ISTANBUL TECHNICAL UNIVERSITY ★ ENERGY INSTITUTE

USE OF SOLAR AND WIND ENERGY IN HYDROGEN PRODUCTION FOR TRANSPORTATION

M.Sc. THESIS

Berk ÇETİNER

Energy Science and Technology Division

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Thesis Advisor: Dr. Lecturer Burak Barutçu

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ ENERJİ ENSTİTÜSÜ

ULAŞIM İÇİN HİDROJEN ÜRETİMİNDE GÜNEŞ VE RÜZGAR ENERJİSİNİN KULLANIMI

YÜKSEK LİSANS TEZİ

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To my precious family,

FOREWORD

Thanks for my dear teacher Dr. Lecturer Burak BARUTÇU who helps and guides me with comments and ideas throughout my studies. I would also like to thank my father Serdar ÇETİNER and my mother Seray ERDOĞAN who give me inexhaustible spiritual supports and adds strength to me.

December 2019

Berk ÇETİNER
(Mechanical Engineer)

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ABBREVIATIONS

AEL : Alkaline Electrolysis
AFC : Alkaline Fuel Cell
APUs : Auxiliary Power Units
CGHTE : Coal Gasification Integrated High Temperature Electrolysis
DOE : U.S. Department of Energy
FCEB : Fuel Cell Electric Buses
H-FCEVs : Heavy Duty Fuel Cell Electric Vehicles
HHV : Higher Heat Value
HTEL : High Temperature Electrolysis
L-FCEVs : Light Duty Fuel Cell Electric Vehicles
LHV : Lower Heat Value
LTVs : Light-Duty Vehicles
MOF : Metal Organic Frameworks
NASA : National Aeronautics and Space Administration
NTP : Natural Temperature and Pressure
PEM : Proton Exchange Membrane
PEMFC : Polymer Electrolyte Membrane Fuel Cell
SOE : Solid Oxid Electroyzer
UAV : Unmanned Aerial Vehicles

SYMBOLS

A : Rotor swept area of the wind turbine
C_p : Power coefficient
$CaTiO_3$: Perovskite
Cr : Chromium
Cu : Copper
ρ_{air} : Air density
P_{disp} : Power of wind turbine
P_{mec} : Mechanical power of wind turbine
Rh : Rhenium
Ru : Ruthenium
v : Wind speed

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USE OF SOLAR AND WIND ENERGY IN HYDROGEN PRODUCTION FOR TRANSPORTATION

SUMMARY

Fossil fuels have been used in lots of important sectors such as production of electricity, heating and transportation for years and especially after the industrial revolution its usage has been increased. The fossil fuels which have comprised of decaying through thermochemical reactions of the remainings of plants and animals in millions of years have not been seen as renewable energy source. In addition, the number of fossil fuels which are known worldwide are limited.

The biggest disadvantage of the usage of fossil fuel is the emission gases spreading around when they burn. These emission gases are not only harmful to the human health, but also create greenhouse effect and lead to problems such as global warming. The tendency towards clear energy sources like wind, sun, geothermal and hyrogen have been increased because of the risks such as climate change and the corruption of ecological balance.

Because of the risks such as climate change and the corruption of ecological balance, the tendency towards clear energy sources like wind, sun, geothermal and hyrogen have been increasing day by day with various incentives and investments of governments in order to reduce dependence on fossil fuels. Renewable energy systems are expensive in terms of setup; however, they have been maintaining their technological development. It is aimed to increase the efficiency of that systems and thus decrease the initial investment costs with the new technological developments.

A great deal of emission gases spreading to environment from fossil fuels have been coming from the transportation sector. In the transportation sector, using hydrogen as a fuel instead of fossil fuels is an important alternative in reducing harmful emissions to the environment because hydrogen-powered vehicles often use Polymer Electrolyte Membrane (PEM) fuel cells, which combine with hydrogen oxygen as a result of electrochemical reactions, so only water vapor is released to the outside when producing energy; therefore, without giving harm to nature, a clean energy is produced. Today, there are lots of studies which are state-sanctioned or aiming to increase the efficiency and durability of fuel cell technology of private institutions, in addition to these it is still a technology that is open to improvement.

A huge part of transportation sector is represented by especially public transport and it is aimed to reduce the harmful emission gases with the use of fuel cell buses which function with hydrogen instead of diesel fuel. There are lots of examples of public transpaort lines of fuel cell buses around the world but especially in America and Europe.

Since hydrogen does not existed in the nature as in its pure form, it is obtained through such processes. To obtain pure hydrogen, one of the most common methods is the electrolysis of water.

By providing the energy required for the electrolysis of water from clean energy sources such as solar, wind or hydroelectricity, the dependency of the transportation sector on fossil fuel is reduced, thus it reduces the harmful emission gases. In this thesis, various hydrogen production methods, hydrogen storage, hydrogen conduction, also fuel cell technology, the use of fuel cells in the transport sector, fuel cell performance, durability and the use of renewable energy types in the production of hydrogen are examined.

Although Turkey is dependent on the abroad in terms of fossil fuels, it is a country that lives 4 seasons due to its geographical location and the richness in renewable energy sources. This thesis subject aims to reduce Turkey’s dependence on fossil fuels and improve the environment and human health by obtaining pure hydrogen with clean energy sources and using this hydrogen in transportation sector.

In this thesis, the public transport line of 74 kilometres which is between Datça and Marmaris which are the counties of the city Muğla is discussed.

It is calculated how much hydrogen is needed based on the number of annual trips using hydrogen fueled buses instead of diesel fueled buses in the public transport line between Datça and Marmaris. Also, how the energy required for electrolysis to be supplied by solar and wind power plants to obtain the total hydrogen to be used in this public transport line by electrolysis is evaluated both separately and hybrid, in different scenarios.

In addition, optimization calculations of monthly energy production were made for the hybrid system by adjusting the tilt plane angle of the solar panels according to the seasons.

Muğla is an efficient region in terms of sun, in addition to this, the county Datça is efficent in wind due to its geographic features, that is why the line between Datça and Muğla is chosen for this study. For this transportation line, the energy required to produce hydrogen through electrolysis from wind power plants in Datça and from solar power plants in Marmaris is analyzed in detail.

Both solar and wind power plants are designed as connected to the grid, therefore, it is aimed to provide surplus electricity to the grid when there is excess electricity production and to provide the energy required to produce hydrogen from the grid when electricity production is low.

While the annual electricity production of wind power plant in Datça was calculated by different sized wind turbines through WAsP program, polycrystal solar panels are used in Marmaris and the annual energy production from the panels was calculated with the PVSyst program for different sized areas.

By promoting domestic production, renewable energy systems such as hydrogen, wind and sun, which have a high initial investment cost, might become advantageous in the long term for countries dependent on foreign fossil fuels such as Turkey.

Except for the transport line between Datça and Marmaris, by examining which renewable energy resources the region has in various regions, similar systems can be established that are completely independent of fossil fuels and do not spread emission gas to the nature.

With the current and future studies, through increasing the efficiency of both renewable energy systems and fuel cell technology, hydrogen powered vehicles can reach the level of not only durability but also economic competitiveness with fossil fuels; therefore, they can be an alternative to the fossil fuel powered vehicles.

ULAŞIM İÇİN HİDROJEN ÜRETİMİNDE GÜNEŞ VE RÜZGAR ENERJİSİNİN KULLANIMI

ÖZET

Fosil yakıtlar özellikle sanayi devrimi ile kullanımı artan ve uzun yıllardan beri elektrik üretimi, ısıtma, ulaştırma sektörü gibi birçok önemli sektörde en çok kullanılan yakıt tipi olmuştur. Milyonlarca yıl içerisinde bitki ve hayvan artıklarının termokimyasal tepkimeler ile çürümesiyle oluşan fosil yakıtlar, yenilenebilir bir enerji kaynağı olarak kabul edilmezler buna ek olarak dünya üzerindeki bilinen fosil yakıt kaynakları da sınırlıdır.

Fosil yakıt kullanımının en büyük dezavantajı yandıklarında çevreye yaydığı emisyon gazlarıdır. Bu emisyon gazları, insan sağlığına zararlı olmasının yanında sera gazı etkisi yaratmakta ve küresel ısınma gibi sorunları beraberinde getirmektedir. İklim değişikliği ve ekolojik dengenin bozulması gibi risklerden ötürü günden güne rüzgar, güneş, jeotermal ve hidrojen gibi temiz enerji kaynaklarına eğilim artmıştır.

Son yıllarda fosil yakıtlara bağımlılığı azaltmak amacıyla hükümetlerin çeşitli teşvik ve yatırımları ile dünya genelinde özellikle rüzgar, güneş, biyokütle, jeotermal gibi alternatif enerji kaynaklarına eğilim günden güne artmaktadır. Yenilenebilir enerji sistemleri kurulum maliyeti açısından pahalı sistemlerdir ancak halen teknolojik olarak gelişmesini sürdürmektedirler. Yeni teknolojik gelişmelerle yenilenebilir enerji sistemlerinin verimliliğini arttırmak ve böylelikle ilk yatırım maliyetlerinin zamanla azaltılması hedeflenmektedir.

Fosil yakıtlardan çevreye yayılan emisyon gazlarının büyük bir miktarı ulaşım sektöründen gelmektedir. Ulaşım sektöründe fosil yakıtlar yerine hidrojenin yakıt olarak kullanılması çevreye salınan zararlı emisyon gazlarını azaltma açısından önemli bir alternatif olmaktadır çünkü hidrojen ile çalışan araçlarda genellikle Polimer Elektrolit Membran (PEM) yakıt pilleri kullanılmaktadır ve bu teknoloji sayesinde elektrokimyasal tepkimeler sonucu hidrojen oksijen ile birleşir ve bu işlemin sonunda enerji üretilirken dışarıya sadece su buharı salınmaktadır bu sebeple doğaya bir zararı olmayan temiz bir enerji üretilmiş olur. Günümüzde devlet destekli veya özel kurumların yakıt pili teknolojisinin verimini ve dayanıklılığını arttırmayı hedefleyen bir çok araştırma ve geliştirme çalışması bulunmakla birlikte günümüzde halen gelişmeye açık bir teknolojidir.

Özellikle toplu taşıma, ulaşım sektörünün büyük bir bölümünü temsil etmektedir ve toplu taşımada dizel yakıtla çalışan otobüslerin yerine hidrojen ile çalışan yakıt pilli otobüslerin kullanımı ile zararlı emisyon gazlarının ciddi şekilde azaltılması hedeflenmektedir. Dünya üzerinde özellikle Amerika ve Avrupa kıtalarında yakıt pilli otobüslerin çalıştığı bir çok toplu taşıma hattı örneği bulunmaktadır. Hidrojen üretim ve dolum tesislerinin sayısı son yıllarda artmıştır ve her geçen gün sayıları daha da artmaktadır.

Hidrojen doğada saf halde bulunmadığı için ancak bir takım işlemler vasıtasıyla saf hidrojen olarak elde edilmektedir. Saf hidrojenin elde edilmesi için en çok kullanılan yöntemlerden biri suyun elektrolizi yöntemidir.

Suyun elektrolizi için gerekli enerjinin güneş , rüzgar veya hidroelektrik gibi temiz enerji kaynaklarından sağlanması ile ulaşım sektörünün fosil yakıta bağımlılığı azaltılır böylelikle zararlı emisyon gazları düşürülmüş olur. Tez çalışmamızda çeşitli hidrojen üretim yöntemleri, hidrojen depolama, hidrojen iletimi gibi konuların yanında yakıt pili teknolojisi, yakıt pillerinin taşıma sektöründe kullanılması, yakıt pillerinin performansı, dayanıklılığı ve hidrojen üretiminde yenilenebilir enerji türlerinin kullanımı gibi konular incelenmiştir.

Türkiye fosil yakıtlar konusunda dışa bağımlı bir ülkedir ancak coğrafi konumu ve özellikleri sebebiyle dört mevsimi yaşayan bir ülke olduğu için yenilenebilir enerji kaynakları açısından da zengindir. Tez çalışması, temiz enerji kaynaklarından elde edilecek enerji ile saf hidrojenin elde edilmesi ve bu hidrojenin ulaşım sektöründe kullanılması ile Türkiye'nin hem fosil yakıtlarda dışa bağımlılığını azaltmayı hem de çevre ve insan sağlığı açısından daha iyi bir seviyeye getirmeyi amaçlamaktadır.

Tez çalışmamızda Türkiye'nin Ege bölgesinde bulunan Muğla ilinin Datça ve Marmaris ilçeleri arasında kullanılan 74 km'lik toplu taşıma hattı ele alınmıştır.

Datça ve Marmaris arası toplu taşıma hattında kullanılan dizel yakıtla çalışan otobüslerin yerine hidrojen yakıtlı otobüslerin kullanılması sonucu yıllık yaptığı sefer sayısı baz alınarak ne kadar hidrojene ihtiyaç duyulduğu hesaplanmıştır. Ayrıca bu çalışmada, bu toplu taşıma hattında kullanılacak toplam hidrojenin suyun elektroliz yoluyla elde edilmesi durumunda elektroliz için gereken enerjinin güneş ve rüzgar santralleri ile nasıl karşılanacağı hem ayrı hem de hibrit olacak şekilde farklı senaryolar şeklinde değerlendirilmiştir. Ayrıca tez çalışmamızda, güneş panellerinin eğim düzlemi açıları mevsimlere göre ayarlanarak hibrit sistem için aylık enerji üretimi için optimizasyon hesaplamaları yapılmıştır.

Muğla ili güneşlenme süresi açısından verimli bir bölgedir buna ek olarak Datça ilçesi coğrafi özellikleri sebebiyle rüzgar açısından verimli olduğundan tez çalışmamız için Datça ile Marmaris arasındaki toplu taşıma hattı seçilmiştir. Bu toplu taşıma otobüs hattı için elektrolizle hidrojenin üretimi için gereken enerjinin Datça ilçesinde rüzgar santrallerinden ve Marmaris ilçesinde güneş santrallerinden karşılanma durumları tez çalışmamızda detaylı olarak incelenmiştir. Rüzgar türbinleri için üç farklı senaryo incelenirken, güneş santralleri için iki farklı senaryo incelenmiştir

Hem güneş santrali, hem de rüzgar santrali şebekeye bağlı olarak tasarlanmıştır böylelikle fazla elektrik üretiminin olduğu zamanlarda elektrik fazlasının şebekeye verilmesi ve elektrik üretiminin az olduğu zamanlarda hidrojen üretimi için gerekli enerjinin şebekeden sağlanması amaçlanmıştır.

Datça'daki rüzgar santralinin yıllık enerji üretimi WASP programı ile farklı büyüklüklerdeki rüzgar türbinleri kullanılarak hesaplanırken, Marmaris'deki güneş santralinde polikristal güneş panelleri kullanılmıştır ve panellerden yıllık enerji üretimi farklı boyutlardaki alanlar için PVSyst programı ile hesaplanmıştır.

İlk yatırım maliyeti yüksek olan rüzgar, hidrojen ve güneş gibi yenilenebilir enerji sistemleri yerli üretim teşviği ile Türkiye gibi fosil yakıtlar konusunda dışa bağımlı ülkeler için uzun vadede avantajlı hale gelebilir.

Datça ve Marmaris arasındaki toplu taşıma hattı dışındaki çeşitli bölgelerde bölgenin hangi yenilenebilir enerji kaynaklarına sahip olduğu incelenerek tamamen fosil yakıtlardan bağımsız ve çevreye emisyon gazı vermeyen buna benzer sistemler kurulabilir.

Mevcut durumda yapılmakta olan ve gelecekte yapılacak çalışmalar ile hem yenilenebilir enerji sistemlerinin hem de yakıt pili teknolojisinin verimlerinin arttırılmasıyla hidrojen ile çalışan araçlar hem dayanıklılık hem de ekonomik olarak fosil yakıtlarla çalışan araçlarla rekabet edecek seviyeye gelebilir ve dolayısıyla fosil yakıtla çalışan araçlara iyi bir alternatif olabilir.

1. INTRODUCTION

Hydrogen is an important energy carrier and it can be produced with water and electricity. Heat or energy conversion of hydrogen is clean and simple. When hydrogen is burned with oxygen, it forms water and does not emit contaminated gases. In this way, water has the chance to return to nature, that is where it came from. Although hydrogen is the most abundant element in nature, however it is not pure in nature. Hydrogen is separated from chemical compounds by electrolysis of water also it can be obtained by chemical process of other hydrogen carriers such as hydrocarbons, ethanol. The energy requirement for electrolysis can be harnessed from renewable energy sources such as solar, wind or geothermal. Thus, hydrogen can matter between renewable energy sources and chemical energy carriers in terms of clean energy. In this thesis, the comparison of hydrogen with other fuels, chemical properties of hydrogen, the use of hydrogen as a fuel in vehicles, hydrogen delivery and hydrogen storage are examined.

There are many hydrogen production techniques. Hydrogen production is carried out using fossil fuels, steam reforming of light hydrocarbons, partial oxidation of heavy hydrocarbons, partial oxidation of coal and electrolysis of water. In terms of environmental health and global warming, it is the healthiest method since the emission gas is not emitted in the production of hydrogen by the electrolysis method of water, but if the electricity used in the electrolysis process is provided with fossil fuels, it does not have any importance in terms of environmental health. Research and developmental studies are continuing to increase the efficiency of electrolysers. Although the initial investment costs of these technologies are high, electrolysis of water should be applied for the production of a completely clean hydrogen and renewable and clean energy sources such as sun and wind should be used while generating the electrical energy to be used in the electrolysis process.

For this reason, the electrolysis method of water was used in the production of hydrogen in this study. To produce required energy for the electrolysis process, wind turbines and solar panels were examined. Furthermore, both electrolysis types and other hydrogen production methods were evaluated in terms of operating temperature and efficiency. In addition, our study includes the use of renewable energy sources such as solar, wind and hydroelectric in the production of hydrogen.

The use of fossil fuels has increased significantly in the world, especially with the industrial revolution. With increasing population and industrialization, emission gases over the world has increased day by day and reached critical levels. Our world is faced with dangers such as global warming and disruption of ecological balance due to emission gases. The transport sector is one of the most important sectors that play a role in the increase of emission gases. Hydrogen or electric powered vehicles can be a good alternative to vehicles which use fossil fuels. Today, many electric and hydrogen-powered vehicles have been produced and are still under development. Hydrogen powered vehicles can operate with internal combustion or fuel cell technology which is the most popular method recently. Fuel cells are devices for transforming clean and renewable energy sources into efficient energy. The electrochemical reaction of the fuel and air converts the chemical energy of the fuel directly into electrical energy. The reaction produces pure water and heat, so that no emission gas is released to the outside. After the fuel cell reaction, which can be defined as the reverse reaction of electrolysis, electricity is produced in the form of direct current (DC). Recently, many researches and developments are carried out in order to increase the durability and performance of fuel cells. In our study, fuel cell technology, usage areas, new studies on durability and efficiency increase, usage of fuel cells in transportation sector, hydrogen filling stations and hydrogen storage in vehicles were examined.

