per unit mass of geothermal water used may be expressed by defining a parameter $y_{\text{prod, H2}}$ as the ratio of the work output from the power plant to the work input to the electrolysis. For reversible or irreversible operations, it is expressible as,

$$y_{production,H_2} = \frac{w_{geothermal}}{w_{electrolysis}} \text{ (mass of H}_2\text{ produced/mass of geothermal water used)} \qquad (28)$$

Here the parameter $y_{\mathrm{prod,H2}}$ represents the mass of hydrogen production per mass of geothermal water entering the power plant.

## 2.5 Hydrogen Liquefaction System

We investigated the use of geothermal energy for hydrogen liquefaction within the scope of this study. Three models were considered for the analysis including the use of geothermal power for liquefaction cycle, the use of absorption cooling system for precooling gas before liquefaction and a cogeneration option for which both geothermal electricity and geothermal heat for absorption system are used. The cogeneration option appeared to provide significant savings in the energy requirement in the liquefaction process.

For the liquefaction of a gas, we consider the precooled Linde-Hampson cycle because it is a well-known and relatively simple system used for hydrogen liquefaction (Fig. 2.7). Makeup gas is mixed with the uncondensed portion of the gas from the previous cycle, and the mixture at state 1 is compressed to state 2. Heat is rejected from the compressed gas to a coolant. The high-pressure gas is cooled to state 3 in a regenerative counterflow heat exchanger (I) by the uncondensed gas, and is cooled further by flowing through two nitrogen baths (II and IV) and two regenerative heat exchangers (III and V) before being throttled to state 8, where it is a saturated liquid-vapor mixture. The liquid is collected as the desired product, and the vapor is routed through the bottom half of the cycle. Finally, the gas is mixed with fresh makeup gas, and the cycle is repeated.

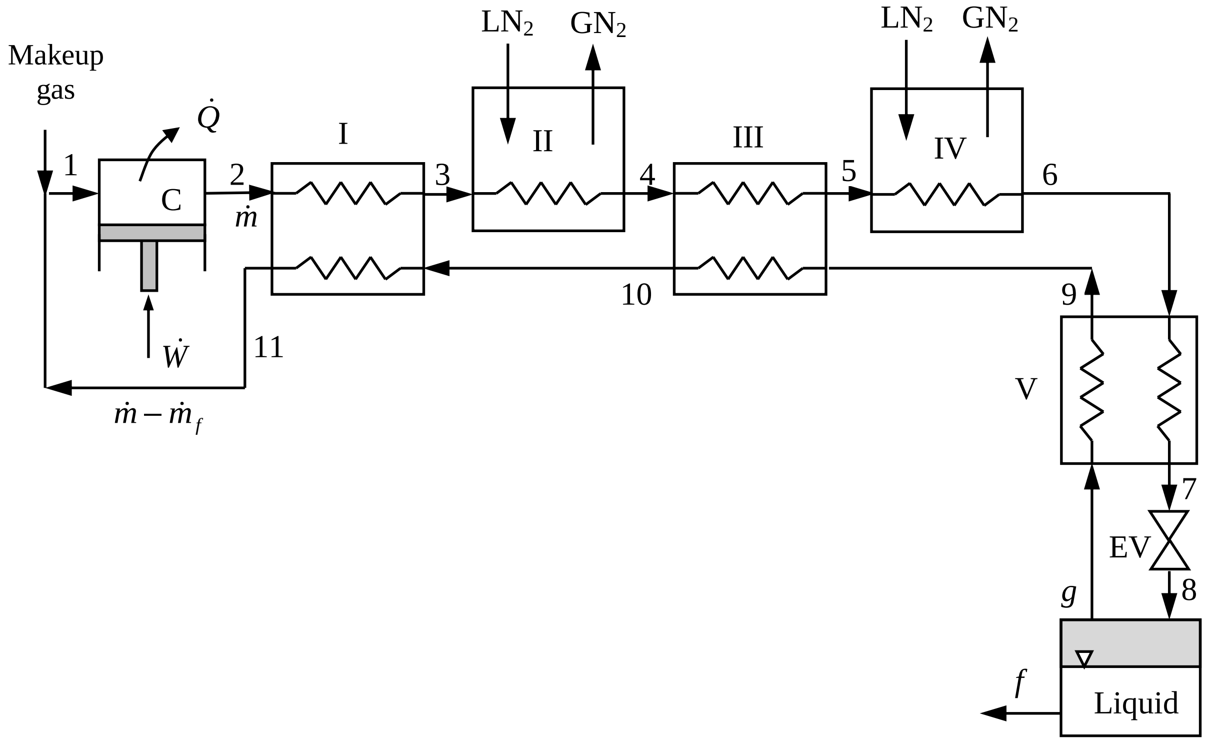


Figure 2.7 Precooled Linde-Hampson liquefaction cycle. C: compressor, EV: Expansion valve, I, II, III, IV, and V: Heat exchangers, $LN_2$: Liquid nitrogen, $GN_2$: Gasified nitrogen, *f*: liquid, *g*: gas, $\dot{m}_f$ : mass flow rate of liquid withdrawn from the system, $\dot{m}$ : total mass flow rate of hydrogen [74].

The minimum (i.e., reversible) work input for the liquefaction of a unit mass of a gas in a liquefier (i.e., liquefaction unit) can be written as,

$$w_{\text{rev,in,liq}} = h_2 - h_1 - T_0(s_2 - s_1) \tag{29}$$

Where, state 1 is the state of the gas and state 2 is the state of the liquid.

We define a parameter *y* as the ratio of the work output from the power plant to the work input to the liquefaction cycle. For reversible operations, it is expressible as

$$y = \frac{w_{\text{rev,outgeo}}}{w_{\text{rev,in,liq}}} \quad \text{(mass liquefied/mass of geothermal water used)} \tag{30}$$

The parameter y in this case represents the maximum mass of gas that can be liquefied per mass of geothermal water entering the power plant.

Using an energy balance of heat exchanger V and the throttling valve taken together, the fraction *f* of the liquefied gas can be determined to be,

$$f_{\text{liq}} = \frac{h_9 - h_6}{h_9 - h_f} \tag{31}$$

Energy balances for the heat exchangers can be written as

$$h_2 - h_3 = (1 - f_{\text{liq}})(h_{11} - h_{10}) \tag{32}$$

$$h_4 - h_5 = (1 - f_{\text{liq}})(h_{10} - h_9) \tag{33}$$

$$h_6 - h_7 = (1 - f_{\text{liq}})(h_9 - h_g) \tag{34}$$

Since the gas behaves ideally during compression, the specific compression work may be determined from,

$$w_{\text{in}} = \frac{RT_0 \ln(P_2 / P_1)}{\eta_{\text{comp}}} \quad \text{(per unit mass of gas in the cycle)} \tag{35}$$

Where, $\eta_{\text{comp}}$ is the isothermal efficiency of the compressor, $R$ is the gas constant and $P$ is the pressure. The numerator of the right side represents the work input for a corresponding isothermal process. The specific work input to the liquefaction cycle per unit mass of liquefaction is

$$w_{\text{in,liq}} = \frac{w_{\text{in}}}{f_{\text{liq}}} \quad \text{(per unit mass of liquefaction)} \tag{36}$$

The parameter $y$ defined in Eq. 30 may be expressed for this non-ideal cycle operation as

$$y_{liquied,H_2} = \frac{w_{\text{outgeo}}}{w_{\text{in,liq}} + w_{\text{in,nitrogen}}} \quad \text{(mass liquefied/mass of geothermal water used)} \tag{37}$$

Here, the parameter $y_{liquid,H2}$ represents the mass of gas liquefied per mass of geothermal water entering the power plant for non-ideal case. The term $w_{\text{in,nitrogen}}$ is the work consumed per unit mass of nitrogen liquefaction for use in the liquefaction cycle.

In the analysis, the compressor exit pressure is taken to be 10 MPa and the gas inlet state is taken to be 1 atm (101 kPa) and 25°C. The nitrogen bath temperatures are taken to be 77.5 K and 65 K with corresponding saturation pressures of 101 kPa and 17 kPa, respectively, and it is assumed that each nitrogen stream exits the heat exchanger 15 K lower than it enters. The isothermal efficiency of the compressor is taken to be 65% and the effectiveness of the heat exchangers are taken to be 90%. These values follow the works of Barron (1985) [75], Timmerhaus and Flynn (1989) [76] and Nandi and Sarangi (1993). The specific work consumption of liquid nitrogen is estimated as 5050 kJ/kg by considering the states of nitrogen at the inlet and exit and the operation of some current liquefiers [77].

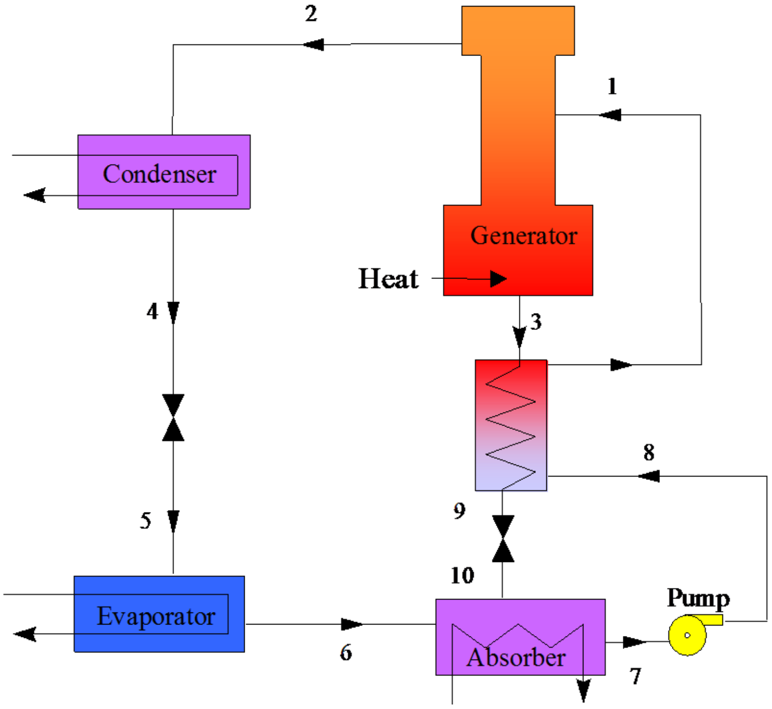


Figure 2.8 Schematic representation of the absorption cooling system [78].

The coefficient of performance (COP) of a reversible absorption refrigeration unit may be expressed as:

$$\mathrm{COP}_{\mathrm{rev}} = \frac{q_L}{q_{\mathrm{gen}}} = \left(1 - \frac{T_0}{T_s}\right)\left(\frac{T_L}{T_0 - T_L}\right) \tag{38}$$

where, $q_L$ is the specific refrigeration load, $q_{\mathrm{gen}}$ is the specific heat transfer to the generator of the system and $T_L$ is the refrigeration temperature.

For the absorption refrigeration system, an ammonia-water system is considered to allow subzero temperatures in the system. For the investigation of the second and third cases for non-ideal operation, we need to assume a value for the COP of the system. We may do this by defining the second-law efficiency as

$$\eta_{\mathrm{II,ARS}} = \frac{\mathrm{COP}_{\mathrm{act}}}{\mathrm{COP}_{\mathrm{rev}}} \tag{39}$$

where, $\mathrm{COP}_{\mathrm{act}}$ is the actual COP and $\mathrm{COP}_{\mathrm{rev}}$ is the reversible COP as expressed by Eq. 39. We take this second-law efficiency to be 25%, which appears to be reasonable for processes involving the cooling of a gas to -20°C [79].

# CHAPTER 3

# THERMODYNAMIC ANALYSIS OF MODELS USED IN GEOTHERMAL PRODUCTION AND LIQUEFACTION

## 3.1 Introduction

Energy is the most fundamental term in the thermodynamic and energy engineering. Energy analysis is often one of the most significant parts of engineering analysis. Energy can be stored within a system in various macroscopic forms, it can be transformed from one form to another, and it can be transferred between systems. The total amount of energy is conserved in all transformations and transfers. Energy balances are widely used in the design and analysis of energy conversion systems. Although energy balances can determine energy supply requirements in the form of material streams, heat, and shaft work, they do not provide sufficient information on how efficiently energy is used.

In this chapter we present general formulations of thermodynamic analyses including energy equations of each model. The formulations are applicable to hydrogen production and liquefaction models with alkaline electrolysis, high temperature steam electrolysis, Precooled Linde-Hampson liquefaction and absorption refrigeration cooling from geothermal energy sources. And also, we consider both ideal (reversible) and non-ideal (irreversible) operations for thermodynamic analysis.

Electrolysis was evaluated as a hydrogen production method. In all of these applications are considered a liquid geothermal resource at the temperature of 200°C. Assumed in ideal models, to produce maximum power in geothermal power plant, consumed of minimum work for liquefaction of hydrogen gas and COP is assumed that the maximum value for absorption refrigeration system. Models were analyzed in three categories: First, the analysis of hydrogen production models (Model 1, Model 2 and Model 3); the second, hydrogen liquefaction analysis (Model 4, Model 5 and Model 6); and the third, production and liquefaction of hydrogen model analysis (model 7).

## 3.2 Thermodynamic Analysis of Hydrogen Production Models

### *Ideal conditions*

### Model 1

In Case 1 (Fig. 2.1a), geothermal work output is used as the work input for an electrolysis process. For a geothermal source temperature of 200°C and a dead state temperature of 25°C, the maximum specific work output is calculated from Eq. 1 to be 157.9 kJ/kg. . Gibbs free energy of the liquid water at the temperature of 25°C needed for electrolysis of water ($H_2O$) calculate to be 237,180 kJ/mol. Taking the inlet state of the liquid to be 1 atm and a saturated liquid, the reversible specific work input for the electrolysis of hydrogen can be calculated from Eq. 26 to be 117,649 kJ/kg. With Eq. 28, we can determine that for 1 kg of geothermal water at 200°C, $y_{\text{prod, H2}}$ = (157.9 kJ/kg water)/ (117,649 kJ/kg $H_2$) = 0.001343 kg $H_2$/kg water. Thus, 1.343 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 745 kg of geothermal water is needed to produce 1 kg of hydrogen.

### Model 2

In Case 2 (Fig. 2.1b), part of geothermal heat is used to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat water. In this model we obtained under ideal conditions maximum work output of geothermal power plant is not a change from here. Low-temperature electrolysis method used in this model can be applicable at temperatures between 50-85°C. Geothermal water enters the plant at 200°C and leaves at 95°C. This water heats the water from 25°C to 85°C before electrolysis. The maximum specific work output is calculated to be 157.9 kJ/kg. Gibbs free energy of the liquid water at the temperature of 85°C needed for electrolysis of water ($H_2O$) calculate to be 230.5 kJ/mol. The reversible specific work input for the electrolysis of hydrogen can be calculated to be 111,421 kJ/kg. With Eq. 28, we can determine that for 1 kg of geothermal water at 200°C, $y_{\text{prod, H2}}$ = 0.001418 kg H2/kg water. Thus, 1.418 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 705 kg of geothermal water is needed to produce 1 kg of hydrogen.

### Model 3

In Case 3 (Fig. 2.1c), geothermal heat is used to preheat water in a high temperature steam electrolysis process. This method has the highest efficiency of electrolysis method in the known as electrolysis method. Electrolysis water temperature is between the 800-1000°C in this method. The water for electrolysis is heated to 200°C as a steam by geothermal water. This steam is heated to 900°C by using the heat generated during electrolysis. The maximum specific work output is again calculated to be 157.9 kJ/kg. From equation 25 $\Delta G(T)$ calculated to be 166.7 kJ/mol $H_2O$. The reversible specific works input for the high temperature electrolysis of hydrogen can be calculated to be 86,672 kJ/kg. We can determine that for 1 kg of geothermal water at 200°C, $y_{\mathrm{prod,H2}}$= 0.001911 kg $H_2$/kg geothermal water. Thus, 1.911 grams of hydrogen could be produced using 1 kg of geothermal water in the high temperature electrolysis. In another words, 524 kg of geothermal water is needed to produce 1 kg of hydrogen.

**Model 4**

In Case 4 (Fig. 2.1d), for a geothermal source temperature of 200°C and a dead state temperature of 25°C, the maximum specific work output is calculated from Eq. 1 to be 157.9 kJ/kg. Taking the inlet state of the gas to be the standard dead state (25°C, 1 atm) and of the liquid to be 1 atm and a saturated liquid, the reversible specific work input for the liquefaction of hydrogen can be calculated from Eq. 29 to be 11963 kJ/kg. With Eq. 5, we can determine that for 1 kg of geothermal water at 200°C, $y_{\mathrm{liq,H_2}}$ = (157.9 kJ/kg water)/ (11963 kJ/kg gas) = 0.0132 kg gas/kg water. Thus, 13.2 grams of gas could be liquefied using 1 kg of geothermal water.

**Model 5**

In Case 5 (Fig. 2.1e), geothermal water is used as the heat source for a reversible absorption refrigeration cycle (ARC) which is used to precool the gas before it is liquefied. For $T_s$ = 200°C, $T_0$ = 25°C and $T_L$=-20°C, the COP of this reversible refrigerator is determined using Eq. 6 to be 2.81. Assuming geothermal water leaves the generator at 95°C, the specific heat transfer to the generator can be shown to be $q_{gen}$ = 447.5 kJ/kg. Then using Eq. 38, the specific heat removed from the gas can be calculated as $q_{L,1}$ = 931 kJ/kg. The specific heat that must be removed from hydrogen as its state changes from 25°C and 1 atm to -20°C and 1 atm is $q_{L,2}$ = 639 kJ/kg.

We define another parameter z as the ratio of these two heat removal terms:

$$z = \frac{q_{L,1}}{q_{L,2}} \text{ (mass of gas cooled in ARC/mass of geothermal water used)} \tag{3.1}$$

The parameter z represents the mass of gas that can be cooled to the refrigeration temperature in the absorption system by a unit mass of geothermal water entering the absorption system. Using Eq. 3.1, we see that z = 1.457 (= 931/639). Thus, 1.457 kg of hydrogen can be cooled from 25°C to -20°C using 1 kg of geothermal water at 200°C.

## Model 6

In Case 6 (Fig 2.1f), the geothermal water at 200°C is used as the heat source for a reversible absorption refrigeration cycle which is used to precool the gas before it is liquefied. The geothermal water leaving the generator of the absorption system at 190°C is used to produce work in a geothermal power plant. The refrigeration temperature is again taken to be -20°C. It is determined that, in the absorption system, z = 0.143 kg of gas can be cooled from 25°C to -20°C by 1 kg geothermal water. In the power plant, the reversible work output is 142.3 kJ/kg while the reversible work input in the liquefier is 11,918 kJ/kg for hydrogen. This corresponds to the liquefaction of y = 0.01193 kg = 11.93 grams hydrogen by 1 kg geothermal water at 190°C.

## Model 7

In Case 7 (Fig. 2.1g), part of geothermal work is used for electrolysis and the remaining part for liquefaction. We define β as the ratio of electrolysis work to the liquefaction work:

$$\beta = \frac{w_{rev,electrolysis}}{w_{rev,liquid}} \tag{3.2}$$

Electrolysis takes place at 25°C. In Case 1, the minimum work for electrolysis was determined to be 117,649 kJ/kg H2. The minimum work required to liquefy 1 kg of hydrogen is determined to be 11,963 kJ/kg H2. Then the ratio defined in Eq. 3.2 becomes 9.83. That is, 90.8% of produced work should be used for electrolysis and the remaining 9.2% for liquefaction process. The maximum specific work output was calculated to be 157.9 kJ/kg. Then, 143.4 kJ/kg is used for electrolysis and the remaining 14.5 kJ/kg for liquefaction process. Using Eq. 4, we can determine that for 1 kg of geothermal water at 200°C, $y_{\mathrm{prod,H2}}$ = (143.4 kJ/kg water)/ (117,649 kJ/kg H2) = 0.001219 kg $H_2$/kg water. Thus, 1.219 grams of hydrogen could be produced and liquefied using 1 kg of geothermal water. In another words, 820.4 kg of geothermal water is needed to produce and liquefy 1 kg of hydrogen.

### *Non-ideal conditions*

### Model 1

When analyzing the real conditions of geothermal power plants for non-ideal condition, the net work output is calculated from the equation to be 57.75 kJ/kg. Electrolysis efficiency is calculated from equation to be 75% as follows. Taking the inlet state of the liquid to be 1 atm and a saturated liquid, the actual electrolysis work input for the electrolysis of hydrogen can be calculated from Eq. 27 to be 156,865 kJ/kg. With Eq. 4, we can determine that for 1 kg of geothermal water at 200°C, $y_{\text{prod, H2}}$ = (57.75 kJ/kg water)/ (156,865 kJ/kg $H_2$) = 0.0003682 kg $H_2$/kg water. Thus, 0.3682 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 2716 kg of geothermal water is needed to produce 1 kg of hydrogen.

### Model 2

Actual work output of geothermal power plant is the same as first model. Electrolysis efficiency is calculated from equation to be 78% as follows. Actual electrolysis work for hydrogen production can be found from equation 142,880 kJ/kg. With Eq. 28, we can determine that for 1 kg of geothermal water at 200°C, $y_{\text{prod,H2}}$ = 0.0004043 kg $H_2$/kg water. Thus, 0.4043 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 2473 kg of geothermal water is needed to produce 1 kg of hydrogen.

### Model 3

The actual work output is again calculated from geothermal power plant to be 57.75 kJ/kg. In this model, electrolysis efficiency is available as 90% from equation 2.15. From equation 11 actual electrolysis works for hydrogen production is calculated to be 185,222 kJ/mol $H_2O$. The irreversible works input for the high temperature electrolysis of hydrogen can be calculated to be 91,876 kJ/kg. We can determine that for 1 kg of geothermal water at 200°C, $y_{\text{prod,H2}}$= 0.0006816 kg $H_2$/kg geothermal water. Thus, 0.6816 grams of hydrogen could be produced using 1 kg of geothermal water in the high temperature electrolysis. In another words, 1467 kg of geothermal water is needed to produce 1 kg of hydrogen.

### Model 4

Work output from a geothermal power plant is used as the work input for a liquefaction cycle in this model. Actual work produced 57.75 kJ/ kg by geothermal power plant. Taking the inlet state of the gas to be the standard dead state (25°C, 1 atm) and of the liquid to be 1 atm and a saturated liquid, the irreversible work input for the liquefaction of hydrogen can be calculated from Eq. 3 to be 70,379 kJ/ kg. With Eq. 37, we can determine that for 1 kg of geothermal water at 200°C, $y_{\mathrm{liq,H_2}}$ = (57.75 kJ/kg water)/ (70,379 kJ/kg gas) = 0.0008206 kg gas/kg water. Thus, 0.8206 grams of gas could be liquefied using 1 kg of geothermal water. In another words, 1219 kg of geothermal water is needed to liquefied 1 kg of hydrogen.

**Model 5**

Geothermal water provides heat to the absorption refrigeration system (ARS) and hydrogen gas is cooled in the ARS and liquefied in the liquefaction cycle. So, maximum work required is decreased for hydrogen production. Calculations made, -20°C chilled hydrogen gas, the actual amount of work required for liquefaction of hydrogen gas is found 58,594 kJ/kg of hydrogen in this system. The actual COP of ASR system is available as 0.52. It can be cooled amount of hydrogen gas is available as 0.07058 kg $H_2$/kg geothermal water. In other words, 25°C and 1 kg of hydrogen, pre-liquefaction -20°C to cool is actually 14.17 kg geothermal fluid is required in this system.

**Model 6**

Geothermal water provides heat to the ARS and then is used to generate work in a power plant, while hydrogen gas is cooled in ARS and then liquefied in the liquefaction cycle. Under the actual conditions, the geothermal fluid produced work is 49.25 kJ/kg in this system. Actual liquefaction work is calculated to be 57.999 kJ/kg of hydrogen for this process. Amount the unit mass of coolable hydrogen is calculated as the amount of 0.03469 kg $H_2$/kg geothermal water. This corresponds to the liquefaction of $y_{\mathrm{liq,\ H2}}$ = 0.0008491 kg = 0.8491 grams hydrogen by 1 kg geothermal water at 190°C. In another words, 1178 kg of geothermal water is needed for cooling and then liquefaction 1 kg of hydrogen.

**Model 7**

The minimum value of electrolysis enthalpy at 25°C and 1 atmosphere pressure was found 285,830 kJ/kmol. The value of Gibbs free formation was found 237,180 kJ/kmol. Electrolysis efficiency is can be found 0.75 of these values form equation 2.15. For non-ideal conditions we can be found minimum work of electrolysis from equation 2.27. The minimum work for electrolysis of hydrogen is calculated to be 156,865 kJ/kg in the non-ideal condition. The work required for hydrogen liquefaction was calculated to be 70,379 kJ/kg of hydrogen. So, part of geothermal work is used for electrolysis and the remaining part for liquefaction.

We want to be finding the amount of hydrogen production and liquefaction, the geothermal power output divide by necessary power input for the electrolysis, to obtain the value of 0.0002541 kg $H_2$/kg geothermal water. The amount of liquefaction hydrogen is found 0.0002541 kg $H_2$/kg geothermal. In another words, 3935 kg of geothermal water is needed for production and liquefaction 1 kg of hydrogen.

As a result, each of a model for ideal and non-ideal circumstances, the results obtained from the thermodynamic analysis is also briefly summarized in Table 3.1 and 3.2.

Table 3.1 Performance of the models under ideal conditions.

| | |
|---|---|
| Model 1 | 1.343 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 745 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 2 | 1.418 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 705 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 3 | 1.911 grams of hydrogen could be produced using 1 kg of geothermal water in the high temperature electrolysis. In another words, 524 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 4 | We can determine that for 1 kg of geothermal water at 200°C, 0.0132 kg $H_2$/kg water. Thus, 13.2 grams of gas could be liquefied using 1 kg of geothermal water. |
| Model 5 | 1.457 kg of hydrogen can be cooled from 25°C to -20°C using 1 kg of geothermal water at 200°C. |
| Model 6 | 0.143 kg of hydrogen can be cooled from 25°C to -20°C using 1 kg of geothermal water at 200°C. This corresponds to the liquefaction of y = 0.01193 kg = 11.93 grams hydrogen by 1 kg geothermal water at 190°C. In another words, 1 kg of hydrogen could be liquefied using 83.81kg of geothermal water. |
| Model 7 | 1.219 grams of hydrogen could be produced and liquefied using 1 kg of geothermal water. In another words, 820.4 kg of geothermal water is needed to produce and liquefy 1 kg of hydrogen. |

Table 3.2 Performance of the models under non-ideal conditions.

| | |
|---|---|
| Model 1 | 0.3682 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 2716 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 2 | 0.4043 grams of hydrogen could be produced using 1 kg of geothermal water. In another words, 2473 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 3 | 0.6816 grams of hydrogen could be produced using 1 kg of geothermal water in the high temperature electrolysis. In another words, 1467 kg of geothermal water is needed to produce 1 kg of hydrogen. |
| Model 4 | 0.8206 grams of gas could be liquefied using 1 kg of geothermal water. In another words, 1219 kg of geothermal water is needed to liquefied 1 kg of hydrogen. |
| Model 5 | It can be cooled amount of hydrogen gas is available as 0.07058 kg $H_2$/kg geothermal water. In other words, 25°C and 1 kg of hydrogen, pre-liquefaction -20°C to cool is actually 14.17 kg geothermal fluid is required in this system. |
| Model 6 | This corresponds to the amount of liquefaction hydrogen is 0.0008491 kg or 0.8491 grams by 1 kg geothermal water at 190°C. In another words, 1178 kg of geothermal water is needed for cooling and then liquefaction 1 kg of hydrogen. |
| Model 7 | The amount of liquefaction and production hydrogen is found 0.0002541 kg $H_2$/kg geothermal. In another words, 3935 kg of geothermal water is needed for production and liquefaction 1 kg of hydrogen. |

### 3.3 Evaluation of Thermodynamic Analysis of the Model Results

We consider a liquid geothermal resource and investigate the seven cases using both the ideal (i.e., reversible) and non-ideal (i.e., irreversible) operations. Fig. 3.2 and 3.3 gives the effect of geothermal water temperature on the $y_{prod,\ H2}$ parameter (kg $H_2$ produced/kg geothermal water used) for both reversible and irreversible operations for Case 1. As the temperature of geothermal resource increases the parameter increases for both ideal and non-ideal operations. The increase is almost linear. This is due to higher thermal efficiency of power generation in a geothermal power plant. At a temperature of 200°C, 1.343 grams of hydrogen can be produced by 1 kg of geothermal water in the reversible case (Fig. 3.2); and about 0.3682 grams (Fig. 3.3) of hydrogen can be produced by 1 kg of geothermal water in the irreversible case. If we take the ratio of these two values, we find 0.3682/1.3430 = 0.274 = 27.4%

This is in fact, the second-law efficiency of the system as it compares actual performance to the maximum performance. The second-law efficiency is about 31.1% (0.600/1.927=0.311) at a geothermal water temperature of 240°C (Figs. 3.2 and 3.3).

Fig. 3.2 and 3.3 give the effect of geothermal water temperature on the $y_{prod,H2}$ parameter (kg $H_2$ produced/kg geothermal water used) for both reversible and irreversible operations for Case 2. The trends are similar to those obtained for Case 1. At a temperature of 200°C, 1.418 grams of hydrogen can be produced by 1 kg of geothermal water in reversible case (Fig. 3.2); and about 0.4043 grams (Fig. 3.3) of hydrogen can be produced by 1 kg of geothermal water in the irreversible case. Then the second-law efficiency of this system becomes 28.5% (0.4043/1.4180 = 0.285). The second-law efficiency is about 32.7% ( 0.666/2.034=0.327) at a geothermal water temperature of 240°C (Figs. 3.2 and 3.3).

Fig. 3.2 and 3.3 give the results of the study for Case 3 for which high temperature electrolysis is used. The trends are similar to those obtained for Case 1 and Case 2. At a temperature of 200°C, 1.9110 grams of hydrogen can be produced by 1 kg of geothermal water in reversible case (Fig. 3.2); and about 0.6816 grams (Fig. 3.3) of hydrogen can be produced by 1 kg of geothermal water in the irreversible case. Then the second-law efficiency of this system becomes 35.6% (0.6816/1.9110 = 0.3567). The second-law efficiency is about 40% (1.117/2.742=0.40) at a geothermal water temperature of 240°C (Figs. 3.2 and 3.3).

The effect of electrolysis temperature on the energy demand for the process is shown in Fig. 3.4 Electrolysis operating temperature increases the demand for electrical energy decreases. This is made possible by the increase in heat energy as the temperature increases. The total energy demand decreases in high temperature electrolysis process.

The results of investigation for the three liquefaction of hydrogen cases considered for the reversible and irreversible operations are given in Tables 3.4 respectively. When the hydrogen gas enters the reversible liquefier at -20°C (by means of cooling it in an absorption refrigeration system) instead of 25°C, the work required per unit mass of liquefaction decreases from 11,973 kJ to 11,930 kJ, with a decrease of 43 kJ (Table 1). The corresponding decrease in the irreversible analysis is 58406 kJ (=70,379-11,973) or 80%. Note that the reversible system analysis in this case is unable to provide the extent of work decrease due to precooling gas with absorption refrigeration. The percentage decreases in work consumption for different refrigeration temperatures are plotted in Fig. 3.7. When the gas is precooled to -50°C the liquefaction work decreases by about 1.3% in ideal case and 27% in non-ideal case.

The percentage decrease in liquefaction work consumption due to cooling hydrogen gas by an absorption refrigeration system before it is liquefied is shown in Fig. 3.8. The lower the precooling temperature, the higher is the work reduction. At a precooling temperature of -20°C, the work consumption for liquefaction decreases by about 0.45% for the reversible case and 17% for the non-ideal case.

The mass of gas liquefied per unit mass of geothermal water used in the geothermal power plant (the parameter y) is illustrated as a function of geothermal water temperature in Fig. 3.5-6 for both reversible and non-ideal operation for Case 4. The parameter y increases with increasing geothermal water temperature, as expected. At a geothermal water temperature of 200°C, one kg of geothermal water can liquefy about 13.2 grams of hydrogen in the reversible case and 0.820 grams gas in the non-ideal case. The ratio of the mass liquefied in the actual case to that in the reversible case may be considered as the exergy efficiency of the non-ideal liquefaction process, which is also known as the figure of merit (FOM). The exergy efficiency of a liquefaction process, in general, is defined as the ratio of the reversible work required to the actual work consumption to liquefy a unit mass of gas. It can easily be shown that these two definitions are identical. At a geothermal water temperature of 200°C, the exergy efficiency is found to be 6.2%.

The mass of gas cooled in the absorption refrigeration system per unit mass of geothermal water (the parameter *z*) is shown as a function of the gas refrigeration temperature in Fig. 3.8 for both reversible and non-ideal operation for Case 5. The parameter z increases exponentially with the refrigeration temperature of the gas. At a refrigeration temperature of -20°C, about 1.457 kg of gas can be cooled for ideal case by one kg of geothermal water used in the absorption refrigeration system when the outside temperature is 25°C and the inlet and exit temperatures of geothermal water are 200°C and 95°C, respectively (Fig. 3.8).

In the analysis of case 6, the effect of geothermal water temperature at the exit of the generator of the absorption refrigeration system (i.e., the geothermal power plant inlet) on the parameters y is illustrated for hydrogen in Fig. 3.9 for reversible operation and in Fig. 3.5 for non-ideal operation. As the geothermal water temperature increases, the heat transferred to the absorption system, and thus the amount of cooling, decreases. This in turn decreases the amount of gas that can be cooled to the refrigeration temperature. The higher geothermal water temperature at the power plant inlet yields a higher work output and consequently higher values of $y$.