Due to its geographical location, Turkey is a country that lives four seasons. Thus, especially in the South Western region of Turkey is efficient in terms of the solar energy. In addition, due to their geographic shapes, some regions of Turkey are efficient in terms of wind energy. Instead of using fossil resources, Turkey should be directed to clean energy sources and thus would have reduced the dependence on fossil fuels and also will have achieved an important step both for the environment and human health. Muğla Province is located in South-West of Turkey.

Due to its proximity to the sea, it is a summer place and population in summer usually is more crowded than other periods. Muğla province is a rich region in terms of solar radiation values. Thus, this condition makes Muğla an important place for obtaining energy from the sun. Datça is a district of Muğla province and it receives a lot of wind due to its orographic shape. This situation makes Datça attractive for electricity generation from wind energy. As it is efficient in terms of wind and solar energy, the public transportation line between Datça and Marmaris is chosen for our project. Since the electricity required for the production of hydrogen will be produced by wind and solar, it will be advantageous to establish a hydrogen production facility in Muğla. Furthermore, the establishment of filling stations in Muğla to meet the hydrogen needs of fuel cell buses will eliminate the costs of hydrogen delivery.

The public transport line between Datça and Marmaris is approximately 74 km and currently 12 m diesel buses are used in this route. Currently used diesel buses require a significant amount of diesel fuel for 1 year and emission gases are released to the environment due to the combustion of this diesel fuel. In our study, the emission amounts per km emitted by diesel buses operating on the public transportation line between Datça and Marmaris for 1 year were calculated as CO_2 , NO_x, particulate matter and total hydrocarbon. In addition, our thesis includes the calculation of the amount of diesel fuel required for this public transportation line in liters. Our study proposes the use of renewable energy sources for hydrogen production and the replacement of diesel buses used in public transport with fuel cell buses. In this way, Turkey can reduce the dependency on foreign countries for fossil fuels and also the amount of emissions which emitted by diesel buses would be reduced to 0 which will be beneficial in terms of human health and environmental health.

12-meter fuel cell buses were used instead of 12-meter diesel buses in our study. The amount of hydrogen required by fuel-celled buses for 1 year was determined by calculating the route covered on the public transport line for 1 year and using the average value burned per 100 km of various 12-meter fuel cell buses. U.S. Deparment of Energy's 2011 data were used to calculate the amount of electricity required for the hydrogen production by water electrolysis.

Datça and Marmaris regions were selected for the location of the power plants that will generate the necessary electrical energy for our project. The system is designed as on-grid. Datça region was selected for the installation of wind turbines. The vector map of the region was created with the Global Mapper software by using satellite data. Calculations were made with WAsP program. Wind measurement station of Turkish State Meteorological Service in Datça which is located at 36.42 °N latitude and 27.41 °E longitude is used for the measurements of the wind speed and direction. Wind speed and direction data were recorded per hour. Totally 1 year wind speed and direction data were used. Vestas and Nordex branded wind turbines with 3 different power outputs of 225 kW, 800 kW and 3 MW are used to calculate the annual energy production.

Marmaris region were chosen to supply the energy required from the sun. PVSyst software is used in calculations of annual yield and nominal power. Muğla MeteoNorm 7.1 station is used for solar measurement which is located at 37.20 °N latitude and 28.35 °E longitude (Massachusetts Institute of Technology, 2019). The system is designed to be on-grid. Standard is selected as module type and polycrystalline technology is selected as technology. Also system is designed to be ground based and free standing. Two different scenarios of 11,150 and 15,750 m^2 were designed for the generation of electricity from solar power plants in Marmaris.

In the conclusion part of our study, it is examined which wind turbine with power output is required only in case of using wind energy for hydrogen production. In addition, the potential of the region in terms of larger scale projects was evaluated by calculating the energy to be obtained from the 3 MW Vestas brand wind turbine. In addition, it is examined that how many square meters area is needed for solar power plant only if solar energy is used for hydrogen production. Furthermore, a hybrid system in which both solar and wind energy is utilized in hydrogen production was evaluated. 225 kW Vestas brand wind turbine and polycrystalline cells installed on an area of 11,150 m^2 were used for the evaluation of hybrid system.

The first part of the thesis presents the general properties of hydrogen, the benefits of using hydrogen as a fuel, the use of fuel cells in the transport sector, why the public transport line between Datça and Marmaris was chosen for our project and which programs and data were used for the calculations.

In the second part of the thesis, the properties of hydrogen as fuel, hydrogen production, storage and transportation methods, the use of fuel cells in the transport sector, fuel cell durability and performance, usage of renewable energy sources in terms of hydrogen production also current and still developing technologies in these areas were discussed.

The third part of the thesis presents calculation of the amount of emission to be reduced as a result of replacing the diesel buses used in the bus line between Datça and Marmaris with fuel cell buses. In this section, wind and solar power plants of different scales were designed for the generation of the electrical energy required for hydrogen production and annual power generation for each power plant were calculated. Furthermore, the third section includes the amount of fossil fuel to be saved by using fuel cell buses and the amount of hydrogen required for the total distance covered for 1 year.

In the final section, three different systems were evaluated for the supply of 1 year energy requirement to produce hydrogen. Annual energy productions were calculated in terms of usage hybrid systems, usage only solar energy or wind energy.

2. LITERATURE REVIEW

2.1 Hydrogen Properties and Comparison with Other Fuel Types

The smallest atom hydrogen is considerably acknowledged by its physical properties (G. H. Aylward, 1999). As a result, the hydrogen is the lighest gas. For instance, methane is eight times heavier than hydrogen. Gravimetric higher heating value (HHV)(R. F. Probstein R, 1982) of one of these fuel gases does not have a significant applicability for practical utilizations. In most cases, the convenient volume for fuel tanks has a limitation in some applications such as automotive application also there is a restriction of increment of pipelines' diameters arbitrarily. In the light of this information, using a reference volume is more accountable to explain the energy content of fuel gases. The actual energy content of the fuel is established on the energy conservation principle which is the 1st Law of Thermodynamics. Therefore, it is more appropriate to use the higher heating value (HHV) and heat of formation for this energy analysis.

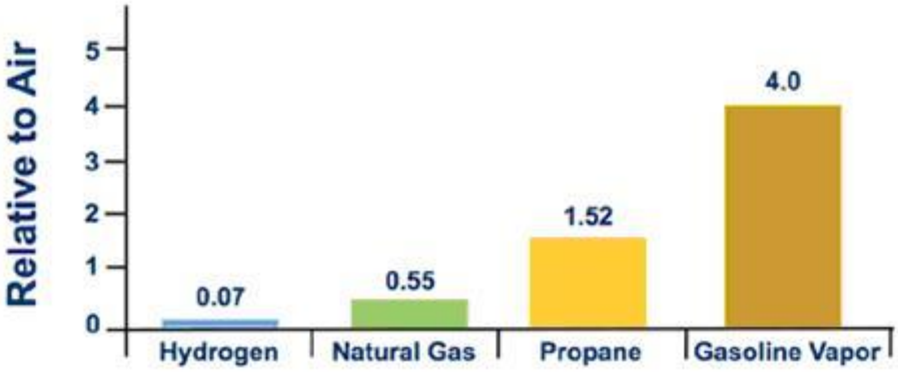


Figure 2.1 : Relative Vapor Density (H2 Tools, 2019).

Nevertheless, in 19th century boiler engineers created a technical standard called the lower heating value (LHV) when they confronted with the problems of corrosion caused by condensation of sulfuric acid and other 5 aggressive substances in the chimneys of coal-fired furnaces. The hydrogen production is administered by the higher heating value (HHV) or the heat of formation therefore the usage of the production should be relevant to its HHV energy content as well.

The following table demonstrates the volumetric higher heating values for hydrogen and methane at 1 bar and 25 °C.

Table 2.1 : Volumetric Higher Value for Hydrogen and Methane at 1 bar and 25°C(Ulf Bossel, 2019).

	Units	Hydrogen	Methane
Density at NTP	kg/m 3	0.09	0.72
Gravimetric HHV	MJ/kg	142.0	55.6
Volumetric HHV	MJ/m3	12.7	40.0

It is distinctly can be seen that octane, propane, methanol or methane carries more energy per volume than hydrogen gas at any pressure. As it is shown in the Figure 2.2 below, the volumetric energy density of liquid hydrogen is 10 GJ / m^3. However, the gaseous hydrogen reaches the same volumetric energy density at 800 bar pressure. But apart from this, methane gas' volumetric energy density surpasses that of hydrogen gas by a factor of 3.2 at any pressure. It should also be stated that it is claimed by neglegting the non-ideal gas effects. It is also clear that octane (gasoline), propane and methanol outreach liquid hydrogen by factors from 3.4 to 1.8 as other liquid energy carriers. Another important fact is whereas liquid fuels can be preserved in unsophisticated contaniers, liquid hydrogen at 800 bar pressure must be kept in hi-tech pressure tanks or cryogenic containers.

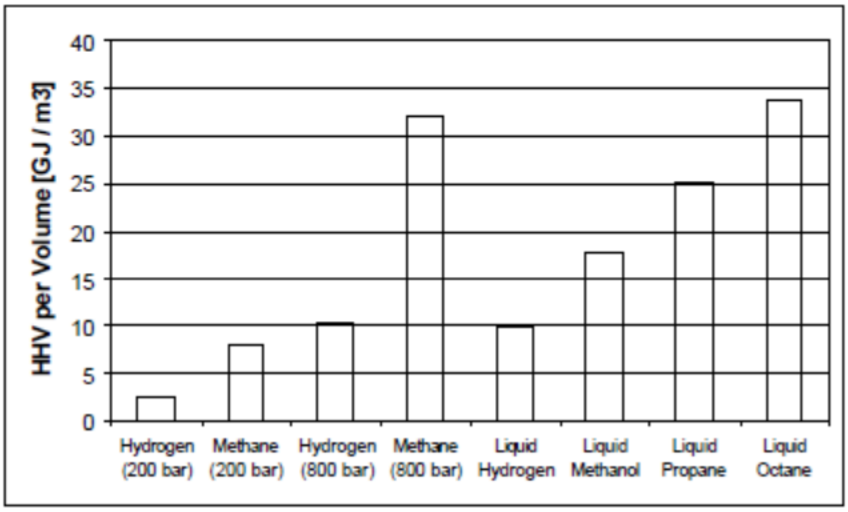


Figure 2.2 : Comparison of HHV per volume of different fuels (Ulf Bossel, 2019).

<u>Chemical properties of hydrogen</u> (Yumurtacı, 2002):

Atomic Number: 1

Atomic Mass: 1,008

Melting Temperature: -259,14 °C

Boiling Temperature: -252,87 °C

Oxidation Degree: +1

Specific Mass: 0,071 g/cm^3

Isotopes: 2 and 3

2.2 Hydrogen Production

Hydrogen is not a natural fuel, it is a synthetic fuel which can be produced from different raw materials by using primary energy sources. All energy sources can be used in hydrogen production. The raw materials used are water, fossil fuels and biomass materials. The basic principle is to produce fuel hydrogen from water with renewable energy. Hydrogen production methods include fossil fuels, hydroelectric resources, geothermal energy, solar and wind energy. The most important method for the future is to utilize renewable energy types such as photovoltaic solar panels or wind turbines (Yumurtacı, 2002).

Conventional technologies for hydrogen production include catalytic vapor reforming of natural gas, partial oxidation of heavy oil, gasification of coal, steam-iron process and electrolysis of water. Conventional technologies where hydrogen is obtained as a by-product are the production of counter-chlorine from chlorine-alkali, coke production from coal in coke ovens and chemical dehydrogenation processes. In addition, although hydrogen can be obtained by decomposition of ammonia and methanol, these two processes are not essential for hydrogen production (Yumurtacı, 2002).

There are also technologies under development. These include electrolysis of steam at high temperature, electroconductive membrane process of gasified coal and coal gasification integrated high temperature electrolysis (CGHTE). In addition, thermochemical disintegration of water, plasma-sun and radiation processes, solar photovoltaic water electrolysis are other advanced methods. Direct electrolysis of water, thermochemical production and photobiological production methods have gained weight for the production of hydrogen to be used as fuel.

With the desire to benefit from solar energy in the production of hydrogen, the importance of solar photovoltaic-hydrogen energy systems is emphasized in order to produce electrical energy to be used in electrolysis from photovoltaic panels (Yumurtacı, 2002).

2.2.1 Hydrogen production from fossil fuels

Nearly all of the 500 Nm^3 hydrogen used as fuel in the world is produced by using fossil fuels. However, due to environmental health and the depletion of fossil fuels in the long term, a cleaner and more modern method will be used (Yumurtacı, 2002).

2.2.2 Steam reformation of light hydrocarbons

This method is among the methods applied today. Steam reformation is the endothermic, catalytic conversion of light hydrocarbons such as methane, gasoline with water vapor. This process usually occurs at a temperature of 850 °C and a pressure of 2.5 MPa.

The equation of the reaction is:

$$C_nH_m + nH_2O \leftrightarrow \ n\,CO + (n + \tfrac{m}{2}) \tag{2.1}$$

Pure hydrogen is formed from the exothermic catalytic conversion of the resulting carbon monoxide, The equation of the reaction is:

$$CO + H_2O \leftrightarrow \ CO_2 + H_2 \tag{2.2}$$

The carbon monoxide in the mixture is removed by suction. Hydrogen production by this method is quite common. A steam reforming facility can produce 100,000 Nm^3 of hydrogen per hour. In this method, natural gas is mostly used as light hydrocarbon (Yumurtacı, 2002).

2.2.3 Partial oxidation of heavy hydrocarbons

Waste produced during the refining process of crude oil is called heavy hydrocarbon. Hydrogen can be obtained by exothermic or autothermal conversion of heavy hydrocarbons with the help of oxygen and steam.

The amount of oxygen and water vapor can be controlled autothermally without the need for an external energy input.

The process occurs as it is stated below:

$$CH_{1.4} + 0.3H_2O + 0.4\,O_2 \leftrightarrow 0.9\,CO + 0.1\,CO_2 + H_2 \tag{2.3}$$

It is a method used today and production facilities with a capacity of 100,000 Nm^3/h hydrogen can be established (Yumurtacı, 2002).

2.2.4 Partial oxidation of coal

It is similar to partial oxidation method with heavy hydrocarbon from the viewpoint of process. However, the coal to be used must be pulverized and pumped. This method is mostly used in countries has rich coal reserves (Yumurtacı, 2002).

2.2.5 Hydrogen Production from natural gas

This method is in the trial phase rather than in common use. Hydrocarbons are first separated into hydrogen and pure carbon at 1600 °C by plasma – arc (welding) process. Natural gas or fuel-oil is used as the primary energy source for this method.

In addition, cooling water and electricity are required for the process. Studies on this field in Norway, 2000 Nm^3/h hydrogen and 500 kg/h pure carbon were produced by using 2100 kWh electricity from 1000 Nm^3/h natural gas.

As a result of the process, steam is formed at high temperature. The facility operates at full efficiency as all of the products released have potential for use.

In mobile applications, due to the high energy density and ease of storage, the reforming and partial oxidation of methanol and diesel is gaining importance in hydrogen supply for fuel cells (Yumurtacı, 2002).

2.2.6 Hydrogen production with water electrolysis

As can be seen in Figure 2.3, The electrolysis process generally consists of electrodes (anode and cathode), electrical source (direct current), and a conductive electrolyte.

For both basic and acid electrolytes, oxidation formation at the anode and lowering in cathode are observed by subsequent hydrogen production. Differences in species occurring in oxidoreduction process; proton and hydroxylions.

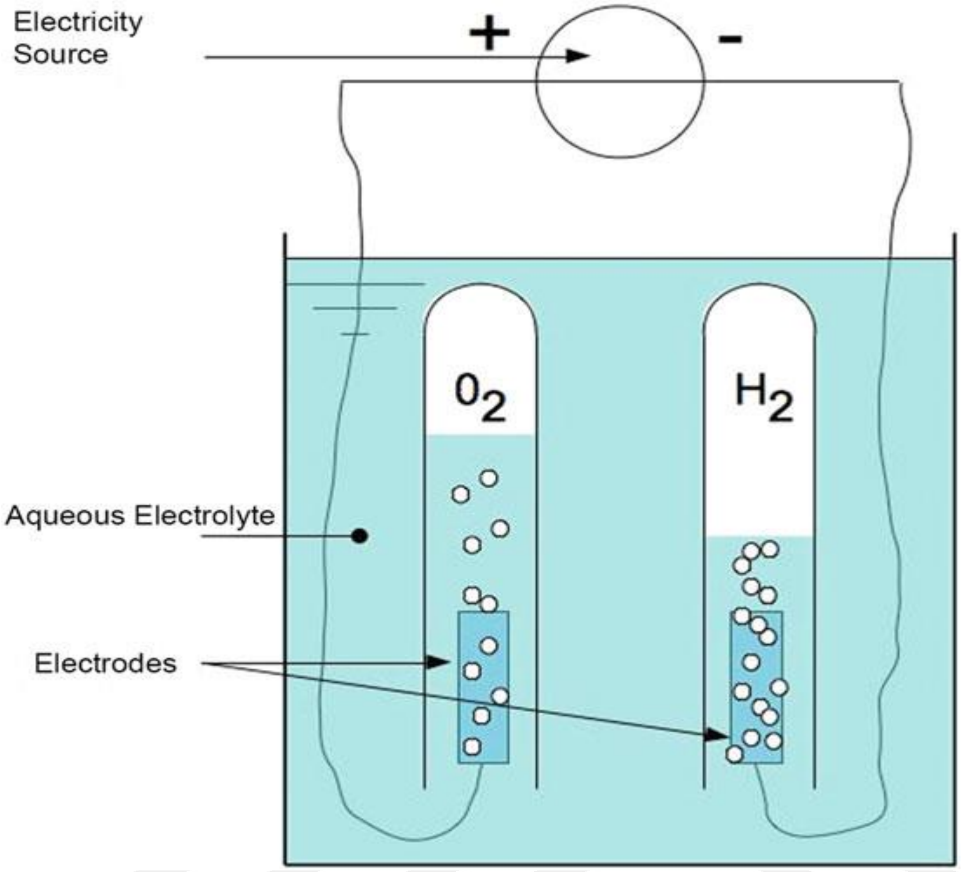


Figure 2.3 : Electrolysis Process (Luz Silveira, 2016).

One of the problems in the electrolysis process is that high thermal energy is required to separate the water as a compound. It is assumed that the energy to perform the electrolysis is almost the same as that obtained from hydrogen production.

Therefore, considering the loss of energy, the energy consumed to perform electrolysis is greater than what occurs (Lopez, 2004).

If hydrogen is used as an energy input, it generates the required energy as a renewable source for the process and makes the process workable. Instead of the previously used asbestos diaphragms, the negative and positive electrodes are separated by a microporous diaphragm (Sorensen, 2005).

Thanks to the electrical potential difference, hydrogen ions are transferred through the electrolyte. Alkaline components increase the ionic conductivity which is low in water, but this process should only be performed under 100 °C due to the danger of increasing corrosion in alkaline (Sorensen, 2005).

2.2.6.1 Electrolysers

Conventional electrolysis uses alkaline electrolyte solution as ionic conductor. While the electrodes are made of materials such as steel and carbon, the surface of anode is coated with nickel to prevent corrosion. Operating temperatures range from about 70 to 80 °C, with operating efficiencies ranging from 70 to 80 percent (Basso, 2013).

In conventional cells, the adjustment of the electrodes is in two ways, as shown in figure 2.4 and figure 2.5, and can be examined as unipolar or bipolar.

In the unipolar electrolysis, the conduction is mostly done with parallel electrodes and in the bipolar electrolysis, the electrodes are connected serially. In the cell, one electrode works as a anode and the other works as a cathode (Silva, 1991).

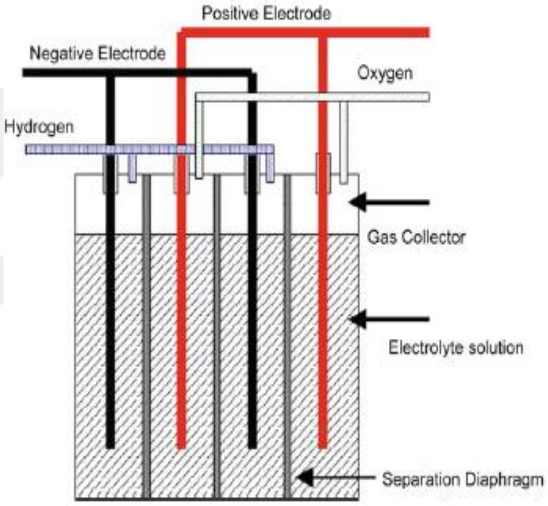


Figure 2.4 : Unipolar electrolyser (Kroposki, 2006).

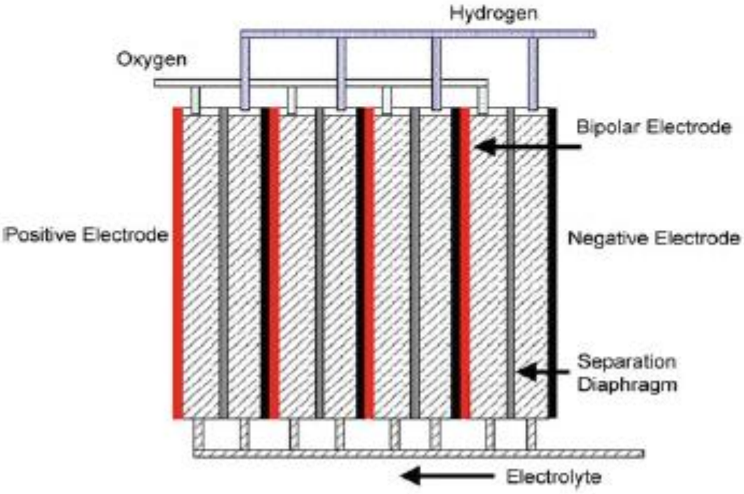


Figure 2.5 : Bipolar electrolyser (Kroposki, 2006).

Unipolar electrolysers are simpler and less expensive to maintain and these electrolysers are typically used for the production of 100 Nm^3/h of hydrogen. On the other hand, bipolar electrolysers are used for production greater than 100 Nm^3/h (Carnieletto, 2011).

The current electrolysers are similar to conventional models, but the electrodes are coated with a special coating and rough surface.

Some of them have membranes separated by Teflon or other materials and these models have a working temperature between 80 °C and 120 °C, work with a efficiency of 80-90% (Carnieletto, 2011).

2.2.6.2 Alkaline electrolysis (AEL)

Technologically, alkaline electrolysers are designed to produce significant amounts of hydrogen. The equipment is good for reliability with a 30-year life span and the electrodes and membranes change every 8 years.

Production capacity is up to 760 Nm^3/h and system efficiency ranges from 62 to 82% (Smolinka, 2011).

It contains 2 electrodes immersed in 25-30% KOH and NaOH solution and hydrogen is produced at the cathode, while oxygen is produced at the anode. The reactions in this process can be expressed as follows:

$$\text{Anode: } 4OH^- \rightarrow\ O_2 + 2H_2O + 4\,e^- \tag{2.4}$$

$$\text{Cathode: } 4H^+ +\ 4\,e^- \rightarrow 2H_2 \tag{2.5}$$

$$\text{Sum: } 2H_2O \rightarrow O_2 + 2H_2 \tag{2.6}$$

The electrodes are divided by a microporous membrane which is permeable to OH^- ions but not gas, and the anode is usually made of nickel or nickel-coated steel, while the cathode side is made of steel coated with different catalysts.

The electrodes operate at a distance of 5 mm and the operating temperature is usually about 80 °C (Bhandari, 2014). Figure 2.6 shows the working scheme of alkaline electrolyser.

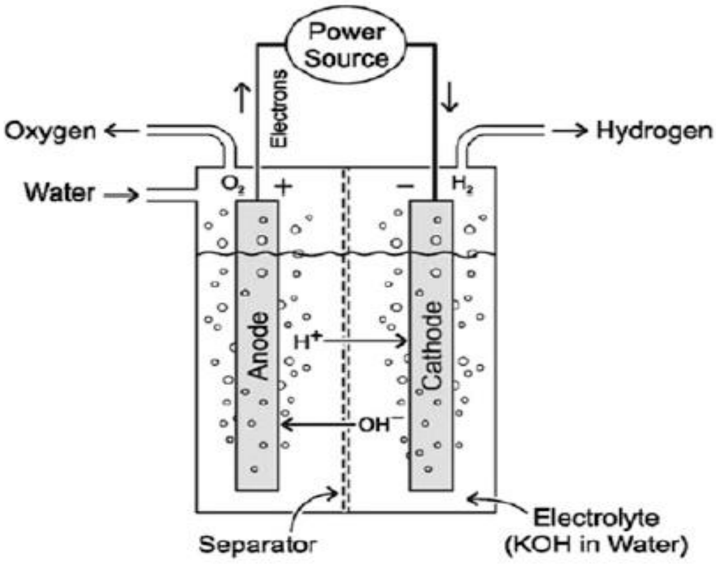


Figure 2.6 : The working principle of alkaline electrolyser (Koroneos, 2004).

Low pressure alkaline electrolysers operating up to 6 bar and high pressure alkaline electrolysers operating from 6 bar to 30 bar. There is no need for the final compression of hydrogen produced in high pressure alkaline electrolysis, but because of the high pressure, the permeability of the membrane will increase and the purity of hydrogen decreases (Bhandari, 2014).

The operating conditions and the design characteristics of the electrodes determine the energy requirements of the alkaline electrolysers. Low pressure electrolysers may require energy from 4.1 to 4.5 kWh/Nm^3H_2 , but they can reach 7 kWh/Nm^3 H_2 depending on compression, High pressure alkaline electrolysers have energy requirements of 4.5 to 5 kWh/Nm^3 H_2 (Smolinka, 2011).

Technological developments in this area have been focused on directions as increasing the efficiency of electrolysis, reducing the operating costs , thus reducing the amount of electricity consumed and reducing the investment costs by increasing the operating current density. According to Ursu´a (2012), technological developments in this field are as follows:

- Achieving higher operating currents and reduce ohmic losses by reducing gaps between electrodes
- There are various studies on the development of new materials instead of asbestos diaphragms. Significant progress has been made especially in the use of ionic-exchange inorganic membranes.

- Electrolysers operating at high temperatures have been developed. At temperatures higher than 150°C, the electrical conductivity of the electrolyte increases and thus positively affects the electrochemical reaction. Electrolysers of this type are used for the production of large amounts of high purity hydrogen (Ivy, 2004).
- Production of advanced electro catalyzing materials to decrease overvoltage at the electrode.

Alkaline electrolyser is a known technology and many manufacturers have been selling it for a long time.

2.2.6.3 Electrolysis in acid medium (PEM Electrolysis)

This technology, known as Proton Exchange Membrane (PEM) or Solid Polymer Electrolyte (SPE), is characterized by the use of a thin splitting polymer membrane instead of liquid electrolytic, which makes the electrodes closer to each other. Nafion, developed by Dupont and thinner than 0.2 mm, was used as a membrane (Ursu´a, 2012). Electrodes are made by alloying metals such as platinum and iridium. Electrochemical reactions in PEM electrolysers are as follows:

$$\text{Anode: } H_2O \rightarrow \frac{1}{2}\, O_2 + 2H^+ + 2\, e^- \tag{2.7}$$

$$\text{Cathode: } 2H^+ +\ 2\, e^- \rightarrow H_2 \tag{2.8}$$

On the anode side, water is oxidized to form oxygen, protons and electrons. Protons pass through the membrane to the cathode where hydrogen is generally 99.9% pure. The operating temperature is 80°C and can operate at pressures up to 15 bar. The energy consumption of PEM electrolysers is between 4.5 and 7 kWh/Nm^3 H_2, and production capacities can be increased from 0.06 to 30 kWh/Nm^3 H_2, and the system efficiency is between 67 and 82%. (Smolinka, 2011; Ursu´a, 2012).

It has been found that PEM electrolysers have less corrosion in their electrodes than alkaline electrolysers (Sorensen, 2005). It is also a viable option for storing renewable energy sources as it is not overly affected by imbalances in power supply. The lower efficiency of alkaline electrolysers compared to PEM electrolysers is due to a higher inertia in the movement of ions (Bhandari, 2014).

Despite these advantages, the biggest problem is the high investment costs due to membranes and the precious metals used for electrodes. This technology is still being developed by several companies such as ITM Power, Siemens and ProtonOnSite. Figure 2.7 shows the operating principle of PEM electrolysers and Figure 2.8 shows the commercial type of electrolysis battery.

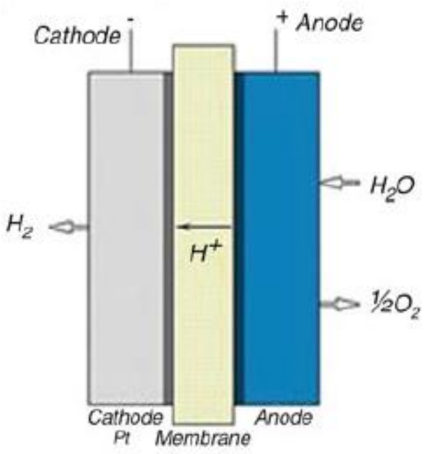


Figure 2.7 : Operating principle of PEM electrolysers.

Figure 2.8 : Electrolysis battery.

2.2.6.4 High temperature electrolysis (HTEL or SOE)

SOE electrolysers (solid oxide electrolyser) operate at temperatures of 600 °C to 1000 °C when a sufficient energy source is provided, so they have higher efficiency than alkaline and PEM type electrolysers. However, low thermal stability and the low durability of waterproof materials are disadvantages of this process.

The water vapor enters the cathode at high temperature, where hydrogen is formed and simultaneously oxide anions are transferred to the anode by solid electrolyte, where oxygen is formed, while the cathode contains hard nickel-based particles and elements such as yttrium and zirconium. The electrodes are made of solid zirconium, while the anode is made of perovskite ($CaTiO_3$) (Ursu´a, 2012).

In this type of electrolyser, 25% of the required power supply can be supplied from produced heat at 1000 °C (Brisse, 2008). Thus, hydrogen production with SOE can be advantageous in places where there is a high temperature heat source such as geothermal,solar and nuclear. Currently, such electrolysers are under development (Bhandari, 2014). It is expected to be commercially available for 3 to 5 years and will have aestimated cost of 2000 €/kW (Bertuccioli, 2014). Figure 2.9 shows the working principle of high temperature electrolysers.

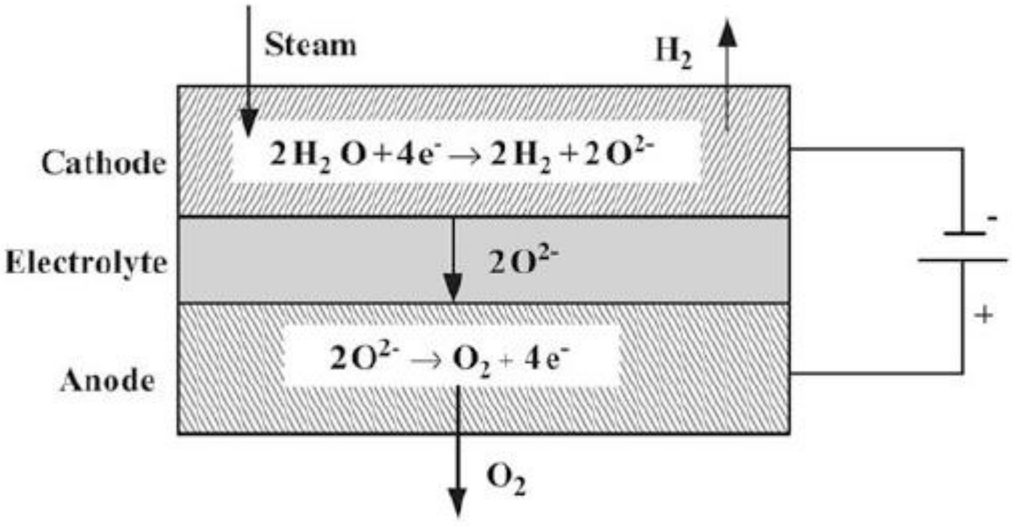


Figure 2.9 : The working principle of a solid oxide electrolyser (Wang, 2014).

Table 2.2 : General comparision of alkaline and PEM electrolysis (Fuel Cells and Hydrogen Joint Undertaking, 2014).

		Alkaline	PEM
Development status		Commercial	Commercial medium and scale applications (≤300 kW)
System size range	Nm^3/h	0.25-760	0.01-240
	kW	1.8-5,300	0,2-1,150
Hydrogen purity		99.5%-99.9998%	99.9%-99.9999%
Indicative system cost	€/kW	1,000-1,500	1,900-2,300

2.3 Hydrogen Storage

Today, hydrogen can be stored in a variety of forms. Table 2.3. shows the storage methods of hydrogen and hydrogen capacity, energy capacity and application areas of these methods. The data in the table are experimentally calculated maximum values (Hottinen, 2001).

One of the most important storage methods of hydrogen is the storage of hydrogen in compressed gas, storage in liquid form and storage in metal hydrides. Underground storage of hydrogen is another form of compressed gas storage. Each storage method has its own advantages and disadvantages. For example, in the case of hydrogen storage in the liquid state, hydrogen has the highest storage density in liquid form compared to other storage methods, but also requires isolated storage containers and a liquefaction process which requires energy (Amos, 1998).

Table 2.3 : Hydrogen Storage Methods (Yumurtacı, 2002).

Storage Material	Hydrogen Capacity	Energy Capacity
Gaseous Hydrogen	11.3 %	5.0 kW/kg
Liquid Hydrogen	25.9 %	13.8 kW/kg
Metal Hydride	2-5.5 %	0.8-2.3 kW/kg
Zeolite	5.2 %	2.2 kW/kg
Carbon	0.8 %	0.3 kW/kg
Glass sphere	6 %	2.5 kW/kg
Chemical	8.9- 15.1 %	3.8-7 kW/kg

2.3.1 Storage of compressed gas hydrogen

The simplest and most widely used method for the present time is a compressor and a pressure tank, the only equipment required to store hydrogen in a compressed gas state (Amos, 1998).

This method is the most cost-effective, most convenient and suitable for short-term applications among all the above hydrogen storage methods (Carpetis, 1985). The main problem in the storage of compressed gaseous hydrogen is the low storage density which is related to storage pressure.

High storage pressures require high investment and operating costs. The storage of gas hydrogen in small quantities and pressurized tanks can be very easy and cost-effective, but as the amount of hydrogen to be stored increases, so does the cost.

Thus this method is not economical for large amounts of hydrogen (Styrkovich, 1986).

2.3.2 Underground storage of gas hydrogen

Underground storage of hydrogen is another form of compressed gas storage. Underground storage of hydrogen is the lowest cost storage method for the large quantities of hydrogen. Hydrogen can be stored in natural or unnatural caves. Underground gas depots require minimum investment costs.

The disadvantage of this method is that the stored pressurized hydrogen is lost by 5% by volume. One of the cost increasing reasons in underground storage is the gas that occurs when the storage system is at the end of the discharge cycle. Disposal of this gas requires an additional cost. There are 3 different formations to store the pressurized hydrogen gas in the underground.

These are;

- Emptied oil / gas wells,
- Pit rock caves,
- Great salt caves.

The features that should be available in any underground storage area are:

- Water permeable structure below the surface (150-900 m) porous layer, usually sand or sandstone,
- Airtight rock head with sufficient thickness,
- Suitable dome-shaped geological structure.

Before the storage of hydrogen gases in underground, cavities are created on layers and surfaces are covered with cement or similar chemical materials. Then the hydrogen is injected into the cavities by the compressor (Yumurtacı, 2002).

2.3.3 Storage of hydrogen in metal hydride

Metal hydrides are formed by absorption capacity of hydrogen with metals. Absorption and release of hydrogen by a metal depends on a number of parameters (Türe, 1999).

The main parameters are:

- Pressure of hydrogen,
- The temperature of the metal,
- Flow rate of hydrogen (Cicconardi, 1997).

By this method, hydrogen can be stored with chemically bonding to metals, metalloid elements or alloys. Metal hydrides are composed of metal atoms that have lattice structure and hydrogen atoms held in intermediate places within this lattice structure. Metal and hydrogen can generally combine two different forms. One of these forms is suitable for hydrogen storage and the other is a fully filled form;

During the filling phase, hydrogen is spread through the full surface to create a suitable form for storage.

During the unloading process, hydrogen spreads out to create a storage state and forms H molecules (Amos, A.W., 1998).

Metal hydride storage systems are the safest one for hydrogen storage that can be stored under pressure of 3 to 6 MPa. Suitable metal alloys have empty spaces in their cages where hydrogen atoms can settle. Most of metal alloys can store hydrogen very safely that can be chemically converted while forming metal hydride. Hydrides store both of hydrogen and heat with the combination of chemical bonding, reaction heat of hydrogen and metals which can be used in both stationary and mobile technical process by means of heat-hydrogen combination (Buchner, H, 1984).

Metal hydrides store hydrogen as a decomposable chemical compound. There are many elements, metals and alloys that can react with gas hydrogen to form metal hydride. Such reactions can be seen in Figure 2.10 as below;

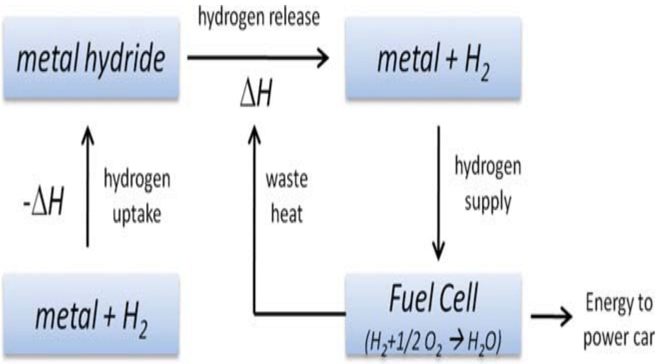


Figure 2.10 : Reaction of Gas Hydrogen-Metals (Philipp Adelhelm, 2011).

During storage, the heat is released that must be removed to maintain the reaction continuity. During the hydrogen release process, the heat must be supplied to the storage tank.

Advantage of the storage of hydrogen in the hydrating agents is the safety aspect. Serious damage to a hydride tank (such as a collision) does not pose a fire hazard as the hydrogen remains in the metal structure.