Fig. 3.2-3 gives the effect of geothermal water temperature on the $y_{prod,liq,H2}$ parameter (kg $H_2$ produced and liquefied/kg geothermal water used) for both reversible and irreversible operations for Case 7. At a temperature of 200°C, 1.219 grams of hydrogen can be produced and liquefied by 1 kg of geothermal water in reversible case (Fig. 3.2); and about 0.2541 grams (Fig. 3.3) of hydrogen can be produced and liquefied by 1 kg of geothermal water in the irreversible case. Then the second-law efficiency of this system becomes 20.8% (0.254/1.219 = 0.2084). The second-law efficiency is about 17.6% (0.308/1.75=0.176) at a geothermal water temperature of 240°C (Fig. 3.2 and 3.3).

Also, as can be seen from the fig. 3.1 the geothermal power plant work output capacity increases linearly with increasing the temperature of geothermal water.

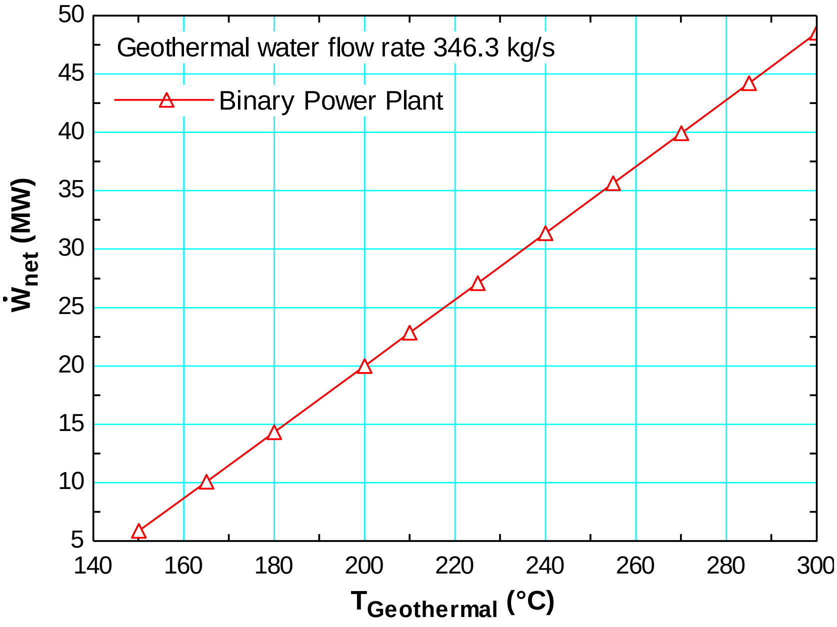


Figure 3.1 Binary geothermal power plant work output change of according to the temperature of geothermal resources.

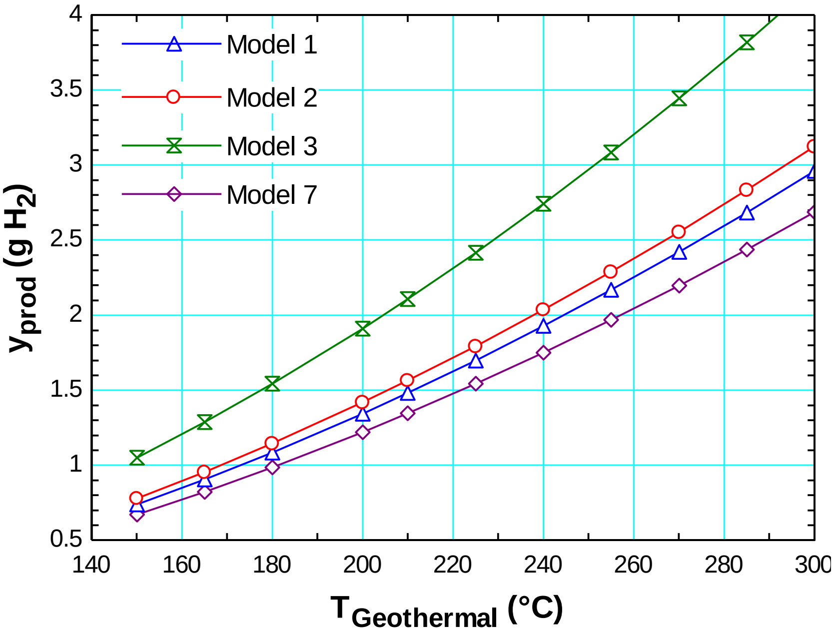


Figure 3.2 Variation of parameter $y_{prod,H2}$ (amount of hydrogen produced by electrolysis in grams per kg of geothermal water) with geothermal water temperature for Case 1,2,3,7 in ideal condition.

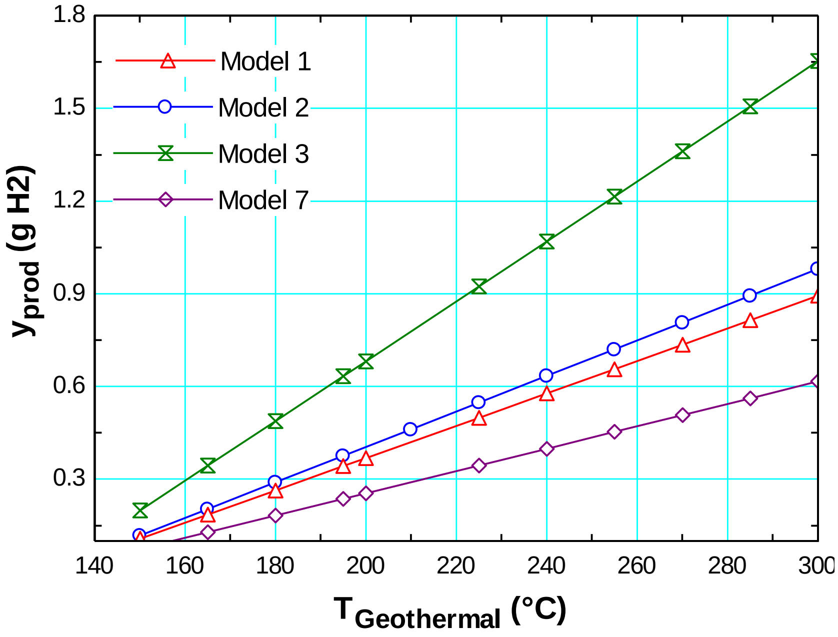


Figure 3.3 Variation of parameter $y_{prod,H2}$ (amount of hydrogen produced by electrolysis in grams per kg of geothermal water) with geothermal water temperature for Case 1,2,3,7 in non-ideal condition.

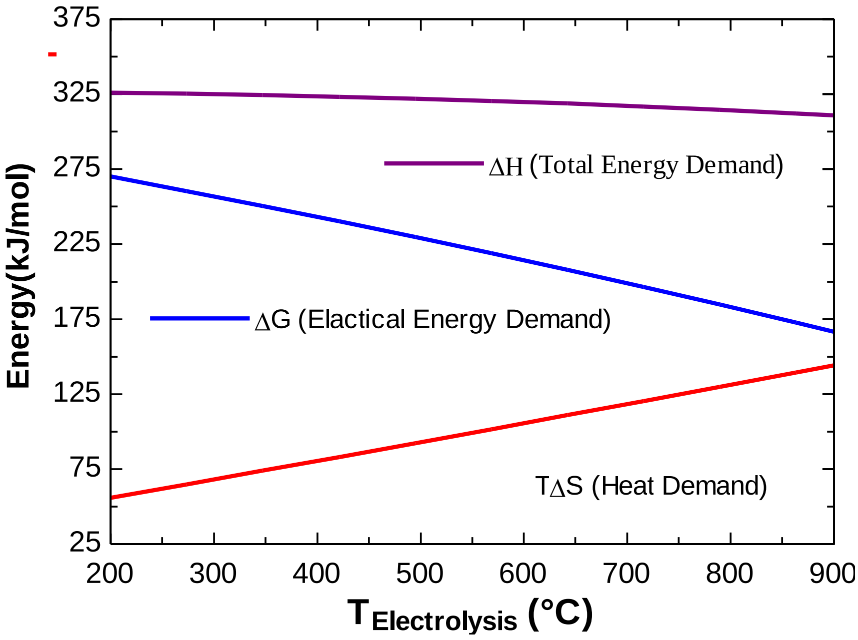


Figure 3.4 Energy demand for electrolysis processes (Case 1,2,3 and 7).

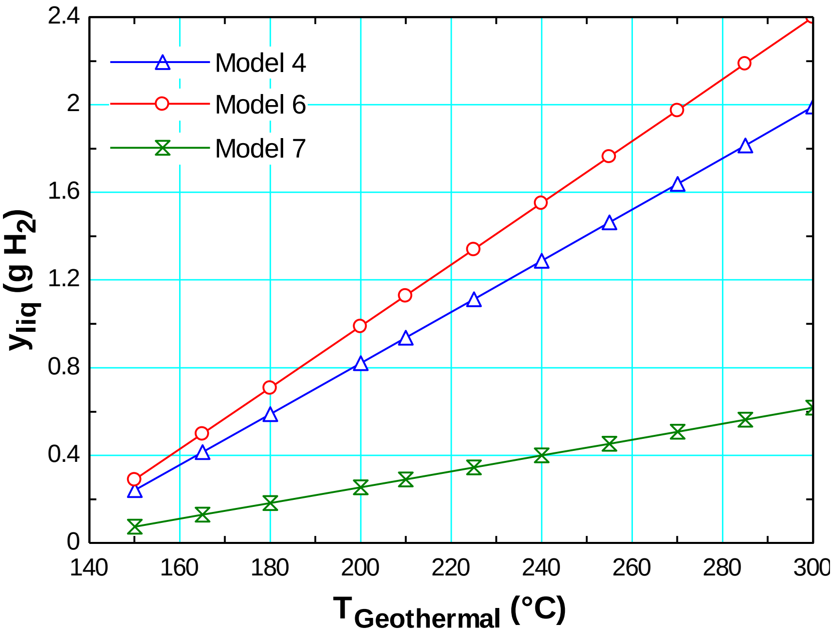


Figure 3.5 Variation of parameter $y_{liq,H2}$ (amount of gas liquefied in grams per kg of geothermal water) with geothermal water temperature for Case 4,6,7 in non-ideal condition.

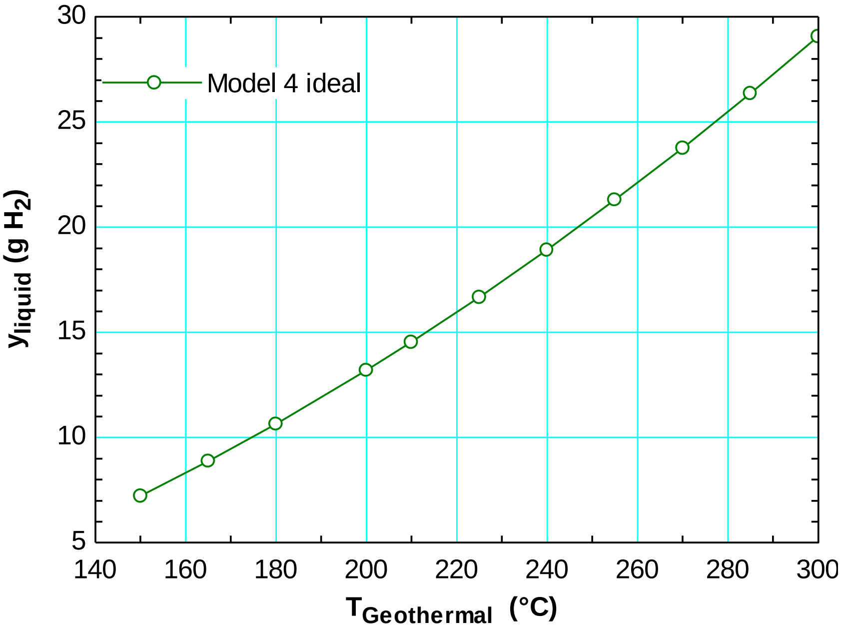


Figure 3.6 Variation of parameter $y_{liq,H2}$ (amount of gas liquefied in grams per kg of geothermal water) with geothermal water temperature for Case 4 in ideal condition.

(a)

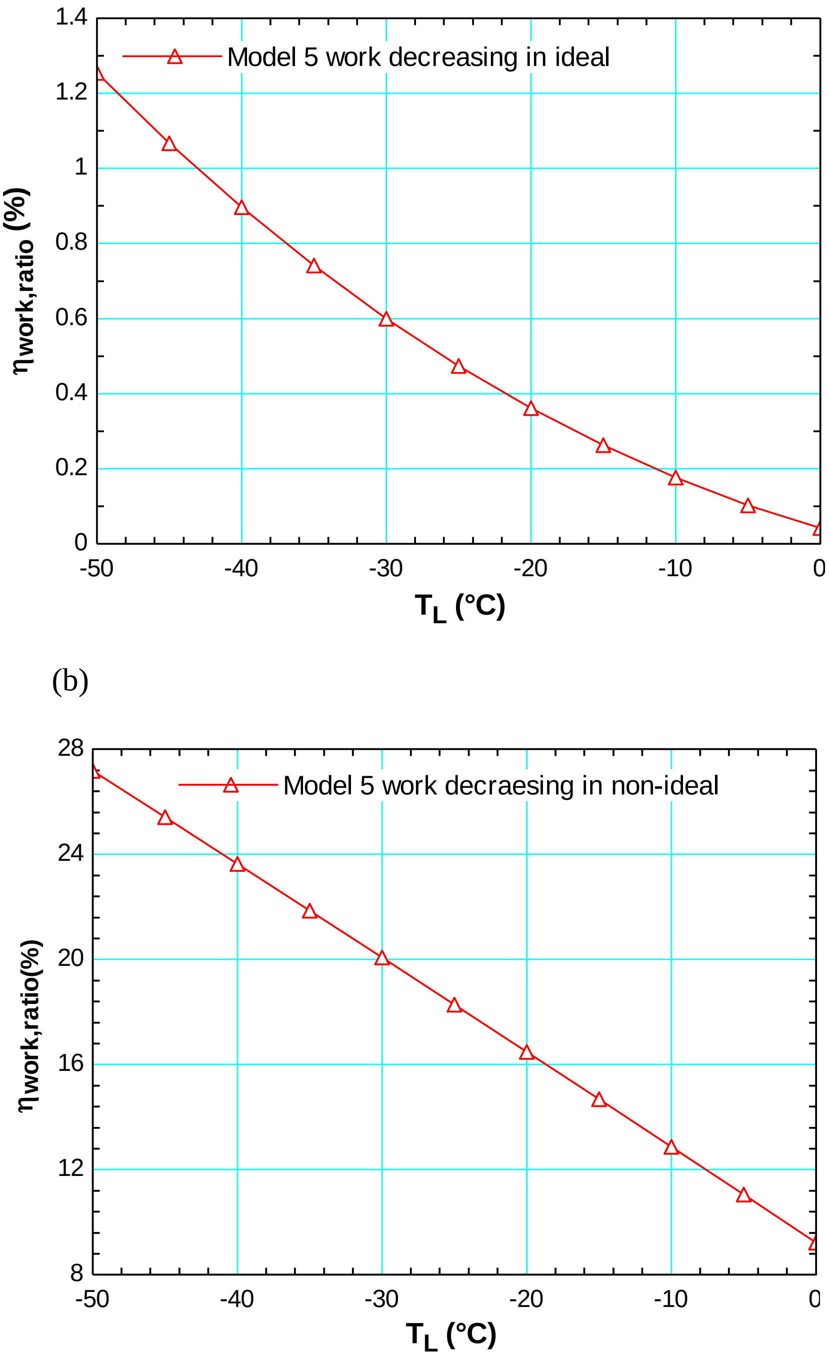


Figure 3.7 Percentage decrease in work consumption of hydrogen liquefaction for different gas precooling temperatures (a) ideal (b) non-ideal.

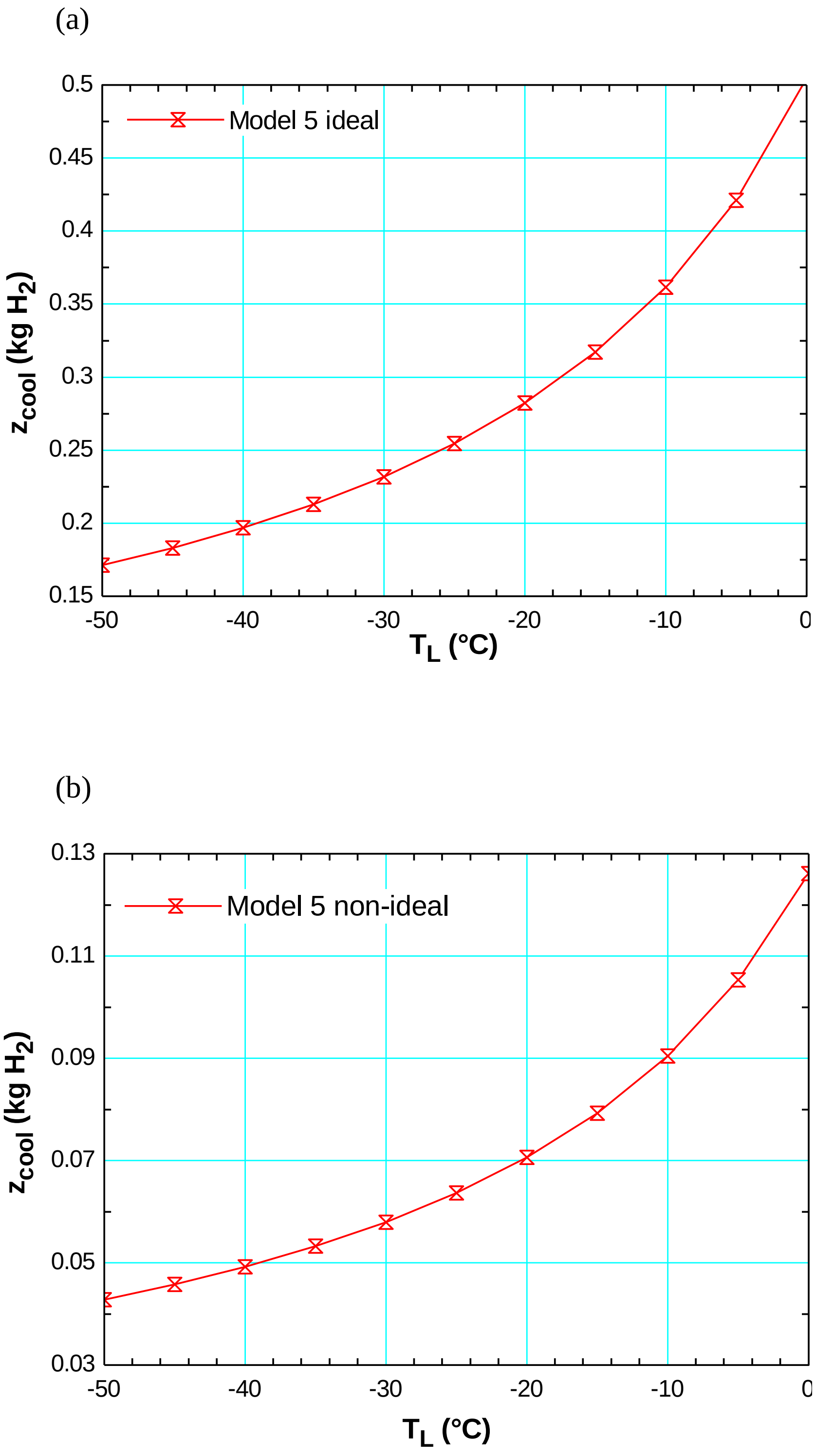


Figure 3.8 Variation of parameter *z* (mass of gas cooled in the ARS in kg per kg geothermal water) with gas refrigeration temperature for Case 5 (a) reversible operation (b) non-ideal operation.

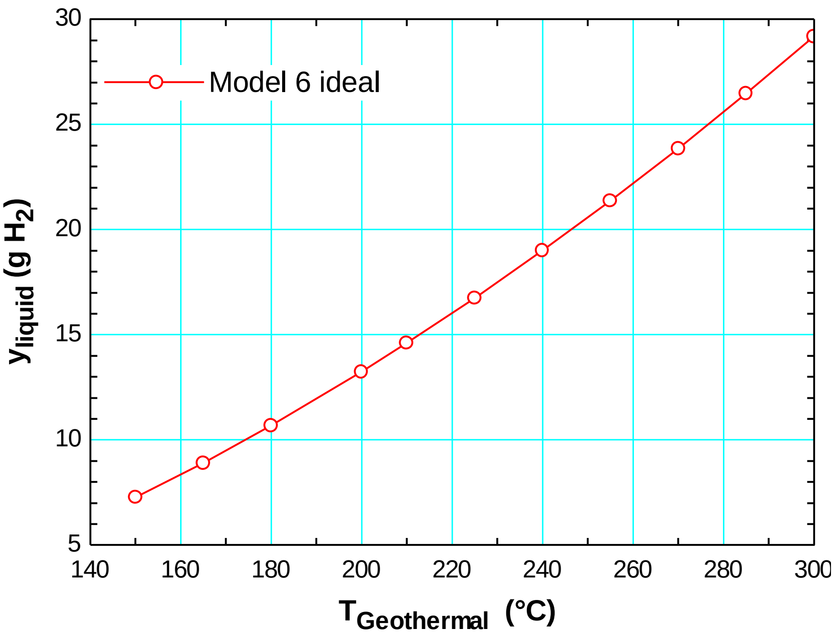


Figure 3.9 Variation of parameter $y_{liq,H2}$ (amount of gas liquefied in grams per kg of geothermal water) with geothermal water temperature for Case 6 in ideal condition.

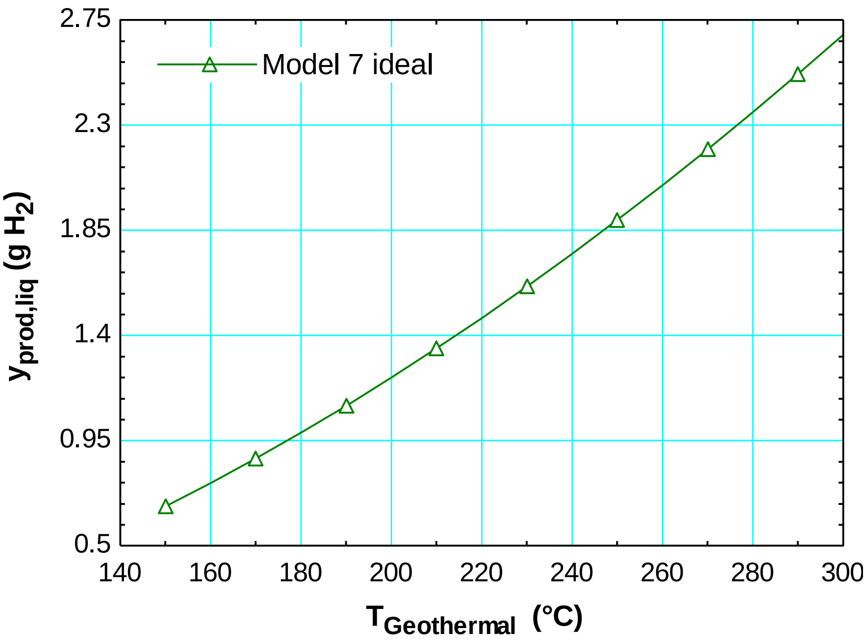


Figure 3.10 Variation of parameter $y_{prod,liq,H2}$ (amount of gas liquefied in grams per kg of geothermal water) with geothermal water temperature for Case 7 in ideal condition.

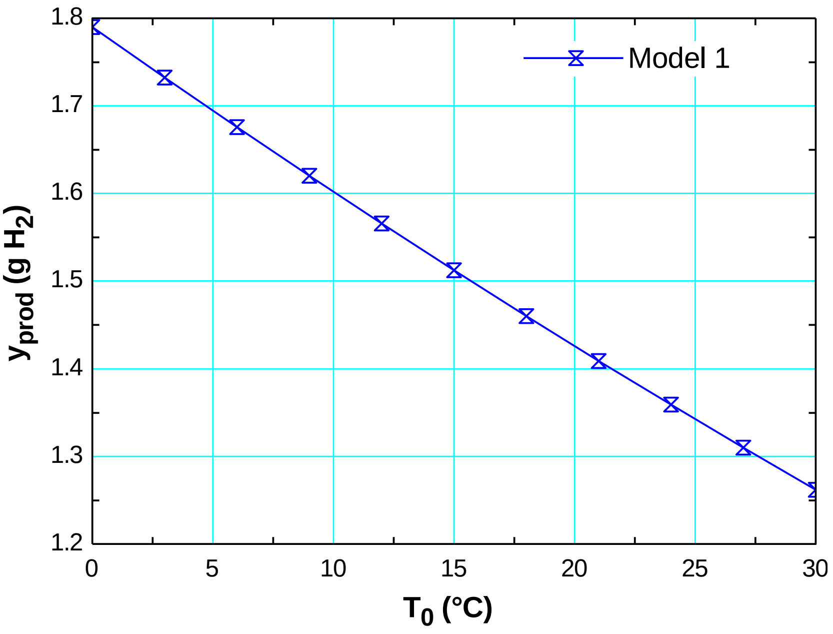


Figure 3.11 Variation of parameter $y_{prod,H2}$ (amount of hydrogen produced in grams per kg of geothermal water) with environment temperature for Case 1 in ideal condition.

The results of thermodynamic analysis are summarized in Table 3.3-4 allowing a useful comparison of the models. At a geothermal water temperature of 200°C and under reversible conditions, the amount of hydrogen that can be produced by 1 kg of geothermal water are 1.343 grams, 1.418 grams, and 1.911 grams, in Case 1, Case 2, and Case 3, respectively. Case 2 performs better than Case 1 because we are able to use the used geothermal water for preheating water for electrolysis. This used water still at a relatively high temperature is reinjected back to the ground in Case 1. Case 3 performs better than Case 2 because of the advantages associated with high temperature electrolysis. Providing a considerable amount of energy demand in heat form decreases the electricity demand, and as a result, the total energy demand decreases in the process.

High-temperature geothermal resources (above approximately 175°C) can be used for combined power generation and absorption cooling. Using the high-temperature geothermal energy for power generation and then using the relatively lower temperature geothermal energy for absorption cooling is probably be a better thermodynamic approach for minimizing entropy generation. For relatively low-temperature geothermal resources, it seems that the resource can be better utilized as energy input to an absorption refrigeration system as in case 5 investigated in this paper. The efficiencies of geothermal power plants are low particularly for lower-temperature resources (typically fewer than 5% based on the energy of the resource relative to the ambient state). Higher thermodynamic efficiencies and better matching between the resource and use are observed when geothermal energy is used for space and process heating applications and for absorption refrigeration systems.

Table 3.3 The summary of the production results from thermodynamic analysis.

| | The mass of hydrogen produced per unit mass of geothermal water at 200°C (gr $H_2$/kg water) | | Second-law efficiency (%) | |
|---|---|---|---|---|
| | Reversible operation | Irreversible operation | $T_{geo}$ = 200°C | $T_{geo}$ = 240°C |
| Case 1 | 1.343 | 0.368 | 27.40 | 30.00 |
| Case 2 | 1.418 | 0.404 | 28.50 | 31.17 |
| Case 3 | 1.911 | 0.712 | 35.67 | 39.00 |
| Case 7* | 1.219 | 0.196 | 20.85 | 22.80 |

* In Case 7, hydrogen is produced and liquefied.

Table 3.4 The summary of the liquefaction results from thermodynamic analysis.

| | The mass of hydrogen liquefied and cooled per unit mass of geothermal water at 200°C (gr $H_2$/kg water) | | Second-law efficiency (%) | |
|---|---|---|---|---|
| | Reversible operation | Irreversible operation | $T_{geo}$ = 200°C | $T_{geo}$ = 240°C |
| Case 4 | 13.190 | 0.820 | 6.22 | 6.80 |
| Case 5* | 1.457 kg | 0.705 kg | 4.84 | 5.50 |
| Case 6 | 11.930 | 0.849 | 7.11 | 8.05 |
| Case 7** | 1.219 | 0.196 | 20.85 | 22.80 |

* In Case 5, hydrogen is only pre-cooled with geothermal water.

**In Case 7, hydrogen is produced and liquefied.

In Case 7, at a geothermal water temperature of 200°C, 1.219 grams of hydrogen can be produced and liquefied by 1 kg of geothermal water under reversible conditions. This is a lower amount compared to the first three cases. However, this operation allows both the production and liquefaction at the same site by the same resource. This also means that the storage of hydrogen in liquid form is automatically taken care of on the production site. This may be advantages for remote geothermal resources where the transportation of geothermal water to the residential and commercial sites for heating/cooling purposes is not viable for thermal and economic reasons.

As part of the analysis, the effect of varying environment (dead state) temperature $T_0$ on the hydrogen production is studied for Case 1 (Fig. 3.11). As the environment temperature increases the amount of hydrogen production decreases. This can be explained by investigating the expressions in Eq. 1 and Eq. 2. As $T_0$ increases both the reversible work output from the geothermal power plant and the reversible work input for electrolysis decrease. The first one has negative effect and the second one has positive effect on the amount of hydrogen production. The trend in Fig. 3.11 indicates that the negative effect of decreasing work output more than offset the positive effect of reducing work input.

# CHAPTER 4

# ECONOMIC ANALYSIS OF MODELS USED IN GEOTHERMAL PRODUCTION AND LIQUEFACTION

## 4.1 Introduction

The design of all thermal systems require the explicit consideration of engineering economics, as cost is always an important consideration. In this study, seven models are considered for the production and liquefaction of hydrogen by geothermal energy. In these models, we use electrolysis and high-temperature steam electrolysis processes for hydrogen production, a binary power plant for geothermal power production, and a pre-cooled Linde-Hampson cycle for hydrogen liquefaction. Also, an absorption cooling system is used for the pre-cooling of hydrogen before the liquefaction process. A methodology is developed for the economic analysis of the models. It is estimated that the cost of hydrogen production and liquefaction ranges between 0.979 \$/kg $H_2$ and 2.615 \$/kg $H_2$ depending on the model. The effect of geothermal water temperature on the cost of hydrogen production and liquefaction is investigated. The results show that the cost of hydrogen production and liquefaction decreases as the geothermal water temperature increases. Also, capital costs for the models involving hydrogen liquefaction are greater than those for the models involving hydrogen production only.

In this study, for sevens models of hydrogen productions and liquefactions are considered economic analysis in the third chapter, on the basis of thermodynamic analysis results simple and advanced economic analysis for each of these models. Economic analysis is great importance for comparison of the models in them, and the feasibility of market comparison. For this purpose we have set some criteria by reference to market values and economic analyses of seven models were performed separately in this report.

Economic analysis is examined several section. The unit cost of electricity, the cost of operating and maintenance and, depreciation of money and amortization period of seven models within the scope of economic analysis are examined with these important parameters. [80]. Economic analysis was performed two parts in this report. Firstly, economic analyses are considered relative to the unit cost of electricity, the second part of the economic analysis are conducted of operation, investment, maintenance and repair costs on the total system cost. According to reports in the market of hydrogen production company, the most important factor is the cost of electricity for producing hydrogen by electrolysis [81]. For this reason, depending on the unit price of electricity has been appropriate to make an economic analysis.

The most important factor is the price of electricity in the hydrogen economy. Because the cost of hydrogen the mostly depends on the price of electricity. According to the data produced by electrolysis of hydrogen in 2004, electricity costs of hydrogen is \$ 2/kg $H_2$, the electricity price of \$ 0.01/kWh from which shall not be lower [82].

### 4.2 Simple Economic Analysis of Hydrogen Production and Liquefaction Models

In this section, hydrogen production and liquefaction models only on the price of electricity cost analysis were conducted in here. The cost of electricity determines, to a very large extent, the production cost of electrolytic hydrogen. Typically, electrolytic hydrogen, from advanced alkaline water electrolyzers with efficiencies in the range of 65-75%, cost around \$2.84 to \$4.26/kg depending on the price of electricity. Approximately 70-80% of the cost is attributable to electricity cost, while capital related charges amount to as little as 15-20%. Cost associated with O&M amount to approximately 5% of production cost [83].

Therefore, the geothermal power plant, electrolysis system and liquefaction systems of the initial investment cost, maintenance and repair costs of these systems will not be included in this analysis. In this analysis, necessary for a kilogram of hydrogen production and liquefaction of electricity costs will be calculated. For comparison, one liter of gasoline costs that will be given, the equivalent of hydrogen energy costs.

H2A uses \$/kg as the standard unit of hydrogen price because one kilogram of hydrogen has roughly the same energy content of a gallon of gasoline. If a kilogram of hydrogen and a gallon of gasoline have the same cost and are burned in engines with the same efficiency, the resultant \$/mile will be similar [84].

For this study, electricity prices were based on standard H2A projections from 2005 to 2045. Industrial rates were \$0.044−\$0.050/kWh, with a value of \$0.045/kWh in 2005. Commercial rates were \$0.067−\$0.077/kWh, with a value of \$0.069/kWh in 2005. The study shows that electricity costs are the most significant contributor to hydrogen costs produced via electrolysis, contributing 60% and 68% of the total cost when industrial and commercial electricity rates are used, respectively. The capital costs are the second highest cost contributor [85].

In addition, in this economic analysis, the five companies that produce hydrogen using electrolysis with electricity costs are taking a reference. These companies are Stuart IMET; Teledyne HM and EC; Proton HOGEN; Norsk Hydro HPE and Atmospheric and Avalence Hydrofiller. By reference to studies done in 2004 and 2007 economic values of these companies. According to these data, the cost of electricity for hydrogen production used in the industrial applications of the 0.044 and 0.05$/kWh ranged. Hydrogen production cost of electricity used in the commercial area of the 0.067 and 0.077 $/kWh ranged.

The U.S. Department of Energy (DOE) has set the cost target for hydrogen at $2.00-$3.00/kg to serve the transportation market [86]. The costs calculated in Figure 4.1 include production, not delivery. As a result, to meet this target, the cost of hydrogen produced via electrolysis from industrial electricity needs to be reduced by at least $1.00, and likely more than $2.00 (2005 dollars) to meet the DOE cost goals.

Unit cost of electricity changes with inflation and other various reasons. Given the variability of electricity costs, hydrogen production of unit cost will look like changing in Figure 4.1. The cost of hydrogen production increases linearly with increased electricity price [81].