2.3.4 Liquid hydrogen storage

Favorable characteristics of liquid hydrogen include high heating value per unit mass and large cooling capacity due to its high specific heat (Winter C J, 1988).

The liquefaction temperature of hydrogen at atmospheric pressure is a relatively low temperature, such as -253 °C.

Therefore, the liquefaction process would require approximately 30% of the ignition energy of hydrogen that must be in the form of electrical energy.

Evaporation losses are the main problem in the production and storage of liquid hydrogen. Total losses from liquefaction unit to final use are between 30-70%.

Liquid hydrogen can be stored in both large and small capacities. If it is stored in the larger tank, losses will be at a lower level (Styrkovich, M.A., 1986). However, liquid hydrogen cannot be stored in cylindrical tanks where natural gas is stored.

This is due to high evaporation losses. Heat leakage losses are generally proportional to the ratio of the surface area to the volume of storage vessel. Therefore, the most suitable shape is spherical because the surface / volume ratio is the lowest.

The storage of liquid hydrogen is the most economical method for large amounts of gas and long-term storage.

The tanks where liquid hydrogen is stored are vacuum insulated between the inner and outer walls, as it can be seen in Figure 2.11 (Wurster, R., 1994).

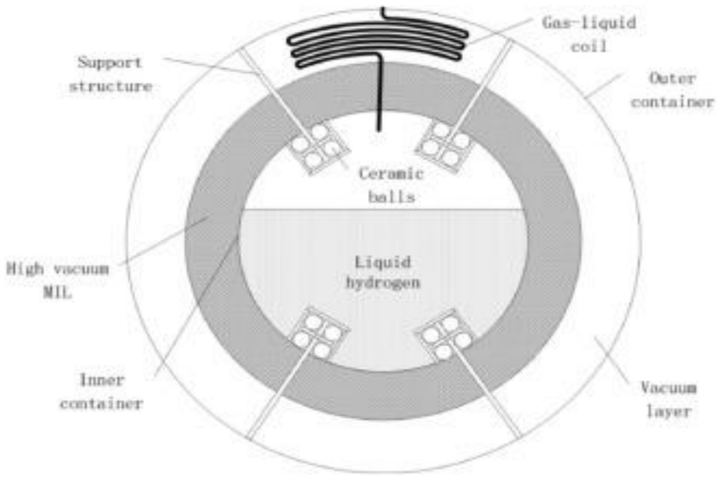


Figure 2.11 : Design of Liquid Hydrogen Storage Tank (Weiqiang Xu, 2015).

2.4 Hydrogen Delivery

Hydrogen can be delivered in solid state with compressed gas, liquid and metal hydrides. The cheapest delivery method depends on the amount of hydrogen to be carried and the transport route. As shown in the Figure 2.12, the using methods for the delivery of hydrogen are roadway, railway, maritime and pipelines.

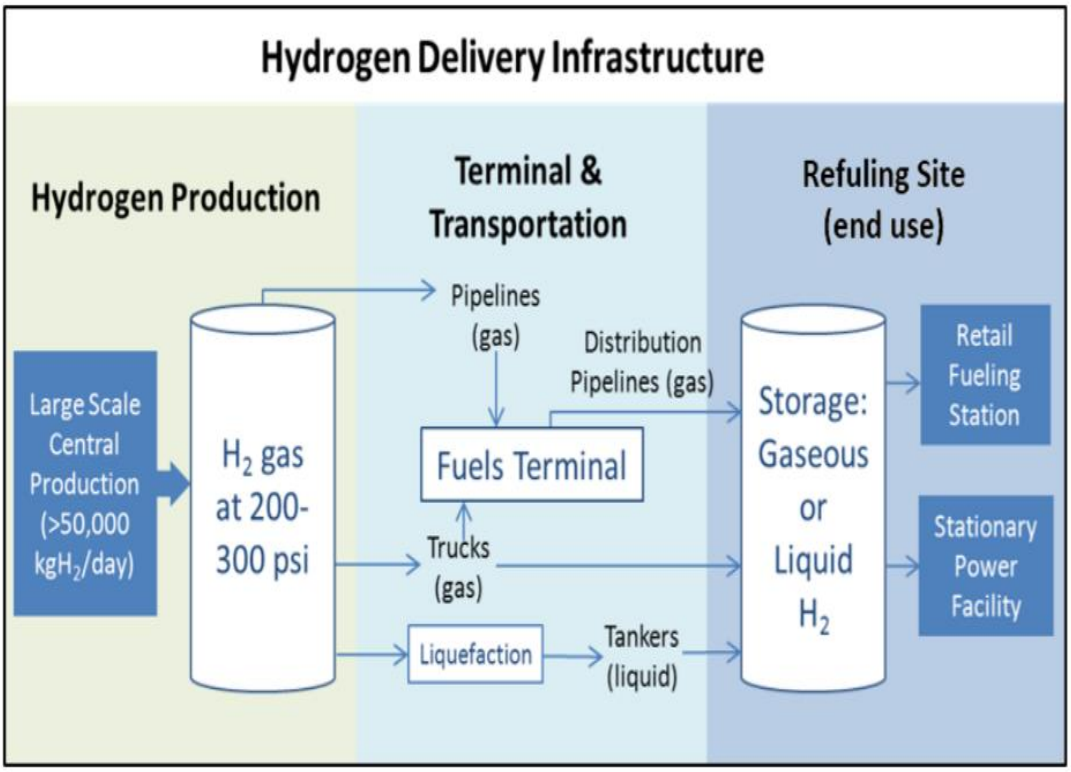


Figure 2.12 : Hydrogen Delivery Scheme (US DRIVE, 2018).

2.4.1 Compressed gas hydrogen delivery

The compressed gas hydrogen can be delivered using high pressure cylinders, tube trailers and pipelines. When delivering hydrogen in the gaseous state that shall be compressed at very high pressure to maximize tank capacity. High pressure gas cylinders with 1.8 kg hydrogen capacity (40 MPa) is very expensive for transport and transmission. (Encyclopedy of Chemical Technology, 1991).

Tubular trailers consisting of steel cylinders can carry between 63-460 kg of hydrogen, depending on the number of cylinders which have 20-60 MPa operating pressure. Hydrogen is delivered by pipelines in America, Canada and Europe. Operating pressure are 1-3 MPa. The longest hydrogen pipeline in the world is the 400 km between northern France and Belgium belong to Air Liquide Company. (Amos, A.W., 1998).

2.4.2 Liquid hydrogen delivery

Liquid hydrogen can be delivered to prevent evaporation with special double-wall insulated tanks. In order to cool the outer surface of the liquid hydrogen tank to minimize heat transfer, liquid nitrogen heat shields are used for some tankers. (Huston, E.L., 1984).

Truck tanks can carry 360-4300 kg of liquid hydrogen that much larger amounts of liquid hydrogen can be transported by train wagons (2300-9100 kg). Evaporation losses in both transport types are between 0.3-0.6% per day. Ship tankers are used for long distance transport. Evaporation losses in ships are between 0.2-0.4% per day.

In another way, liquid hydrogen may be carried in isolated lines containing superconducting wire that act as a coolant for the superconductor and allows electricity to be delivered over long distances without high current losses of conventional power lines. The main problem for delivery of liquid hydrogen is the special isolation need and the pumping-cooling losses of that.

2.4.3 Metal hydride delivery

After the hydrogen is absorbed by the metal hydride, the metal hydride is loaded into the truck or train and delivered to the end user that is replaced with an empty hydride container or used as a conventional tanker.

The main factor which affects the cost of delivering metal hydrides most is the cost of metal hydride and container as initial investment cost. Once filled, the hydride containers are transported at cost based on distance and weight (Amos, A.W., 1998).

2.4.4 Comparison of hydrogen delivery types

The main factors that will affect the selection in the delivery of hydrogen are application, quantity and distance from the production site to the end user. Hydrogen should be delivered to the process site in liquid form, if it is necessary as a liquid in practice.
Effective factors in delivery ;

Quantity : The cheapest transport method for large amounts of hydrogen is pipeline. However, if the oceans have to be crossed, the cheapest method will be to delivery liquid hydrogen by tankers. The delivery of liquid hydrogen is the second cheapest method of transmission. Although the operating costs of pipeline transportation are very low, the initial investment cost is very high. On the other hand, the operating costs of liquid hydrogen are high, but initial investment costs are lower, depending on the amount of hydrogen and the distance to be delivered. The pipeline is not profitable method for small amount of hydrogen. In this case, the most suitable delivery method is compressed gas state that has lower energy consumption and initial investment cost when it is compared with liquid hydrogen. Although more cylinder trailers are needed for the same amount of hydrogen, the initial investment cost is much lower.

The choice between these two should be decided economically, depending on the distance. The high energy cost of liquefaction for long distances will disrupt the balance. If the distance is short and the quantity is too small, compressed gas hydrogen will be the most appropriate choice. It may also be possible to use the same tube trailer more than once in a day for short distances.

The cost for metal hydride delivery is between gas and liquid hydrogen. Although the initial investment cost is very high, metal hydride may be preferred because it has much higher hydrogen carrying capacity than compressed gas hydrogen (Yumurtacı, 2002).

Distance : The pipelines are very economical for short distances that is closed to the investment cost of the tanks and tankers and there is no additional transportation and liquefying cost. As the distance increases, the initial investment cost of the pipeline increases rapidly and the economy depends on the amount to be delivered.

The distance can be decision factor between liquid and compressed gas hydrogen. The quantity of lorries are needed to carry the same amount of gas hydrogen will be much greater than that of liquid hydrogen. The delivery cost of long-distance gas hydrogen is higher than the cost of liquid hydrogen delivery with the addition of liquefaction costs (Yumurtacı, 2002).

Power Supply : The production of hydrogen and the supply of pipelines and heat and electrical energy where it is needed are becoming much cheaper due to low energy losses. Methods of transporting hydrogen ;

-Pipelines ; for power transmission over large quantities and long distances,

-Liquid hydrogen ; for delivery over long distances

-Compressed gas ; small quantities and short transports at distances,

-Metal hydride ; short-distance transport is the most appropriate methods to use (Yumurtacı, 2002).

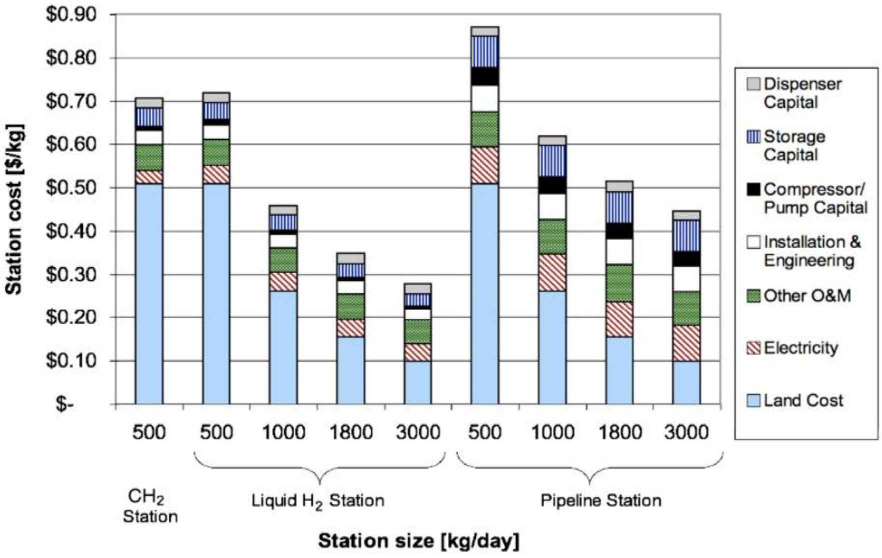


Figure 2.13 : The distribution of delivery station costs by station size (Christopher Y., 2007).

2.5 Fuel Cell Technology and Its Role For Transportation

The place of renewable energy systems in the transportation sector is increasing year by year due to global concerns such as depletion of petroleum-based energy resources, environmental pollution and climate change which caused by the use of fossil fuels. Fuel cells have recently attracted attention with their high efficiency and low emission values. Fuel cells are an electrochemical power sources that convert chemical energy in fuel into electrical energy. Unlike other electro-chemical power sources such as batteries, fuel cells store their reactants in a cell and these reactants are continuously supplied from the external source. In addition, electrodes in fuel cells are not consumed as in batteries. The primary cell is irreversible, the secondary cell is reversible, and the cells do not take part in the reaction. Today, fuel cells are used for electricity generation in different fields such as spacecraft and emergency generators (A. Alaswad, 2016).

The transport sector is one of the most harmful to the environment in terms of toxic emission gases in recent years. There are many studies on energy consumption and comparison of fuel types with alternative fuel systems and these studies contribute to the development of fuel technology (Ou X, 2012). These studies may help to reduce the amount of oil consumed in the transport sector in the coming days (Hao Han, 2010).

There are two different approaches to emission problems of vehicles. The first approach is related to the type of fuel, improving the quality of conventional fuel or using alternative fuel systems. The second approach is the development of engine technology, including emissions of vehicles in use and emission standards for new vehicles.

Although the concept of fuel cells was developed by Sir William Grove in England in the 1800s, the first operating fuel cells were made in the 1950s. In the aftermath of the 1950s, NASA's research into power generation for space flights increased interest in fuel cells (USDOD, 2010).

There are different types of fuel cells depending on the electrode type used. The most popular of these are the proton exchange membrane fuel cells (PEMFC), also known as polymer electrolyte membrane (PEM).

Proton exchange membrane fuel cells use a solid polymer as the electrolyte and generally uses porous carbon electrodes containing platinum or platinum alloy catalyst. PEMFC is supplied with pure hydrogen from fuel storage tanks, as it can be seen in Figure 2.14.

Protons on the surface of the platinum-based catalyst are separated from electrons at the anode where the hydrogen fuel is processed. When the protons pass to the cathode side of the cell, electrons move in the circuit and electricity is obtained from the fuel cell. The metal electrode combines electrons and protons with oxygen to form water as a waste product on the cathode part. Oxygen can be supplied in pure form or can be taken from the air with an electrode.

PEM fuel cells are generally used in the transport industry and some other applications. It is suitable for passenger cars such as buses and cars with features such as quick start time, adequate power-weight performance.

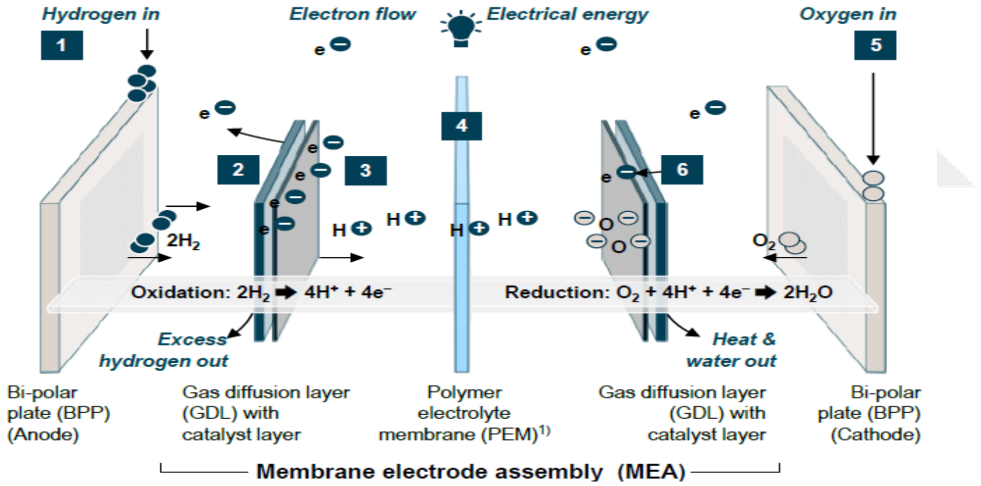


Figure 2.14 : Working diagram of polymer electrolyte membrane fuel cell (PEMFC) (Heiko Ammermann, 2015).

The transportation sector consumes approximately one quarter of the energy consumed in the world. In internal combustion engines, most of the energy in the fuel is emitted as heat due to exhaust gas and friction loss (A. Alaswad, 2016).

In 2012, the number of fuel cell systems almost doubled compared to the previous year, reaching a total of 45,700 which was a significant development in the transport sector. In addition, there have been major developments in the production of fuel cell vehicles in the transport industry.

2.6 Fuel cell usage in transportation

Developments in clean energy technologies are important for the transport sector, as 17 percent of greenhouse gas emissions generated each year come from this sector (Omar Sharaf, 2014). For this reason, major changes are required in this sector in order for the Kyoto protocol to reach its purpose (Cacciola, 2001). Expectations from industry investments are both reducing harmful emissions and achieving better energy conversion efficiencies.

Electric vehicles powered by energy stored in batteries or powered by fuel cell technology can play an important role in reducing emissions from the transport sector. Electric vehicles have proven to be more efficient than internal combustion engines. As shown in Figure 2.15, Automotive manufacturers were encouraged to convert some of their production from internal combustion engine to electric vehicles (Bing Li, 2010), (Cacciola, 2001).

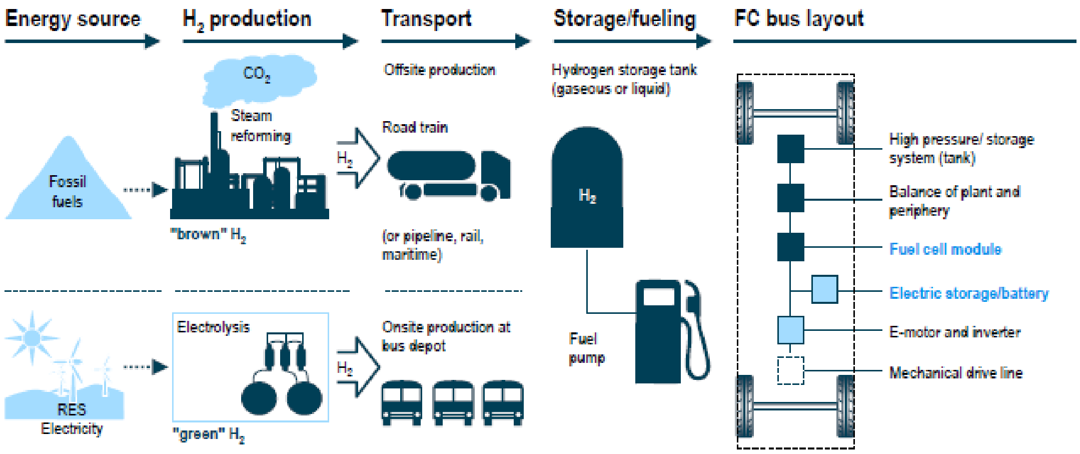


Figure 2.15 : Schematic representation of hydrogen production, transportation, storage and usage in fuel cell bus (Heiko Ammermann, 2015).

While the electric motor transmits more than 90% of the energy in the storage cells as a motive force, however internal combustion engines can convert less than 25% of the energy in a gallon of gasoline into motive force. In addition, unlike internal combustion engines, electric motors are directly connected to the wheels. This means that there is no energy consumption when the vehicle is stationary or moving freely. In addition, thanks to the regenerative braking system, nearly half of the kinetic energy in electric vehicles is returned to the storage cells.

Moreover, electric vehicles are more environmentally friendly than vehicles with internal combustion engines (Hofman P., 2004), (Elzen B., 2004).

Vehicles using fossil fuel can release greenhouse gases and other pollutant gases through the exhaust. Also, emission gases are released from refineries where petroleum-based fuels are produced. Electric vehicles do not produce greenhouse gases while they are running, but greenhouse gases can be generated when producing hydrogen fuel, depending on how the electrical energy required for electric vehicles is generated. The decrease in the weight of electric vehicles compared to internal combustion vehicles is an important advantage in terms of energy efficiency and it is considered to be of great importance in terms of reducing greenhouse gas emissions.

According to the Carbon Trust, there could be 491 million vehicles running on fuel cells which will be 30% of all cars on the road by 2050 (Carbon Trust, 2012). The use of polymer electrolyte membrane fuel cell technology in transportation can provide several advantages with its high energy efficiency, high power density, light weight, compactness, low operating temperatures. However, the suitability of fuel cells to the transport sector has several difficulties in terms of gravimetric and volumetric power density, price and reliability compared to other technologies. The biggest challenge in making this technology commercial is its high cost.

The applications of the fuel cell in the transport sector can be divided as follows;

-Light-duty vehicles (LTVs) such as personal wheel-chairs, scooters, motorbikes, golf carts, airport tugs

-Auxiliary power units (APUs) such as air conditioning of road vehicles and the electronics, and units that cover the power demand of small yachts

-Light duty fuel cell electric vehicles (L-FCEVs)

-Heavy duty fuel cell electric vehicles (H-FCEVs) such as locomotives, buses, heavy-duty trucks, service fleets, vans, utility trucks and other large load vehicles

-Aerial propulsion such as mall unmanned aerial vehicles (UAV)

-Marine propulsion such as boats, ferries, cargo ships and yachts mostly underwater vehicles and submarines

Although motorcycles are small in size, technological developments related to fuel cell-based motorcycles will be one of the most important applications in the transportation sector as they are the biggest environmental pollution in cities (Andujar JM, 2009).

One of the most successful applications of fuel cells in the transportation sector is forklifts. Until now, there are nearly 1,300 fuel cell-powered forklifts in the United States. According to their advantages, Polymer electrolyte membrane fuel cells are the most popular fuel cell in low-fuel electric vehicles (L-FCEVs) (Omar Sharaf Z, 2014).

The working principle of electric vehicles with fuel cells is simple. Low-temperature fuel cells are used to generate electricity from hydrogen(Usually PEM). The generated electricity is used in the operation of the vehicle and is also stored in batteries or ultracapacitors (Pollet Bruno G, 2012). Since fuel cells generate electricity from chemical reactions rather than fuel combustion, they produce less heat and do not produce harmful gases. For this reason, the final product from hydrogen-fueled fuel cells becomes water.

Many car manufacturing companies such as Toyota, Honda, Volvo, General Motors, Mazda, Volkswagen are making significant improvements to the commercialization of L-FCEVs (Omar Sharaf Z, 2014). In 2007, Honda introduced the FCX Clarity at the automotive show in Los Angeles, which has been available since the summer of 2008 which was the first fuel-celled vehicle produced in series (Andujar JM, 2009). An important development for industry progress was the announcement at the fuel cell show in Tokyo in 2010 where Japanese carmakers declare their plan to launch close to 2 million fuel cell vehicles in 2025 (Pollet Bruno G, 2012).

In recent years, the number and status of fuel-powered buses around the world have been noted (Andujar JM, 2009).

In 2012, 25 fuel cell buses operated in the United States and more than 30 fuel cell buses in Western Europe. Operation of buses with fuel cells in public transportation are of great importance for public reputation of fuel cell technology. In addition, the data obtained from these buses is crucial for the H-FCEV industry in terms of research and development.

Due to the advantages of regenerative braking energy recovery, storage of braking dissipated energy and retention by vehicle for the next use, PEMFCs are the most common fuel cell stack used in public transport.

However, fuel cell technology is not yet fully developed and FCEBs are scarce in production, making economic competition more difficult than conventional buses or other emerging technologies.

The use of fuel cell applications in marine transportation is increasing day by day. The potential for fuel cells to be used in auxiliary power units and the propulsion of fuel cell systems in combination with diesel engines can be possible in the near future on ships, boats, cargo ships and especially underwater vehicles (Leo TJ, 2009).

Fuel cells are suitable for ferries and ships with standard advantages such as low emissions, high efficiency, but need to be improved in terms of life expectancy, shock resistance, salt resistance and reliability (Omar Sharaf Z, 2014).

Therefore, fuel cell technologies used in maritime transportation have not developed as much as in other sectors such as automotive sector (Carbon Trust, 2012). When designing fuel cells designed for marine applications, fuel cells are considered to be designed for a sufficient life span considering the danger of corrosion and dynamic loads.

The major obstacle to the spread of this technology in maritime transport is the lack of infrastructure and the difficult competition of this technology economically with internal combustion engines.

The space industry is one of the first areas where fuel cells are integrated. NASA used PEMFC and alkaline fuel cells(AFC) in the 1960s manned space programs. The fact that water is the final product from fuel cell in space where water, air and food are important therefore producing electricity from fuel cell technology is more attractive than other technologies.

The use of fuel cells for unmanned aerial vehicles, which allow observation and exploration without risking human life, is advantageous in terms of low heat dissipation and static operation over internal combustion engines, but is not suitable due to its requirements of high energy and power density, reliability and durability.

2.6.1 Current developments and challenges for fuel cell technology

Fuel cell technology is growing day by day and many new prototypes are being introduced. The successful examples of this technology in the transport sector were made in America and Europe. However, the durability, performance and high cost of the fuel cell are the major obstacles to commercialization. In addition, the development of infrastructure for the production, transport and storage of hydrogen is crucial for the use of hydrogen in the transport sector.

2.6.1.1 Cost of Fuel Cell Technology

The cost of fuel cells can be examined in 3 different parts as labor, investment cost of manufacturing equipment and component costs of fuel cells (Wang Junye, 2015; Marcinkoski J, 2011). Capital and labor costs can be reduced by mass production. Component and material costs, such as catalysts, membranes and bipolar layers, depend on technological innovation (OdehAO, 2013; Sun Y, 2011). According to Carbon Trust, fuel cells should approach approximately 36 $/kW in terms of competitive compared to internal combustion engines. Platinum (Pt) is a valuable element in the world with an annual production of 250 tons. It is currently being mined in Russia, North America and South Africa, and the world reserve is thought to be greater than 30,000 tons. The platinum used in the FCEVs is recycled once the vehicle has expired its life time (Alaswad A, 2016)

Costs can be reduced by increasing the power density, reducing material costs(especially in the use of platinum), reducing system complexity, improving durability. By reducing the use of platinum in the electro-catalyst layer, the overall cost of the PEMFC technology will be reduced thus making it suitable for mass production for use in transport applications (Baroutaji A, 2016).

Platinum alloy catalysts or core shell catalyst applications can reduce platinum use. Platinum alloys can be made with low cost metals such as chromium(Cr), ruthenium(Ru). Core shell catalysts are made by covering low cost cores such as copper(Cu) and rhenium(Rh) with platinum shell (Nagabhushana KS, 2006). By increasing the catalyst power from 2.8 kW/g in 2008 to 5.8 kW/g, which is more than doubled in 2012, the amount of platinum contained in the fuel cells decreased. The power of the present catalyst reaches the target of 2017, 8.0 kW/g, and in addition, 80% reduction was observed in the use of platinum group metals since 2005.

Several United Kingdom organizations are developing technologies that will increase power density, simplify system design, and reduce platinum use.

Development of platinum-free catalysts to reduce the cost of fuel cells can be considered as an alternative method. Metals such as Iron (Fe) and Cobalt (Co) can be used for PEMFC technology. In the FlowCath product, patented by ACAL Energy (CostamagnaPaola, 2001; ACAL, 2019), liquid polymer cathode solution was used instead of platinum-weighted solid cathode used in PEM fuel cells. While hydrogen in the anode is catalyzed in the conventional manner, electrons and protons are absorbed into the solution containing redox catalyst systems and pass incessantly from the stack to the external regeneration vessel (Figure2.16). This design has the potential to reduce the use of expensive plantinium by 66 percent. In addition, there are some advantages of this system such as usage of less components by avoiding fuel humidification and water recovery, and, also this design is more durable than solid cathode systems which with limits in lifetime. The targeted fuel cell cost for the FlowCath is 36 $/kW.

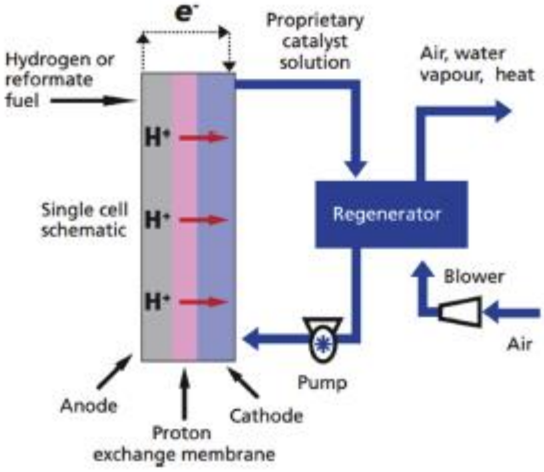


Figure 2.16 : Regenerator system and half fuel cell of FlowCath (ACAL).

ITM Power made a another patent and high power densities have been achieved by replacing the current industry standard perfulorosulfonic acid membranes which and manufactured from ionic polymers (CostamagnaPaola, 2001; ITM, 2019). More power is provided per cell, resulting in the same energy output with lighter, smaller, and cheaper stacks. 35 $/kW was given by ITM Power as a fuel cell cost. A new patent was made by Imperial College & University College London through developing of fuel cell stack design (Costamagna Paola, 2001).

Some of systems used in conventional fuel cell systems have been eleminated by using new generation boards, thus the number of components has been reduced. Air as a fuel, water management, stack assembly and sealing are areas to be examined in terms of cost reduction. According to this project, planned fuel cell cost is 26 $/kW.

2.6.1.2 Durability and performances of Fuel Cell Technology

Low durability and reliability occur as water and heat wear out catalysts materials (Bıyıkoglu, 2005; Bae SJ, 2014). Materials and catalysts can often be damaged by corrosion, improper water management, flooding or dehydration due to chemical reactions of cell components and lack of fuel and oxidant. Corrosions of the catalyst layers, electrodes, membrane and the gas diffusion media are caused by floods and dehydration can cause damage to the membrane. The life of the fuel cells can be increased by changing the flow conditions such as humidity, flow rate and temperature or changing the flow design.

In order to increase the durability of PEM fuel cells, cheap bipolar plates with high corrosion resistance can be designed and developed. Generally, when producing bipolar layers, graphite is used because of low surface contact resistance, high surface conductivity and high corrosion resistance. Nevertheless, since graphite is fragile, usage of graphite in the transport sector is not convenient as it will encounter many vibrations and loads. For this reason, metals, metal alloys and some carbon composites should be replaced with graphite ones by producing bipolar plates that are more cost effective and more durable (Baroutaji, 2014; Carton JG, 2016).

In fuel cells used in the transport sector, metals and metals' alloys provide higher mechanical strength than carbon-based composites thus this fact gives possibilities to make them thinner, resulting in higher power density and durability (Wang H, 2003). The use of metals such as Ti, Al, Ni in fuel cells can cause corrosion of metallic flow plates which reduces the power and efficiency of the fuel cell and increases electrical resistance (Wang H, 2003; Pozio A, 2003; Herman A, 2005; Antunes RA, 2010). For this reason, carbon based or metal based corrosion-resistant coatings are used to prevent corrosion in metallic bipolar plates (Mehta V, 2003).

Carbon corrosion in the catalyst layer is another major cause of wear in PEM fuel cells.

Although platinum nanoparticles on carbon black (Pt/C) are known to be the most promising method used in PEMFC, the catalyst layers must have access to protons, electrons and gases in order to be efficient.

In the case of high current operation, platinum nanoparticles in the thin catalyst layers are separated from the carbon, reducing electrochemical performance. In the case of high current density, the transport of electrons has proved to be more efficient if graphene and Pt / C are mixed (U.S. Department of Energy, 2011). Graphene provides better conduction for a high number of electrons and shows slow electrical resistance. Graphene has the potential to show higher durability than black carbon (Choi Hyun-Jung, 2012).

Proton exchange membranes require low level of hydration to increase ionic conductivity thus, high hydration poses reliability problems due to low current density, low voltage at low current, unstable voltage at low temperatures, unreliable start-up at low temperatures, and hydrogen deficiency of carbon in the catalyst (Choi Hyun-Jung, 2012). Especially considering the varying load and environmental conditions in the transport sector, the balance between too little or too much hydration should be well analyzed and accordingly the material used with the membrane design should be selected well. Another approach to improve proton exchange membranes in terms of durability and performance is the use of membrane made from Nafion.

In June 2013, ACAL Energy Ltd (U.S. Department of Energy, 2011) announced that in a third-party automotive industry, PEM hydrogen fuel cells successfully passed the 10,000-hour durability test and showed no wear at the end of the test. This is equivalent to 300,000 miles, which is comparable to the best light-weight diesel engines in terms of durability. This durability exceeds the US Department of Energy (DoE) 2017 target of 5,000 hours with about 10% wear. ACAL Energy's technology uses a liquid that acts as both catalyst and coolant instead of platinum as catalyst, thus removing mechanisms that can wear out over time.

The 2016 plan of FCH 2 JU (The Fuel Cell and Hydrogen 2 Joint Undertaking) focused on the development of PEMFC technologies for the transport sector.

Although PEMFC is not an old technology, there are many challenges in terms of production efficiency, production cost and manufacturability. FCH 2 JU develops various projects related to the production of PEMFC's stacks and other components in line with its 2020 targets and in 2020, FCH 2 JU aims for the production of 50,000 stacks with a total power range of 5MW per year from the current capacity of 100 stacks per year.

2.6.1.3 Hydrogen refuelling infrastructure

Hydrogen is the lightest chemical element with the lowest storage density among all fuels. From the past to the present, hydrogen fuel filling infrastructures are generally not preferred due to their high cost, but with the increase in the sales of fuel cell vehicles, the hydrogen fueling infrastructure has a chance to develop (Hydrogen production R&D, 2006). Unfortunately, the system used in gasoline delivery from refinery to gas stations cannot be used for hydrogen, so new facilities and systems have to be established for hydrogen production, transfer and hydrogen delivery to clients (Matthias Altmann, 2003). Today, industry experts are working on issues such as hydrogen compression, supply chain, high pressure storage elements and standardized filling station design to reduce the cost of filling stations. The infrastructure required for hydrogen storage, hydrogen refueller and hydrogen supply in the hydrogen filling plant is shown in the following Figure 2.17.

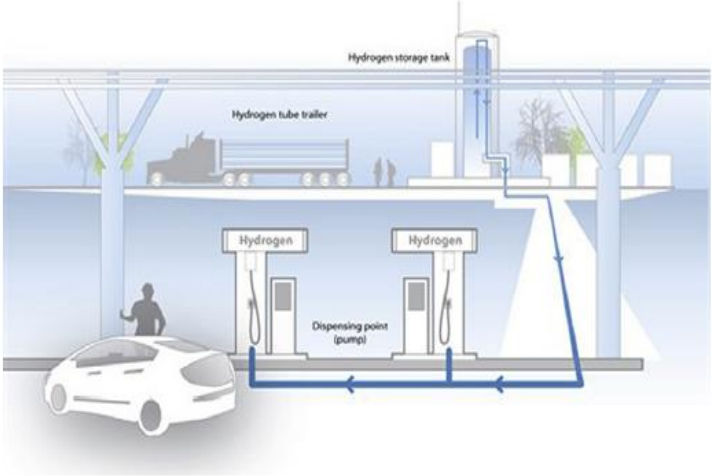


Figure 2.17 : Hydrogen storage, refuelling and supply system (Alaswad A,2016).

There are two separate cases for the supply of hydrogen, such as hydrogen transfer to the site or production of hydrogen on site (Ogden Joan M, 2005).

The hydrogen transfer is carried out by tankers in the hydrogen liquid state or by cylinders in the hydrogen gaseous state. Liquefied hydrogen is suitable for large volumes and compressed gas is more suitable for small volumes. On-site production is carried out by reforming natural gas or by electrolysis of water, and today mostly hydrogen is produced by reforming natural gas, but in the future it can be replaced with energy types such as wind, solar and biomass.

Hydrogen storage systems vary according to the physical state of hydrogen. When transferring hydrogen as a liquid, a cryogenic storage container is used to keep the hydrogen in a liquid state.

If hydrogen is to be transferred as gas, the storage container is usually left to the site by trucks and replaced when finished, but in the case of on-site hydrogen generation, produced hydrogen is transferred to the compressed filling container by means of a compressor.

Liquefaction of hydrogen is an intensive energy process and a large plant is needed, so it should be considered for places where large amounts of hydrogen are produced. Hydrogen refuellers provide controlled and accurate pressure delivery of hydrogen to the tanks of vehicles (US Department of Energy, 2019).

Hydrogen is filled into vehicles by means of flexible hose and nozzle which is very similar to the fuel filling of diesel and petrol vehicles.

For many years, significant infrastructure and financial investments have been made for the supply and production of oil and natural gas, and for this investment and effort to be made for hydrogen, governments need to come together and take steps to promote the production and consumption of hydrogen for the transport sector (Singh Sonal, 2015).

In order to solve the infrastructure problem of hydrogen filling stations at European level, FCH J2U and many European partners are developing projects to increase the number of hydrogen filling stations such as Hydrogen Mobility Europe (H2ME,2019).

There are a total of 45 hydrogen filling stations in Europe and 100 filling stations will be built in 2023 with the H2ME project (H2ME, 2019).

2.6.1.4 Hydrogen storage in vehicles

Hydrogen has one-tenth of the energy compared to the same volume of gasoline and the driving distances of the vehicles depend on the amount of hydrogen in the tanks, so it is necessary to increase the efficiency of the system and the amount of hydrogen in the tank in order to be able to compare fuel cell vehicles to gasoline-powered vehicles. Some fuel cell vehicles(FCVs) can go 300 miles without refuelling the tank but still storage systems are expensive, heavy and large.Three different solutions have been developed for the storage of hydrogen in FCVs. One of these is the storage of hydrogen in high pressure tanks as shown in the Figure 2.18. This method is the current method used in FCVs. This system is a different system compared to compressed natural gas vehicles because it works with higher pressure than hydrogen vehicles and works with pressure between 20-25 MPa. Today, 70 MPa tanks aim to carry more hydrogen, but there will still be costly, big and heavy systems. In addition, hydrogen diffusion will be greater in losses as it can pass through the gaps in conventional materials used in tanks (McWhorter S, Ahn CC, 2016).

Figure 2.18 : Storage tank of a Mazda RX-8 Hydrogen car (Alaswad A, 2016).

Today, high-pressure tank technology achieves DOE’s 2017 targets of 40 g/L volumetric capacity and 5.5% gravimetric capacity. The current bursting pressure of 150 MPa is achieved by special carbon reinforcement, but the storage system with 70 g/L volumetric capacity and 7.5% gravimetric capacity, which is the target of DOE with tank technology, is almost impossible (Stetson NT, 2016).