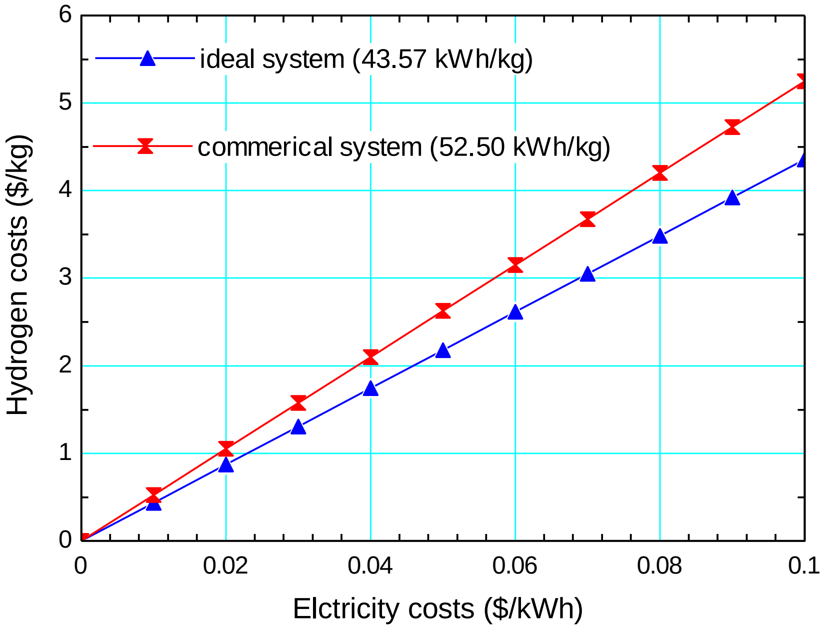


Figure 4.1 Cost of hydrogen versus electricity without equipment costs.

There are opportunities for reducing the capital and operating costs of the electrolyzer, but electricity prices are a key driver to hydrogen cost. Figure 4.1 shows electricity versus hydrogen costs, but takes into account only the cost of the electricity used to split the water into hydrogen and oxygen. This figure represents a boundary analysis of the electrolysis technology. If the electrolyzer were free, had no operation and maintenance costs (other than electricity), operated at a 100% capacity factor, and had no delivery or dispensing costs, this figure would show the cost at which hydrogen could be produced. The results demonstrate that to meet the DOE target of $3.00/kg, electrolyzers with today's efficiencies would need to have access to electricity prices lower than $0.045–$0.055/kWh. Ideal systems would need to have access to electricity prices lower than $0.075/kWh, which represents the highest possible electricity price, that low-temperature electrolyzers would be able to use to produce hydrogen at $3.00/kg. The importance of electricity price is a key reason why utilities need to be involved if the future hydrogen economy includes electrolysis.

One of the most promising ways to provide clean, domestic, carbon-free energy to electrolysis units is via electricity produced from geothermal, wind and solar technologies. However, these technologies face challenges with electrolysis in the areas of cost and energy output variability. Geothermal, wind and solar sources produce electricity that varies with the natural processes that drive them.

According to these data, an ideal system, i.e., a working 100% efficiency of electrolysis system, the unit cost of hydrogen produced by these five companies of 3 $ is for under. Conventional electrolysis method is an electrolysis method used by these companies [87]. According to these calculations are made for prescribed models and their variations are shown graphically. This change in values for each model with the following changes were calculated and graphically shown in the EES program.

First of all, according to the price of electricity we should examine the change of unit cost of hydrogen. The cost of hydrogen directly to electricity price due to the effective increase in the price per kilowatt-hour in the unit cost of hydrogen is expected to increase linearly. The unit cost of hydrogen can be calculated by electrolysis with the following statement:

$$Cost_{H2} = C_{electricity} \times H_{electrolysis} \tag{4.1}$$

where, $C_{electricity}$ is unit cost of electricity in \$/kWh, $H_{electrolysis}$ is the necessary of electrolysis work in kWh/kg $H_2$ .

$$H_2O + \text{Electricity work} \rightarrow H_2 + \tfrac{1}{2}\,O_2 \tag{4.2}$$

Electrolysis processes of gives the minimum electrical work, can be written above the equation [88].

$$w_{\min,elec} = \Delta G_{H_2O} = -G_{H_2O(l)} + G_{H_2} + 1/2G_{O_2} \tag{4.3}$$

The method of simple electrolysis of alkaline water electrolysis work needed to 237,180 kJ/kmol $H_2O$ is found for 1 kmol water electrolysis. 1 kmol of hydrogen molar mass is 2.016 kg/kmol, given that the work required to produce 1 kg of hydrogen by electrolysis can be find the following expression:

$$w_{\min,elec,H_2} = \frac{w_{\min,elec}}{M_{H_2}} \tag{4.4}$$

Required minimum electrolysis work is calculated to be 117,649 kJ/kg $H_2$ for 1 kg hydrogen production from the equation 4.4. Using this value, the amount of work in the electricity required to produce 1 kg of hydrogen can be compute as follows:

$$H_{electrolysis} = \frac{w_{\min,elec,H_2}}{3600kJ}\ (\text{kWh/kg } H_2) \tag{4.5}$$

Accordingly, taking into account that 1 kWh = 3600 kJ, a simple method of alkaline electricity work required to produce 1 kg of hydrogen is 32.68 kWh (117649/3600 = 32.68 kWh). Calculations took into account the principles of the reference companies. Same procedures applicable the required for liquefaction of 1 kg hydrogen gas by calculating above the amount of electrical work.

### *Ideal (Reversible) Economic Analysis of Models*

### Model 1

Maximum work potential of geothermal water 157.9 kJ/kg was found in the thermodynamic analysis. Ideal electrolysis work 117,649 kJ/kg $H_2$ was found from equation 2.26 for 1 kg of hydrogen production by alkaline water electrolysis. The electricity needed for electrolysis operation is calculated to be 32.68 kWh from equation 4.5. Hydrogen production cost of 1 kg of hydrogen is calculated to be 1.634 \$/kg $H_2$ for Model 1, depending on the unit price of electricity, from equation 4.1 in ideal conditions.

### Model 2

In this model we obtained under ideal conditions of the maximum work of geothermal power plant is not change. Geothermal water enters the plant at 200°C and leaves at 95°C. This water heats the water from 25°C to 85°C before electrolysis. So, the electrical work necessary for the production of 1 kg of hydrogen is decreasing due to an increase in electrolysis of water temperature. Then, using equations 2.26 to 1 kg of hydrogen production ideal work is calculated to be 111421 kJ/kg $H_2$ (224624.7/2.016 = 111,421). Amount of electrical work for required electrolysis is calculated to be 30.95 kWh from 3.5 (111421/3600 = 30.95). As a result, the ideal condition for model 2 the cost of electricity due to the cost of hydrogen production cost, electricity unit price is 0.05 $/kWh by taking, is calculated to be 1.547 $/kg (0.05*30.95/1kg $H_2$ = 1.547).

### Model 3

High temperature steam electrolysis of water is necessary for Gibb's free energy 166,662.72 kJ/kmol was found in our thermodynamic analysis for 1 kmol electrolysis of water. This value divided by the molar mass of hydrogen from the equation 3.4, electrolysis of 1 kg of hydrogen is an ideal work or the minimum necessary work is calculated to be 82,670 kJ/kg $H_2$, (166,662.72/2.016 = 82,670). Then using the equation 3.5 required for high temperature steam electrolysis of electrical work is calculated to be 22.96 kWh (82,672/3600 = 22.96) for the ideal condition. As a result, the condition for model 3, depending on the price of electricity per unit cost of hydrogen production is calculated is to be 1.148 $/kg $H_2$ (0.05*22.96=1.148) , electricity unit price of $ 0.05 per kWh by taking, from equation 4.1.

### Model 4

Maximum specific work obtained from geothermal power plants 157.9 kJ/kg was found. Hydrogen gas taken as the input status the dead state (25 ° C, 1 atm) out of the saturated liquid is assumed in liquefaction cycle. The reversible (ideal) work required for liquefaction of hydrogen was calculated to be 11,963 kJ/kg $H_2$. This value is using equation 3.6 as required ideal liquefaction electrical work is calculated to be 3.323 kWh (11,963/3600 = 3.323). If the costs of liquefaction process to be calculated, depend on the cost per unit of electricity, from equation 3.1, it is calculated to be 0.166 $/kg $H_2$ (0.05*3.323 = 0.166).

**Model 5**

Geothermal water is used as the heat source for a reversible absorption refrigeration cycle (ARC) which is used to precool the gas before it is liquefied. This pre-cooling is contributed to the work of liquefaction. Liquefaction work is a certain percentage of the declined. Cost impact of this decline is considered. Ideally a small decline in the necessary of liquefaction works in thermodynamic analysis. In this system the work necessary for the liquefaction was found 11918 kJ / kg $H_2$. As we have seen, only 0.4% decline observed (11918/11963*100 = 99.6) in ideal condition. But the fact that a significant decreases was calculated in the thermodynamic analysis. The electrical work required is calculated 3.311 kWh from equation 3.5. Liquefaction cost is calculated to be 0.165 \$/kg $H_2$ from equation 3.1.

**Model 6**

Geothermal water at 200°C is used as the heat source for a reversible absorption refrigeration cycle which is used to precool the gas before it is liquefied. The geothermal water leaving the generator of the absorption system at 190°C is used to produce work in a geothermal power plant. The refrigeration temperature is again taken to be -20°C. Ideal work from geothermal power plants 142.3 kJ/kg was found in geothermal water. The ideal work of hydrogen liquefaction was found 11,918 kJ/kg $H_2$. Electricity work in the liquefaction is calculated to be 3.311 kWh from equation 4.6. Unit cost of liquefied hydrogen is calculated to be 0.165 \$/kg from equation 4.1.

**Model 7**

Liquefaction of hydrogen gas is produced at the same time. Part of geothermal work is used for electrolysis and the remaining part for liquefaction. We can find used in the rate of work the following formula:

$$w_{ratio} = \frac{H_{elec,prod.}}{H_{elec,prod.} + H_{elec,liq.}} \tag{4.6}$$

The amount of electrical work is necessary for both production and liquefaction of $H_{elec}$ as follows:

$$H_{elec} = w_{ratio} \times H_{elec,prod.} + (1 - w_{ratio}) \times H_{elec,liq.} \tag{4.7}$$

Equation from 4.6 the work rate is calculated to be 9834, according to this rate electricity work is calculated to be 29.97 kWh from equation 4.7. Finally, for model 7 produced and liquefied of 1 kg of hydrogen cost, depending on the price of electricity unit cost, is calculated to be 1.499 \$/kg $H_2$ from the equation 4.1.

### *Non-Ideal (Irreversible) Economic Analysis of Models*

#### Model 1

Non-ideal, when analyzing the real conditions of the geothermal power plant thermodynamic analysis of the net work was found 57.75 kJ/kg. Conventional water alkaline electrolysis efficiency is chanced between 60 and 80% in the literature. For example, had used company Norsk Hydro electrolysis system efficiency is around 74-78%. We are the thermodynamic and economic analysis models for simple alkaline water electrolysis efficiency calculated as roughly 75%. So, the actual electrolysis work input for the electrolysis of hydrogen can be calculated to be 156,865 kJ/kg (117648.87/0.75= 156865). The electricity work needed for electrolysis is calculated to be 43.57 kWh from equation 4.5. Model 1 for the actual cost of production of 1 kg of hydrogen depending on unit price of electricity, from equation4.1, is calculated to be 2.179 \$/kg $H_2$.

#### Model 2

In this model we obtained under non-ideal conditions of the maximum work of geothermal power plant is not change. Actual work of electrolysis, with increasing electrolysis temperature, is calculated taking into account changes in electrolysis efficiency; we can be found the actual work of electrolysis. Thermodynamic analysis of our and Mirable (2006) in these study found that around 78% efficiency of electrolysis system. This reference is taken for the actual work of electrolysis is calculated to be 142847.43 kJ/kg $H_2$ (111421/0.78 = 142847.43). The electricity work needed for electrolysis process is available as 39.68 kWh (142847.43/3600 = 39.68) from the equation 4.5. As a result, actually required for model 2, 1 kg of hydrogen production cost, depending on the unit price of electricity, from equation 4.1, is calculated to be 1.984 \$/kg $H_2$ (0.05*39.68 = 1.984).

#### Model 3

Actual work of electrolysis is taking into account the reduced efficiency at high temperature steam electrolysis method. In other words, we use literature as a reference in research and high temperature steam electrolysis system is used Hot Elly's efficiency was calculated as 90%. Actually work is required for electrolysis of model 3 is calculated to be 91,877 kJ/kg $H_2$

is found (82670/0.9 = 91877) from equation 4.6. The electricity work needed for electrolysis process by using equation 3.5 is calculated to be 25.52 kWh (91877/3600 = 25.52). As a result of model 3 in actual condition, unit production cost of 1 kg of hydrogen, depending on the unit cost of electricity, is calculated to be 1.177 \$/kg $H_2$ (0.05*25.83 = 1.177).

**Model 4**

Actual work of geothermal power plants from thermodynamic analysis was found 57.75 kJ/kg, the actual work of liquefaction process was found 70,155 kJ / kg in $H_2$. Using the equation 4.5, actually electrical work required for liquefaction is calculated to be 19.49 kWh (70155/3600 = 19.5). Cost of hydrogen liquefaction process cost, depending on the unit cost of electricity, is calculated to be 0.974 \$/kg $H_2$ (0.05*19.5 = 0.974) from equation 4.1.

**Model 5**

Geothermal water is used as the heat source for a reversible absorption refrigeration cycle (ARC) which is used to precool the gas before it is liquefied. This pre-cooling is contributed to the work of liquefaction. Ideally, this process was worth as little as 0.4% contribution to the work of liquefaction, but in actually 16.5% of the observed decline in liquefaction work. In other words, actual work in the liquefaction was found to be 58743 kJ/kg $H_2$ in thermodynamic analysis for model 5. So, using the equation 4.5, required of liquefaction electrical work is calculated to be 16.317 kWh (58743/3600 = 16.317). Finally, the actual electrical cost of hydrogen liquefaction for model 5 is calculated to be 0.979 \$/kg $H_2$ (16.317*0.05 = 0.813). Environmental conditions necessary for the liquefaction of hydrogen gas had been found 4 5.19 kWh of electricity as a work for model 4. These two value is divided by each other, we find work ratio gain of the pre-cooling 16.5% for us (16.317/19.5 = 0.836).

**Model 6**

Actual work from the geothermal power plants was found 49.24 kJ/kg. The actual work needed to liquefaction was found 58,854 kJ/kg in $H_2$. Using by equation 4.5 required the actual electricity work is calculated to be 16.34 kWh for hydrogen liquefaction. The unit cost of liquefied hydrogen is calculated to be 0.793 \$/kg $H_2$ from the equation 4.1.

**Model 7**

There is only actually work ratio changes used in this model. We can be calculating actually cost of hydrogen production and liquefaction using by equation 4.6 and 4.7. Actual work of geothermal power plants work was calculated to be 57.75 kJ/kg in geothermal water and the actual work of electrolysis process was calculated to be 156,865 kJ/kg in $H_2$. Actual work of liquefaction was calculated to be 70,155 kJ/kg in $H_2$. Actual production of geothermal power plant work distribution of production and liquefaction cycles and the work ratio is calculated to be 0.691 from the equation 4.6. This means that, the production of work calculated as 39.01 kJ/kg, and liquefaction work calculated as 18.74 kJ/kg. This work ratio taking into account from equation 4.7 produced the actual work required at the same time liquefaction of hydrogen as the work is calculated to be 36.13 kWh. As a result, actually required for the 1 kg of hydrogen production and the liquefaction cost of electricity is calculated to be 1.808 $/kg from equation 3.1 (36.13*0.05 = 1.808).

## 4.3 Results and Discussions of Simple Economic Analysis of Models

Hydrogen production cost is directly connected to the unit cost of electricity. Geothermal resources temperature is directly affect produced on the work output or the cost of electricity. Simple economic analyzes the geothermal source temperature of 200°C for each model according to which hydrogen is produced and liquefying unit costs were calculated (Table 4.1). As the table shows the actual conditions of hydrogen production and liquefaction costs differ significantly change than ideal conditions.

Table 4.1 Simple economic analysis results of models for hydrogen production and liquefaction.

| | **Ideal ($/kg $H_2$)** | **Non-ideal ($/kg $H_2$)** | **Increasing unit cost of $H_2$ %** |
|---|---|---|---|
| Model 1* | 1.634 | 2.179 | 25 |
| Model 2* | 1.584 | 1.984 | 20 |
| Model 3* | 1.148 | 1.177 | 2.5 |
| Model 4** | 0.166 | 0.974 | 83 |
| Model 5** | 0.165 | 0.813 | 16.5 |
| Model 6** | 0.165 | 0.793 | 80 |
| Model 7*** | 1.499 | 1.808 | 17 |

*production

**liquefaction

***production and liquefaction

In addition, hydrogen production costs by changing the temperature of the geothermal resource in the graphical representation of the changes made (Figure 4.2-4.5). Hydrogen production and liquefaction cost is decreasing with increasing temperature of geothermal resources both in the ideal and actual case. According to the analysis, for example; instead of 200°C source temperature using the 240°C source temperature for model 1, model 2, model 3 and model 7 in actual conditions, it can be observed a reduction in the cost of hydrogen produced in the ratio of 36% (Figure 4.2 and Figure 4.3). Similarly, the temperature of geothermal resource increased for liquefaction models; also significantly decrease the cost of liquefaction has been observed (Figure 4.4 and Figure4.5).

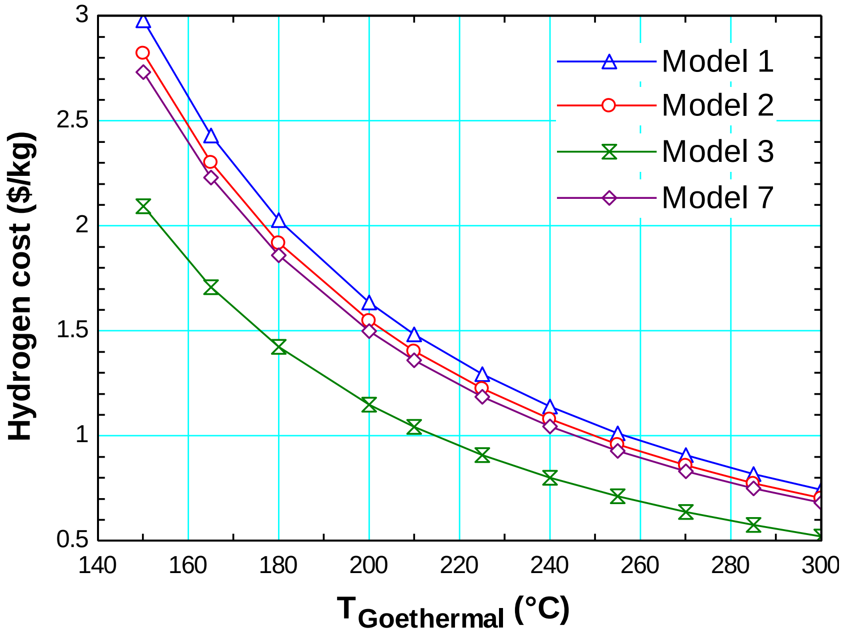


Figure 4.2 Variation of hydrogen production cost depending on the temperature change of the geothermal water in ideal condition.

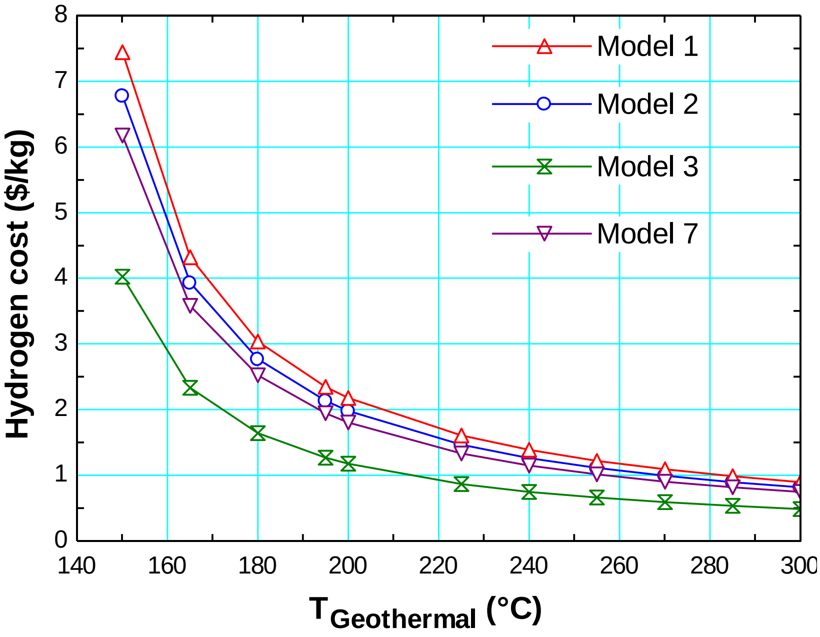


Figure 4.3 Variation of hydrogen production cost depending on the temperature change of the geothermal water in non-ideal condition.

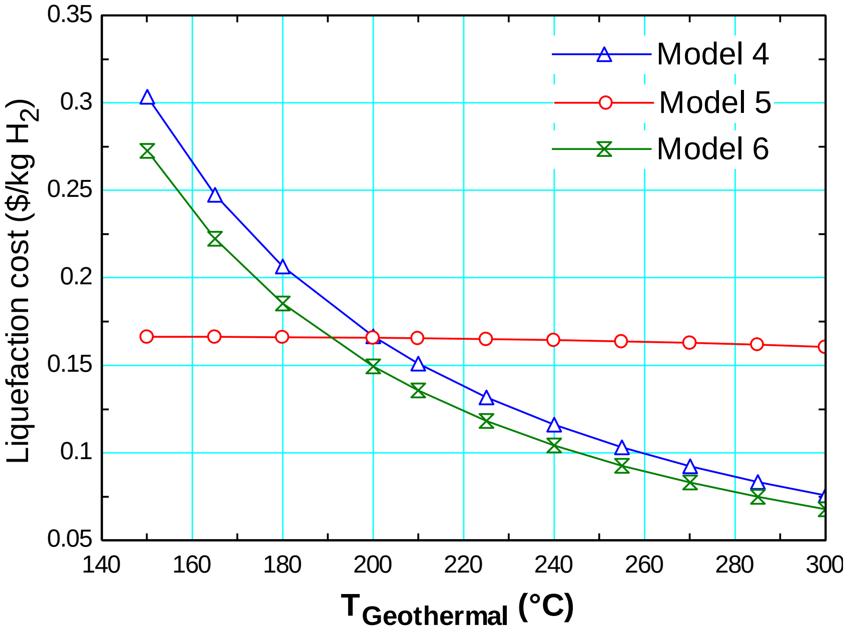


Figure 4.4 Variation of hydrogen liquefaction cost depending on the temperature change of the geothermal water in ideal condition.

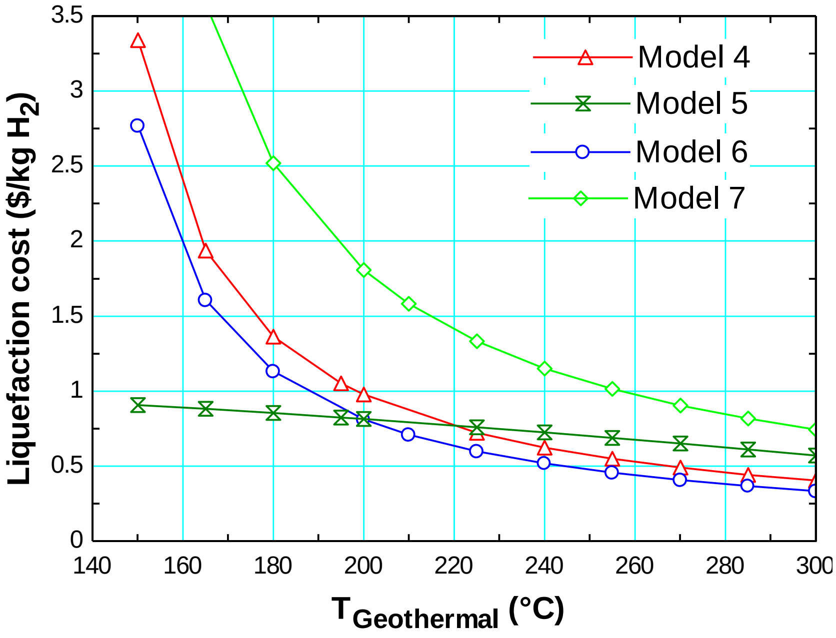


Figure 4.5 Variation of hydrogen liquefaction cost depending on the temperature change of the geothermal water in non-ideal condition.

### 4.4 Total Cost Analysis

In this section, we present a total cost analysis of the seven models considered. Total cost includes capital cost, operating and maintenance cost, and electrical cost. The models considered in this study involve the installations of a geothermal power plant, electrolysis or high-temperature electrolysis units, an absorption refrigeration system, a hydrogen liquefaction plant, and heat exchangers. The costs for these installations vary according to the system type and size, and with the location.

#### 4.4.1 Unit Cost Analysis of Geothermal Power Plant

The costs associated with building and operating geothermal power plant vary widely and depend on such factors; Resource types (steam or hot water), resource temperature, reservoir productivity, power plant size (rating), power plant type (single-flash, binary, etc.), environmental regulations, cost of capital, cost of labor. On the most basic level, an operational geothermal power plant consists of a geothermal resource well, power generation equipment, and an injection well.

Hot geothermal fluid is pumped up from the production well and processed for energy conversion and expanded through a turbine, thereby powering an electric generator. The utilized geo-fluid is then re-injection into the geothermal reservoir [89].

As one would anticipate, the economic viability of a geothermal development is clearly related to the reservoir temperature, higher temperatures resulting in lower capital costs and decreased hot water consumption

Unit cost expresses the cost of long-term analysis of power plant. Unit cost analysis, investment and operating costs are combined taking into account the time value of money. In this study, expressed spent will be produced per unit cost of 1 kWh in cents. Using the U.S. dollar as a currency, the energy market, electricity prices, the initial investment and input costs due to the calculation of the currency. Unit cost also allows comparisons ($/kWh) of different technologies (natural gas, coal, nuclear, wind, etc...) costs.

Geothermal power plants, as the other manufacturers of base-load (coal, nuclear) plants, have high initial cost of investments. Geothermal power plant of operating costs is very low, because the no need for any fuel. As an example, the unit cost of natural gas create the most important part of combined power plants, the initial investment cost is relatively lower than the cost of fuel.

All power generation plants as well as the cost of geothermal power plants consist of two main parts. These are investment and operation costs. Investment cost of the most important assumption that the conversion of the unit cost is financing structure of the investment. Unit cost analysis, accounts and financial structure are shown in Table 4.2. Geothermal power plant investments examined in four stages [90].

**1. Exploration:** At this stage, if any the existence of geothermal reservoir, properties is examined in the field. In this stage, the field ends with the opening of the first commercial geothermal wells.

**2. Confirmation:** At this stage, well drillings will continue producing in the field. This stage ends with the project to confirm the capacity of 25%. To give an example of a 20 MW production stage of the project confirmed the need to carry out the 5 MW production wells. This stage is not necessary for all the geothermal projects. But some financial institutions are looking to credit, as a condition of this stage of the project especially in projects seeking external funding. The calculation of the cost of geothermal expenditures made up to this stage assumed to be capital investment.

**3. Building:** At this stage, the construction of the plant is completed.

**4. Operation:** Operation of the plant is started.

In our country, recently commissioned study of geothermal power plants considering the standard 20 MW capable binary geothermal power plant project is intended to be power plant. Table 4.3 shows the investment cost items. As you can see wells and power plant investment costs is about 70% of the total investment cost. The costs should not be typed in the Table 3.3 the calculations shown in detail, as a single parameter and the total investment cost of operations will be included in the calculations. Another point to note that the expenses of the plant presented in the table per night (overnight) is that the cost reflects. During the construction of interest expense value of (Interest During Construction - IDC) 10-15%, operation stage of the following depending on the length of time up to of costs, should be added from exploration stage to operation stage. This value of 10% will be considered as the initial investment cost in the study.

Table 4.2 Geothermal power generation plant investment cost items.

| **Financial costs** | **Rate (%)** |
|---|---|
| Plant Procurement Package | 55.3 |
| Project Expenses | 0.7 |
| Drilling and Testing Expenses | 15.0 |
| Construction and Infrastructure Costs | 1.8 |
| Mechanical fabrication and assembly costs | 6.8 |
| Electrical & Automation in manufacturing & Installation Costs | 4.9 |
| Material Supplies | 4.7 |
| Land Costs | 1.9 |
| Investment Period of administrative and personnel expenses | 3.8 |
| Other Expenses | 5.1 |
| **Total** | **100** |

The investment cost of geothermal power plants depends considerably on site, depth and characteristics of the geothermal resources. A value of $4000/kWe (US$ 2008) may represent an average indicative cost, with considerable variations. Assuming an average annual operation and maintenance (O&M) cost of 3.5% of the investment cost (approximately $140/kWe per year), the resulting generation cost is approximately $90/MWh. For geothermal based combined heat and power plants, the investment cost is higher (typically, $10,000/kWe), the O&M costs are around $250/kWe per year, and the generation cost may reach approximately $200/MWh. For geothermal heating systems, an average investment cost is estimated at $1800/kWh, and the O&M costs at $35/kWh. The heat generation cost is approximately $45/MWh. However, depending on world energy markets, input prices of power plant investment costs increased by approximately 30-50% for the last two years.

According to the research literature that expresses the change in the capacity of power plant investment costs are expressed in the following empirical equation [91]:

$$CC = 2500e^{-0.0025(P-5)} \tag{4.8}$$

where, CC is the cost of capital cost, P is refers to the capacity of the power plant. Equation 4.8 taking into account the range of 5-155 MW of power plant capacity to change according to the capital investment cost is observed in Figure 4.6. The capital cost decreases with the plant size.

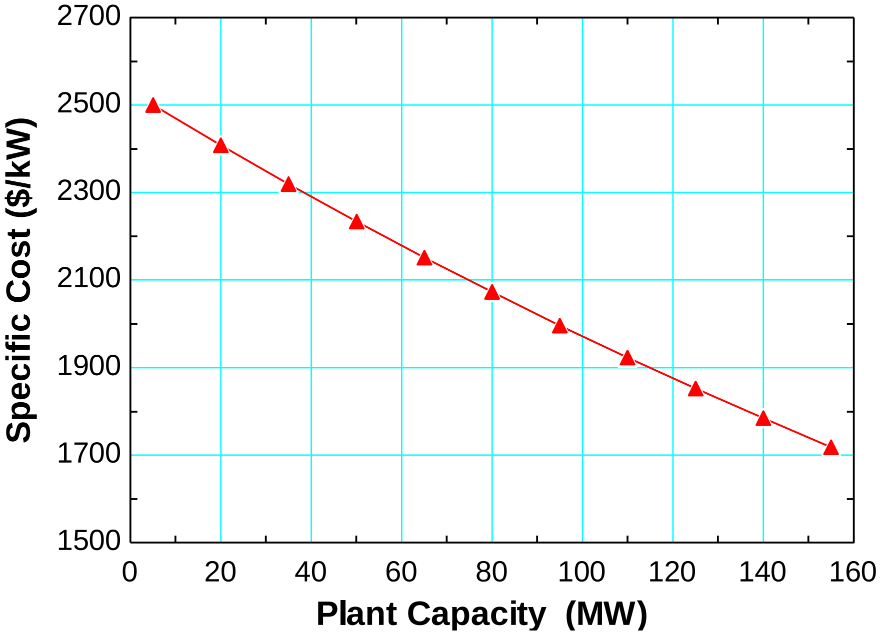


Figure 4.6 Power plant capacities to change according to the investment cost.

In our study, was taken as reference temperature 200°C and 346 kg/s flow rate in a working capacity of 20 MW binary geothermal power plants. For a binary geothermal power plant the average capital cost can be taken as 2700 $/kW [91]. For the analysis of the models considered in this study, we consider a 20 MW power plant. Then, the capital cost of geothermal power plant becomes $54 millions. The following financial structure is considered to determine the net value of the capital cost:

Table 4.3 Financing structure of the study predicted.

| **Financing structure** | **Quantity** |
|---|---|
| Life period (Years) | 20 |
| Debt ratio | %50 |
| Internal investment ratio | %50 |
| Debt interest rate | %8 |
| Debt period (years) | 15 |
| Monthly interest rate | %2.75 |
| Total Tax Rate | %20 |
| Internal profit rate | %15 |

Using the table 4.3 values with the Discounted Cash Flow method, the net value of the capital cost is determined to be $34 millions.

Investment rate of repayment has been calculated, the second stage to convert the unit cost of investment repayments. In our project we consider a 20 MW binary power plant that has investment costs 2400 $/kW, the amount of investment into the unit cost shown in the following calculations.

Plant capacity : 20 MW

Total investment cost : 20 MW×2408 $/kW = 48160000 $

Annual investment refund : %12.4×54,000,000 $ = 5779200 $

Annual plant capacity factor : % 95

Annual total production : 20,000×365×24×95% = 166440000 kWh

Unit cost of investment :100×6,696,000/148,920,000kWh=3.580 ¢/kWh

As a result, the initial investment amount of the unit of study, the our selected model of geothermal project unit cost is calculated to be 3.580 ¢/kWh. Geothermal projects are mainly the high initial investment costs and operating costs are low, we consider this amount (3.58 ¢/kWh), the unit cost can be said of the majority.