Another method of storage is the conversion of hydrogen from gaseous to liquid form at temperatures of 20 K and atmospheric pressure. More hydrogen can be stored by storing hydrogen in liquid form, but double-walled and insulated systems should be used to maintain low temperature in the tanks used (Riis Trygve, 2006).

The third method is a material-dependent storage system, which is the storage of hydrogen in solid form and is made by absorption of hydrogen in high density by different alloys. These alloys are lighter and smaller than the tanks used in other systems. Hydrogen is separated from its components by the addition of heat or water. Various research and development is needed to develop the materials required for this method (Zhevago NK, 2016) The applications developed by Metal Organic Frameworks (MOFs) for hydrogen storage have attracted high attention with their advantages such as rich chemical content, high structural diversity, pore size adjustment, surface functionality, efficient permeability and surface area. Compared to other systems, the MOF applications have allowed more hydrogen to be stored per unit volume, as shown in Figure 2.19. Despite the researchs of the MOF, DOE 's targets have not yet been met (HW, Ren J, 2016; Olabi AG, 2014).

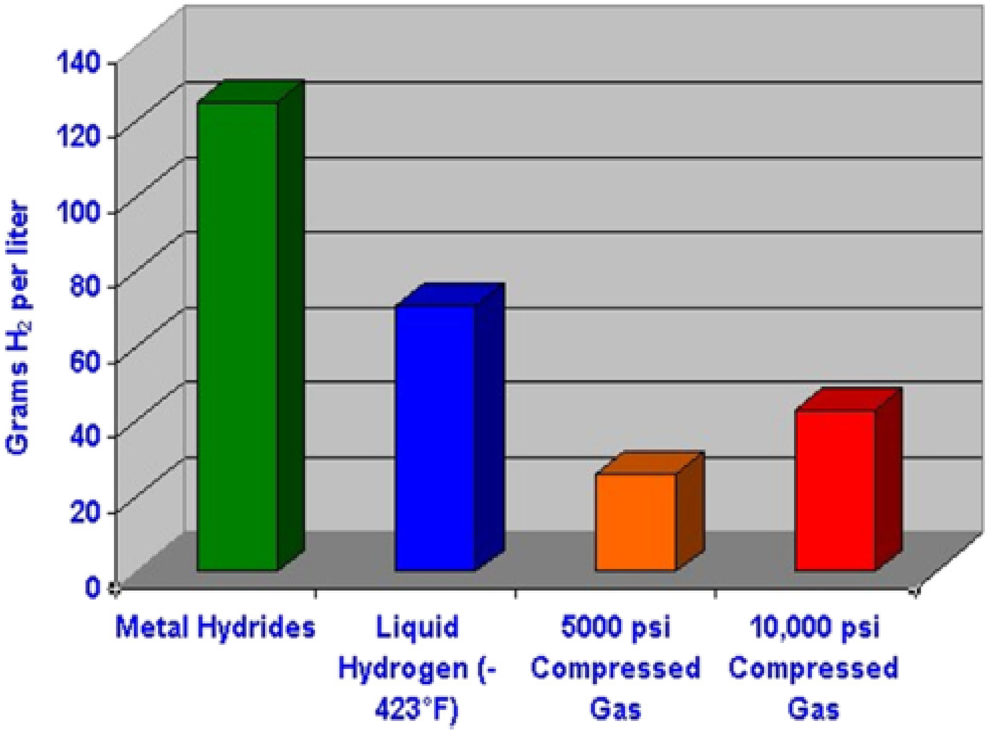


Figure 2.19 : The amount of stored hydrogen per litre with different technologies (Hydrogen Gas, 2019).

2.7 The Role of Renewable Energies for Hydrogen Production

2.7.1 Wind Energy

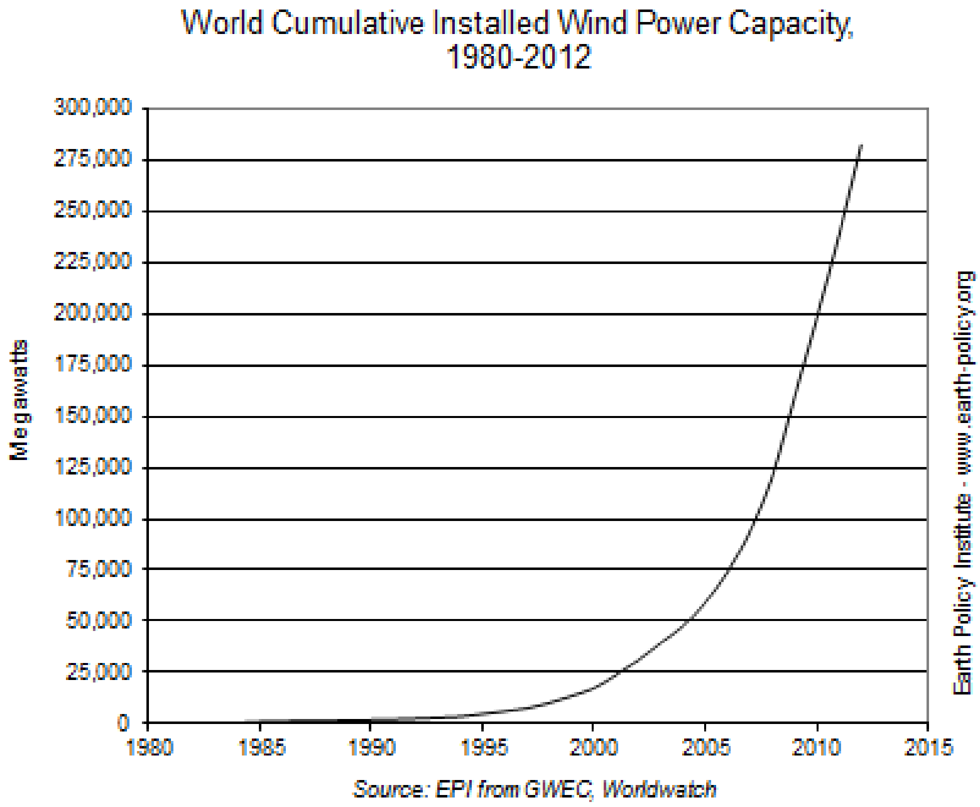
Obtaining energy from the wind is related to solar radiation and is caused by the non-homogeneous heating of the earth's surface.

According to Dutra's (2008), about 2% of the solar energy absorbed by the Earth corresponds to the kinetic energy of wind energy.

Although this ratio appears to be small, it represents approximately 100 times the total annual power generated by installed power plants around the world.

The understanding of the importance of using renewable energy sources instead of fossil fuels as well as the technological advancement of wind turbines increases the energy obtained from wind power day by day (Figure 2.20).

Countries promoting the construction of wind farm such as Germany, Spain, China and United States of America accelerated the installation of wind power plants (Table 2.4).


World Cumulative Installed Wind Power Capacity, 1980-2012

Source: EPI from GWEC, Worldwatch

Figure 2.20 : Cumulative wind power installed in the world between 1980 and 2012 (J. Matthew Roney, 2013).

Table 2.4 : Distribution of installed wind power capacity in the world (Gwec, 2016).

Country	MW	%Share
PR China	168,732	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil*	10,740	2.2
Italy	9,257	1.9
Rest of the world	75,576	15.5
Total TOP 10	**411,214**	**84**
World Total	**486,790**	**100**

This can be attributed to the high logistical costs in the case of project implementation, the limited availability of domestic producers and the restriction on imported products (Dantas and Leite, 2013).

Small scale or large scale winds can be affected by many factors. Therefore, the height of the wind turbines, the surface roughness and obstacles in the land should be taken into consideration (Dutra, 2008).

The kinetic energy to be obtained from the power of the wind is related to the constant speed and uniform air density passing through the wind turbine and it can be calculated according to the following equation Furlan (2012).

$$P_{disp} = \frac{1}{2}\rho_{air}\, \mathrm{A}\, v^3 \tag{2.7}$$

where:

P_{disp}—power of wind turbine (W)

ρ_{air}—air density (kg/m^3)

A—Rotor swept area of the wind turbine (m^2)

v—wind speed (m/s);

When the speed of the moving air is reduced, the kinetic energy in the wind is converted to mechanical energy by rotating the blades of the wind turbine. However, the avaliable energy in the wind cannot be completely converted into mechanical energy by the wind turbine.

Effiency of energy conversion by blades of wind turbines depends on the energy difference between the upstream and downstream of the rotor blades, as shown in Figure 2.21 (Roberts, 2012).

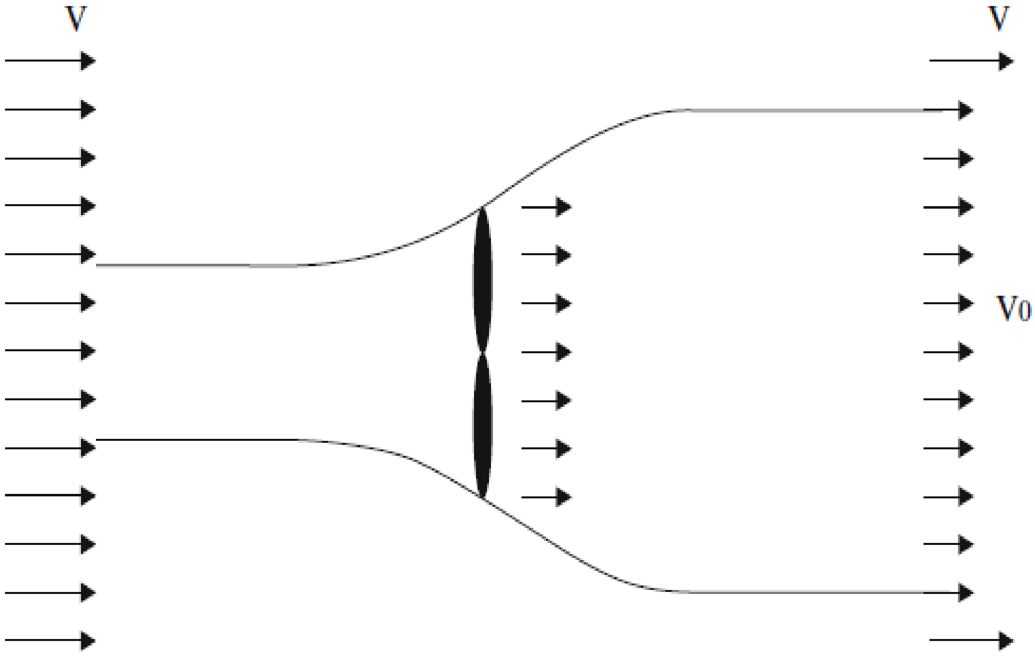


Figure 2.21 : Wind speed difference caused by wind turbine (Roberts, 2012)

According to Figure 2.22, if we assume from the macroscopic point of view that the wind speed varies between V and V_0 speeds on the rotor plane, the average speed of the wind will be ½ (V +V_0).

Mechanical power extracted by the rotor after a few mathematical operations can be obtained by the following Eq. (Roberts, 2012).

$$P_{mec} = \frac{1}{2}\rho_{air} \mathrm{A}\, v^3 C_p \tag{2.8}$$

where:

P_{mec}—mechanical power of wind turbine (W)

C_p—power coefficient

C_p was introduced by Betz Law. According to the Betz limit, a maximum of 59% of the wind power can be harnessed. Therefore, the maximum C_p should theoretically be about 0.59. According to Roberts (2012), maximum efficiency achieved by modern wind turbines actually ranges from 0.2 to 0.4.

The energy required for the electrolysis process can be obtained under conditions where the average wind speed is 6 m/s and the minimum wind speed is 4 m/s (Silveira, 2012).

From Figure 2.22, you can examine the system where wind turbines provides energy to the grid and additionally supplies energy to the electrolyser for hydrogen production.

As can be seen from the Figure 2.22, the hydrogen produced by the electrolysis is directed to the storage system. The stored hydrogen can be used in filling stations, generating electricity for the grid, or in fuel cells of vehicles.

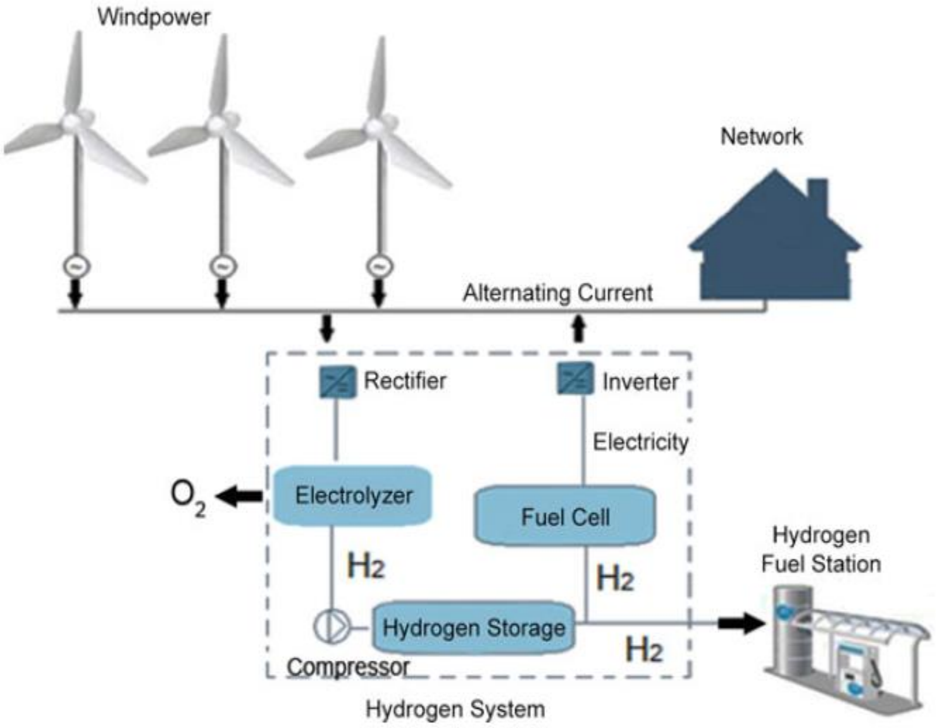


Figure 2.22 : Hydrogen production system which is based on wind energy (Silveira, 2016)

2.7.2 Solar Energy

Solar energy is caused by the spread of electromagnetic energy produced by nuclear reactions to the surface of the sun. Many renewable energy sources such as wind, hydropower and tides are directly related to the sun (Roberts, 2012).

The total solar energy reaching the Earth's surface from the sun annually is more than 10,000 times the annual consumed energy by all people in the world (CRESESB, 2012).

According to Aksungur (2016), the average solar radiation in Turkey is 500 W/m^2. Only 45-100 W/m^2 of this solar radiation can be converted into electrical energy by photovoltaic power plants, depending on the panel type and the location of the sun during approximately 6 hours of the day. Battery banks, which are used for storage of electricity when solar radiation cannot be converted to electrical energy, increase the investment costs in solar power plants.

Semiconductor materials are used in the production of photovoltaic panels. These materials are generally made of silicone and may also be monocrystalline, polycrystalline, concentrated or amorphous (CRESESB, 2012). According to Roberts (2012), silicone is the most preferred material because of its non-toxic structure, its abundance in nature, and many developments on its technology.

A single photovoltaic cell produces energy approximately 1-1.5 W at voltage of 0.5-0.6 V in standard conditions (1 kW/m^2 solar radiation and 25 °C cell temperature). Photovoltaic batteries are usually connected in series in order to obtain appropriate current and voltage values. Such installations are usually modules that contain 30-36 cells (Roberts, 2012).

The conversion efficiency of photovoltaic cells is calculated according to the ratio of the solar radiation falling on the surface of the cell to converted electrical energy. Table 2.5 shows the conversion efficiency of various silicon-based photovoltaic panels.

Table 2.5 : Efficiency difference between silicon-based photovoltaic panels (Silveira, 2016).

Photovoltaic panel type	Efficiency (%)
Monocrystalline silicon	12–14
Concentrated silicon	13–15
Polycrystalline silicon	11–13
Amorphous silicon	3–5

As can be seen from the Table 2.5, photovoltaic panels have an average efficiency of 14% which is low compared to wind and hydroelectric turbines.

In solar hydrogen production systems, the panels feed the electrolyser with direct current. According to Gibson and Kelly (2008), the photovoltaic modules are connected to DC converters and charge controllers to ensure that the batteries can be fully charged and prevent excessive discharge.

In addition, these inverters are required to provide the necessary voltage characteristics to the electrolysers. The working principle of the system can be seen from the Figure 2.23 below.

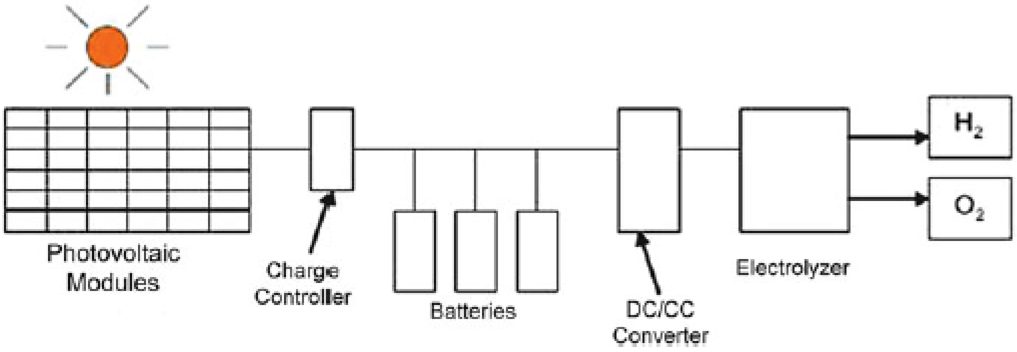


Figure 2.23 : Hydrogen production from solar system (Gibson and Kelly, 2008).

When a photovoltaic panel is connected to any device, the voltage drops below the open circuit due to the module and the internal resistance of the device. The direct current applied to the electrolyser will be the output current of the panel hence DC converter is needed to optimize voltage and current before electrolyser (Gibson and Kelly, 2009).

2.7.3 Hydroelectric Energy

Hydroelectric energy is obtained by converting hydraulic energy into electricity by making a dam or reservoir in any part of the river (Pimentel, 2012).

Hydropower plants can be examined in three different categories which are micro hydroelectric power plants (up to 1 MW), small hydropower plants (1.1 MW to 30 MW) and large hydropower plants (above 30 MW). According to Republic of Turkey Ministry of Energy and Natural Resources (2018), Turkey has 636 registered hydroelectric plants with total installed capacity of 27,912 MW.

We can store water in hydroelectric dams, but energy cannot be stored, so in some periods excess water is spilled through channels and this significantly reduces energy production. This poured water could be spent for electricity generation or used to feed electrolysers to produce hydrogen.

Since hydrogen is a storable element, it can be useful in reducing the water spillage by taking energy from the spilling water which can lead more efficiency in power plants, also contributing to the use of clean energy due to global warming.

As the Figure 2.24 below shows, a significant amount of energy has been wasted since 2006 by the Itaipu dam in Brazil.