Operating costs should be taken into account other types of expenditure in unit cost analysis. In Table 4.4 are summarized in the geothermal power plant operating expense items. Depending on the location and establishment of the plant cooling system water can be up to 50% of the share of total expenditures. Traditionally, the operating costs of power plants divided into two groups of fixed expenses ($/kW-year) and variable costs (¢/kWh). Fixed costs are independent of the plant and production capacity per unit is calculated as an annual payment. This distinction is particularly evident in company of energy and capacity pricing as a separate. Geothermal power plants operating costs are collected in a single part ¢/kWh, as indicated in the literature. Geothermal power plant operating costs is estimated to 1-3 ¢/kWh in the literature. This cost is estimated around to be 1.2 ¢/kWh in our country. Drilling during the operation is included in these costs.

Table 4.4 Geothermal power plant operating costs

| **Plant costs** | **Rate (%)** |
|---|---|
| Fixed costs (rent, insurance, etc.). | 40 |
| Maintains costs | 20 |
| Personnel and administrative costs | 22 |
| Water costs | 2 |
| Fuel costs | 2 |
| Other costs | 14 |
| **Total** | **100** |

We can be calculated of unit total costs of electricity of geothermal to be 4.780 ¢/kWh (3.58+ 1.5) with contribute the operations and investment costs.

### 4.4.2 Economic Analysis of Electrolysis System

Electrolysis of water to the normal pressure and temperature voltage is ideally 1.23 V (volts). The reaction is slow, or for other reasons, higher voltages used in the process of electrolysis. Hydrogen production rate, is proportional to the actual current intensity, high current density is desirable for economic reasons. Therefore, in practice, applied voltage per cell for decomposition of water usually is about 2 Volts [92].

Hydrogen and electricity energy are easily converted to each other, either directly or indirectly influences all sectors, social development and welfare in terms of being decisive is a very critical position.

Most developed countries, as well as the hydrogen economy of many countries in transition are determined in accordance with the policies, national plans and programs preparation, development and adaptation of relevant technologies for the wide-ranging and extensive research done, the legal regulations and standards prepared. Hydrogen is traditionally produced by hydrocarbons and water [93].

We have used our model of electrolysis are simple alkaline and high temperature steam electrolysis methods. Separately in their own economic analysis of these methods is given below.

#### *Economic Analysis of Simple Alkali Electrolysis*

We consider a simple alkaline electrolyzer unit for hydrogen production. Total cost of electrolyzer unit consist of capital costs (55%), electricity cost (35%) and operating and maintenance cost (10%) [94].

The cost of hydrogen production may change between 2.16 and 6.75 \$/kg $H_2$ depending on the capacity and the unit cost of electricity. Hydrogen production systems are classified as small capacity (about 20 kg/day), medium capacity (about 100 kg/day), and large capacity (about 1000 kg/day) [95].In Models 1, 2 and 7, the hydrogen production capacity is 11,016 kg $H_2$/day for a 20 MW geothermal power plant.

The minimum electricity required to produce 1 kg hydrogen may be calculated from Gibbs energy to be 32.68 kWh. For an electrolyzer efficiency of 75%, the actual electricity requirement becomes 43.6 kWh. Then, the electricity cost may be expressed as [96]

$$E_{\mathrm{C}} = 43.6 C_{\mathrm{electricity}} \tag{4.9}$$

For an average electricity cost of 0.05 \$/kWh, the electricity cost of hydrogen production becomes 2.615 \$/kg $H_2$. In Model 1, the rate of hydrogen production was determined to be 0.128 kg $H_2$/s. Then, the annual electricity cost of hydrogen production becomes

$$(0.128 \text{ kg H}_2\text{/s})(365\times24\times3600 \text{ s})(2.615 \text{ \$/kg H}_2) = \$10{,}555{,}700 \text{ or } \$10.56 \text{ million}$$

The operating and maintenance cost may be expressed as [96]

$$M_{\mathrm{O\&M}} = 0.41H^{-0.23} \tag{4.10}$$

where, $H$ is the production capacity (in kg $H_2$/s). In Model 1, the production rate is 0.128 kg $H_2$/s and thus the operating and maintenance cost is 0.65 \$/kg $H_2$. Taking discount rate 10%, construction time 1 year, plant life 40 years and production capacity rate 95%, the cost of hydrogen for the capital cost may be calculated from [96]

$$I_{\mathrm{C}} = 0.5H^{-0.025} \tag{4.11}$$

Combining Eq. 4.9,10, and 11the cost of hydrogen production is expressed as

$$C_{\mathrm{H2,total}} = E_{\mathrm{C}} + M_{\mathrm{O\&M}} + I_{\mathrm{C}} = 43.6C_{\mathrm{electricity}} + 0.41H^{-0.23} + 0.5H^{-0.025} \tag{4.12}$$

In Model 1, the rate of hydrogen production is 0.128 kg $H_2$/s, and therefore the unit cost of hydrogen is 3.8 \$/kg $H_2$. The corresponding annual cost is 14.209.445 \$/year

***High-temperature electrolyzer unit***

For the economics of high-temperature electrolysis, we consider the Hot Elly process. In this process, the electricity requirement for high-temperature electrolysis is 46% less than that in ordinary electrolysis [97]. In Model 3, 0.217 kg $H_2$ (20,000 kJ/s ×91,858 kJ/kg $H_2$ = 0.217 kg $H_2$/s) is produced per second for a 20 MW power plant. For a 93% operation capacity, the annual production is 6,385,633 kg H2/year. From Eq. 4.12, the unit cost of hydrogen is determined to be 2.6 \$/kg $H_2$. The corresponding annual cost is 16,845,970 \$/year.

The electricity consumption for this process was determined to be 23.57 kWh/$H_2$. For a unit electricity cost of 0.05 \$/kWh, the cost of hydrogen production is 1.412 \$/kg H2. For an annual hydrogen production of 6,522,959 kg $H_2$/year, the annual electricity cost becomes 9,210,418 \$/year. For a production rate of 0.217 kg $H_2$/s, the operating and maintenance cost is determined from Eq. 4.10 to be 0.582 \$/kg $H_2$. The annual cost is 3,800,518 \$/year and the initial cost of a high-temperature electrolysis unit with a 20 MW electricity input is estimated as 23,614,000 \$ [98].

### 4.4.3 Economics of Linde-Hampson Liquefaction Plant

We used the in our model of a Joule-Thompson expansion valve with liquid nitrogen pre-cooled Linde-Hampson liquefaction cycle (Figure 4.7).

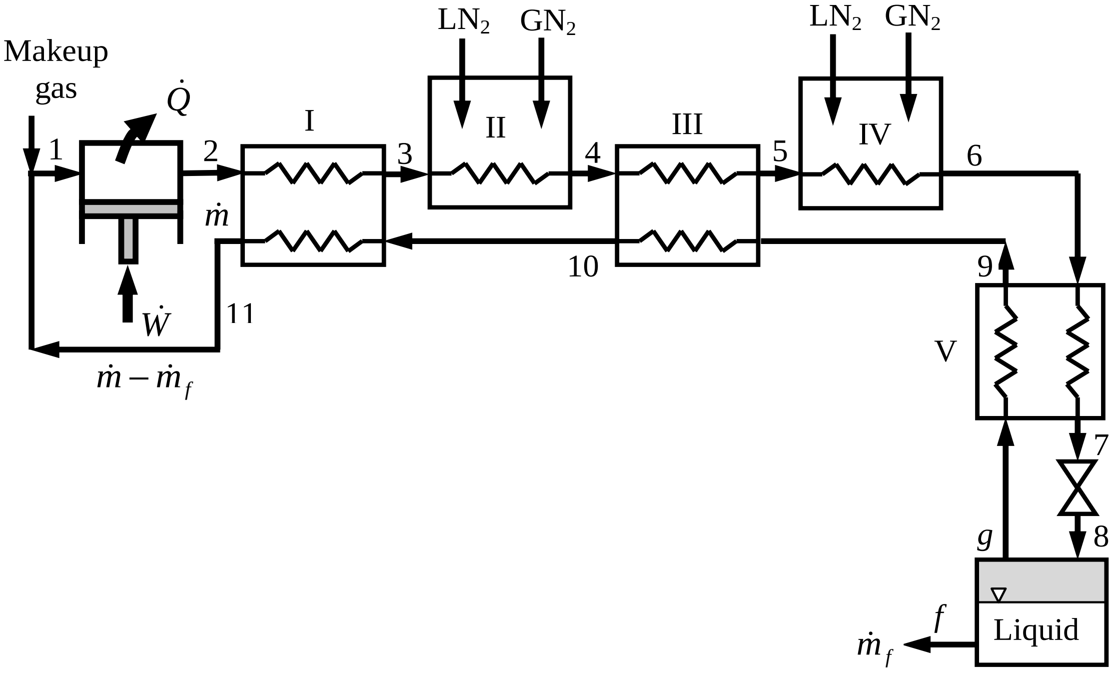


Figure 4.7 Precooled Linde-Hampson liquefaction cycle. C: compressor, EV: Expansion valve, I, II, III, IV, and V: Heat exchangers, $LN_2$: Liquid nitrogen, $LN_2$: Gasified nitrogen, *f*: liquid, *g*: gas, $\dot{m}_f$ : mass flow rate of liquid withdrawn from the system, $\dot{m}$: total mass flow rate of hydrogen.

Liquefaction plants analyzed in three stages in total cost analysis in here. These are: electricity and power costs, operating and maintenance costs and the plant initial investment costs. The cost of a liquefaction plant depends on liquefaction capacity, type of unit, and installation area among others.

***Liquefaction plant electrical cost analysis***

In Model 4, the work requirement for hydrogen liquefaction is 70,155 kJ/kg $H_2$ or 19.5 kWh/kg $H_2$, and the electricity cost is 1.167 $/kg $H_2$. For a 20 MW power output from the plant with a 95% annual capacity, the cost of hydrogen liquefaction is calculated as 9,964,280 $/year.  Liquefied hydrogen flow rate was calculated to be 0.285 kg/s, respectively.

***Operating and maintenance cost of liquefaction plants***

Veziroglu's findings with reference to our analysis in this section, the following formula will be used to determine an average cost of operation and maintenance [99].

The operating and maintenance cost of liquefaction plants may be determined from

$$C_{\mathrm{O\&M}} = 3.31\left(\frac{P}{110{,}372}\right)^{0.65}\left(\frac{301.88}{\dot{m}}\right) \tag{4.13}$$

where $P$ is the power input to the unit (in kW) and $\dot{m}$ is the hydrogen liquefaction rate (in kg/h). The result of Eq. 4.13 is 0.303 $/kg and the corresponding annual cost is 2,587,127 $/year.

***The capital cost of a hydrogen liquefaction plant***

The capital cost of a hydrogen liquefaction plant with a 16 million kg/year capacity is given as $137 millions [100]. Using this value, the corresponding cost for the liquefaction unit considered in our models becomes $71,973,000.

***Total cost of liquefaction system***

Total cost according to the parameters for the total cost of the net can calculate as follows.

$$C_{\mathrm{Toplam}} = C_{\mathrm{Elektrik}} + C_{\mathrm{O\&M}} + C_{\mathrm{Kapital}} \tag{4.14}$$

In equation, as the cost of electricity is calculate to be $8,292,207.751, operating and maintenance cost is calculate to be $2,739,789.5 and the initial investment cost is calculate to be $71,973,000 as the price of the capital had been found. The total cost is $ 83,004,997.27 in this equation. Of course, should be noted that one-time cost of the initial investment. This value represents the total cost of initial installation.

### 4.4.4 Economic Analysis of Absorption Refrigeration System

Working fluids used in mechanical vapor compression refrigeration and air conditioning systems, and today the harmful affects of ozone layer due to the bottleneck in the energy, alternative systems, and absorption systems has gained a great importance in particular. Today, technological developments made economic and efficient alternative of absorption cooling against to vapor compression refrigeration cycle [101]. Does not destroy the ozone layer of fluid pairs used in the absorption systems, also the energy input of solar energy, waste heat, geothermal energy resources, such as the use of this system has brought a more advantageous position [102].

Absorption refrigeration is economic when there is a source of inexpensive thermal energy at a temperature of 100 to 200°C. Some examples include geothermal energy, solar energy, and waste heat from cogeneration or process steam plants, and even natural gas when it is at a relatively low price (Figure 4.8).

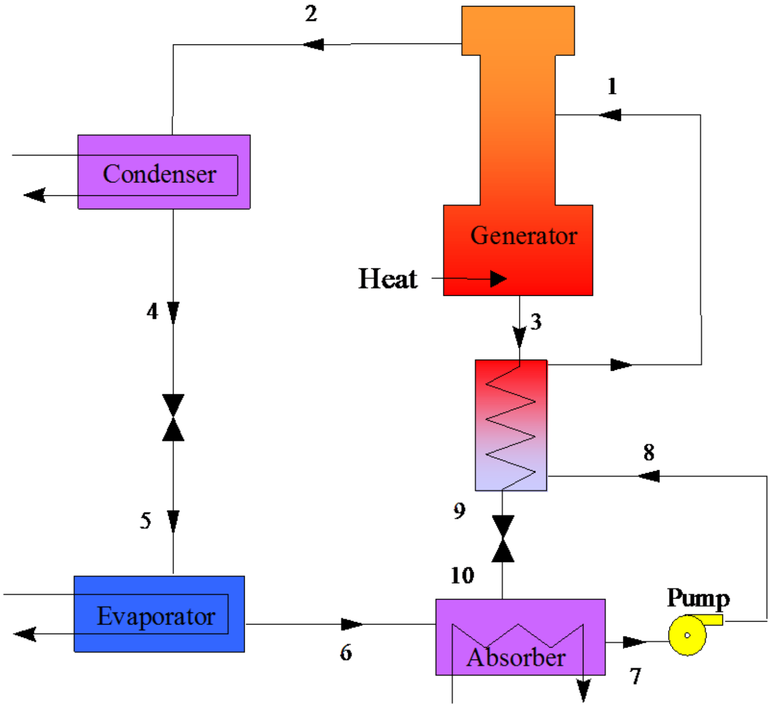


Figure 4.8 A schematic representation of the absorption cooling system.

Absorption cooling system can produce a higher cooling capacity than vapor-compression system; also it can be operated with other sources of energy instead of electricity. In this system, generating heat energy is used instead of mechanical energy [103]. In the absorption system fluid is compressed instead of steam. Operation of these systems is based on the external heat source is provided. Work is provided in the order of one percent of the heat in the heater, it is often neglected in the thermodynamic cycle analysis. The absorption system is running with heat energy conversion [78].

In Models 5 and 6, hydrogen is cooled by an absorption system before the liquefaction process. The following relation is proposed for the total cost of an absorption unit [104].

$$C_{\mathrm{ARS}} = CC + R_{\mathrm{O\&M}} \frac{(1+i)^n - 1}{i(1+i)^n} - JV \frac{1}{(1+i)^n} \tag{4.15}$$

where, *CC* is capital cost, $R_{O\&M}$ is the operating and maintenance cost, *JV* is the junk value, *i* is the interest rate, and *n* is the life of the unit. Considering the cooling rate of the absorption system, the following values are obtained: $CC$ = \$94,391, $R_{O\&M}$ = \$10,287, $JV$ = \$9439, $i$ = 0.02, $n$ = 20 years. Then, the total cost becomes 256,246 \$.

### 4.4.5 Result of Total Cost Analysis of Models

In this section, each of model evaluated according to their own in the economic analysis of the data obtained. Within the scope of their existing systems for each model and their total economic costs are considered.

**Model 1**

Model 1 is a 20 MW geothermal power plant and the annual hydrogen production capacity with 95% work intensity is 3,819,743 kg/year, which is an alkali electrolysis plant. The first year of the installation cost of a geothermal power plant was calculated as the total annual cost of \$34 million. The total annual cost of the electrolysis process, capital cost was calculated to be \$14,676,694.14. Electricity costs calculated to be 9,988,627.945 \$/year, and operating and maintenance costs calculated to be 2,482,833 \$/year, respectively. The total cost, including installation costs of the whole system from equations 4.14 is calculated to be \$61,148,155 for the first year.

**Model 2**

Previously, calculated as 20 MW geothermal power plant cost is 34 million dollars a year, electrolysis plant is the first installation cost \$14.6 million, respectively. Electrolysis temperature of 85°C and the ratio of production cost arising from the fact that there are a little cost differences. Total annual production of hydrogen is calculated as 4,194,585.816 kg/year. Accordingly, the electrical cost is calculated to be 9983114.241 \$/year. Operation and maintenance costs is calculated 2,703,108.589 \$/year in the equation. Model 2, the annual total cost, including initial investments is calculated 61,2862,23.41 in dollars.

**Model 3**

High temperature steam electrolysis of water to support 20 MW geothermal power plant of electricity input from outside a plant. Hydrogen production capacity was calculated to be 6,522,958.881 kg/year with annual operating density of 95%. The cost of initial investment Hot Elly system by reference to production capacity for a system this production capacity that was calculated to be $2,3614,143. Electrical cost is calculated to be 9986650 $/year. Operation and maintenance costs is calculated to be 432298.833 $/year. The plant, including the initial investment costs, the total cost is calculated to be $34,033,091.83 form equation 4.14 for the first year.

**Model 4**

In this model, with the liquefaction cycle cost and geothermal power plant cost are contributing the total cost of plant. The plant has 8,540,859.525 kg/years of liquefaction capacity capital cost was calculated 71994051.66 $. Electrical cost was calculated 9992805.644 $/years. Operation and maintenance costs was calculated to be 2,587,880.436 $/years. These data show that the liquefaction system, total investment costs is calculated to be $118,574,737.7 from equation 4.14 for the first year.

**Model 5**

Cooling capacity of geothermal water is 0.07076 kg $H_2$/kg some references to the literature by using the cost of this system, was calculated approximately to be $ 256,246. Liquefaction cycle as the initial investment cost was $ 71,994,051.66. Annual production capacity of 1, 020, 0091.93 kg/year in this system electrical costs is calculated 9,985,889.9 $/year. Operation and maintenance cost of liquefaction from equation 4.13 is calculated to be $ 0,268 for the unit as a mass, and a total cost is calculated 2743444,681 $/year. Total cost of system with initial investment costs is 84979632.24 $ from equation 4.14 for model 5.

**Model 6**

Absorption cooling system total cost was calculated to be $ 256,246. Liquefaction cycle a set-up cost was taken as $ 71 million. Geothermal power plant total cost was calculated by taking the $ 34 million. The annual electrical cost of liquefaction system is calculated to be $ 8489305,375 for production capacity 8653726.17 kg/year. Operation and maintenance costs were calculated to be $ 2472316,124 from the equation 4.13. The total cost of model 6 with the initial investment costs of systems is calculated to be 115961621.5$.

**Model 7**

Geothermal power plant total cost was calculated 34$ million per year. Liquefaction system initial investment cost was $71 million relatively. Operation and maintenance cost of system for annual production capacity of 2580236.454 kg/year is calculated to be 1318611.777 $/year from equation 4.13.eloectrolysis system investment cost is the same as model 1, mean is 14$ million. Operation and maintenance cost was found to be 1859484.826 $/year, the cost of the electrical system was found to be 5593952.641 $/year, respectively. So, the total cost of this system is calculated to be 1290532216.2$ with the initial costs of system equipments.

### 4.5 Result and Discussion of Total Economic Analysis of Models

Geothermal energy supported for hydrogen production and liquefaction models of the simple and detailed economic analysis based on the results, respectively, are listed in Table 4.5 and Table 4.6. Hydrogen production and liquefaction of the amounts necessary for the unit cost of electricity for the ideal and actual systems are given in Table 4.1. The models studied by examining the total annual costs of all cost parameters are given in Table 4.6.

The results of the cost analysis for all seven models are obtained based on the analysis above and are listed in Table 1. It appears that the models involving hydrogen liquefaction (models 4, 5, 6, and 7) cost more than the models involving hydrogen production (models 1, 2, and 3). This is due to higher capital cost of liquefaction units. The operating and maintenance cost is higher in model 3 compared to other models due to the use of high-temperature electrolysis unit. Electrical costs are close to each other for the first five models while it is somewhat less in model 6 and considerably less in model 7.

Hydrogen liquefaction systems examined, the total annual cost figures is higher than the cost of hydrogen production systems at Table 4.6. Model 3, the annual cost of hydrogen production (37.6 million $ / year), Model 1 ($ 61.1 million / year) and Model 2 (61.6 million $ / year) is significantly lower than those. Hydrogen sıvılaştırması Model 5, the annual cost ($ 84.9 million / year), the Model 4 ($ 118.6 million / year) and Model 6 ($ 116.0 million / year) is significantly lower than those. Hydrogen produced and liquefied of the Model 7 cost is the highest annual costs represents 130.0 million $/year in the table. The reason for this is that, the number of the system of the Model 7 is more than other models.

Table 4.5 Hydrogen production and liquefaction unit costs are given for ideal and actual operations by geothermal energy.

| **Model** | **Electricity (ideal) (kWh/kg $H_2$)** | **Electricity (actual) (kWh/kg $H_2$)** | **Cost (ideal) ($/kg $H_2$)** | **Cost (actual) ($/kg $H_2$)** |
|---|---|---|---|---|
| 1 | 32.680 | 43.570 | 1.634 | 2.179 |
| 2 | 30.950 | 39.680 | 1.548 | 1.984 |
| 3 | 22.960 | 25.511 | 1.148 | 1.275 |
| 4 | 3.327 | 19.550 | 0.166 | 0.974 |
| 5 | 3.314 | 16.280 | 0.165 | 0.813 |
| 6 | 3.314 | 16.110 | 0.165 | 0.793 |
| 7 | 29.970 | 36.130 | 1.499 | 1.808 |

Table 4.6 Cost analysis of models used for hydrogen production and liquefaction by geothermal energy**.**

| **Model** | **Capital cost (million $)** | **Electrical cost (million $/year)** | **Operating and maintenance cost (million $/year)** |
|---|---|---|---|
| 1 | 48.67 | 9.99 | 2.5 |
| 2 | 48.90 | 9.98 | 2.7 |
| 3 | 23.6 | 9.21 | 3.80 |
| 4 | 106 | 9.99 | 2.5 |
| 5 | 72.25 | 9.985 | 2.74 |
| 6 | 106.25 | 8.43 | 2.47 |
| 7 | 120 | 5.6 | 3.17 |

The results show that at a geothermal water temperature of 200°C, the cost of hydrogen production and liquefaction ranges between 0.979 \$/kg H2 and 2.615 \$/kg H2 depending on the model considered. Case 2 performs better than case 1 because we are able to use the waste geothermal water for preheating of water for electrolysis. This waste water that is at a relatively high temperature is reinjected back to the ground in case 1. Case 3 performs better than case 2 because of the advantages associated with the high temperature electrolysis. Providing a considerable amount of energy demand in the form of heat decreases the electricity demand. This, in turn, decreases the total energy demand in the process.

The analyses of the liquefaction processes in cases 4, 5, and 6 indicate that geothermal absorption cooling for pre-cooling of hydrogen gas yields significant savings in the work requirement for hydrogen liquefaction, and is more advantageous than using geothermal work output alone in the liquefaction cycle. Case 7 allows both the production and liquefaction of hydrogen at the same site by the same resource. This also means that the storage of hydrogen is automatically taken care of on the production site. This may be advantages for remote geothermal resources where the transportation of geothermal water to the residential and commercial sites for heating/cooling purposes is not feasible for thermodynamic and economic reasons. The total cost analysis of the seven models reveal that the models involving hydrogen liquefaction (models 4, 5, 6, and 7) cost more than those involving hydrogen production (models 1, 2, and 3) due to the higher capital cost of the liquefaction units. Also, the greater number of installations, the greater the capital and operating and maintenance costs.

# CHAPTER 5

# APPLICATION TO TURKISH GEOTHERMAL SOURCES

## 5.1 Introduction

Geothermal energy and the other renewable energy sources are becoming attractive solutions for clean and sustainable energy needs of Turkey. Geothermal energy is being used for electricity production and it has direct usage in Turkey, which is among the first five countries in the world for the geothermal direct usage applications. Although, Turkey is the second country to have the highest geothermal energy potential in Europe, the electricity production from geothermal energy is quite low. The main purpose of this study is to investigate the status of the geothermal energy for the electricity generation in Turkey. Currently, there is one geothermal power plant with an installed capacity of 20.4MWe already operating in the Denizli-Kizildere geothermal field and another is under the construction in the Aydin-Germencik field [105].

This study examines the potential and utilization of the existing geothermal energy resources for production of electricity in Turkey region. Therefore, the possibility of electrical energy generation by a binary cycle has been researched and the preliminary feasibility studies have been conducted in the field. For the environmental reasons, the working fluid used in this binary power plant has been chosen as isobutane as the same as our project application of this geothermal electricity potential areas.

Also, energy crises in the world, renewable energy resources appear to be a potential solution to energy and environmental problems and a key tool for sustainable development in the world. Geothermal energy, by nature, has high availability because the source is not dependent on weather conditions, so it is among the most stable renewable energy sources. Among the renewable energy sources, the geothermal energy offers a good potential for producing electrical power with a high energy level in the short and medium terms. Also, geothermal energy systems are simple, safe, and adaptable with modular 1-50MW plants capable of providing continuous base-load, load following, or peaking capacity and benign environmental attributes (negligible emissions of CO2, SO2, NOx, and particulates) [106].

## 5.2 Electricity Generation by Geothermal Resources in Turkey

The most stable renewable energy source is geothermal energy. Therefore, the geothermal power plants are designed to operate 24h a day, and the operation is independent of the weather or fuel delivery [106]. The geothermal energy source that can be easily converted into electrical power is generally considered renewable, because reservoirs may be recharged by rain or by re-injection of the wastewater. Optimum utilization of a geothermal energy source, from an economical and thermodynamically point of view is strongly dependent on the characteristics of the geothermal fluid. Particularly, temperature, pressure, composition, and liquid to vapor ratio are important in determining the best method and conditions for the energy conversion [107].

Turkey has been one of the fastest growing power markets in the world with its young and growing population, rapid urbanization, strong economic growth and low per-capita electricity consumption for two decades. Although almost all kinds of energy resources exist in Turkey, the resources other than the lignite and hydropower have not been used to meet the energy need of the country, and thus, more than half of the energy supply is provided by the importation [108]. The geothermal, hydropower, solar, wind, and biomass energies are the major resources to provide Turkey’s energy needs in the future. Geothermal resources represent an important renewable energy source for Turkey, where the water and steam dominated geothermal fields exist and have been exploited for decades. Provided that the geothermal energy, which has a considerable potential in Turkey, is used for the electrical generation besides its usage for heating and greenhouses, the energy problem in Turkey will be remarkably solved. The recent developments have proven that the most important field of the geothermal energy usage in the future will focus on the electrical energy production.

Presently, nine geothermal fields in Turkey have a high enthalpy and have the necessary conditions for generating electricity in a binary cycle or flash plants. Conventional electrical power production is limited to fluid temperatures above 150 °C, but considerably lower temperatures can be used in binary cycle systems, also called organic Rankine cycles. In this cycle, the outlet temperatures of the geothermal fluid are commonly above 85 °C [109]. Fig. 5.1 illustrates nine geothermal fields of Turkey are suitable for generating electricity together with their possible utilization opportunities. High temperature geothermal fields suitable for conventional electricity generation are as follows: Denizli–Kizildere (242°C), Aydin–Germencik (232°C), Canakkale–Tuzla (173°C), Aydin–Salavatli (171°C), Aydin–Yilmazkoy (165°C), Kutahya–Simav (162°C), Manisa–Salihli (155°C), Izmir Seferihisar (153°C), and Izmir–Balcova (126°C) [110]. These fields may be evaluated if the government offers the financial and/or institutional support that is required for successful development.

Figure 5.1 General tectonic and volcanic features and important geothermal fields of Turkey.

The three most important geothermal areas of West Anatolia, namely Denizli–Kizildere, Aydin–Germencik, and Kutahya–Simav, are characterized by Na–SO4, Na–HCO3, and Na–Cl–HCO3, and enrichment, respectively. The chemical composition of the resource of pollution is discharged into the environment. In this way, geothermal fluids should be re-injected into the reservoir [111].

Renewable energy sources such as geothermal energy, biomass energy, solar energy, wind power and hydropower are the major resources available in Turkey. Although the geothermal industry is highly developed in Turkey, excellent geothermal sources still remain undeveloped since cost for a new natural gas plant is just half of a new geothermal plant [112].

Turkey has an important place among the richest countries (the first in Europe, seventh in the world) in geothermal potential. Around 1000 hot and mineralized natural self flowing springs exist in Turkey. The geothermal resources in Turkey can be classified into three groups: low temperature fields (<70°C), moderate temperature fields (70–150°C), and high temperature fields (more than 170°C). Although they exist all over the country, most of them lie in the Western, North-Western, and Middle Anatolia. The temperature limit is accepted to be 20°C for balneological purposes. With the exception this, there are 170 geothermal fields with a temperature over 35°C in Turkey. Aydın-Germencik (232°C), Denizli-Kızıldere (242°C), Çanakkale-Tuzla (173°C), and Aydın-Salavatlı (171°C) fields those are suitable for electricity generation. Depending on the use of new technologies, the Manisa-Salihli-Caferbeyli (155°C), Kütahya-Simav (162°C), Izmir-Seferihisar (153°C), Dikili (130°C), and Denizli-Gölemezli (under search) fields [113].

Turkey's geothermal power generation plants are:

1. Kızıldere-Denizli was commissioned in 1984, has 17.8 MWe capacity at maximum temperature 243°C

2. Dora-I Salavatlı-Aydın was commissioned in 2006, has 7.35 MWe capacity at maximum temperature 172°C

3. Bereket Energy-Denizli was commissioned in 2007, has 7.5 MWe capacity at maximum temperature 145°C

4. Gürmat-Germencik-Aydın was commissioned in 2009, has 47.4 MWe capacity at maximum temperature 232°C

5. Tuzla-Çanakkale was commissioned in 2009, has 7.5 MWe capacity at maximum temperature 171°C

6. Dora-II Salavatlı-Aydın was commissioned in 2010, has 9.7 MWe capacity at maximum temperature 174°C [112].

Geothermal resources of the country are wide spread but the favorable reserve for heating and generating electricity is limited and even this limited reserve has not yet been used. Parallel to the developments of the geothermal energy utilization in Turkey, it is planned that by the years 2010 and 2020, the total installed capacity will increase to 3500MWt (500,000 residence equivalent, which is about 30% of the total residences in the country) and 8300MWt (1,250,000 residence equivalent) for space heating, and to 500 and 1000MWe for electricity production, respectively, [113].

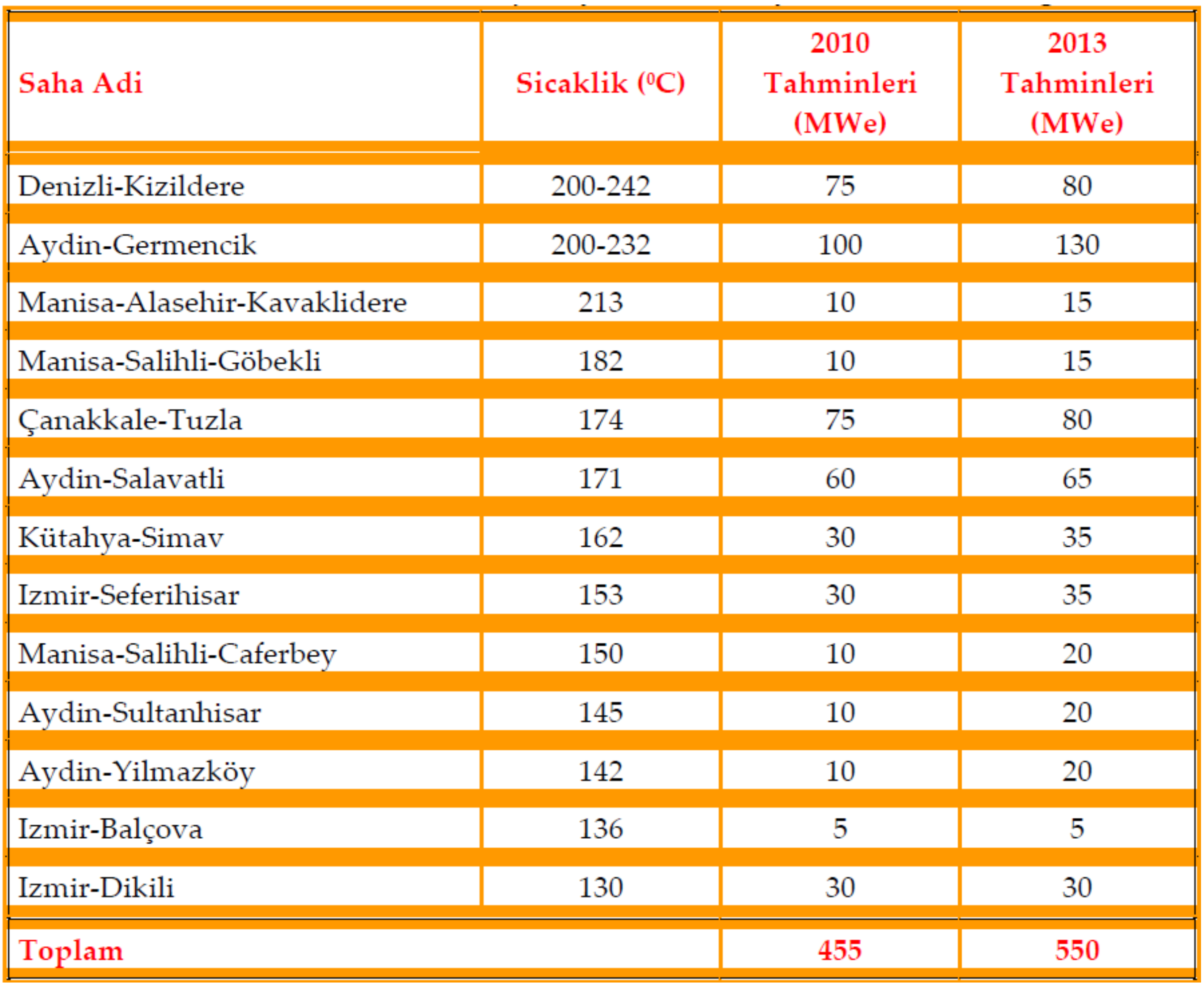
Turkey's geothermal electricity power production target of 2013 is predicted by 550 MWe (4.4 billion kWh/year). Turkey's total geothermal electricity power potential is estimated by 2,000 MWe (16 billion kWh/year) [114].