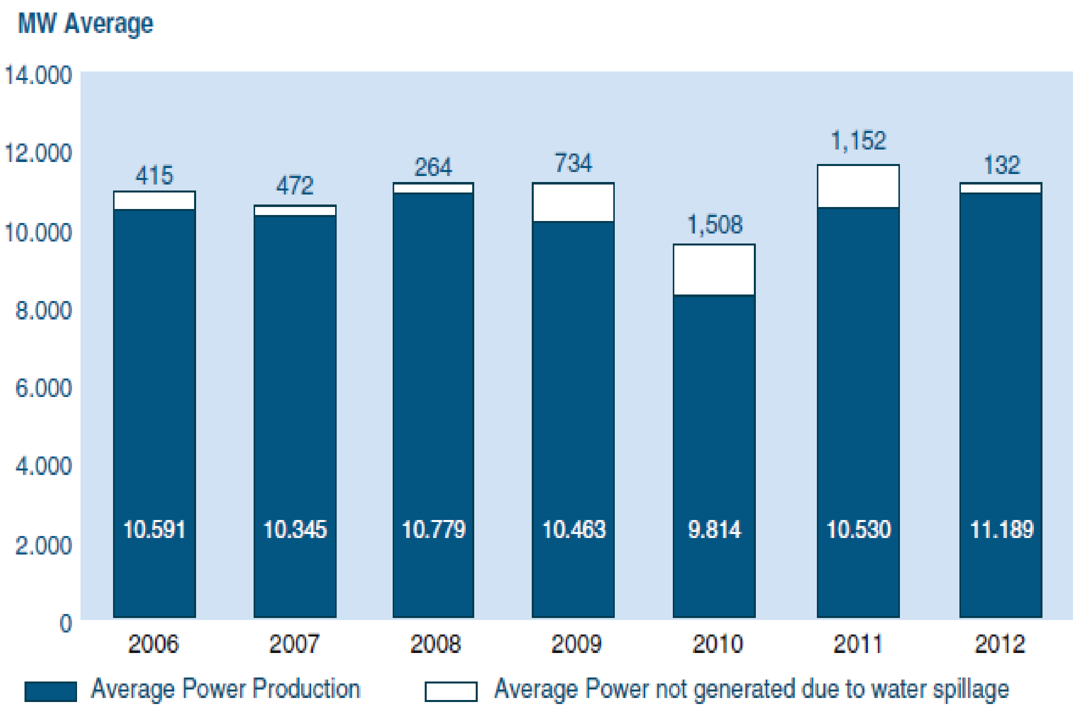


Figure 2.24 : Difference between power production of Itaipu Dam and not produced power due to water spillage spillage (ITAIPU, 2014).

Unfortunately, there are various barriers to dams being a clean and cheap energy source. Studies have shown that the largest hydroelectric power plants such as Tucuru, Balbina, and Samuel which operating in the Amazon region emit dirty gases at the same rate as coal power plants.

After 10 years of operation of power plant, water starts to acidify due to the decomposition of organic matter in the water and this causes the formation of methane gas (CH_4) which is 21 times deleterious than carbon dioxide (CO_2) (Azenha, 2013).

The purpose of hydroelectric power plants is to convert the hydraulic energy of rivers into electrical energy, so it would be reasonable to use only spilled water for electrolysis i.e., the surplus energy of the plant should be used for hydrogen production.

Figure 2.25 shows hydrogen production system by electrolysis which uses hydraulic energy as a source.

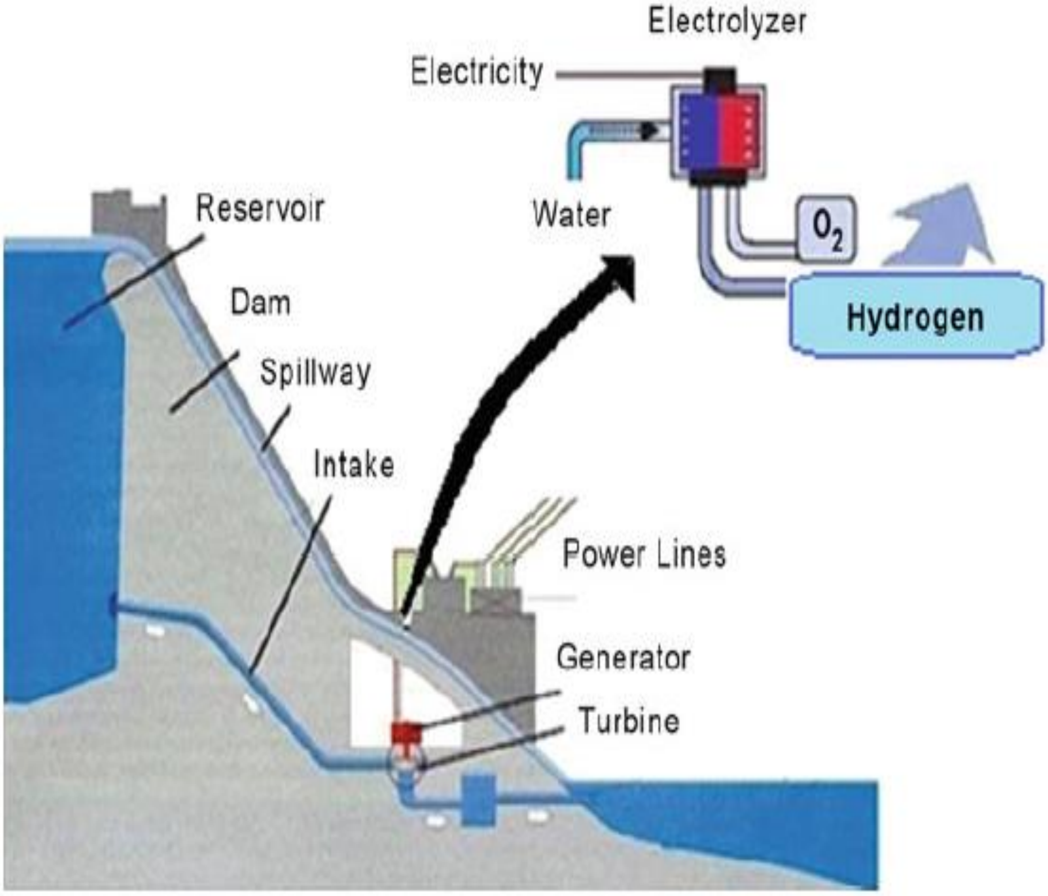


Figure 2.25 : Electrolysis process from water spillage by using hydraulic energy (Silviera, 2016).

As can be seen from the Figure 2.25, the water passing through the flow path enters the generator and electricity is obtained which provides sufficient electricity for electrolysis to produce hydrogen.

In the case of Turkey, harnessing energy from spillage water can be quite promising.

As stated in the previous figure, in Itaipu, energy loss due to water spillage can be used to supply small towns with electricity, however it is not used due to lack of demand and transmission lines (FAPESP, 2013).

In this way, solution can be found to supply energy to small towns which have problems with lack of transmission lines.

3. IMPLEMENTATION STUDY OF WIND AND SOLAR ENERGY INTO HYDROGEN GENERATION TO BE USED IN PUBLIC TRANSPORT BETWEEN DATÇA AND MARMARİS

Our study focuses on replacing the buses used in the public transportation line between Datça and Marmaris with hydrogen-powered buses. In our project, the hydrogen required as fuel is produced by electrolysis, while the electrical energy required for electrolysis will be supplied from wind and solar power plants which are connected to the grid. In order to meet the energy required for the production of hydrogen, a hybrid system with both solar and wind energy is evaluated. In addition, various conditions such as using only wind energy or using only solar energy are evaluated.

3.1 Examination of The Bus Route

The route of public transport between Marmaris and Datça is 74 km and public transportation between the two districts is provided by Muğla Municipality.

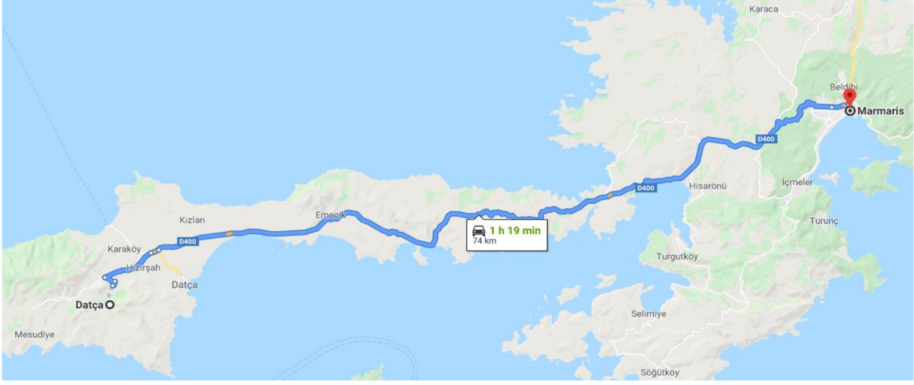


Figure 3.1 : Demonstration of the public transport route between Datça and Marmaris with Google Maps.

Since the province of Muğla is a summer region, the number of bus services increases as the population gets crowded in summer. As shown in Table 3.1, during the 9-month period which the summer period is not taken into account, 30 trips are made every weekday and 28 daily trips on weekends.

This corresponds to a total of 206 trips per week. During the 3-month summer period, the number of bus services is increasing and 50 trips are made every weekday, 48 daily trips on weekends. This corresponds to a total of 346 trips per week.

Calculation of total annual kilometers by taking into account the total number of bus trips:

During 3-month period (summer);

[(3 months x 4 weeks/month) + 1 week] x 346 trips/week = 4,498 trips.

4,498 trips x 74 km/trip = 332,852 km.

During 9-month period;
[(9 months x 4 weeks/month) + 3 weeks] x 206 trips/week = 8,034 trips.

8,034 trips x 74 km/trip = 594,516 km.

Total km covered between Marmaris and Datça for 1 year = 332,852 km + 594,516 km = 927,368 km.

Table 3.1 : Demonstration of bus services between Datça - Marmaris on weekdays and weekends during 9 months period (Muğla Municipality, 2019).

From Datça to Marmaris		From Marmaris to Datça	
Weekdays	Weekend	Weekdays	Weekend
Departure: 06:00	Departure: 06:00	Departure: 08:30	Departure: 09:00
Departure: 07:00	Departure: 07:00	Departure: 09:15	Departure: 10:00
Departure: 08:00	Departure: 08:00	Departure: 10:00	Departure: 11:00
Departure: 08:30	Departure: 09:00	Departure: 11:00	Departure: 12:00
Departure: 09:00	Departure: 10:00	Departure: 12:00	Departure: 13:00
Departure: 10:00	Departure: 11:00	Departure: 13:00	Departure: 14:00
Departure: 11:00	Departure: 12:00	Departure: 14:00	Departure: 15:00
Departure: 12:00	Departure: 13:00	Departure: 15:00	Departure: 16:00
Departure: 13:00	Departure: 14:00	Departure: 16:00	Departure: 16:45
Departure: 14:00	Departure: 15:00	Departure: 16:45	Departure: 17:30
Departure: 15:00	Departure: 16:00	Departure: 17:30	Departure: 18:30
Departure: 16:00	Departure: 17:00	Departure: 18:30	Departure: 19:30
Departure: 17:00	Departure: 18:30	Departure: 19:30	Departure: 21:00
Departure: 18:30	Departure: 20:00	Departure: 21:00	Departure: 22:30
Departure: 20:00		Departure: 22:30	

3.2 Fuel Consumption of Fuel Cell Buses and Calculation of 1 Year Total Hydrogen Required for the Public Transportation Line Between Datça Marmaris

Table 3.2 presents the average fuel consumption of hydrogen-based buses in Europe based on their length.

According to Muğla Municipality (2019) , it is sufficient to use a 12 m buses in terms of passenger capacity in the public transportation line between Datça and Marmaris. 12 m fuel cell buses consume 9 kg of hydrogen per 100 km.

When calculating the total hydrogen requirement of our project for 1 year, it is calculated on the basis of 9 kg H2/100km value, but if the same two fuel cell buses operate in different places, this value can vary between 8.0 kg H2/100km and 9.9 kg H2/100km according to the condition of the road.

In the case of 12 m FC buses are used on the public transportation line between Datça and Marmaris, the 1 year hydrogen requirement of the buses can be found as follows;

Total km covered between Marmaris and Datça for 1 year = 927,368 km.

Average fuel consumption of 12 m FC Bus = 9 kg H2/100km .

The 1 year hydrogen requirement of the buses = 927,368 km x 9 kg H2/100km = 83,463.12 kg H2.

Table 3.2 : Average fuel consumption of the FC buses differentiated by length of the buses in Europe (Lozanovski, 2018).

			Average Fuel Consumption		
	Bus Length	Number of Vehicles	At Each Site	All 54 FC Buses	Only 12m Solo Buses (25/54)
Site	[m]	[No.]	[kg H2/100km]		
Cologne	18.5	2	16.5	12.0	
Whistler	12.7	20	14.9		
Cologne	13.2	2	14.4		
Oslo	13.2	5	13.2		
Hamburg	12.0	4	8.7		9.0
Aargau	12.0	5	8.0		
Bolzano	12.0	5	8.6		
London	12.0	8	9.6		
Milan	12.0	3	9.9		

3.3 Demonstration of Current System Efficiency Data for Hydrogen Production by Electrolysis of Water and Calculation of Energy Required for 1 Year Hydrogen Needs of Datça and Marmaris Transportation Line

According to the U.S. Department of Energy, Table 3.3 shows 2011 status, 2015 and 2020 targets for hydrogen levelized cost (production), electrolyser system capital cost, system energy efficieny and stack energy efficiency. To calculate energy requirement for our project, the system efficiency is used considering the 2011 data of 50 kWh/kg and 1 year required electrical energy for the project is calculated as follows:

The 1 year hydrogen requirement of the buses = 83,463.12 kg H2.
System energy efficiency = 50 kWh/kg H2.
1 year required electrical energy for the project = 4,173,156 kWh.

Table 3.3 : Current situation and technical objectives related to the use of water electrolysis in hydrogen production (DOE, 2019).

Characteristics	Units	2011 Status	2015 Target	2020 Target
Hydrogen levelized cost	$/kg	4.20	3.90	2.30
Electrolyser system capital cost	$/kg	0.70	0.50	0.50
	$/kW	430	300	300
System energy efficieny	% (LHV)	67	72	75
	kWh/kg	50	46	44
Stack energy efficiency	% (LHV)	74	76	77
	kWh/kg	45	44	43

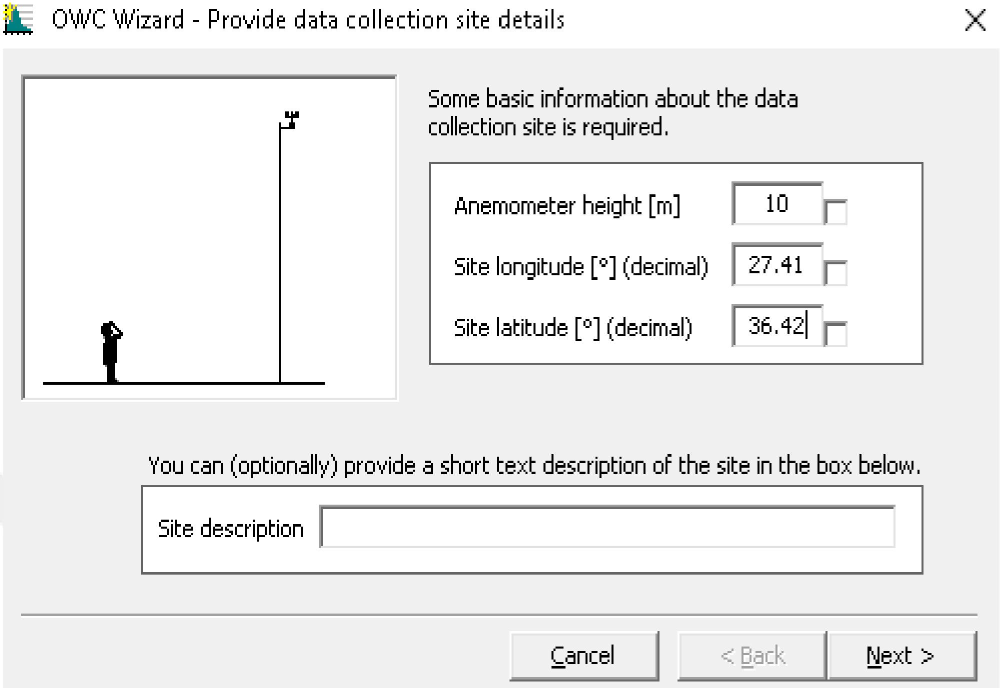
3.4 Calculation of 1 Year Energy to Be Produced by Wind Turbines with WAsP Program

Calculations were made with WAsP program. Wind measurement station of Turkish State Meteorological Service in Datça's data is used which is located at 36.42 °N latitude and 27.41 °E longitude.

Wind speed and direction data were recorded per hour. Totally 1 year wind speed and direction data are used.

Vestas and Nordex branded wind turbines with 3 different rated power of 225 kW, 800 kW and 3 MW are used to calculate the annual energy production.

3.4.1 Integration of wind speed and direction data into the WAsP program with OWC wizard


OWC Wizard - Provide data collection site details

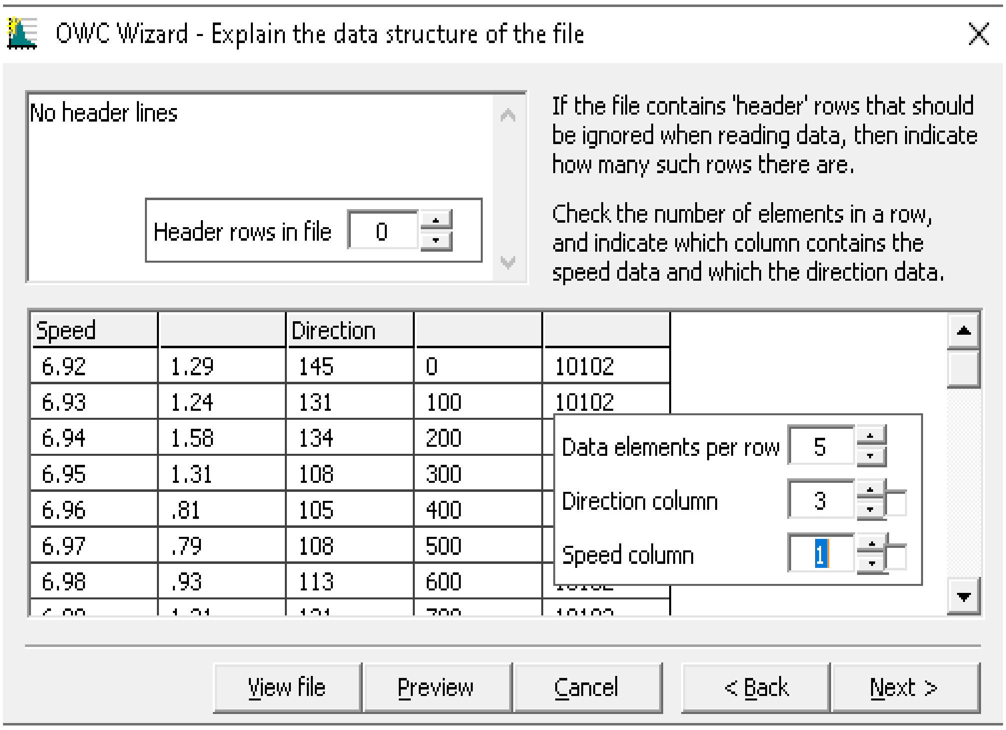
Some basic information about the data collection site is required.