As a result of government and private sector research and forecasts, current status and future use of geothermal energy of geothermal power production estimates are also available in Table 5.1 and Table 5.2.

Table 5.1 Current status of the geothermal energy use in Turkey [115].

| **USING AREA** | **CAPACITY** |
|---|---|
| GEOTHERMAL CENTRAL HEATİNG<br>(City, housing, thermal plant, greenhouse, etc...) | **827 MWt**<br>103.000 residential equivalents. |
| THERMAL TOURISM (kaplıcalar) | **402 MWt**<br>215 Kaplıca ( 10 million person/year) |
| TOTAL USE OF HEAT | **1229 MWt**<br>900.000 ton/year in oil money 1 billion YTL/year |
| ELECTRICITY GENERATION | ▪ **20 Mwe** (Denizli – Kızıldere).<br>▪ **47,5 Mwe** (Aydın –Germencik)<br>▪ **7,35 Mwe** (Aydın – Salavatlı) Dora-I binary geothermal power plant<br>▪ **7,5 Mwe** (Denizli – Bereket Energy plant)<br>▪ **7,5 Mwe** (Çanakkale – Tuzla)<br>▪ **9,7 Mwe (**Salavatlı-Aydın) Dora-II. |
| CARBONDIOKSIT PRODUCTION | **120 000 ton/year** |

Table 5.2 Electricity production of projection in Turkey Geothermal resources (technical approach, the estimated power) [116].



| Saha Adi | Sicaklik ($^0$C) | 2010 Tahminleri (MWe) | 2013 Tahminleri (MWe) |
|---|---|---|---|
| Denizli-Kizildere | 200-242 | 75 | 80 |
| Aydin-Germencik | 200-232 | 100 | 130 |
| Manisa-Alasehir-Kavaklidere | 213 | 10 | 15 |
| Manisa-Salihli-Göbekli | 182 | 10 | 15 |
| Çanakkale-Tuzla | 174 | 75 | 80 |
| Aydin-Salavatli | 171 | 60 | 65 |
| Kütahya-Simav | 162 | 30 | 35 |
| Izmir-Seferihisar | 153 | 30 | 35 |
| Manisa-Salihli-Caferbey | 150 | 10 | 20 |
| Aydin-Sultanhisar | 145 | 10 | 20 |
| Aydin-Yilmazköy | 142 | 10 | 20 |
| Izmir-Balçova | 136 | 5 | 5 |
| Izmir-Dikili | 130 | 30 | 30 |
| **Toplam** | | **455** | **550** |

## 5.3 Economics of Geothermal Electricity Generation

The unit cost of electricity generated by geothermal energy is lower than other energy sources. This cost decreases even more when it comes to integrated systems. Unit cost of electricity production is, geothermal fluid temperature above 150°C and the 30 MW of geothermal power plants with a capacity 2.5 -5 ¢/kWh, with a capacity of medium-sized (5-30 MW) geothermal power plants 4.0-6.0 ¢/kWh and small capacity (5 MW small) for geothermal power plants 5.0-7.0 ¢/kWh is around [117].

According to various energy sources in electricity production unit costs are compared in Table 5.3.

Table 5.3 Unit cost of electricity according to the production source [117].

| **Resource** | **Unit cost (¢/kWh)** |
|---|---|
| Fuel-oil (Ambarlı Fuel-oil Santrali) | 9.80 |
| Natural gas (Ambarlı Doğalgaz) | 6.25 |
| Linyit (Seyitömer Termik Santrali) | 5.15 |
| Geothermal (Sarayköy Jeotermal) | 2.91 |

Geothermal electricity generation of the total investment cost is 40%, of to the research field of production and reinjection wells are 50%, of the power plant for the establishment and the remaining is 10% spent on other activities. Investment costs will be varies depending on the features of the type of geothermal power plant, the capacity of the plant and installed geothermal field. Geothermal fluid temperature for above 200°C and the large capacity of geothermal power plants (30-100 MW), unit investment cost is around 1150 to 1750 $/kW, for medium-sized with a capacity of geothermal power plants (5-30 MW) is around 1300 to 2100 $/kW, for small capacity geothermal power plants (5 MW minors) is around 1600 to 2300 $/kW [118].

### 5.4 Production and Liquefaction of Hydrogen Use Geothermal Resources in Turkey

This section can be detected of the 10 geothermal resources in Turkey for electricity production and the thermodynamic and economic analysis was performed. Binary cycle power plant used in this study. Generated electricity, the process of electrolysis to produce hydrogen for use as a work or liquefy the hydrogen gas to the liquefaction and cooling cycles are given as a work. There is no previously encountered such a study for geothermal resources in Turkey about the hydrogen production and liquefaction. The research systems are used accordingly, just as the combined systems as given above, electricity generation and heating. Here is the maximum temperature and flow rates of geothermal resources will be considering into account the calculations. At the same time different temperature ranges for each source will be obtained the amount of hydrogen with the changing of graphs showing the cost per unit mass of hydrogen. Geothermal resources used in the calculations, mass flow rate and temperatures as shown in Table 5.4.

Table 5.4 Potential mass flow rate and temperature of geothermal fields [119].

| **Geothermal resources** | **Flow (kg/s)** | **Temperature (°C)** |
|---|---|---|
| Denizli-Kızıldere | 250 | 200-242 |
| Aydın-Germencik | 765 | 200-232 |
| Aydın-Salavatlı | 454 | 171 |
| Çanakkale-Tuzla | 120 | 174 |
| Kütahya-Simav | 223 | 162 |
| İzmir-Şerefhisar | 264 | 153 |
| Aydın-İmamköy | 40 | 142 |
| Manisa-Alaşehir-Kavaklıdere | 6.5 | 215 |
| Manisa-Caferbeyli | 6.5 | 155 |
| Aydın-Yılmazköy | 27.96 | 142 |

Our project we have identified seven models in this section will be done hydrogen production and liquefaction of the thermodynamic and economic evaluation of operations, as shown in the above table, for Turkey geothermal electricity production from these sources of heat and electrical power. For each of these resources than the models that we have done in previous sections of the thermodynamic and economic analysis of the EES program, including procedures used and results tables, and/or graphics will be presented as.

### 5.4.1 Thermodynamic and Economic Analysis of Geothermal Resources

Average geothermal water temperature of the geothermal area for the Denizli-Kizildere is 217 °C and mass flow rate is 250 kg/s. According to this geothermal resource makes calculations for model 1 maximum power output of this source is calculated to be 69.31 kJ/kg. Our net actual power output is calculated 16,816 kW from geothermal resource. With the result of the process of electrolysis of hydrogen produced per unit mass of geothermal is calculated to be

0.4419 g/kg of geothermal water. The maximum hydrogen can be produced in mass flow rate is calculated to be 0.1105 kg/s. Unit mass of hydrogen cost can be calculated to be 2.245 $/kg. According to the temperature change of the source the cost of hydrogen and production rate are shown in Figure 5.1. As can be seen, with the temperature increase in a hyperbolic decrease in cost and an increase close to the linear for mass flow rate were seen from the figure.

All calculation makes of the 7 model for Denizli-Kızıldere geothermal area, so we obtain the results showing the table 4.5. As the same as if all calculations make the other geothermal resources for seven model in Turkey. We can be obtained the mass and cost values of each resource. All result of each resource shown in the below tables. Just only Denizli-Kızıldere geothermal area of thermodynamics and cost results are shown in the figure with EES program. Other model calculations make and listed but not shown in here, because all figures are going to be very long. Kizildere Denizli region of thermodynamic calculations and economic consequences is seen in as a summary in Table 5.5.

Determined that the other nine resources have the potential for electricity production at all of the above calculations and the results were given in Table 5.6-5.14. Binary cycle is considered as the operation of existing resources, for the simple alkali and high temperature steam electrolysis process used to all systems. The minimum work required for the one kilogram of hydrogen production of calculations was made taking into account the irreversible work. For the liquefaction process is based on the pre-cooled Linde-Hampson process. Liquefaction of hydrogen pre-pre-cooling, the absorption refrigeration system (ARS) have been considered to reduce the amount of work necessary for liquefaction. For all models irreversible or actual case are plotted graphs based on the EES program, and calculations were made.

Table 5.5 Thermodynamic and economic analysis result of the Denizli-Kizildere.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 217 | 16816 | 0.110 | | | 2.245 |
| Model 2 | 217 | 16816 | 0.121 | | | 2.044 |
| Model 3 | 217 | 16816 | 0.158 | | | 1.516 |
| Model 4 | 217 | 16816 | | 0.222 | | 1.117 |
| Model 5 | 217 | 16816 | | | 21.715 | 0.905 |
| Model 6 | 217 | 16816 | | 0.250 | 1.780 | 1.007 |
| Model 7 | 217 | 16816 | 0.073 | 0.073 | | 1.855 |

Table 5.6 Thermodynamic and economic analysis result of the Aydın-Germencik.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 220 | 52667 | 0.3415 | | | 2.216 |
| Model 2 | 220 | 52667 | 0.3750 | | | 2.018 |
| Model 3 | 220 | 52667 | 0.49.12 | | | 0.731 |
| Model 4 | 220 | 52667 | | 0.687 | | 1.066 |
| Model 5 | 220 | 52667 | | | 68.724 | 0.905 |
| Model 6 | 220 | 48537 | | 0.773 | 1.797 | 0.9912 |
| Model 7 | 220 | 52667 | 0.226 | 0.226 | | 1.869 |

Table 5.7 Thermodynamic and economic analysis result of the Aydın-Salavatlı.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 157.5 | 13075 | 0.154 | | | 4.025 |
| Model 2 | 157.5 | 13075 | 0.1691 | | | 3.665 |
| Model 3 | 157.5 | 13075 | 0.2213 | | | 1.516 |
| Model 4 | 157.5 | 13075 | | 0.310 | | 2.002 |
| Model 5 | 157.5 | 13075 | | | 15.868 | 0.905 |
| Model 6 | 157.5 | 13075 | | 0.377 | 1.398 | 2.291 |
| Model 7 | 157.5 | 13075 | 0.102 | 0.102 | | 3.395 |

Table 5.8 Thermodynamic and economic analysis result of the Çanakkale-Tuzla

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 160 | 3697 | 0.0141 | | | 3.820 |
| Model 2 | 160 | 3697 | 0.1691 | | | 3.665 |
| Model 3 | 160 | 3697 | 0.2213 | | | 1.516 |
| Model 4 | 160 | 3697 | | 0.310 | | 2.002 |
| Model 5 | 160 | 3697 | | | 15.868 | 0.905 |
| Model 6 | 160 | 3697 | | 0.377 | 1.398 | 2.291 |
| Model 7 | 160 | 3697 | 0.102 | 0.102 | | 3.395 |

Table 5.9 Thermodynamic and economic analysis result of the Kütahya-Simav.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction(kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 145 | 3977 | 0.06925 | | | 5.950 |
| Model 2 | 145 | 3977 | 0.07604 | | | 5.418 |
| Model 3 | 145 | 3977 | 0.980 | | | 1.539 |
| Model 4 | 145 | 3977 | | 0.139 | | 2.960 |
| Model 5 | 145 | 3977 | | | 5.816 | 0.905 |
| Model 6 | 145 | 1656 | | 0.146 | 1.304 | 5.495 |
| Model 7 | 145 | 3977 | 0.0462 | 0.0462 | | 4.968 |

Table 5.10 Thermodynamic and economic analysis result of the İzmir-Şrefhisar.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 144 | 4455 | 0.0829 | | | 6.236 |
| Model 2 | 144 | 4455 | 0.0892 | | | 5.678 |
| Model 3 | 144 | 4455 | 0.115 | | | 1.539 |
| Model 4 | 144 | 4455 | | 0.163 | | 3.102 |
| Model 5 | 144 | 4455 | | | 6.707 | 0.905 |
| Model 6 | 144 | 4455 | | 0.170 | 1.296 | 6.425 |
| Model 7 | 144 | 4455 | 0.0542 | 0.0542 | | 5.208 |

Table 5.11 Thermodynamic and economic analysis result of the Aydın-İmamköy.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 142 | 596.4 | 0.0121 | | | 6.694 |
| Model 2 | 142 | 596.4 | 0.0132 | | | 6.314 |
| Model 3 | 142 | 596.4 | 0.0171 | | | 1.540 |
| Model 4 | 142 | 596.4 | | 0.024 | | 3.449 |
| Model 5 | 142 | 596.4 | | | 0.963 | 0.905 |
| Model 6 | 142 | 596.4 | | 0.013 | 1.281 | 0.929 |
| Model 7 | 142 | 596.4 | 0.0087 | 0.0087 | | 5.793 |

Table 5.12 Thermodynamic and economic analysis result of the Manisa-Alaşehir.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 215 | 430.2 | 0.00285 | | | 2.266 |
| Model 2 | 215 | 430.2 | 0.00313 | | | 2.063 |
| Model 3 | 215 | 430.2 | 0.00411 | | | 1.510 |
| Model 4 | 215 | 430.2 | | 0.006 | | 1.127 |
| Model 5 | 215 | 430.2 | | | 0.552 | 0.905 |
| Model 6 | 215 | 430.2 | | 0.006 | 1.769 | 1.018 |
| Model 7 | 215 | 430.2 | 0.0019 | 0.0019 | | 1.873 |

Table 5.13 Thermodynamic and economic analysis result of the Manisa-Caferbeyli.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 155 | 173.8 | 0.00217 | | | 4.267 |
| Model 2 | 155 | 173.8 | 0.00233 | | | 3.886 |
| Model 3 | 155 | 173.8 | 0.00308 | | | 1.535 |
| Model 4 | 155 | 173.8 | | 0.004 | | 2.123 |
| Model 5 | 155 | 173.8 | | | 0.215 | 0.905 |
| Model 6 | 155 | 173.8 | | 0.005 | 1.380 | 2.54 |
| Model 7 | 155 | 173.8 | 0.001448 | 0.001448 | | 3.557 |

Table 5.14 Thermodynamic and economic analysis result of the Aydın-Yılmazköy.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|
| Model 1 | 142 | 416.9 | 0.00845 | | | 6.934 |
| Model 2 | 142 | 416.9 | 0.00928 | | | 6.314 |
| Model 3 | 142 | 416.9 | 0.01196 | | | 1.540 |
| Model 4 | 142 | 416.9 | | 0.0170 | | 3.449 |
| Model 5 | 142 | 416.9 | | | 0.673 | 0.905 |
| Model 6 | 142 | 416.9 | | 0.018 | 1.304 | 2.959 |
| Model 7 | 142 | 416.9 | 0.00564 | 0.0056 | | 5.793 |

Table 5.15 Thermodynamic and economic results of the project envisaged the geothermal field.

| **Model** | **$T_{Geothermal}$ (°C)** | **Power (kW)** | **Flow rate (kg/s)** | **Production (kg/s)** | **Liquefaction (kg/s)** | **Cooling (kg/s)** | **Cost ($/kg H2)** |
|---|---|---|---|---|---|---|---|
| Model 1 | 200 | 20000 | 346 | 0.1439 | | | 2.457 |
| Model 2 | 200 | 20000 | 346 | 0.1580 | | | 2.238 |
| Model 3 | 200 | 20000 | 346 | 0.2068 | | | 1.516 |
| Model 4 | 200 | 20000 | 346 | | 0.289 | | 1.222 |
| Model 5 | 200 | 20000 | 346 | | | 24.458 | 0.905 |
| Model 6 | 200 | 20000 | 346 | | 0.324 | 1.681 | 1.125 |
| Model 7 | 200 | 20000 | 346 | 0.096 | 0.096 | | 2.035 |

### 5.5 Result and Discussion of Turkey Geothermal Resources Potentials

In this section, depending on the change of the temperature and flow rate for each source, amount of cost production and liquefaction hydrogen are shown in graphs (Figure 5.1-5.7). In general, these graphs show the results of the models the thermodynamic and economic. As can be seen from the overall graphics are increasing with the temperature of all sources is observed a linear increase in the amount of produced and liquefied hydrogen. Unit mass of hydrogen of electrical costs in general, there is a reduction in the hyperbolic. The first geothermal area graphs presented here and in practice already used in geothermal power plant data obtained by the Denizli-Kizildere. Here, only the temperature dependent changes of this region have been given. There is a similar changes observed in the results of other fields are not added this report. As shown in the tables above, Turkey has the potential of geothermal power generation sources; there is the potential for hydrogen production and liquefaction. The project is based on data from these sources within this theoretical and irreversible conditions were investigated for 7 models. System improvements and reduce the economic costs of the initial investment for the future, as these systems are lower than in the case of withdrawal will become even more attractive. Electricity costs have an important role for electrolysis used in the production and liquefaction of hydrogen. The most important factor in the cost of electricity can be reduced down to a much more with geothermal power plant. With high-temperature geothermal resources are currently available in countries throughout the world, the unit cost of electricity is known to vary between 0.02 and 0.05 $/kWh generated by geothermal water, [120]. Operation and maintenance costs of geothermal power plants are too low so, this is providing a great advantage of low-cost electricity. Technological advances for our country to work with the binary power plants to reduce the working temperature of 80-100 °C will provide a great advantage.

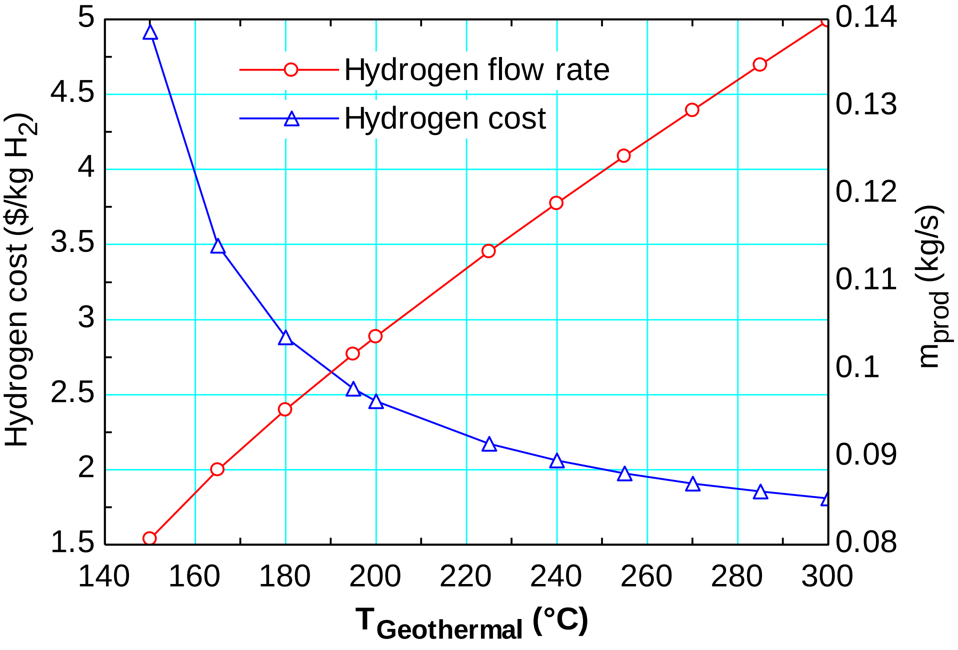


Figure 5.2 Variation of mass flow rate and cost of hydrogen according to temperature variation for the region of the Denizli-Kizildere (Model 1).

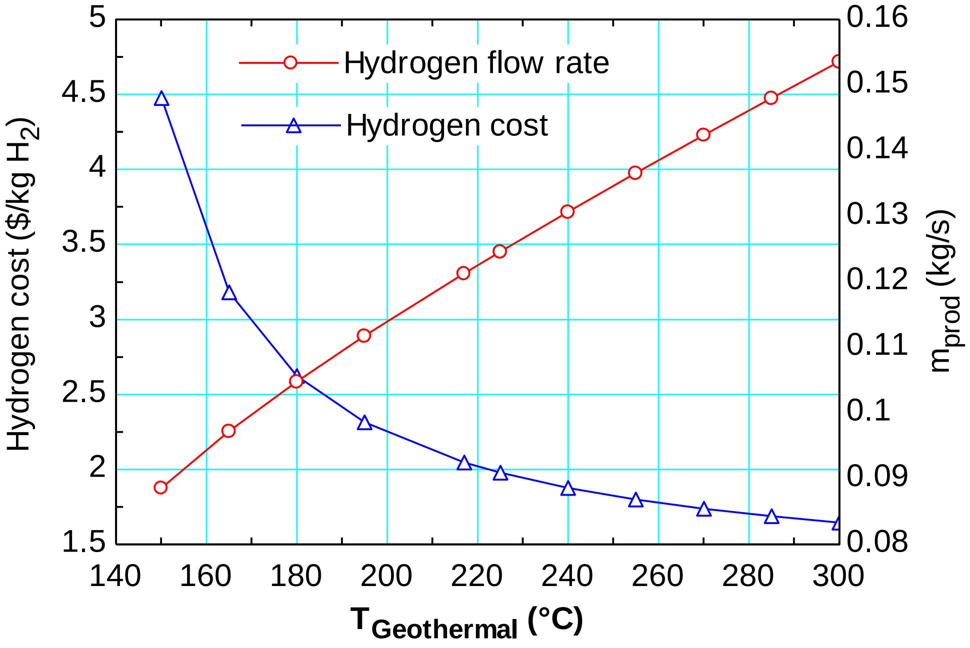


Figure 5.3 Variation of mass flow rate and cost of hydrogen according to temperature variation for the region of the Denizli-Kizildere (Model 2).

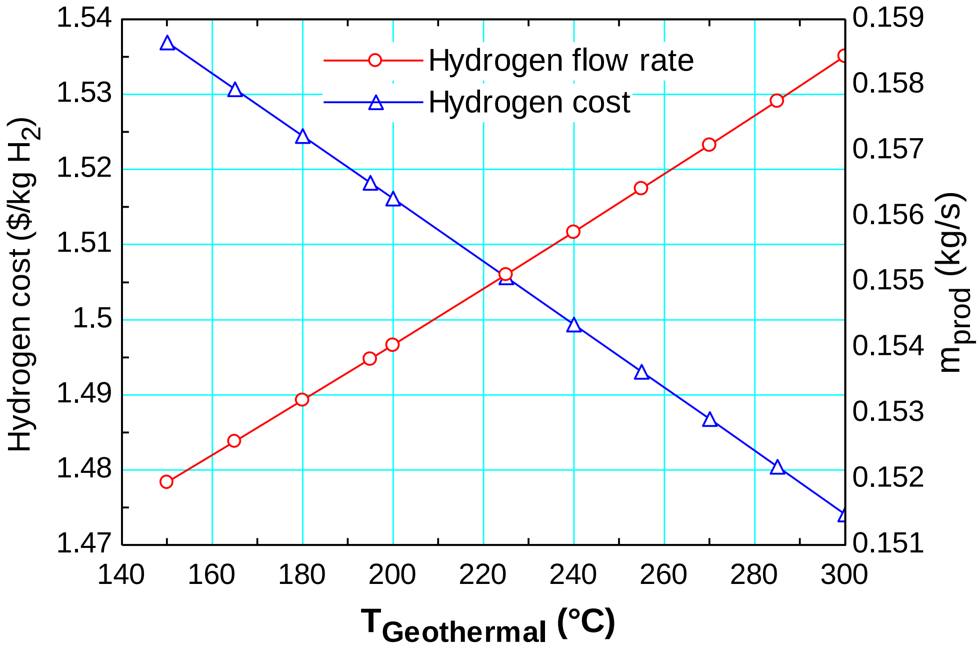


Figure 5.4 Variation of mass flow rate and cost of hydrogen according to temperature variation for the region of the Denizli-Kizildere (Model 3).

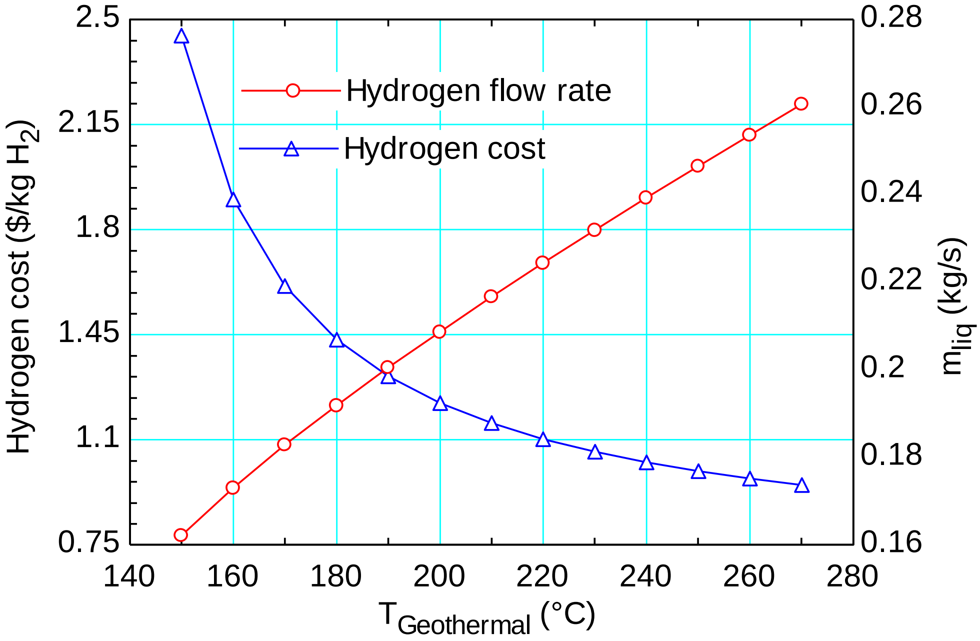


Figure 5.5 Variation of mass flow rate and cost of hydrogen liquefaction according to temperature variation for the region of the Denizli-Kizildere (Model 4).

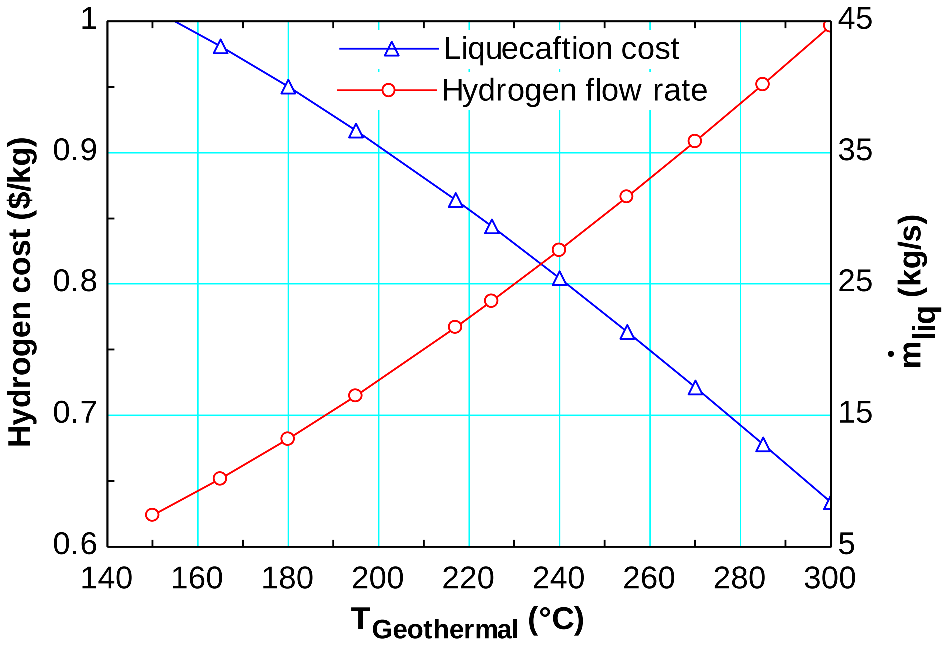


Figure 5.6 Variation of mass flow rate and cost of hydrogen liquefaction according to temperature variation for the region of the Denizli-Kizildere (Model 5).

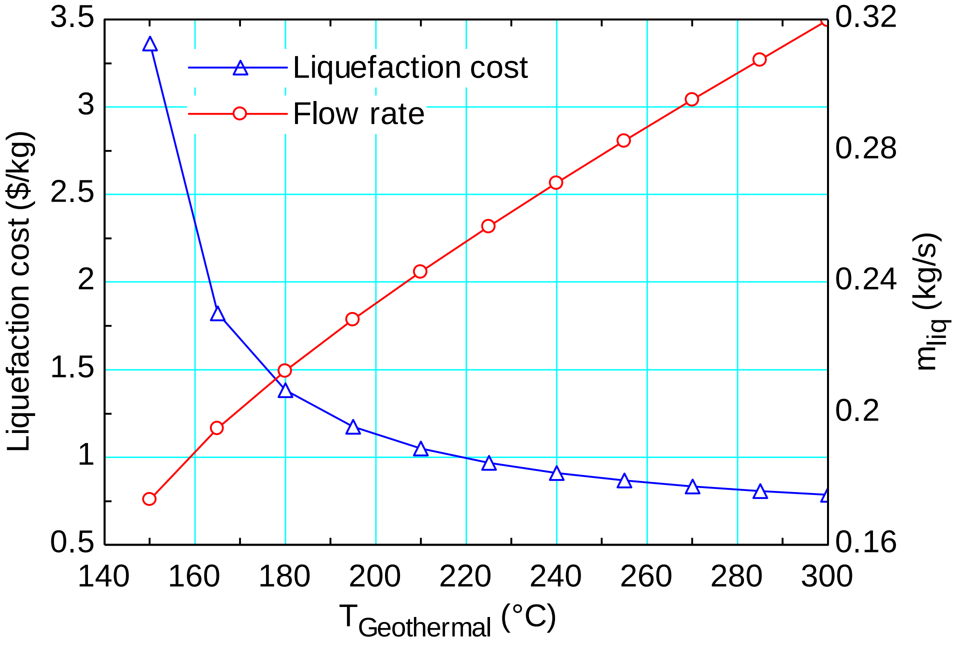


Figure 5.7 Variation of mass flow rate and cost of hydrogen liquefaction according to temperature variation for the region of the Denizli-Kizildere (Model 6).

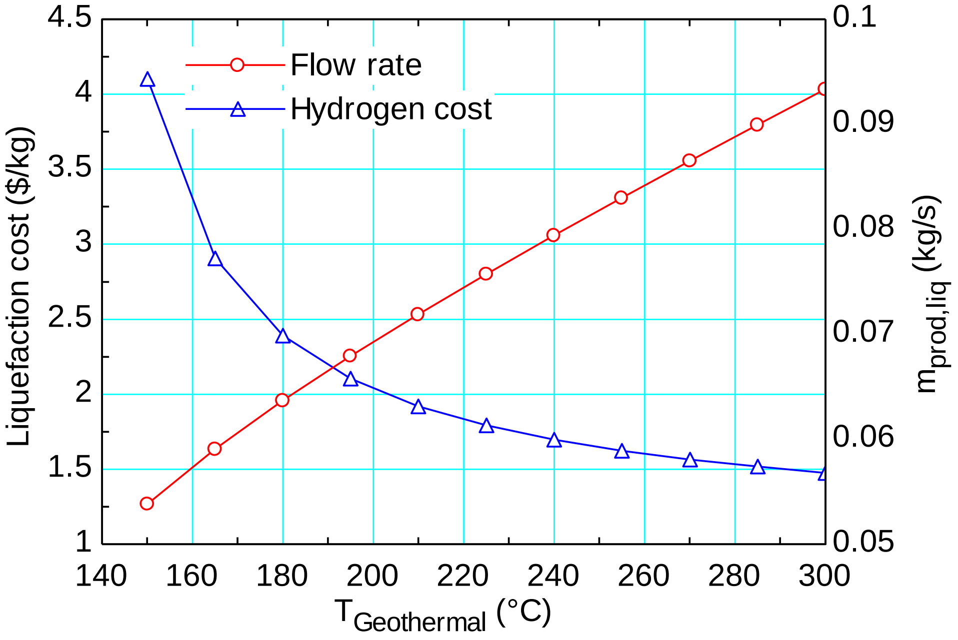


Figure 5.8 Variation of mass flow rate and cost of hydrogen production and liquefaction according to temperature variation for the region of the Denizli-Kizildere (Model 7).

# CHAPTER 6

## COMPARISONS OF RESULTS WITH SOLAR, WIND AND NUCLEAR SOURCES USING BY HYDROGEN PRODUCTION AND LIQUEFACTION SYSTEMS

### 6.1 Introduction

Production and liquefaction of hydrogen using by geothermal energy thermodynamic and economic analysis of done in the previous sections. These results were compared with other hydrogen production methods and systems in this section shall be made available in the literature. According to the most commonly studied in the literature has been reviewed and comparisons were made to them. Comparisons of our project results with the other renewable energy sources production and cost of hydrogen results each other. Solar, wind and nuclear energy are electrical energy work input in this systems used by the process of electrolysis for production and cost of hydrogen. Our aim of selection these resources, they resources look like as the most common use of resources and sustainable energy. These sources, hydrogen production and liquefaction process, two-way systems have been studied.

Energy supply is intended to be hydrogen production costs with the electrolysis or the cost of liquefied hydrogen. The general results reached in the study of this kind of systems, the most important parameter for hydrogen production and liquefaction is the electricity cost and resource property. Hydrogen production and liquefaction systems considering the whole more than 60% of the total system cost, the cost of electricity is a large-scale of system [121]. The remaining costs of the system consist of maintenance and operation costs and initial investment cost. Inferred from the literature survey, these sources of hydrogen produced per unit mass of electrolysis-based systems ranged from for wind 7-11 \$/kg, for solar systems 10-30 \$/kg, for nuclear systems 2-4 \$/kg, and for geothermal 2.2-7.0 \$/kg, [122].

### 6.2 Overview Cost of Hydrogen Production Methods

Hydrogen production methods are different. Each method in itself has a different cost and its application. As mentioned before, the most reliable, current, and in an environmentally appropriate production of hydrogen by electrolysis. For this process is necessary for the work as the provider of electricity used in a variety of sources. Geothermal, nuclear, wind and solar energy sources for electricity production, can be used such as integrating these systems. Generated this electricity is used as electrical work for hydrogen electrolysis production process. In the literature there are many reports of this kind of study. In general, the methods of hydrogen production costs of the average value shows in Table 6.1[123].

Table 6.1 Resources base case hydrogen production cost results.

| **Method** | **Cost<br>($/kg H2)** |
|---|---|
| Steam methane reformation | 1.43 |
| Coal gasification | 0.81 |
| Electrolysis* | 2.33-12.43 |
| Thermochemical (CSP**) | 2.12 |
| Thermochemical nuclear | 1.50 |
| NPO*** | 1.73 |

*Depends on the electrical generating source used. Lower end assumes use of coal and upper end is for solar PV.

** Concentrated solar power

*** Crude oil

The scope of this project is based on the production of electricity with geothermal water. The main subject of the project is thermodynamic and economic analysis of geothermal energy use in hydrogen production and liquefaction. The results obtained here will be compared different methods in the literature (i.e., solar, wind and hydrogen production using nuclear energy and economic consequences of thermodynamics). As can be seen from the table above change of hydrogen production cost with electrolysis is between 2.33 and 13.43 $/kg. These results suggest that hydrogen could be produced for as low as 0.81 $/kg from coal gasification. This wide range depends on the source of the electricity. The lower range assumes 4.5 cents/kWh electricity from newly constructed base load coal generating facilities, while the higher estimate assumes 26 cents/kWh electricity from a solar photovoltaic system.

Hydrogen produced from the SMR process is the second cheapest at 1.41 $/kg. A key rationale for moving to a hydrogen economy is to minimize carbon emissions. Producing hydrogen from coal actually could result in increased carbon dioxide emissions, unless carbon capture and sequestration is an integral part of these plants.

For all studies as compared with the production method is based on electrolysis process. As explained in previous sections, the use of electrolysis process, in terms of environmental impact and sustainability were taken into consideration.

### 6.3 Transaction Cost of Hydrogen Used By the Resource

The cost of delivered hydrogen is the sum of the production, storage, and transportation costs. Table 1.3 summarizes delivered hydrogen costs for a wide range of production methods and three of the most often mentioned delivery options. These three options are underground storage with regional and local pipelines; gaseous storage and truck transport; and liquid storage and truck transport. These costs do not include carbon capture, sequestration, or estimated fueling station costs [124].

Table 6.2 Estimated delivered hydrogen costs according to production methods.

| **Production method** | **Production cost ($/kg)** | **Delivered Cost ($/kg)[1]** | | |
|---|---|---|---|---|
| | | **Storage & Delivery methods[2]** | | |
| | | **Underground<br>pipeline-large<br>pipeline-local** | **Gaseous<br>truck-gaseous<br>none** | **Liquid<br>truck-liquid<br>none** |
| Reformation | 1.43 | 2.16-4.00 | 3.04-6.85 | 2.37-2.39 |
| Gasification | 0.81 | 1.54-3.38 | 2.42-6.23 | 1.75-1.77 |
| Electrolysis | 2.81 | 3.53-5.37 | 4.41-8.22 | 3.74-3.76 |
| Therm-CSP | 2.12 | 2.85-4.69 | 3.73-7.54 | 3.06-3.08 |
| Therm-Nuclear | 1.50 | 2.23-4.07 | 3.11-6.92 | 2.44-2.46 |
| NPO | 1.73 | 2.46-4.30 | 3.34-7.15 | 2.67-2.69 |

[1] Costs range from a flow rate of 100 000 kg/day and delivery of 100 miles to 1 000 000 kg/day and 500 miles.

[2] Scenarios written Storage/Delivery/Local Delivery. End storage not included.

In addition to being used in hydrogen production plant will be a generalization in itself, if the literature can be created based on the data in Table 6.3 [125]. In this table, for all electricity sources for the production of hydrogen electrolysis system used in the system. The costs of the systems, the cost of electricity generated from the source, electrolysis system was evaluated by taking into consideration the capacity and unit cost. Therefore, the calculation of the cost for each power plant is based on three main factors. These are the initial investment cost, the fixed and variable costs of operating, maintenance and operation - based on maintenance costs. Efficiency of electrolysis process was used for all systems were taken from 70-85%. Electricity costs are calculated in $/kWh for advanced coal-fired power plants, natural gas combined cycle power plants, natural gas combustion turbines, nuclear, wind, thermal solar and PV solar modules.

Table 6.3 Production and performance advantages for new-generation power plants.

| **Sources** | **Capital ($/kW)** | **O&M Fixed ($/kW)** | **O&M Changed ($/kWh)** | **Fuel ($/kWh)** | **Construction year (year)** | **Power (MW)** | **Capacity (%)** | **Heat rate (MBtu/kWh)** |
|---|---|---|---|---|---|---|---|---|
| Nuclear | 1694 | 60.06 | 0.00044 | 125 | 6 | 600 | 90 | 10400 |
| Coal | 1134 | 24.36 | 0.00406 | 378 | 4 | 400 | 85 | 8844 |
| Combined natural gas cycle | 517 | 10.35 | 0.00177 | 1735 | 3 | 400 | 85 | 6752 |
| Gas combustion turbine | 356 | 9.31 | 0.0080 | 1735 | 2 | 120 | 30 | 9183 |
| Solar PV | 3868 | 10.34 | 0 | 0 | 2 | 5 | 24 | 10280 |
| Thermal solar | 1983 | 50.23 | 0 | 0 | 3 | 100 | 33 | 10280 |
| Geothermal | 2063 | 104.98 | 0 | 0 | 4 | 50 | 95 | 45335 |
| Wind | 1049 | 26.81 | 0 | 0 | 3 | 50 | 44 | 0 |

Within this project, the cost per unit of electricity produced from energy sources that there are some differences. Within this project, the data obtained from the simulation models are given below in Table 6.4. Tabular data are expressed as this collected from the literature. The above sources of electricity for the same study unit costs of electricity produced from these sources were compared. As can be seen the table 6.4 unit cost of electricity from the resources change with the types of resources. Projected under this project, the water temperature and geothermal power plant capacity, respectively, are in the form of 200 °C and 20 MW, the unit cost of electricity for the power plant 3.58 ¢/kWh, as had been found. When the operation and maintenance cost is relatively 1.2 ¢/kWh, the unit cost of electricity was calculated 4.78 ¢/kWh [126].

Table 6.4 Unit costs of electricity as taken from the literature and projected [127].

| **Resource** | **Electricity cost (¢/kWh)** |
|---|---|
| Nuclear | 5.26 |
| Coal | 4.48 |
| Combined cycle | 5.47 |
| Gas turbine | 8.20 |
| Solar PV | 25.97 |
| Solar thermal | 11.54 |
| Geothermal | 4.90 |
| Wind | 4.62 |

As can be seen from Table 6.4 the geothermal energy is among the most attractive in the electrolysis process for renewable energy sources for hydrogen production methods. This practice has identified the project as an example of hydrogen production methods that model 1 is used as a source of electricity for the electrolysis process hydrogen sources above unit cost was calculated as follows: 75% efficiency of a simple alkaline electrolysis process, the electrical work required to produce one kilogram of hydrogen was calculated in the thermodynamic analysis, 43.57 kWh. This is according to the information for nuclear hydrogen cost calculated as 2.291 \$/kg, 2.091 \$/kg for coal, 2.383 \$/kg for a combined cycle gas, 3.572 $/kg for gas combustion turbine and 11.31 $/kg for solar PV modules, 5.027 $/kg for solar thermal, 2.178 $/kg for geothermal, 2.012 $/kg for wind [128].

In another study, hydrogen production is made economically comparison by the methods. To compare the hydrogen costs for the hydrogen technologies, a model created by Steinberg and Cheng of Brookhaven National Laboratory in 1989 was used. The model was revised to determine the current and future costs of hydrogen production technologies improve and become more viable. The model can be broken down into three main parameters that are included in the cost analysis of the hydrogen production: (1) capital costs of the plant, (2) annual operating costs, and (3) return on investment (profit margin). Fig. 6.1 summarizes the resulting hydrogen production costs associated with each of the plants modeled [129]. Steam reformation is currently the cheapest method of hydrogen production and electrolysis powered by the PV powered electrolysis is the most costly. However, the economic analysis of different $H_2$ production technologies seems to be incomplete without the consideration of environmental cost associated with these processes [130].

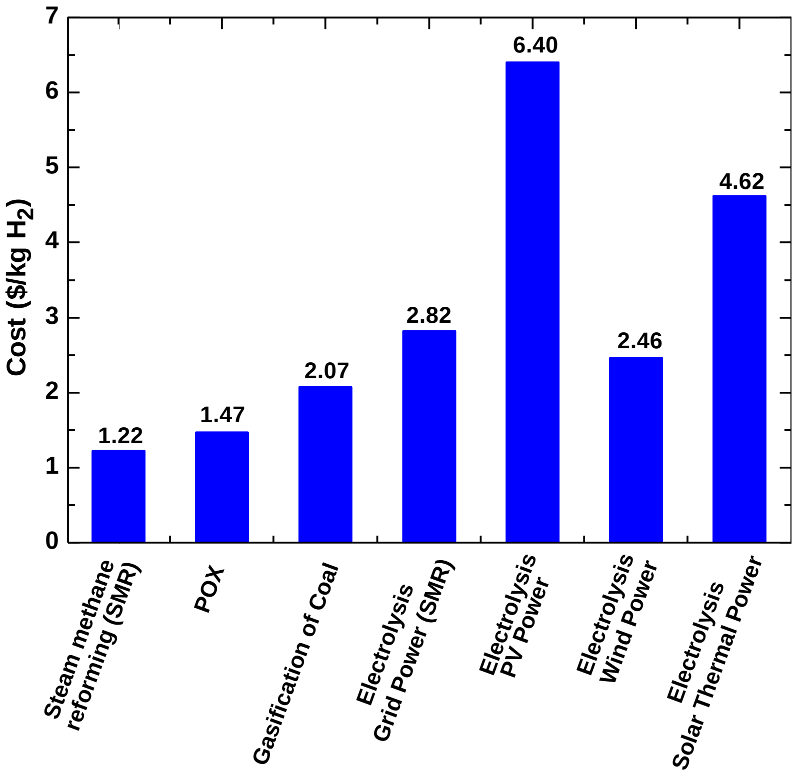


Figure 6.1 Hydrogen production cost for modeled technologies for 11,870,000 GJ/year production capacities [129].

New geothermal plants are generating electricity from $0.045/kWh to $0.074/kWh. Once capital costs for the plant are recovered, the price of power can decrease to below

$0.05/kWh. The price of geothermal energy is within the range of water electricity choices available today when the costs over the lifetime of a plant are considered. Fig. 6.2 presents cost of electricity production for various technologies [131].

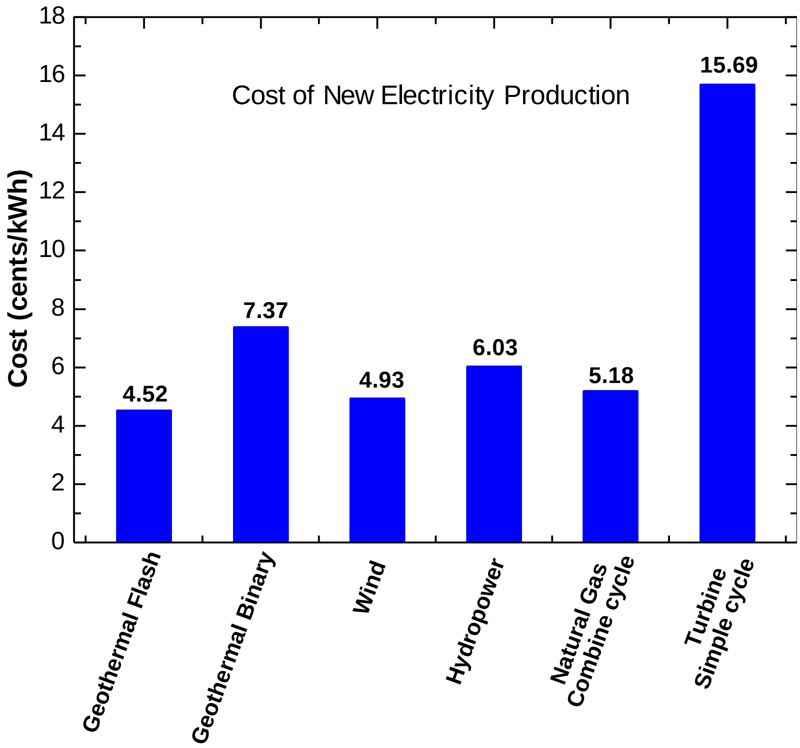


Figure 6.2 Cost of electricity production for various technologies.

In hydrogen production, the most widely used commercial technology is alkaline water electrolysis. The mean electricity energy consumption in the electrolysis of water is about 50 kWh/kg hydrogen. The cost of the electric energy makes large-scale electrolytic production of hydrogen uneconomical compared with the steam-methane reforming method. Work is underway to improve the AWE technology with an advanced alkaline electrolyser that would increase cell efficiency somewhat and reduce the electricity requirement to about 43 kWh/kg [132].

Comparative cost of hydrogen production for various technologies is given in Fig. 6.3. Here, hydrogen is produced by electrolysis method. Wind, hydropower and combined cycle involve much lower costs compared to simple Rankine cycle [131].

When comparing costs of various power producing methods, renewable and non-renewable, it should be noted that renewable technologies provide other system and environmental benefits that are not generally reflected in market prices.

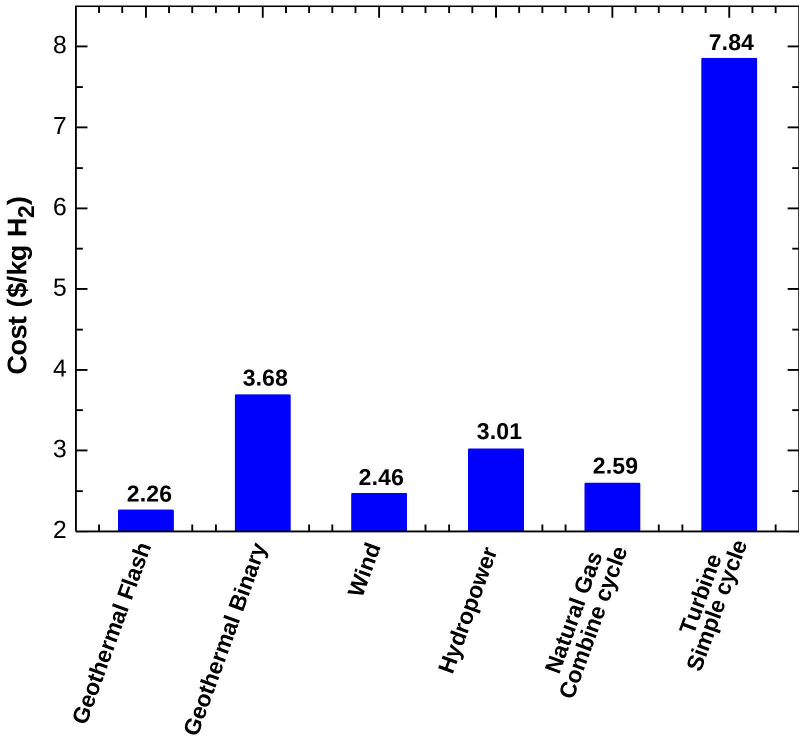


Figure 6.3 Comparative cost of hydrogen production for various technologies.

Electricity rates proved to be a major contributor to the overall hydrogen cost. Based on reasonable efficiencies, an electricity cost of slightly less than $0.10/kWh would be needed to produce and deliver central gaseous hydrogen that is cost-competitive (Fig. 6.4). Cost of hydrogen increases linearly with increasing cost of electricity [133].

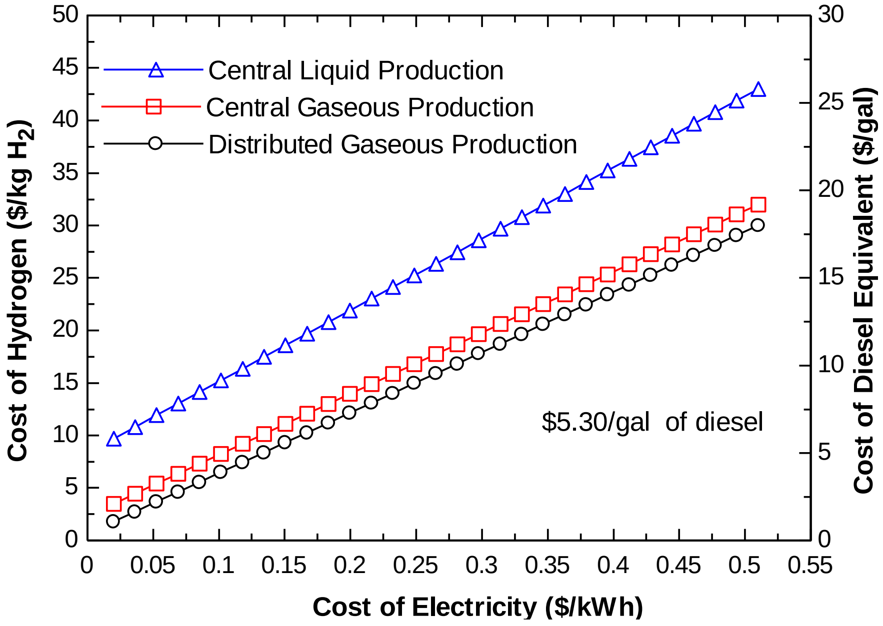


Figure 6.4 The effect of electricity cost on hydrogen cost [133].

High temperature electrolysis is an alternative to the conventional electrolysis process. Some of the energy required to split the water is provided as heat instead of electricity, thus reducing the overall energy required and improving process efficiency. Because the conversion efficiency of heat to electricity is low compared to using the heat directly, the energy efficiency can be improved by providing the energy to the system in the form of heat rather than electricity. Thermal energy from a geothermal source is very inexpensive compared to thermal energy from a high temperature cooled reactor (HTR) (Fig. 6.5).

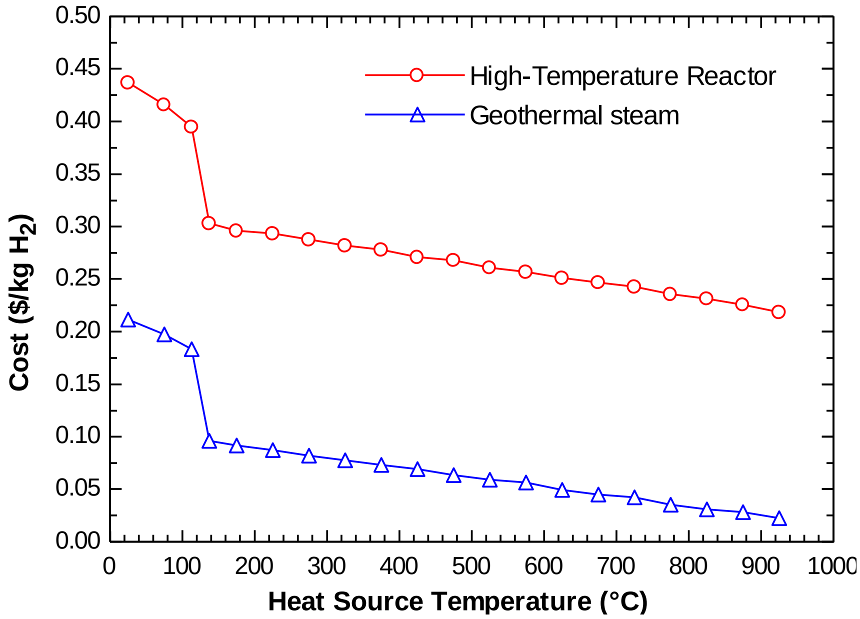


Figure 6.5 Cost of vaporizing and heating water to the required temperature for the electrolyser [134].

### 6.4 Hydrogen Production Using By Solar Energy

It has been estimated that solar energy has the potential to meet global energy demand well into the future [135]. Hydrogen from solar energy can be produced through two methods. In one method, solar energy is converted into electricity using a photovoltaic (PV) cell and then hydrogen is generated through the electrolysis of water. In the alternate method, photo electrochemical cells are used for the direct production of hydrogen. The photo electrochemical methods are still in the early stages of development.

The current cost of solar modules is in the range of $3 to $6 per peak watt (Wp). For solar cells to be competitive with the conventional technologies for electricity production alone, the module cost has to come down below $1/Wp.

There are several options for producing hydrogen from renewable sources. These are listed in above chapter [136]. Solar energy is technologies that are commercially available to provide electricity for electrolysis. The cost of electricity is a significant portion of the cost of making hydrogen with electrolysis. The production of hydrogen through electrolysis from solar and wind energy is not currently cost-competitive because of high electricity cost (relative to grid electricity at today's bulk electricity prices) and because electrolyzers require further development.

The current cost of distributed solar-based hydrogen is approximately $ 28.19/kg or $10 per gallon gasoline equivalent. One opportunity to reduce the cost of hydrogen produced by electrolysis is to replace part of the electricity requirement with heat, achieving higher overall energy efficiency. Concentrated solar energy and high temperature nuclear could supply sufficient heat to reduce the electrical requirement. Such systems are not in operation today, and would require solid oxide or other higher temperature electrolyzers [137].

The photovoltaic/electrolyzers system usually consists of the following major components (see Figure 2): PV array which is made of several units; a maximum power point tracker (MPPT); a DC-DC converter, which is used to operate the system at the maximum power of the photovoltaic system at all times and to supply the necessary DC current to the electrolyzer; an industrial electrolyzer system and a storage system for hydrogen [138].

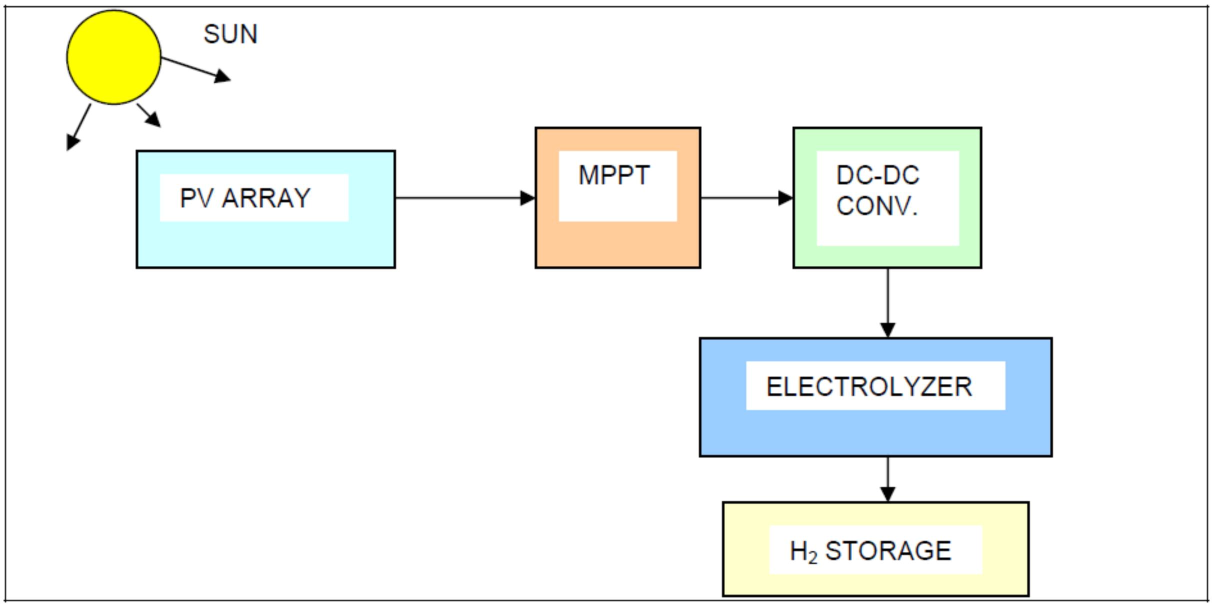


Figure 6.6 Schematic of PV hydrogen production systems [138].

One of the main efforts of R&D worldwide is to reduce the costs of solar technologies. The research programmers in Europe, Japan and the US all fund new developments with respect to material use and consumption, device design, reliability and production technologies as well as new concepts to increase the overall efficiency [139]. The US DOE Solar Program is currently pursuing the development of three generations of photovoltaic (PV) devices: discrete wafers of crystalline silicon, thin-film materials amenable to rapid manufacturing methods, and band gap-engineered materials and novel quantum mechanical approaches (e.g., Periodic Table Group III-V materials, multijunctions, polymer cells, quantumdot sensitized nanoparticle materials). The current electricity cost of PV technology ranges from 16 to 32 ¢/kWh depending on the market application. The long range 2020 goals of the program are to achieve costs in the 8 to 10 ¢/kWh for residential systems, 6 to 8 ¢/kWh for commercial systems, and 5 to 7 ¢/kWh for utility applications. These values assume a grid-tied, battery-free, fully installed photovoltaic system [137].

The hydrogen price using electricity from solar PV devices to power electrolyzers can be calculated as follows: If the current cost of solar modules is in the range of $3 to $6 per peak watt (Wp), for solar cells to be competitive with the conventional technologies for electricity production alone, the module cost has to come down below $1/Wp. In the current technology case, with a favorable installed cost of about $3.28/Wp, the electricity cost is estimated to be about $0.32/kWh and the hydrogen cost to be 28.19 $/kg In the possible future technology case, the installed capital cost of $1.011/Wp provides an electricity cost of 0.098

\$/kWh and a hydrogen cost of 6.18 \$/kg. The 6.18 \$ possible future cost of hydrogen, is the sum of 4.64 \$/kg for PV-generated electricity and 1.54 \$/kg, mostly for capital charges associated with producing (via electrolysis), storing, and dispensing hydrogen. The total supply chain cost is thus about a factor of four higher than that of the central station coal plant in its possible future case, which is estimated to be 1.63 \$/kg H2, inclusive of delivery and dispensing. For the PV-electrolyzer combination to be competitive in the future, either the cost of PV modules has to be reduced by an order of magnitude from current costs, or the electrolyzers' cost has to come down substantially from the low cost of \$125/kW already assumed in the committee's future technology case. A factor contributing to this need for low electrolyzer cost is the low utilization of the electrolyzer capital (solar energy is taken to be available 20 percent of the time). Therefore, while electricity at 0.098 \$/kWh from a PV module can be quite attractive for distributed applications in which electricity is used directly at the site, hydrogen costs via PV-electricity and electrolysis will not be competitive. Energy is consumed in the manufacture of solar modules. It has been estimated by the National Renewable Energy Laboratory (NREL) in the USA, which for a crystalline silicon module, the payback period of energy is about 4 years. For amorphous silicon modules this period is currently around 2 years, with the expectation that it will eventually be less than 1 year [140].

Table 6.5 Cost of PV solar modules, electricity from solar modules and hydrogen from solar modules in the USA.

| | **Solar modules** | **Electricity** | **Hydrogen** |
|---|---|---|---|
| | US \$/$W_p$ | US \$/kWh | US \$/kg |
| Current | 3.28 | 0.32 | 28.19 |
| Future | 1.011 | 0.098 | 6.18 |

All of the current methods and the projected technologies for producing hydrogen from solar energy are much more expensive (greater than a factor of three) when compared with hydrogen production from coal or natural gas plants. This is due partly to the lower annual utilization factor of about 20 percent (as compared with, say, wind of 30 to 40 percent). This creates enormous pressure to reduce the cost of a solar energy recovery device. While an expected future installed module cost of about \$1/Wp is very attractive for electricity generation and deserves a strong research effort in its own right, this cost fails to provide hydrogen at a competitive value. It is apparent that there is no one method of harnessing solar energy that is a clear winner. However, it appears possible that new concepts may emerge that would be competitive.

In the future, if the cost of the fuel cell system approaches $50/kW, the cost of the electrolyzer is also expected to approach a low number (about $125/kW). Such low capital costs for electrolyzer units, together with levelized electricity costs in the neighborhood of $0.02 to $0.03/kWh, would result in a competitive hydrogen cost. It is also estimated that for a photo-electrochemical method to compete, its cost needs to approach $0.04 to $0.05/kWh. The order-of-magnitude reductions in cost for both hydrogen processes are similar.

## 6.5 Hydrogen Production Using By Wind Energy

Hydrogen production from wind power and electrolysis is a particularly interesting proposition since, as just discussed, among renewable sources; wind power is economically the most competitive, with electricity prices at 4 to 5 cents/kWh at the best wind sites (without subsidies). This means that wind power can generate hydrogen at lower costs than those for any of the other renewable options available today.

Wind electricity may be converted to hydrogen through water electrolysis. Alkaline (KOH) electrolyzers are commonly used, but recently the electrolyzers with proton exchange membrane (PEM) are making progress [141]. Although water electrolysis is a mature technology its use in conjunction with wind power has some specifics, which will be discussed below. Hydrogen may be produced from the wind-generated electricity in a variety of applications, and used as a fuel directly, or transmitted through pipelines to the users, or used to enhance the performance of the wind turbine or a wind farm and match its output with the user expectations. Each of these applications is briefly discussed below.

In the future the wind-electrolysis-hydrogen system could be substantially optimized. The wind turbine technology could improve, reducing the cost of electricity to 4 cents/kWh with an increased capacity factor of 40 percent, as discussed previously, and the electrolyzer could also come down substantially in cost and could increase in efficiency (see the discussion in the section “Hydrogen from Electrolysis”). The combination of the increase in capacity factor and the reduction in the capital cost of the electrolyzer and cost of wind-generated electricity results in eliminating the need for using grid electricity (price still pegged at 7 cents/kWh) as a backup. The wind machines and the electrolyzer are assumed to be made large enough that sufficient hydrogen can be generated during the 40 percent of the time that the wind turbines are assumed to provide electricity. Due to the assumed reductions in the cost of the electrolyzer and the cost of windturbine- generated electricity, this option is now less costly than using a smaller electrolyzer and purchasing grid-supplied electricity when the wind turbine is not generating electricity. Hydrogen produced in this manner from wind with no grid backup is estimated to cost \$2.85/kg H2, while for the alternative system with grid backup it is \$3.38/kg H2. Furthermore, there is now the added advantage of a hydrogen production system that is CO2-emission free. The results of the committee's analysis are summarized in Table 6.6 [142].

Table 6.6 Results from Analysis Calculating Cost and Emissions of Hydrogen Production from Wind Energy.

| | **Current Technology** | | **Future Technology** | |
|---|---|---|---|---|
| | **With Grid Backup** | **No Grid Backup** | **With Grid Backup** | **No Grid Backup** |
| Average cost of electricity (¢/kWh) | 6 | 6 | 4 | 4 |
| Wind turbine capacity factor (%) | 30 | 30 | 40 | 40 |
| Hydrogen (\$/kg) | 6.64 | 10.69 | 3.38 | 2.86 |
| Carbon emissions (kg C/kg $H_2$) | 3.35 | 0 | 2.48 | 0 |

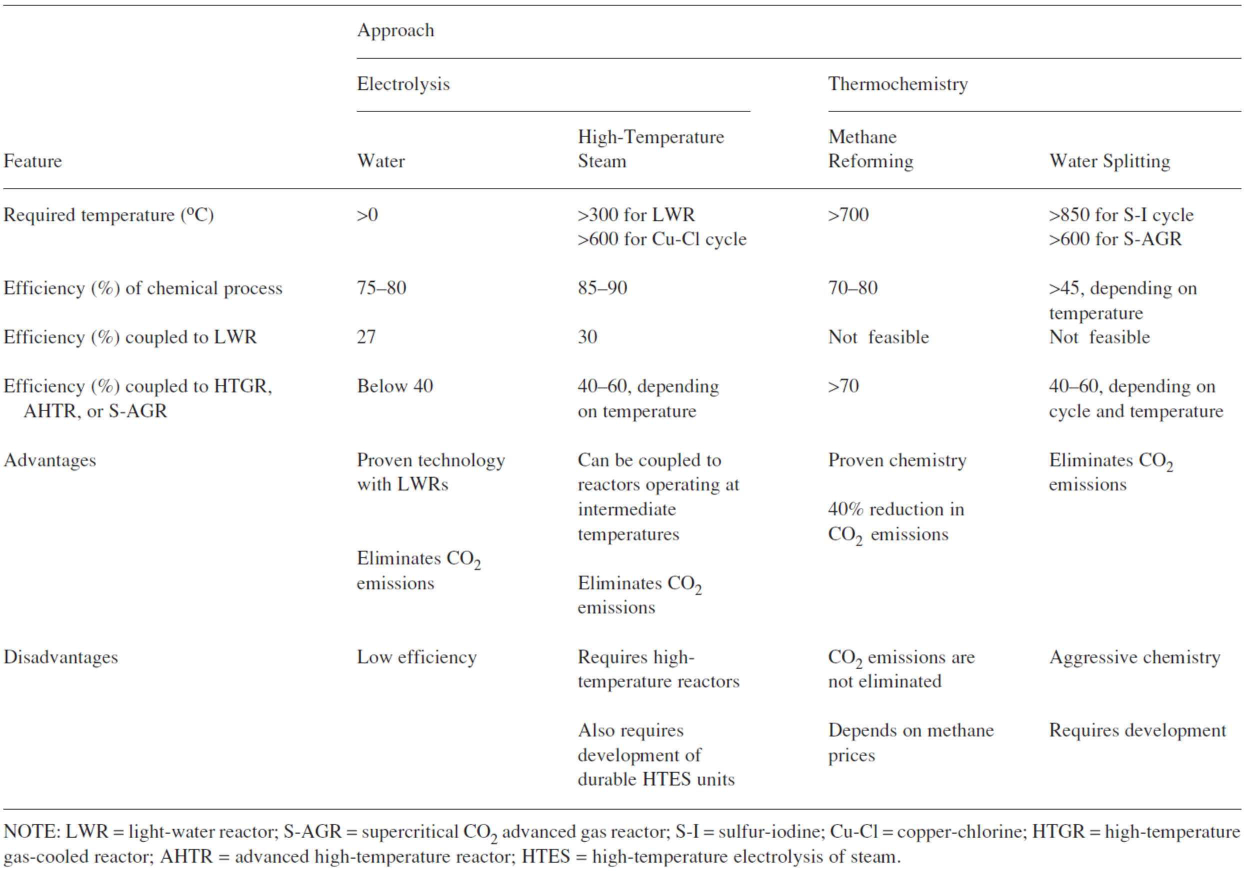
Wind energy has some very clear advantages as a source of hydrogen. It fulfills the two main motivations that are propel- ling the current push toward a hydrogen economy, namely, reducing $CO_2$ emissions and reducing the need for hydrocarbon imports. In addition, it is the most affordable renewable technology deployed today, with expectations that costs will continue to decline. Since renewable technologies effectively address two of the major public benefits of a move to a hydrogen energy system, and wind energy is the closest to practical utilization with the technical potential to produce a sizable percentage of future hydrogen, it deserves continued, focused attention in the hydrogen program.

Although wind technology is the most commercially developed of the renewable technologies, it still faces many barriers to deployment as a hydrogen production system. There is a need to develop optimized wind-to-hydrogen systems.

### 6.6 Hydrogen Production Using By Nuclear Energy

Hydrogen can be produced using reactors for water splitting by electrolysis or by thermochemical processes without any CO2 emissions. Potentially more efficient hydrogen production may be attained by significantly raising the water temperature before splitting its molecules using either thermochemistry or electrolysis. Such approaches require temperatures in the range of 700°C to 1000°C. Current LWRs and near-term, water-cooled ALWRs produce temperatures under 350°C and cannot be used for such purposes. However, other coolants of several Generation IV reactor concepts are proposed to reach such high temperatures (above 700°C) and may be coupled to thermochemical plants [143,144,145]. A recent report by the Electric Power Research Institute (EPRI) pointed out that the use of nuclear reactors to supply the heat needed in the steam methane reforming (SMR) process is potentially more economic than their use for water splitting [145]. Nuclear-assisted SMR would reduce the use of natural gas in the process as well as the CO2 emissions. The various options for nuclear hydrogen production are compared in Table 6.7 [146].

Table 6.7 An Overview of Nuclear Hydrogen Production Options[146].

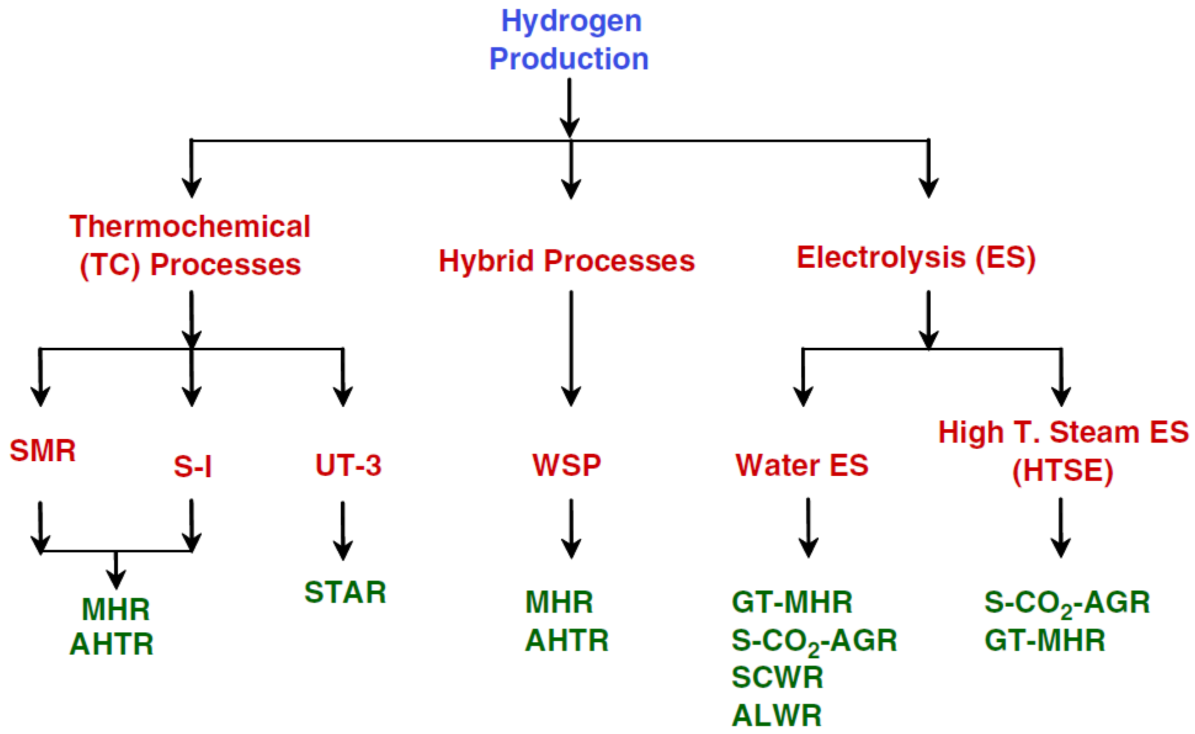


| | Approach | | | |
|---|---|---|---|---|
| | Electrolysis | | Thermochemistry | |
| Feature | Water | High-Temperature Steam | Methane Reforming | Water Splitting |
| Required temperature (ºC) | >0 | >300 for LWR<br>>600 for Cu-Cl cycle | >700 | >850 for S-I cycle<br>>600 for S-AGR |
| Efficiency (%) of chemical process | 75–80 | 85–90 | 70–80 | >45, depending on temperature |
| Efficiency (%) coupled to LWR | 27 | 30 | Not feasible | Not feasible |
| Efficiency (%) coupled to HTGR, AHTR, or S-AGR | Below 40 | 40–60, depending on temperature | >70 | 40–60, depending on cycle and temperature |
| Advantages | Proven technology with LWRs<br>Eliminates $CO_2$ emissions | Can be coupled to reactors operating at intermediate temperatures<br>Eliminates $CO_2$ emissions | Proven chemistry<br>40% reduction in $CO_2$ emissions | Eliminates $CO_2$ emissions |
| Disadvantages | Low efficiency | Requires high-temperature reactors<br>Also requires development of durable HTES units | $CO_2$ emissions are not eliminated<br>Depends on methane prices | Aggressive chemistry<br>Requires development |

NOTE: LWR = light-water reactor; S-AGR = supercritical $CO_2$ advanced gas reactor; S-I = sulfur-iodine; Cu-Cl = copper-chlorine; HTGR = high-temperature gas-cooled reactor; AHTR = advanced high-temperature reactor; HTES = high-temperature electrolysis of steam.

Nuclear energy can be used in hydrogen production mainly in three ways:

- By using the electricity from the nuclear plant for conventional liquid water electrolysis.
- By using both the high-temperature heat and electricity from the nuclear plant for high-temperature steam electrolysis or the hybrid processes.
- By using the heat from the nuclear plant for thermochemical processes.



**AHTR** Advanced high-temperature reactor

**ALWR** Advanced light water reactor

**ES** Electrolysis

**MHR** Modular helium reactor

**GT-MHR** Gas turbine modular helium reactor

**SCWR** Super critical water reactor

**UT-3** University of Tokyo-3 (Ca–Br–Fe thermochemical cycle)

Figure 6.7 Technology options for nuclear hydrogen production [147].

### *High-Temperature Electrolysis of Steam*

The electrical energy demand in the electrolysis process decreases with increasing water (or steam) temperature. While the demand for heat energy is increased, the decrease in the electrical energy demand improves the overall thermal- to-hydrogen heat conversion efficiency. Higher temperatures also help lower the cathodic and anodic over voltages. Therefore, it is possible to increase the current density at higher temperatures, which yields a significant increase in the process efficiency.

The HTES process is potentially advantageous when coupled to high-efficiency power cycles and can consequently yield high overall thermal-to-hydrogen energy efficiency. The efficiency of hydrogen production via coupling of HTES to either of two high-temperature nuclear reactors is given with graphical [147]. One reactor is the gas turbine modular high-temperature reactor (GT-MHR) [148]. The second is an advanced gas-cooled reactor (AGR) coupled to a direct supercritical CO2 power cycle. The cycle was originally proposed for fast reactors [149]. The supercritical AGR (S-AGR), also referred to as the S-CO2, necessitates upgrading the AGR design pressure from the current 4 MPa to about 20 MPa, which has not been attempted before in a concrete containment. A reference HTES design called HOTELLY (high-operating temperature electrolysis) [150]. is chosen as the basis for this example.

Implementation of the GT-MHR-HTES at the temperature of 850°C for the near term appears possible, while achieving temperatures of 950°C and higher might be expected for the years 2025 and beyond. Similarly, for the SAGR- HTES, the near-term and far-term goals may be 650°C and 750°C, respectively.

Nuclear reactors coupled to HTES are capital-intensive technologies, due to both the nuclear plant and the electrolysis plant. The development of economical and durable HTES unit materials, which can be similar to those of the solid oxide fuel cell materials, can contribute to cost reduction. The development of improved HTES units with low electrode overvoltage at lower temperatures can enable their use with lower-temperature and thereby lower-cost nuclear plants. Improved HTES cell designs are currently being investigated at Lawrence Livermore National Laboratory and Idaho National Engineering and Environmental Laboratory [151,152]. In addition, attaining high power cycle efficiency at the nuclear plant with relatively low temperatures can contribute to cost reduction. Finally, development of economic high-temperature radiation resistant graphite or ceramic-coated graphite materials for the nuclear plant is needed.

The cost of hydrogen production by the nth-of-a-kind of MHR using the SI process was assessed by Brown et al. (2003) [153]. The authors considered the cost of producing 800 t H2 per day using heat from four units of 600 MWth, each producing a coolant at 850ºC and having an overall efficiency of 42 percent. Starting with an overnight cost of $470/ MWth for the nuclear electric plant, adding a heat exchanger, and replacing the electric generation capacity with a thermochemical plant, the total plant capital cost was found to be about $750/MWth. (A recent review of the costs of nuclear power at recent plants—built in the past 10 years in Korea, Finland, and Japan—finds the overnight costs of plants to be in the range of $530 to $800/MWth [154].) The cost of running the MHR nuclear plant is estimated to be $93.9 million per year and the hydrogen plant to be $50.7 million per year. This resulted in the cost of hydrogen production being about $1.50/kg. However, it is possible to argue that future developments could facilitate reaching higher efficiency in the conversion of the nuclear thermal energy into hydrogen production.

Furthermore, larger numbers of units in one place could lead to lower costs; thus, larger plants could be associated with lower plant and operating costs. Using optimistic assumptions about advances in nuclear plant construction and thermochemical plant efficiency, the cost of a 1200 t/day MHR-SI hydrogen plant may be assumed to reach a level of $600/MWth as the technology matures. Including the usual contingency and permitting costs could add about one-third to this cost, thus leading to an effective plant cost estimate of $800/MWth and, assuming a 3-year construction time, the hydrogen production cost would be about 1.60 $/kg.

Hydrogen expectations for nuclear and thermo chemical cost would be $1.30/kg. Relative cost of each other hydrogen production by electrolysis 3.0 $/kg (electricity cost 0.06$/kWh), hydrogen produced methane reforming 0.8 $/kg. Electricity cost is changing of 3-10 ¢/kWh for coal, 1-4 ¢/kWh and 0.2- 0.5 ¢/kWh for nuclear energy this range. By one estimate, the costs of producing hydrogen from this type of system could be as low as $1.30 per kg ($9.15/GJ), assuming a combined capital cost of $686 per kW (thermal) for the nuclear reactor ($371/kW) and hydrogen plant ($315/kW) and assuming 50% system efficiency (Henderson, 2002). Another recent estimate by the NRC estimates somewhat higher costs of $1.63 per kg ($11.50/GJ), assuming a production plant capital cost of $2.5 million for a production capacity of 1.2 million kilograms of hydrogen per day. By another estimate, the exact costs of producing hydrogen through this cycle are not specified but are estimated to be about 60% of the costs of hydrogen production via electrolysis [155].

### 6.7 Conclusions of Different Energy Resources Using By Hydrogen Production

In conclusion, hydrogen can be produced in a variety of different ways, from a large number of potential feedstock. Unlike the crude oil used to produce gasoline, the myriad potential sources of hydrogen are generally well distributed around the U.S. and the world. Certain regions have greater or lesser availability and suitability for specific hydrogen feedstock and production methods, but virtually all regions have at least a few and many have several possibilities for hydrogen production.

The feedstock diversity for hydrogen is a critical characteristic in that it suggests the potential for much greater reliance on local resources for energy production around the world, particularly with regard to petroleum use in the transportation sector (if practical hydrogen vehicles can be realized). The diversity also raises another critical issue in that it suggests that in places such as the U.S., where multiple hydrogen production options are possible, strategic decisions about hydrogen production can be made based on multi-criteria analysis of the costs and benefits of various options.

This chapter has focused on the economic costs of hydrogen production for different resources of energy supply the system, and only briefly discussed the broader picture of full environmental and social costs. However, it should be recognized that at present there is an inherent bias toward hydrogen production options that have the highest environmental and social costs. This is because many of these costs are “externalities” that are not presently valued in energy and fuel markets. Thus, in deciding on hydrogen production options as the development of the hydrogen economy unfolds, analyzing these options in ways that value as many of their actual environmental and human health impacts as possible will be important. This is to make sure that individual countries or regions pursue options for hydrogen production that maximize the overall social benefits of the moving to hydrogen, as it may be only in that way the overall hydrogen strategy becomes a truly compelling one.

The main hydrogen production pathways currently known are listed in table 6.8-9 as follows, including a short technical and economic characterization of the pathway.

Table 6.8 Summary of recent hydrogen production cost estimates [156].

| **Production Method** | **Scale of Production** | **Production Cost (HHV basis)** | **Key Details and Market Status** | **Source** |
|---|---|---|---|---|
| **Nuclear** | | | | |
| SI-MHR | n.s.<br>Large. | 0.95-1.6 $/kg | 5-15% interest rate<br>Research and Development | Brown et al., 2002 |
| SI-MHR | n.s.<br>Large. | 1.30 $/kg | $686/kW cap. cost<br>10% interest rate<br>Research and Devt. | Henderson, 2002 |
| Nuclear Thermal of Water | 1.2 million kg/day<br>Large | 1.63 $/kg<br>Future | $2.5 million plant capital cost<br>R&D/Future | NCR,2004 |
| **Wind** | | | | |
| Electrolysis | 1.267 kg/day<br>Small-Medium | 1.56$/kg (6%DR)<br>1.27$/kg (%12DR) | Excellent sites<br>(630 W/m2)<br>Near Commercial | Ogden and Nitsch,1993 |
| Electrolysis | 1,267 kg/day<br>Small-Medium | 2.41 $/kg (%6DR)<br>3.55 $/kg (12%DR) | Good sites<br>(350 W/m2)<br>Near Commercial | Ogden And Nitsch, 1993 |
| Electrolysis | 10 MW of wind power<br>Small-Medium | 3.90$/kg 2000 year<br>3.00$/kg 2010 year | Wind power: 900$/kW(2000) 700$/kW(2010) | Mann et al., 1998 |
| Electrolysis | 10 MW of wind power | 7.10$/kg 2000 year | Stand-Alone<br>Wind power: | Mann et al., 1998 |

|  |  |  |  |  |
|---|---|---|---|---|
|  | Small-Medium | 4.00$/kg 2010 year | $900/kW (2000)<br>$700/kW (2010) |  |
| Electrolysis | Small-Medium | 1.86-2.63$/kg<br>3.20-3.98$/kg w/15%IIR, 37% taxation | Various Design and<br>Econ. Assumption | Padro, 2002 |
| Electrolysis | Small | 1.14$/kg<br>4.33$/kg<br>w/15%IIR,37% tax. | Stand-Alone | Padro, 2002 |
| Electrolysis | 1,600 kg/day<br>Current<br>1,200 kg/day<br>Future<br>Small-Medium | 10.69$/kg current<br>2.86$/kg future | Stand-Alone<br>Near Term/Future | NCR,2004 |
| Electrolysis | 480 kg/day<br>Small | 6.81$/kg şuan.<br>3.50$/kg gelecek dönem. | Grid-Tied<br>Near Term/Future | NCR,2004 |
| **Solar** |  |  |  |  |
| PV Electrolysis | 1,267 kg/day<br>Small-Medium | 6.39-14.3 $/kg (%6DR)<br>10.37-23.71$/kg (%12DR) | ca. 1991<br>Southwest U.S.<br>Near Commercial | Ogden and Nitsch,<br>1993 |
| PV Electrolysis | 1,267 kg/day<br>Small-Medium | 1.42-2.27$/kg (%6DR)<br>2.13-3.55$/kg (%12DR) | Future Projection<br>Southwest U.S.<br>Near Commercial | Ogden and Nitsch, 1993 |
| PV Electrolysis | 10 MWe<br>Small-Medium | $25.84/kg<br>$12.21/kg<br>$6.39/kg | PV; $5,000/kW<br>PV; $2,000/kW<br>PV; $750/kW<br>Near Commercial. | Glatzmaier et al., 1998 |
| Solar Dish-Stirling | 10 MWe<br>Small-Medium | $11.64/kg<br>$10.79/kg | Year 2010<br>Year 2020 | Glatzmaier et al., 1998 |

| | | | | |
|---|---|---|---|---|
| Electrolysis | | | Demonstration | |
| Solar Power-Tower Electrolysis | 200 MWe<br>Medium | $7.10/kg<br>$5.96/kg | Year 2010<br>Year 2020<br>Demonstration | Glatzmaier et al., 1998 |
| High-Temperature Electrolysis | 200 MWe<br>Medium | $5.68-6.25/kg<br>$7.67-11.42/kg | $500/kW electrolyzer<br>$2,000/kW electrolyzer<br>Research and Devt. | Glatzmaier et al., 1998 |
| PV Electrolysis | 10 MW of solar power<br>Small-Medium | $7.40/kg<br>Year 2000<br>$4.50/kg<br>Year 2010 | Grid-Tied<br>Solar power:<br>$3,133/kW (2000)<br>$12,662/kW (2010)<br>*Near Term/Future* | Mann et al., 1998 |
| PV Electrolysis | 10 MW of solar power<br>Small-Medium | $17.60/kg<br>Year 2000<br>$7.50/kg<br>Year 2010 | Stand-Alone<br>Solar power:<br>$3,133/kW (2000)<br>$12,662/kW (2010)<br>Near Term/Future | Mann et al., 1998 |
| PV Electrolysis | Small | $1.78/kg<br>$8.24/kg<br>w/15% IRR, 37% vergi. | Stand Alone<br>Future | Padro, 2002 |
| PV Electrolysis | 2,400 kg/day<br>Small-Medium | $28.19/kg<br>Current<br>$6.18/kg<br>Future | Stand-Alone<br>Near Term/Future | NRC, 2004 |
| PV Electrolysis | 480 kg/day<br>Small | $9.71/kg<br>Current | Grid-Tied<br>Near | NRC, 2004 |

| | | | | |
|---|---|---|---|---|
| | | $4.37/kg<br>Future | Term/Future | |
| **Grid Power** | | | | |
| Electrolysis | 24,000 kg/day<br>Medium | $4.70/kg<br>Current<br>$2.30/kg<br>Future | Electricity at<br>$0.045/kWh<br>Near Term/Future. | NRC, 2004 |
| Electrolysis | 480 kg/day<br>Small | $6.58/kg<br>Current<br>$3.93/kg<br>Future | Electricity at<br>$0.07/kWh<br>Near Term/Future | NRC, 2004 |
| **Solar Photo-Electrochemical** | | | | |
| PEC<br>Water Splitting | Variable | $2.60/kg<br>$11.00/kg<br>w/15% IRR, 37% taxation | Year 2010 Estimate<br>Research and Devt. | Padro, 2002 |
| PEC<br>Water Splitting | Variable | $1.21/kg<br>$5.11/kg<br>w/15% IRR, 37% taxation | Year 2010 Estimate<br>Research and Devt. | Padro, 2002 |

Notes: Production costs are on HHV basis unless otherwise specified. For delivered hydrogen cost estimates, see Table 6.8. DR = discount rate (see list of acronyms at front of report for other abbreviations).

Table 6.9 Summary of recent delivered hydrogen cost estimates [156].

| **Production Method** | **Scale of Production** | **Delivered H2 Cost (HHV basis)** | **Notes** | **Source** |
|---|---|---|---|---|
| **Wind** | | | | |
| Electrolysis | (10 MWp) | 3.17 $/kg (%6 DR)<br>4.32 $/kg (%12 DR) | Future projection<br>Demonstration Scale | Ogden and Nitsch, 1993 |
| Electrolysis | (750 MWp) | 3.42 $/kg (6% DR)<br>4.50 $/kg (12% DR) | Future projection<br>City supply scale | Ogden and Nitsch, 1993 |
| Electrolysis | 1,600 kg/day<br>Current<br>1,200 kg/day<br>Future | $10.69/kg current<br>$2.86/kg future. | Distributed production<br>Stand-Alone | NRC, 2004 |
| Electrolysis | 480 kg/day | $6.81/kg current<br>$3.50/kg future. | Distributed production<br>Grid-Tied | NRC, 2004 |
| **Solar** | | | | |
| PV Electrolysis | (10 MWp) | $2.26-3.14/kg (6% DR)<br>$3.12-4.59/kg (12% DR) | Future projection<br>Southwest U.S.<br>Demonstration Scale | Ogden and Nitsch,1993. |
| PV Electrolysis | (750 MWp) | $2.50-3.38/kg (6% DR)<br>$3.32-4.77/kg (12% DR) | Future projection<br>Southwest U.S.<br>City supply scale | Ogden and Nitsch,1993. |
| PV Electrolysis | 2,400 kg/day | $28.19/kg current | Distributed production | NRC, 2004. |

| | | | | |
|---|---|---|---|---|
| | | $6.18/kg future | Stand-Alone | |
| PV Electrolysis | 480 kg/day | $9.71/kg current<br>$4.37/kg future | Distributed production<br>Grid-Tied | NRC, 2004 |
| **Nuclear** | | | | |
| Nuclear Thermal<br>Conversion of Water | 1.2 million<br>kg/day | $2.33/kg ($16.43/GJ) future | Central production<br>Pipeline delivery | NRC, 2004. |
| **Grid Power** | | | | |
| Electrolysis | 480 kg/day | $6.58/kg current<br>$3.93/kg future | Distributed production | NRC, 2004 |
| Electrolysis | 24,000 kg/day | $7.12/kg current.<br>$3.71/kg future. | Central production<br>Tanker truck delivery<br>(liquid H2) | NRC, 2004 |

Note: Delivered hydrogen costs are on HHV basis unless otherwise specified.

*See report for additional storage and transport methods, including 100-mile pipeline, 1,000-mile pipeline, onsite consumption, and “gas station” delivery.

# CHAPTER 7

# CONCLUSIONS

Economic development is one of the basic elements of energy, is one of humanity's essential requirements. This thesis presented a review of hydrogen energy technologies, namely technologies for hydrogen productions and liquefactions. Possibilities for utilization of geothermal energy to generate hydrogen are discussed in parallel with possibilities to use hydrogen to enhance geothermal power with other renewable competitiveness [157].

Regardless of the energy sources of the future there will always be a need for convenient, clean, safe, efficient and versatile energy carriers or forms of energy that can be delivered to the end user. One of these energy carriers is electricity, which is already being used worldwide. Electricity is a convenient form of energy, which can be produced from various sources and transported over large distances. It is clean, although its production from fossil fuels is not. Hydrogen is another clean, efficient and versatile energy carrier, which supplements electricity very well. Together these two carriers may satisfy all the energy needs and form an energy system that is permanent and independent of energy sources [158].

Also, in this thesis, fossil and nuclear energy are defined as unsustainable because the resources are finite and the waste cannot be absorbed by nature. If one accepts this definition, renewable energy harvested in a sustainable way becomes the key to a sustainable energy future.

With the exception of biomass, all renewable energy is of a physical nature: heat (solar, geothermal), solar radiation (photovoltaic) and mechanical energy (wind, hydro, waves, etc.). Heat obtained from solar collectors, geothermal sources, and waste incineration may also be converted to electricity. Thus, in one vision of a sustainable future, electricity from renewable sources will become the dominant primary energy carrier replacing chemical carriers of today’s economy [159].

For centuries, hydrogen has fascinated people. Hydrogen can be derived from water and other chemical compounds. The conversion of hydrogen to heat or power is often simplified by the popular equation “hydrogen plus air yields electricity and drinking water.” Also, hydrogen, the most common chemical element on the planet, is hailed as an everlasting energy source [160]. But nature does not provide hydrogen in its elemental form. High-grade energy (electricity or heat) is needed to liberate hydrogen from its chemical source.

Economy means trade. A hydrogen economy involves all economic stages between hydrogen production and hydrogen use, i.e., between renewable electricity received to electrolyzers and useful electricity drawn from fuel cells. Between the two ends of the economic chain hydrogen has to be packaged by compression or liquefaction to become a commodity. In the transportation, hydrogen has to be produced, packaged, transported, stored, transferred to cars, then stored and transported again before it is finally admitted to fuel cells.

All these processes require energy. Compared to natural gas (methane) or liquid fuels much more energy is required for the marketing of hydrogen. This is directly related to the physical properties of hydrogen (density 0.09 kg/m3, boiling point 20.3 K [160], [161]). Compared to methane, the volumetric energy density of hydrogen is less than one third. Even in the liquid state, the density of hydrogen (70 kg/$m^3$) is not much above the density of heavy duty styrofoam. Gasoline and even wood pellets carry 3.5 or 1.2 times more energy per volume than liquefied hydrogen. One cubic meter of the cold liquid holds 70 kg, the same volume of gasoline 128 kg of hydrogen. The best way to store hydrogen is in chemical combination with carbon. The volumetric higher heating values (HHV) of common energy carriers are shown in Fig. 7.1.

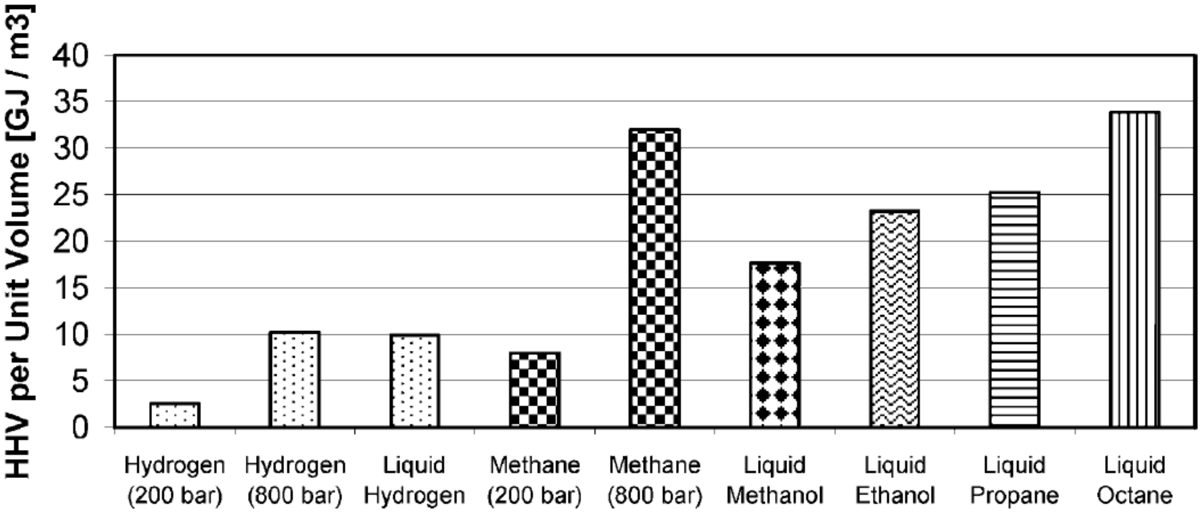


Figure 7.1 Volumetric HHV energy density of different fuels [162].

Figure 7.2 shows a global energy system in which electricity and hydrogen are produced from available energy sources and used in many applications. Both hydrogen and electricity complement renewable energy sources particularly well, by presenting them to the end user in a convenient form and at a convenient time. Depending on location, electricity may be used directly or transformed into hydrogen. For large-scale storage, hydrogen can be stored underground in ex-mines, caverns or aquifers. Fuel cells may be available in MW power plant size or several kW suitable for distributed power generation. Together with renewable energy sources, such as solar, wind and geothermal electricity and hydrogen form a clean energy system capable of permanently satisfying all the energy needs of human civilization.

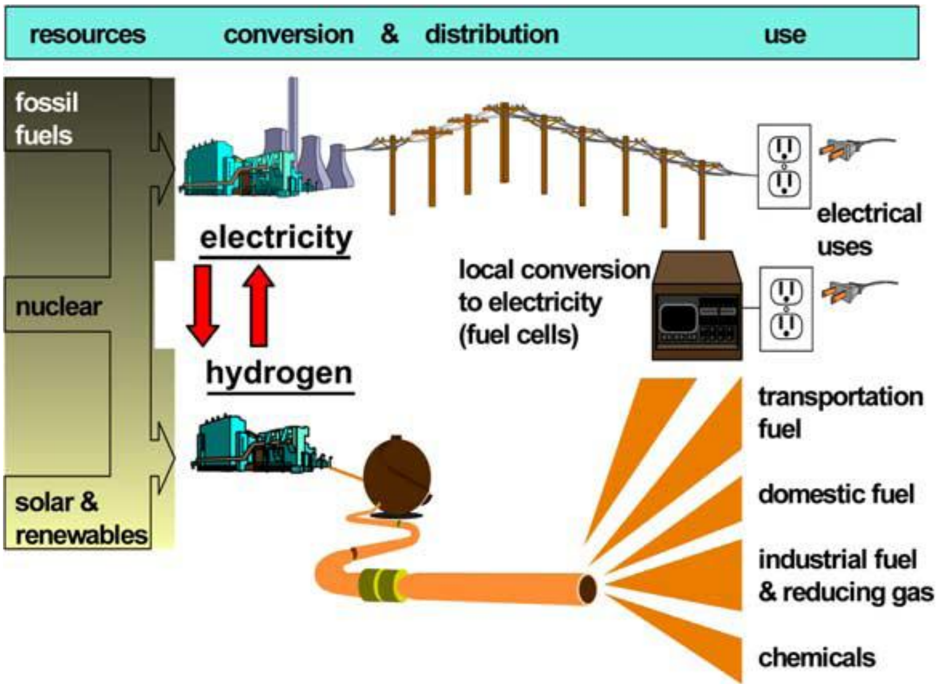


Figure 7.2 Hydrogen/electricity energy systems [163].

Technologies for hydrogen production from fossil fuels have been developed and are used to produce industrial hydrogen. These include steam reforming of natural gas, partial oxidation of hydrocarbons and coal gasification. Depending on the cost of fuel, hydrogen can be produced for 6–14 $/GJ [163]. However, these technologies depend on fossil fuels and emit $CO_2$. The only method that can generate hydrogen from fossil fuels without generation of $CO_2$ is direct thermal and catalytic cracking of hydrocarbons. This method has been used to produce carbon, but for cost effective hydrogen generation it is still in the early development phase [164].

Water electrolysis is relatively efficient (>70%), but because it needs electricity, hydrogen produced by water-electrolysis is expensive (>$20/GJ assuming a cost of about $0.05/kW h). However, there is a potential to generate relatively inexpensive hydrogen from geothermal power and nuclear plants.

Increasing demand for energy and growing awareness of global environmental problems need to produce more power while reducing pollution. Solution of the problem will depend on changing the present energy mix to include a greater portion of clean and safe energy technologies. Geothermal energy, as being a renewable energy resource, will thus have growing importance in meeting this effort.

The viability of geothermal power production is strongly influenced by the efficiency of converting geothermal heat to electricity and by the cost of equipment and construction. Geothermal power generation typically involves high levels of capital investment for exploration, drilling wells and installation of plant, but low operating costs because of the low marginal cost of fuel. Low temperature level of geothermal heat addition into the power plant cycle (120-250 °C) results in low thermal efficiency.

Additional generating capacity and improved efficiency may be obtained by re-powering existing geothermal power plants without drilling additional high cost-demanding geothermal wells. Re-powering without any additional well field cost, improving efficiency and generating capacity, can thus be a favorable option, since it conserves energy while reducing [165].

The use of geothermal energy for hydrogen production has been investigated for four cases: (1) using geothermal work output work as the input for an electrolysis process; (2) using part of geothermal heat to produce work for electrolysis process and part of geothermal heat in an electrolysis process to preheat the water, (3) using geothermal heat to preheat water in a high-temperature electrolysis process, and (4) using part of geothermal work for electrolysis and remaining part for liquefaction.

The effect of geothermal water temperature on the amount of hydrogen production is investigated for all four models, and it is observed that as the temperature of geothermal water increases the amount of hydrogen production increases. The results also indicate that greater amounts of hydrogen may be produced in Case 3 in the ideal process at 200°C (1.91 gr H2/kg water) compared to Case 1 (1.34 gr H2/kg water) and Case 2 (1.42 gr H2/kg water) for the same geothermal resource. Case 2 performs better than Case 1 because of the enhanced use of geothermal resource in the process. Case 4 (1.22 gr H2/kg water) allows both hydrogen production and liquefaction using the same geothermal resource, and provides a good solution for the remote geothermal resources. The second-law efficiencies of the models at a geothermal water temperature of 200°C are determined to be 28.5%, 29.9%, 37.2%, and 16.1% in Case 1, Case 2, Case 3, and Case 4, respectively indicating significant potential for system improvements.

The use of geothermal energy for hydrogen liquefaction has been investigated for three cases: (1) using geothermal output work as the input for a liquefaction cycle; (2) using geothermal heat in an absorption refrigeration process to precool the gas before it is liquefied in a liquefaction cycle; and (3 ) using part of the geothermal heat for absorption refrigeration to precool the gas and part to produce work and use it in a liquefaction cycle (i.e., cogeneration). The results indicate that geothermal absorption cooling for precooling of the gas yields significant savings in the work requirement for hydrogen liquefaction and is more advantageous than using geothermal work output in a liquefaction cycle. The use of renewable energy resources such as geothermal will likely continue to increase and diversify, especially for suitable applications. Using geothermal energy for hydrogen liquefaction may prove to be an important application. Further investigations considering both thermodynamic and economic analyses of technologies for accomplishing this process appear to be merited.

The use of renewable energy resources such as geothermal will likely continue to increase and diversify, especially for suitable applications. Using geothermal energy for hydrogen production may prove to be an important application. Further investigations considering both thermodynamic and economic analyses of technologies for accomplishing this process appear to be merited.

Geothermal energy has a significant potential on hydrogen economy where it can contribute sustainable production of hydrogen. In using geothermal energy the production of hydrogen can be viewed as a carbon free process. The geothermal plant generates the electricity for the electrolysis plant. Once the hydrogen is produced, storage and distribution methods need to be considered. Hydrogen is sometimes liquefied for storage. Geothermal power may be used for hydrogen liquefaction process. Geothermal heat may also be used for precooling hydrogen in an absorption refrigeration system before hydrogen is liquefied. These examples show that geothermal energy can be used in various ways in a sustainable hydrogen economy.

# REFERENCES

[1] Barbier E. (1997). Nature and technology of geothermal energy: a review. *Renewable and Sustainable Energy Reviews-An International Journal*; 1(2):1-69.

[2] Ozgener L., Hepbasli A., Dincer I. (2007). Parametric study of the effect of dead state on energy and exergy efficiencies of geothermal district heating systems. *Heat Transfer Engineering;* 28(4):357-364.

[3] Scott D.S. (2007). Smelling Land: The hydrogen defense against climate catastrophe. *Canadian Hydrogen Association*,

www.h2.ca.com.tr

[4] Syed M.T., Sherif S.A., Veziroglu T.N., Sheffield J.W. (1998). An economic analysis of three hydrogen liquefaction systems. *International Journal of Hydrogen Energy*; 23(7):565-576.

[5] Sherif S.A., Veziroglu T.N., Barbir F. (1999). Hydrogen Energy Systems. *Wiley Encyclopedia of Electrical and Electronics Engineering*, vol. 9, J. G. Webster (Editor). New York: John Wiley & Sons; pp. 370-402.

[6] Simpsona A.P., Lutzb A.E. (2007). Exergy analysis of hydrogen production via steam methane reforming. *International Journal of Hydrogen Energy*; 32(18):4811-20.

[7] Weber M.F., Dignam M.J. (1984). Efficiency of splitting water with semiconducting photoelectrodes. *Journal of Electrochemical Society*, 131 1258–1265.

[8] Konieczny A., Mondal K., Wiltowski T., Dydo P. (2008). Catalyst development for thermocatalytic decomposition of methane to hydrogen. *International Journal of Hydrogen Energy;* 33(1): 264-72.

[9] Mohan SV., Mohanakrishna G., Ramanaiah SV., Sarma PN. (2008). Simultaneous biohydrogen production and wastewater treatment in biofilm configured anaerobic periodic discontinuous batch reactor using distillery wastewater. *International Journal of Hydrogen Energy;* 33(2): 550-8.

[10] Balat M. (2009). Political, economic and environmental impacts of biomass-based hydrogen. *International Journal of Hydrogen Energy*; 34(9):3589-603.

[11] Kenneth A. Phair. (1994). Getting the most out of geothermal power. *Advanced energy system.* Mechanical Engineering, 76 September.

[12] Kunze J.F., Spencer S.G. (1978). The consumptive use of water in geothermal energy applications. *Proceeding of the congress on environmental aspects of non-conversion energy resources.* September.

[13] Hand T.W. (2008). *Hydrogen Production Using Geothermal Energy*, (M.Sc. Thesis), Utah State University, Logan, Utah.

[14] Jonsson VK., Gunnarsson RL., Arnason B., Sigfusson TI. (1992). The feasibility of using geothermal energy in hydrogen production. *Geothermics;* 21:673-81.

[15] Sigurvinsson J., Mansilla C., Lovera P., Werkoff F. (2007). Can high temperature steam electrolysis function with geothermal heat? *International Journal of Hydrogen Energy*; 32(9):1174-82.

[16] Mansilla C., Sigurvinsson J., Bontemps A., Maréchal A., Werkoff F. (2007). Heat management for hydrogen production by high temperature steam electrolysis. *Energy*; 32(4):423-30.

[17] Ingason HT., Ingolfsson HP., Jensson P. (2008). Optimizing site selection for hydrogen production in Iceland. *International Journal of Hydrogen Energy;* 33(14):3632-43.

[18] Farhar B., Dunlevy P. (2003). *Feds identify opportunites for potential geothermal development on public Lands.* U.S. Department of the Interior, April. http://www.doi.gov/news/030414b.htm

[19] Balta MT., Dincer I., Hepbasli A. (2009). Thermodynamic assessment of geothermal energy use in hydrogen production. *International Journal of Hydrogen Energy;* 34(7):2925–39.

[20] Balta MT., Dincer I., Hepbasli A. (2010). Potential methods for geothermal-based hydrogen production. *International Journal of Hydrogen Energy;* 35(10):4949–61.

[21] Kanoglu M., Dincer I., Rosen MA. (2007). Geothermal energy use in hydrogen liquefaction. *International Journal of Hydrogen Energy;* 32(17):4250-7.

[22] NASA. (1997). *Hydrogen in the Universe.* Retrieved on November 13. Palmer D.

[23] Florida Solar Energy Center. *Hydrogen Basics Production*. Retrieved on 2008-02-05. Staff.

[24] Goebel E., Coveney RM., Angino EE., Zeller EJ., Dreschoff GAM. (1994). Geology, Composition, Isotopes of Naturally Occurring H2/N2 Rich Gas from Wells near Junction City, Kansas. *Oil and Gas Journal,* Vol. 82, 217–222.

[25] Frank K., Goswami DY. (2007). *Handbook of energy efficiency and renewable energy.*

[26] Heydorn B.( 1998). *SRI Consulting Chemical Economics Handbook.* SRI Consulting, Menlo Park, CA.

[27] Yalçın A.H. (2006). *Nükleer enerji ile hidrojen üretimi ve küresel isınmaya etkileri.* (Yüksek Lisans Tezi), Gazi Üniversitesi Fen Bilimleri Enstitüsü.

[28] Bockris J.O.M. (1999). Hydrogen economy in the future, *International Journal of Hydrogen Energy,* 24, 1, 1-15.

[29] Fridleifsson I.B. (2003). Status of geothermal energy amongst the world's energy sources. *Geothermics,* 32, 4-6, 379-88,

[30] Florida Solar Energy Center (web site).

[31] Anıl reklam Mat. Ltd.Şti.(2006). *Hidrojen enerjisi teknolojileri*. Ankara: Şahin M.

[32] Glitnir Research (web site).

[33] National resources council/national academy of engineering.( 2004). *Hydrogen economy: opportunity, costs, barriers, and R&D needs.* Washington: National academy pres.

[34] Anderson E., Molter T., Mitlitsky F. ( 2002). Recent advances in hydrogen generation using PEM water electrolysis. *Presented at the 201st Electrochemical Society Meeting*. Philadelphia, May.

[35] Morse RW., Vance PW., Novak WJ., (Acreon Catalysts) and Franck JP., and Plumail JC., (Procatalyse). (1995). Improved reformer yield and hydrogen selectivity with trimetallic catalyst. *Presented at the 1995 NPRA Annual Meeting*. San Francisco, California, May 19-21.

[36] Oğuz AE. (2006). *Hidrojen yakıt pilleri ve PEM yakıt pilinin analizi*. (Yüksek Lisans Tezi), Gazi Üniversitesi, Ankara.

[37] Abraham B.M., Schreiner F. (1974). General principles underlying chemical cycles which thermally decompose water into elements. *I&EC Fundamentals* 13(4):305-310.

[38] Schunk L.O., Lipinski W., Steinfeld A. (2009). Heat transfer model of a solar receiver-reactor for the thermal dissociation of ZnO – Experimental validation at 10 kW and scale-up to 1 MW. *Chemical Engineering Journal* 150(2-3):502-508.

[39] Glandt E.D., Myers A.L. (1976). Hydrogen production from water by means of chemical cycles. *I&EC Process Design and Development* 15(1):100-108.

[40] Funk J.E., Reinstrom R.M. (1966). Energy requirements in the production of hydrogen from water. *I&EC Process Design and Development* 5(3):336-342.

[41] Dutta S. (1990). Technology assessment of advanced electrolytic hydrogen production. *International Journal of Hydrogen Energy*, 15, 379–85.

[42] Kruger P. (2006). *Alternative Energy Resources: The Quest for Sustainable Energy*. John Wiley & Sons, Inc., New Jersey,

[43] Green car congress. (2004). *Energy, technologies, ıssues and policies for sustainable mobility*. Milestone for $H_2$ Production by High-Temperature Electrolysis. 29 November.

[44] DiPippo R. (2008). *Geothermal Power Plants,* Second Edition, Elsevier Ltd.

[45] Nakagawa M. (2009). Lectures on Geothermal Energy. *Mining Engineering Department, Colorado School of Mines*. Spring, MNGN 498/MNGN598.

[46] Geo-Heat Center. (2000). Geothermal Power Generation. *A primer on low-temperature, small-scale applications*. January. Rafferty K.

[47] DiPippo R. (1999). Small Geothermal Power Plants: Design, Performance and Economics, *Geo-Heat Center Quarterly Bulletin*, Vol. 20, No. 2, June, Klamath Falls.

[48] Liu S., Quinlan P., Goggin M., Burns S., Yuzugullu, E., Lee K. (2006). Economic assessment of hydrogen generation for transportation applications using geothermal energy on the Island of Hawaii. *The US Department of Energy Office of Energy Efficiency and Renewable Energy*. Sentech Inc., 50624-011; 1 June.

[49] Sanner B. (2007). Geothermal Power Generation. Renewable Energy Europe 2007, Madrid, Spain, June 2007. http://www.egec.org/target/madrid%20280607.pdf.

[50] Kutscher C. (2004). Geothermal Electric Power. NREL, USA, May 20.

http://www.ncfap.org/documents/Kutscher%20
%20Geothermal%20for%20NASULGC.pdf.

[51] DiPippo R. (1999). Small Geothermal Power Plants: Design, Performance and Economics. *GHC Bulletin*. June, 1999, pp. 1-8. http:// geoheat.oit.edu/bulletin/bull20-2/art1.pdf.

[52] Balta M.T., Dincer ., Hepbasli A., (2009). Thermodynamic assessment of geothermal energy use in hydrogen production, *International Journal of Hydrogen Energy*, 34, 2925-39.

[53] Parrish W.R., Voth R.O. (1975). Cost and availability of hydrogen, selected topics on hydrogen fuel, *NBS Special Publication 419*, May, pp. 1.1/1.26.

[54] Syed MT., Sherif SA., Veziroglu TN., Sheffield JW. (1998). An economic analysis of three hydrogen liquefaction systems. *International Journal of Hydrogen Energy;* 23(7):565-76.

[55] Sarangi S. (1985). Cryogenic storage of hydrogen, in progress in hydrogen energy. *Proceedings of the National Workshop on Hydrogen Energy*, ed. R.P. Dahiya, New Delhi, July 4-6., pp. 123-132.

[56] Justi E.W. (1987). A Solar Hydrogen Energy System. Plenum Press, New York.

[57] Lipman M.S., Cheung H., Roberts P.O. (1963). Continuous conversion hydrogen liquefaction. *Chemical Engineering Progress*, 59, pp. 49-54.

[58] Block D.L., Dutta S., Raissi A.T. (1988). Hydrogen for power applications, Task 2: Storage of Hydrogen in Solid, Liquid and Gaseous Forms. *Florida Solar Energy Center,* Cape Canavral, Florida. Contract Report FSEC-CR- 204-88.

[59] Quack H. Die Schlu¨sselrolle der Kryotechnik in der Wasserstoff-Energiewirtschaft. Dresden, Germany: TU Dresden. [Online].

Available: www.tu dresden.de/mwiem/kkt/mitarbeiter/ lib/wasserstoff/wassertech.html.

[60] Gross R., Otto W., Patzelt A. (1994). Wanner M., Flu¨ssigwasserstoff fu¨r EuropaVdie Linde-Anlage in Ingolstadt Berichte aus Technik und Wissenschaften 71.

[61] Matsuda H., Nagami M. (1997). Study of large hydrogen liquefaction process. *Kanagawa,* Japan: Nippon Sanso Corp. [Online].

Available: http://www.enaa.or.jp/ WE-NET/ronbun/1997/e5/sanso1997.html.

[62] Linde Kryotechnik AG. Pfungen. Switzerland, private communication.

[63] Kestin J. (1978). Available Work in Geothermal Energy, US Department of Energy. *Division of Geothermal Energy*. Washington, DC.

[64] Friend D.G. (1992). NIST Mixture Property Database. Version 9.08. Fluid Mixtures Data Center. Thermophysics Division. *National Institute of Standards and Technology*, Boulder, CO 80303.

[65] Kanoglu M., Cengel Y.A. (1999). Improving the performance of an existing binary geothermal power plant: A Case Study, Trans ASME, *Journal of Energy Resources Technology*, 121, 4, 295-301.

[66] Kanoglu M. (2002). Exergy analysis of a dual-level binary geothermal power plant. *Geothermics,* 31,709–24,

[67] Ulleberg Q. (2003). Modeling of advanced alkaline electrolyzers: A System Simulation Approach. *International Journal of Hydrogen Energy*, 28, 1, 21-33,

[68] Divisek J. (1990). Water electrolysis in low- and medium-temperature regime. In: Wendt H, editor. *Electrochemical hydrogen technologies-electrochemical production and combustion of hydrogen*. Oxford, Elsevier.

[69] Maskalick N.J. (1986). High temperature electrolysis cell performance characterization. *International Journal of Hydrogen Energy*, pp. 563-570.

[70] Abraham B.M., Schreiner F.( 1974). General Principles Underlying Chemical Cycles which Thermally Decompose Water into the Elements. *Industrial Engineering Chemical Fundamentals,* Vol. 13, No. 4.

[71] Fletcher E.A., Moen R.L. (1977). Hydrogen and Oxygen from Water. *Science,* Vol. 197, pp. 1050-1056.

[72] O’Brien J.E., Stoots C.M., Herring JS., Lessing P.A., Hartvigsen J.J., and Elangovan, S. (2005 ). Performance Measurements of Solid-Oxide Electrolysis Cells for Hydrogen Production from Nuclear Energy. *Journal of Fuel Cell Science and Technology*, Vol. 2, August, pp. 156-163.

[73] Liu Mingyi, Yu Bo, Xu Jingming, Chen Jing. *Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China*. Two-Dimensional Simulation And Critical Efficiency Analysis of High-Temperature Steam Electrolysis System For Hydrogen Production.

[74] Kanoglu M., Dincer I., Rosen M.A. (2007). Geothermal energy use in hydrogen liquefaction. *International Journal of Hydrogen Energy*, 32, 4250–7.

[75] Barron R.F. (1985). Cryogenic systems. 2nd ed., New York, Oxford University Press.

[76] Timmerhaus K.D., Flynn T.M. (1989). Cryogenic Process Engineering. *The International Cryogenic Monographs Series.* New York: Plenum Press.

[77] Nandi T.K., Sarangi S. (1993). Performance and Optimization of Hydrogen Liquefaction Cycles. *International Journal of Hydrogen Energy*, 18, 2, 131-9.

[78] Babadağlı A. (2005). *Absorbsiyonlu Soğutma Sistemlerinin Termoekonomik Optimizasyonu*, (Yüksek Lisans Tezi). Süleyman Demirel Üniversitesi Fen Bilimleri Enstitüsü, Makine Eğitimi Anabilim Dalı, Isparta.

[79] Shrikhirin P., Aphornratana S., Chungpaibulpatana S. (2001). A Review of Absorption Refrigeration Technologies. *Renewable Sustainable Energy Rev*, 5, 343–72.

[80] Dickson M.H., Fanelli M., Bloomquist G. (2002). Economics and Financing. *Geothermal Energy* (UNESCO), Chapter 9.

[81] Ivy J., Golden S. (2004). Summary of Electrolytic Hydrogen Production, CO: *National Renewable Energy Laboratory;* NREL Report No. MP-560-36734, September, Pp: 27.

[82] Levene J. (2005). An Economic Analysis of Hydrogen Production from Wind. *Wind power. Production Case Studies.* www.hydrogen.energy.gov/h2a_prod_studies.html and American Wind Energy Association.

[83] Liébard A., Nahon C., Bal J. (2009). Worldwide electricity production from renewable energy sources. http://www.energiesrenouvelables.org/observer/html/inventaire/Eng/preface. asp, Edition.

[84] H2 A Model website. http://www.eere.energy.gov/hydrogenandfuelcells/analysis/model.html., Ocak, (2005).

[85] http://www.eere.energy.gov/geothermal/powerplants.htmlail.com. Energy Efficiency and Renevable Energy.

[86] The committee’s final report. (2004 ). The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D. Needs-was released in February, and is available at www.nap.edu.

[87] Tübitak. (2006). *Hidrojen Yakıt Pilleri Maliyeti*, Tübitak Yayınları.

[88] Eliassen B.E. (2002). Norsk Hydro Electrolyzers Electrolyzer Hydrogen Plant 485 Nm3/h Hydrogen. *Norsk Hydro Electrolyzers,* AS, 8 Aug.

[89] Christopher T., Amy R., Micah J. (2002). Geothermal Power Plant Potential Rico. Colorado.

[90] Klein C.W., Lovekin J.W., Sanyal S.K. (2004). New Geothermal Site Identification and Qualification. *Geotherm Ex*, Inc.

[91] Kemp B. (2007). Integrated Resource Planning in a Complex Market Place. Black & Veatch Presentation, February.

[92] Luzzi, A., Bonadio, L., McCann, M. (2004). In Pursuit of the Future: 25 Years of IEA Research Towards the Realization of Hydrogen Energy Systems, International Energy Agency Hydrogen Implementing Agreement. *International Energy Agency*, Paris, June.

[93] Cox K.E., Williamson Jr. K.D. (1979). *Hydrogen*, CRC Press Inc. Florida.

[94] EV World. (2003). Calculating hydrogen production costs, EV World: The World of Electric, *Hybrid & Fuel Cell Vehicles*, 21 Mart.

[95] Grégoire Padró C.E., Putsche V. (1999). Survey of the Economics of Hydrogen Technologies. *National Renewable Energy Laboratory,* 1617 Cole Boulevard Golden, Colorado. 80401-3393. September.

[96] Sigurvinsson J., Werkoff F. (2005). On The Cost of the Produced by Alkaline Electrolysis. *Proceeding Intenational Hydrogen Energy Congress And Exhibition, IHEC 2005,* Istanbul, Turkey, 13-15 July.

[97] Valdamir K., Jonsson B., Ragnar R., Arnason B. (1992). The Feasibility of Using Geothermal Energy in Hydrogen Production. *Geothermics*, 21, (5/6), 673-681.

[98] Dönitz W., Erdle R., Straicher R. (1990). High Temperature Electrochemical Technology For Hydrogen Production And Power Generation. *Electrochemical Hydrogen Technologies, in H. Wendth, Electrochemical Production And Combustion Of Hydrogen,* pp. 213-259. Elsevier, Amsterdam.

[99] Syed M.T., Sherif S.A., Veziroglu T.N., Sheffield J.W. (1998). An Economic Analysis of Three Hydrogen Liquefaction Systems, *International Journal of Hydrogen Energy*, 23, 7, 565–76.

[100] Block D.L., Dutta S. and Raissi A.T. (1988). Hydrogen for power applications, Task 2: Storage of Hydrogen in Solid, Liquid and Gaseous Forms. *Florida Solar Energy Center,* Contract Report FSEC-CR- 204-88. Cape Canavral, Florida,

[101] Lucas De. (2004). <http://www.ncbi.nlm.nih.gov/pubmed/15091314>.

[102] Şencan A., Yakut A.K., Kalogirou S.A. (2004). Exergy Analysis of Lithium Bromide/Water Absorption Systems. *Renewable Energy,* pp. 1–13.

[103] Adewusi S.A., Zubair S.M. (2004). Second Law Based Thermodynamic Analysis of Ammonia–Water Absorption Systems. *Energy Conversion and Management (inpress),* 45, 2355-69.

[104] Ilbilgi L. (2002). *Jeotermal enerji ile absorbsiyonlu sogutma ve diger sogutma alternatifleriyle ekonomik karsilastirmalar*. (Yüksek Lisans Tezi). Gazi Üniversitesi Fen Bilimleri Enstitüsü, Ankara; in Turkish.

[105] Kose R. (2007). Geothermal energy potential for power generation in Turkey: A case study in Simav, Kutahya. *Renewable and Sustainable Energy Reviews,* Volume 11, Issue 3, April, Pages 497-511.

[106] Huttrer G.W. (2001). The status of world geothermal power generation 1995–2000, Original Research Article. *Geothermics,* Volume 30, Issue 1, February Pages 1-27.

[107] Hepbasli A., Canakci C. (2003). Geothermal district heating applications in Turkey: a case study of Izmir–Balcova. *Energy Conversion and Management,* Volume 44, Issue 8, May. Pages 1285-1301.

[108] Acar H.I. (2003). A Review of Geothermal Energy in Turkey. *Energy Sources,* 25,1083–1088.

[109] Serpen U., Aksoy N., Öngür T., Korkmaz D. (2009). Geothermal energy in Turkey: 2008 update, *Geothermics*, Volume 38, Issue 2, June, Pages 227-237.

[110] Erdogdu E. (2009). A snapshot of geothermal energy potential and utilization in Turkey. *Renewable and Sustainable Energy Reviews,* Volume 13, Issue 9, December Pages 2535-2543.

[111] Köse R. (2005). Research on The Generation of Electricity From The Geothermal Resources in Simav Region, Turkey. *Renewable Energy,* Volume 30, Issue 1, January Pages 67-79.

[112] Ayanoğlu A. (2010). *Exergy And Exergoeconmıc Analysıs of Geothermal Assısted Hıgh Temperature Electrolysıs*, M. Sc. Thesıs In Mechanıcal Engıneerıng, Gaziantep, Turkey, August.

[113] Serpen U., Aksoy N., Öngür T., Korkmaz D. (2008). Geothermal energy in Turkey: 2008 update. *Geothermics*, 38, 227-237.

[114] Serpen U., Aksoy N., Ongur T., Korkmaz D. (2010). Geothermal Energy in Turkey: 2009 update, *Geothermics*, 40(2), 250–30.

[115] DPT. (1996). Jeotermal Enerji Çalışma Grubu Raporu, Madencilik Özel İhtisas Komisyonu Endüstriyel Hammaddeler Alt Komisyonu, T.C. Başbakanlık Devlet Planlama Teşkilatı Müsteşarlığı, Yayın No: DPT: 2441–ÖİK: 497, Mayıs.

[116] Serpen U, Ugur Z. (1998). Estimation of Water in Place of Kizildere Geothermal Reservoir. *Türkiye 12th Uluslararası Petrol Kongresi ve Sergisi,* Ankara, Ekim 12-15, syf. 305-313.

[117] DPT. (2006). Jeotermal Enerji Çalışma Grubu Raporu, Madencilik Özel İhtisas Komisyonu Endüstriyel Hammaddeler Alt Komisyonu, T.C. Başbakanlık Devlet Planlama Teşkilatı Müsteşarlığı, Yayın No: DPT: 2568–ÖİK: 588, Nisan.

[118] Ergün S., Civek E. (2007). Kütahya'da Jeotermal Enerji ve Kullanım Olanakları. *MPM Milli Prodüktivite Merkezi,* Ankara, Mart.

[119] Satman A., Serpen U., Korkmaz B. (2007). An Update on Geothermal Energy Potential of Turkey, Bildiri Kitabı, *32th Stanford Workshop on Geothermal Reservoir Engineering,* Stanford University, CA.

[120] Hand T.W. (2008). *Hydrogen Production Using Geothermal Energy,* (M.Sc. Thesis), Utah State University, Logan, Utah.

[121] Cloumann A., d'Erasmo P., Nielsen M., Halvorsen B.G., Stevens P. (1996). Analysis and Optimisation of Equipment Cost to Minimise Operation and Investment for a 300MW Electrolysis Plant. *Norsk Hydro Electrolysers AS,* Electricité de France, Direction de Etudes et Recherches.

[122] Timothy E. Lipman. (2004). What Will Power the Hydrogen Economy? *Present and Future Sources of Hydrogen Energy,* Analysis and Report Prepared for the Natural Resources Defense Council, UCD-ITS-RR-04-10, July 12.

[123] Thomas E., Drenne N., Jennifer E., Rosthal K. (2007). Pathways to a Hydrogen Future. *Elsevier Linacre House,* Jordan Hill, Oxford OX2 8DP, UK, First edition.

[124] Bollinger R.B., Aaron T.M. (2002). Low Cost Hydrogen Production Platform, Proceedings of the 2002 U.S. *DOE Hydrogen Program Review,* NREL/CP-610-32405, Praxair Corp., Tonawanda, NY.

[125] EV World. (2003). Calculating hydrogen production costs, EV World: The World of Electric. *Hybrid & Fuel Cell Vehicles*, 21 Mart.

[126] Kanoğlu M., Yılmaz C., Bolattürk A. (2009). Jeotermal Enerjinin Hidrojen Üretimi ve Sıvılaştırılmasında Kullanımının Termodinamik ve Ekonomik Analizi. *Tübitak 108ME226.* Dönem Raporu 3.

[127] Drennen T., Baker A., and Kamery W. (2003). Electricity Generation Cost Simulation Model (GenSim). *Sandia National Laboratories,*Version 2.0.

[128] Mann M.K., Spath W.A. (1998). Techno-economic Analysis of Different Options for the Production of Hydrogen from Sunlight, Wind, and Biomass, Proceedings of the 1998 U.S. *DOE Hydrogen Program Review,* NREL/CP-570-25315, Amos.

[129] Mirabal S.T. (2003). *An Economic Analysis of Hydrogen Production Technologies Using Renewable Energy Resources*, (Master's Thesis), University of Florida.

[130] Kanoglu M., Bolatturk A. (2009). Cost of Hydrogen Production by Geothermal Power. *Proceedings of the Fourth International Exergy Energy and Environment Symposium,* April 19-23, AUS, Sharjah, UAE.

[131] Sherif S.A., Barbir F., Veziroglu T.N. (2001). From hydrogen economy to hydrogen civilization, *International Journal of Hydrogen Energy,* Volume 26, Issue 9, September Pages 909-915.

[132] Benjamin M. (2003). Comparative cost of California Central Station Electricity generation technologies. *California Energy Commission,* June.

[133] Yuzugullu E., Genung K., Hoesly R. (2008). Analysis of geothermally produced hydrogen on the big island of Hawaii: A Roadmap For The Way Forward, University of Hawaii, *Hawaii Natural Energy Institute* (HNEI), Sentech Inc., 30 September.

[134] Sigurvinsson J., Mansilla C., Arnason B., Bontemps A., Maréchal A., Sigfusson TI., Werkoff F. (2006). Heat Transfer Problems for the Production of Hydrogen From Geothermal Energy. *Energy Conversion and Management,* 47, 20, 3543-51.

[135] Bak T., Nowotny J., Rekas M., Sorrell C.C. (2002). Photo-electrochemical hydrogen generation from water using solar energy. Materials-related aspects. *International Journal of Hydrogen Energy,* 27 991-1022.

[136] Bilgen E. (2001). Solar Hydrogen from Photovoltaic-electrolyzer Systems. *Energy Conversion and Management,* 42, 1047-1057,

[137] DOE Office of Energy Efficiency and Renewable Energy (January 2004). Solar Energy Technologies Program Multi-Year Technical Plan 2003-2007 and beyond.

[138] Šingliar M. (2007). Solar Energy Using For Hydrogen Production. *Petroleum & Coal,* 49, 2, 40-7.

[139] Jäger Waldau, A. (2007). Photovoltaics and renewable energies in Europe. *Renewable and Sustainable Energy Reviews,* 11, 1414–1437.

[140] The Hydrogen Economy. (2004). Opportunities, Costs, Barriers, and R&D Needs, National Academy of Engineering, Board on Energy and Environmental Systems, available also on web site : http://www.nap.edu/openbook.php?isbn=0309091632&page=103.

[141] http://www.nrel.gov/publications.

[142] Spinadel E., Gil J., Gamallo F. (2002). Wind-powered electrolysis for stand alone operation: An approach to a specific wind converter design. In: Proc. *14th World Hydrogen Energy Conference.* Montreal, Canada, June.

[143] Brown LC., Besenbruch GE., Lentsch RD., Schultz KR., Funk JF., Pickard PS., Marshall AC., Showalter SK. (2003). High Efficiency Generation Of Hydrogen Fuels Using Nuclear Power, Final technical report for the Period August 1, 1999 through September 30, 2002, *Prepared under the Nuclear Energy Research Initiative (NERI)* Program grant no. DE-FG03- 99SF21888 for the US Department of Energy, June.

[144] Besenbruch G.E., Brown L.C., Funk J.F., and Showalter S.K. (2001). High Efficiency Generation of Hydrogen Fuels Using Nuclear Power. In Nuclear Production of

Hydrogen: First Information Exchange Meeting-Paris, France 2-3, October 2000. *Organization for Economic Cooperation and Development,* Paris, France. October.

[145] Forsberg C.W., Peddicord K.L. (2002). Why Hydrogen Production from Nuclear Power? American Institute of Chemical Engineers' Spring National Meeting, New Orleans, LA, Paper139a, March 12.

[146] Singhal S.C., Kendall K. (2003). Solid Oxide Fuel Cells, *Elsevier Advanced Technology,* Oxford, UK.

[147] Yildiz B., Kazimi M.S. (2006). Efficiency Of Hydrogen Production Systems Using Alternative Nuclear Energy Technologies. *International Journal of Hydrogen Energy,* 31, 77–92.

[148] LaBar M.P. (2002). The Gas-Turbine-Modular Helium Reactor: A Promising Option for Near-Term Deployment, Intl. Cong. on Advanced Nuclear Power Plants, Hollywood, Florida.

[149] James E. O'Brien1, Carl M. Stoots, J. Stephen Herring, Grant L. Hawkes. (2006). Hydrogen Productıon From Nuclear Energy Vıa Hıgh Temperature Electrolysıs. *Idaho National Laboratory,* Idaho Falls, ID 83415. Paper: ECHI-I-IL-3.

[150] Srinivasan G., Suresh Kumar K.V., Rajendran B., and Ramalingam P.V. (2006).The fast breeder test reactor – design and operating experiences. *Nuclear Engineering and Design,* Vol. 236, pp.796–811.

[151] Rodrigo R.T., Christine M., Chakib B., François W. (2008). Hydrogen production by high temperature electrolysis coupled with an EPR, SFR or HTR: techno-economic study and coupling possibilities. *International Journal of Nuclear Hydrogen Production and Applications,* Vol. 1, No. 3.

[152] Hotza D., Diniz da Costa J.C. (2008). Fuel Cells Development and Hydrogen Production From Renewable Resources in Brazil. *International Journal of Hydrogen Energy,* 33, 4915-35.

[153] Brown LC., Besenbruch GE., Lentsch RD., Schultz KR., Funk JF., Pickard PS., Marshall AC., Showalter SK. (2003). High Efficiency Generation Of Hydrogen Fuels Using Nuclear Power, Final technical report for the Period August 1, 1999 through September 30, 2002, *Prepared under the Nuclear Energy Research Initiative (NERI) Program grant no.* DE-FG03- 99SF21888 for the US Department of Energy, June.

[154] Deutch J., Moniz E. (2003). MIT Releases Interdıscıplınary Study On The Future Of Nuclear Energy. Professors John Deutch and Ernest Moniz Chaired Effort to Identify Barriers and Solutions for Nuclear Option in Reducing Greenhouse Gases, July 29.

[155] Forsberg C.W. (2003). Production of Hydrogen Using Nuclear Energy. *Presentation to National Research Council Committee on Alternatives and Strategies for Future Hydrogen Production and Use,* Washington, D.C., January 22.

[156] Timothy, E. Lipman, What Will Power the Hydrogen Economy? Present and Future Sources of Hydrogen Energy, Analysis and Report Prepared for the Natural Resources Defense Council, UCD-ITS-RR-04-10, July 12, 2004.

[157] Barbir F. (1999). Integrated renewable hydrogen utility system. In: Proc. *DoE Hydrogen Program Annual Review Meeting,* Lakewood, CO, May1999.

[158] Bockris J.OM., Veziroglu T.N., Smith D. (1991). Solar Hydrogen Energy: The Power to Save the Earth. Optima, London.

[159] Bossel U. (2006). Does a Hydrogen Economy Make Sense, Electricity obtained from hydrogen fuel cells appear to be four times as expensive as electricity drawn from the electrical transmission grid, proceeding of the IEEE, October.

[160] Rifkin J. (2002). *The Hydrogen Economy*. New York: Tarcher.

[161] Properties of fuels. [Online]. Available: http://www.afdc.doe.gov/pdfs/fueltable.pdf.

[162] Weiss M.A., Heywood J.B., Schafer A., and Natarajan V. K., (2003). Comparative assessment of fuel cell cars, MIT LFEE 2003-001 RP, Feb.

[163] Veziroglu T.N., Barbir F. (1992). Hydrogen: The wonder fuel. *International Journal of Hydrogen Energy,*17 (6), 391–404.

[164] Muradov N.Z. (1998). CO2 free production of hydrogen by catalytic pyrolysis of hydrocarbon fuels. In: Bolcich, J.C., Veziroglu, T.N. (Eds.), Hydrogen Energy Progress XII, vol.1, Int. Association for Hydrogen Energy, Coral Gables, FL, pp. 523–532.

[165] Bloomster C. H., Knutsen C. A. (1989). The Economıcs Of Geothermal Electrıcıty Generatıon From Hydrothermal Resources. *Northwest Laboratories Richl and, Washington,* BNWL-, UC-13.