Anemometer height [m]: 10
Site longitude [°] (decimal): 27.41
Site latitude [°] (decimal): 36.42

You can (optionally) provide a short text description of the site in the box below.

Site description:

Figure 3.2 : Determination of anemometer height and the coordinates of the measuring station.


OWC Wizard - Explain the data structure of the file

No header lines

Header rows in file: 0

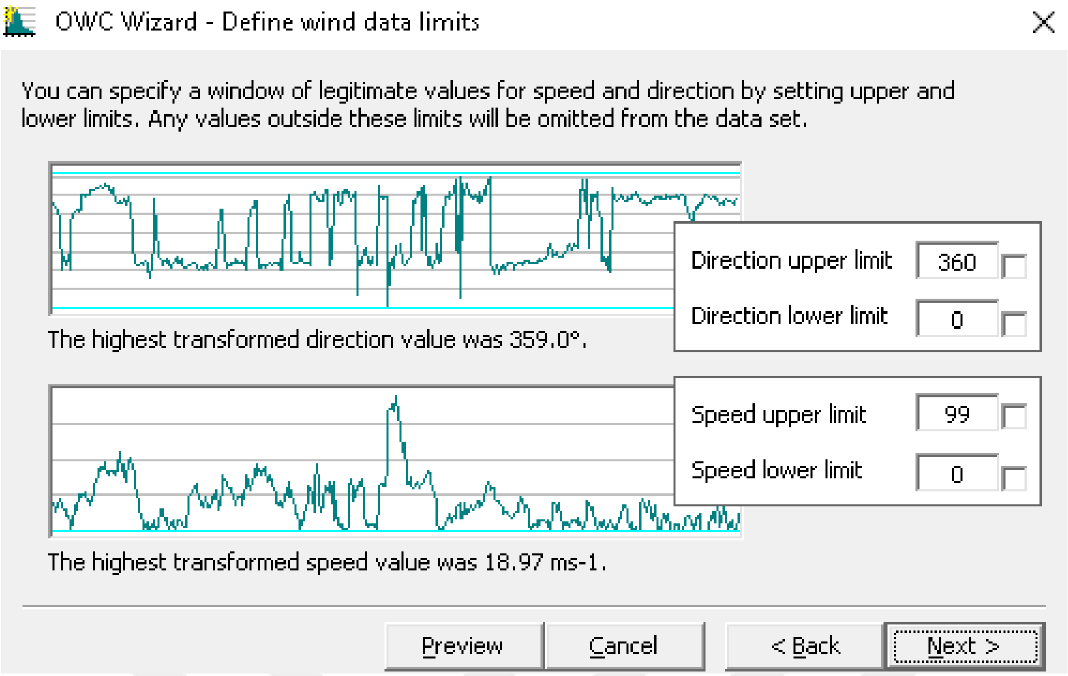
If the file contains 'header' rows that should be ignored when reading data, then indicate how many such rows there are.

Check the number of elements in a row, and indicate which column contains the speed data and which the direction data.

Speed		Direction		
6.92	1.29	145	0	10102
6.93	1.24	131	100	10102
6.94	1.58	134	200	
6.95	1.31	108	300	
6.96	.81	105	400	
6.97	.79	108	500	
6.98	.93	113	600	

Data elements per row: 5
Direction column: 3
Speed column: 1

Figure 3.3 : Determination of wind speed and direction columns with OWC Wizard.



You can specify a window of legitimate values for speed and direction by setting upper and lower limits. Any values outside these limits will be omitted from the data set.

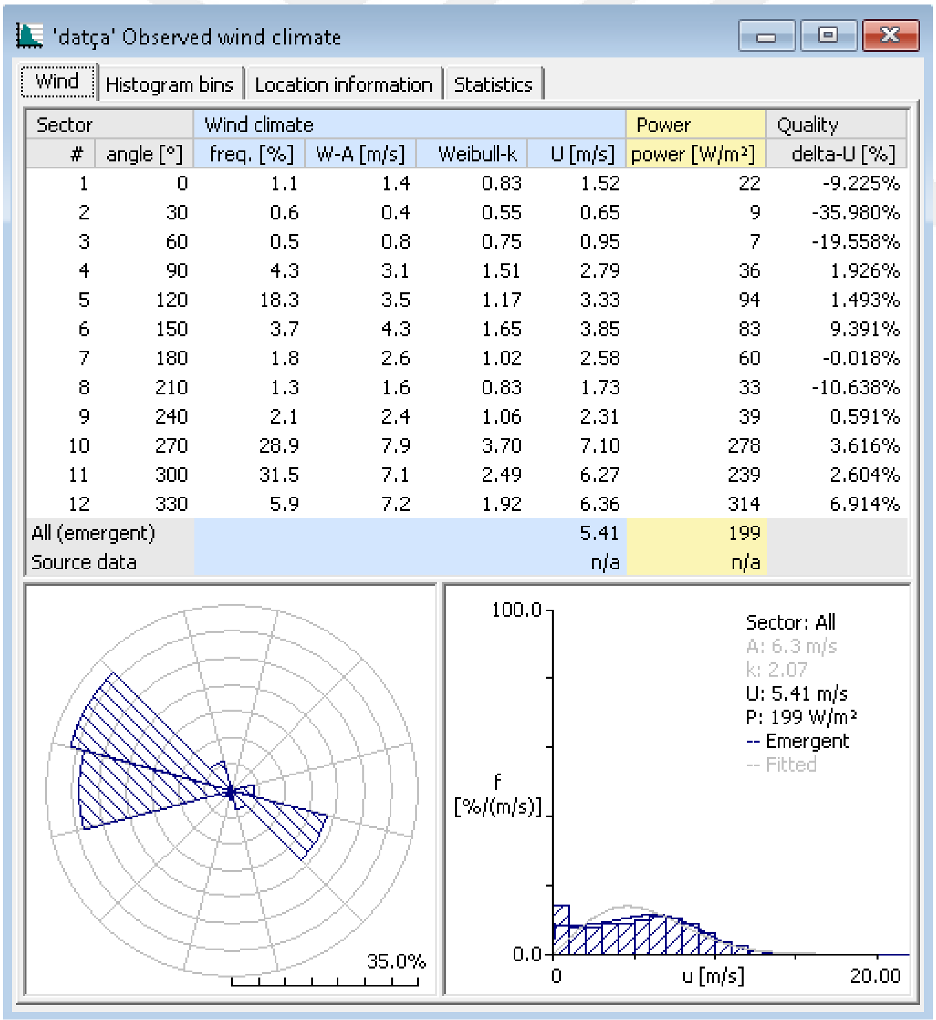
Direction upper limit 360 ☐
Direction lower limit 0 ☐

The highest transformed direction value was 359.0°.

Speed upper limit 99 ☐
Speed lower limit 0 ☐

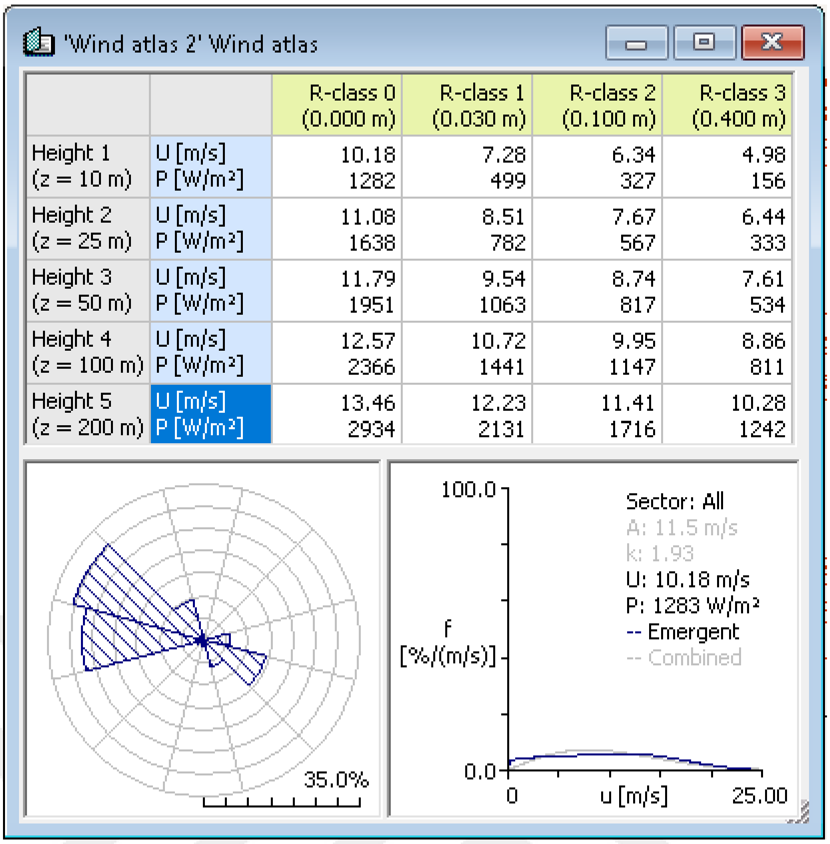
The highest transformed speed value was 18.97 ms-1.

Figure 3.4 : Determination of wind data limits with OWC wizard.



Sector		Wind climate				Power	Quality
#	angle [°]	freq. [%]	W-A [m/s]	Weibull-k	U [m/s]	power [W/m²]	delta-U [%]
1	0	1.1	1.4	0.83	1.52	22	-9.225%
2	30	0.6	0.4	0.55	0.65	9	-35.980%
3	60	0.5	0.8	0.75	0.95	7	-19.558%
4	90	4.3	3.1	1.51	2.79	36	1.926%
5	120	18.3	3.5	1.17	3.33	94	1.493%
6	150	3.7	4.3	1.65	3.85	83	9.391%
7	180	1.8	2.6	1.02	2.58	60	-0.018%
8	210	1.3	1.6	0.83	1.73	33	-10.638%
9	240	2.1	2.4	1.06	2.31	39	0.591%
10	270	28.9	7.9	3.70	7.10	278	3.616%
11	300	31.5	7.1	2.49	6.27	239	2.604%
12	330	5.9	7.2	1.92	6.36	314	6.914%
All (emergent)					5.41	199	
Source data					n/a	n/a	

Figure 3.5 : Demonstration of observed wind climate in WAsP.



		R-class 0 (0.000 m)	R-class 1 (0.030 m)	R-class 2 (0.100 m)	R-class 3 (0.400 m)
Height 1 (z = 10 m)	U [m/s] P [W/m^2]	10.18 1282	7.28 499	6.34 327	4.98 156
Height 2 (z = 25 m)	U [m/s] P [W/m^2]	11.08 1638	8.51 782	7.67 567	6.44 333
Height 3 (z = 50 m)	U [m/s] P [W/m^2]	11.79 1951	9.54 1063	8.74 817	7.61 534
Height 4 (z = 100 m)	U [m/s] P [W/m^2]	12.57 2366	10.72 1441	9.95 1147	8.86 811
Height 5 (z = 200 m)	U [m/s] P [W/m^2]	13.46 2934	12.23 2131	11.41 1716	10.28 1242

Sector: All
A: 11.5 m/s
k: 1.93
U: 10.18 m/s
P: 1283 W/m^2
-- Emergent
-- Combined

Figure 3.6 : Demonstration of wind speed and power density related to height above ground level.

3.4.2 Creating a vector map for WAsP with the Global Mapper software and determination of the coordinates on the vector map for the measuring station in WAsP program

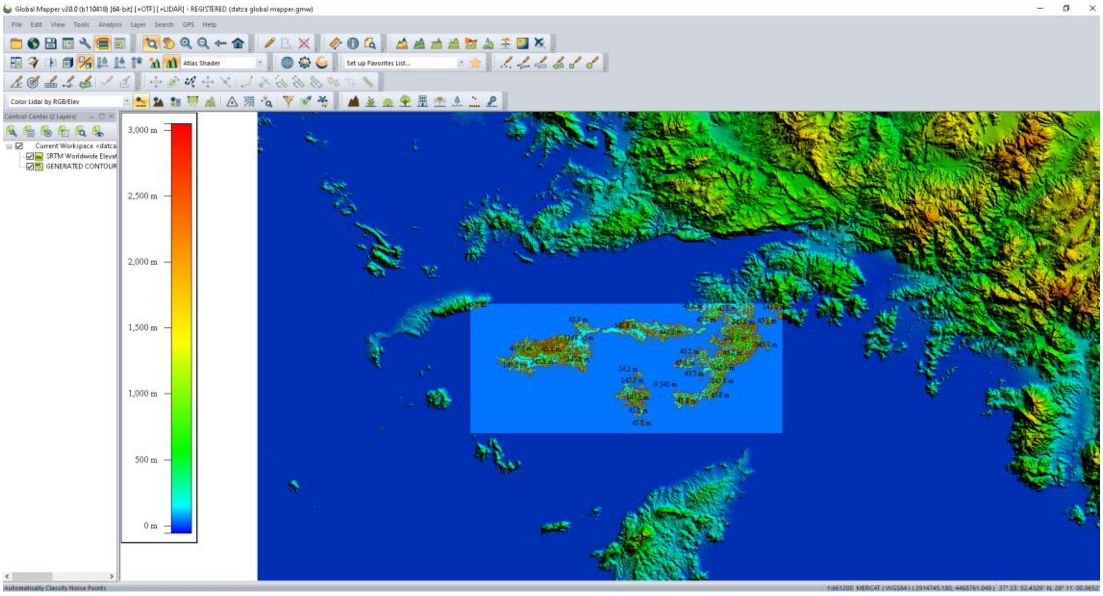
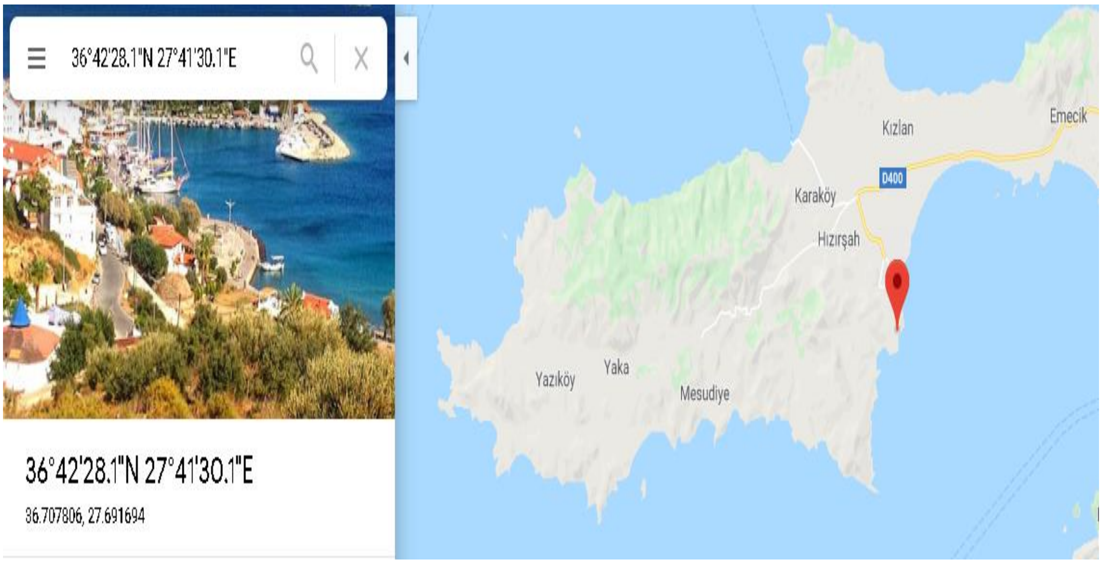


Figure 3.7 : Adjusting the elevations of the map with satellite data in Global Mapper Software.

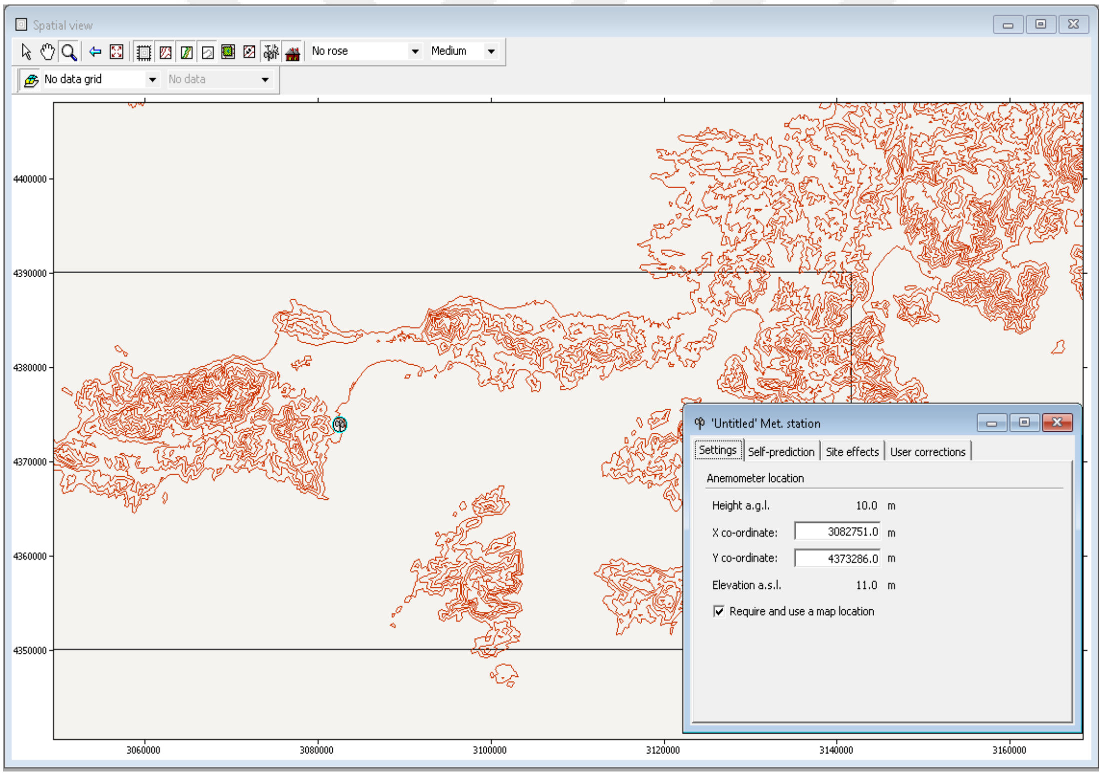


36°42'28.1"N 27°41'30.1"E

36°42'28.1"N 27°41'30.1"E

36.707806, 27.691694

Figure 3.8 : Demonstration of coordinates of wind measurement station in Datça (Turkish State Meteorological Service,2019).



Spatial view

No rose · Medium

No data grid · No data

'Untitled' Met. station

Settings | Self-prediction | Site effects | User corrections

Anemometer location

Height a.g.l. 10.0 m

X co-ordinate: 3082751.0 m

Y co-ordinate: 4373286.0 m

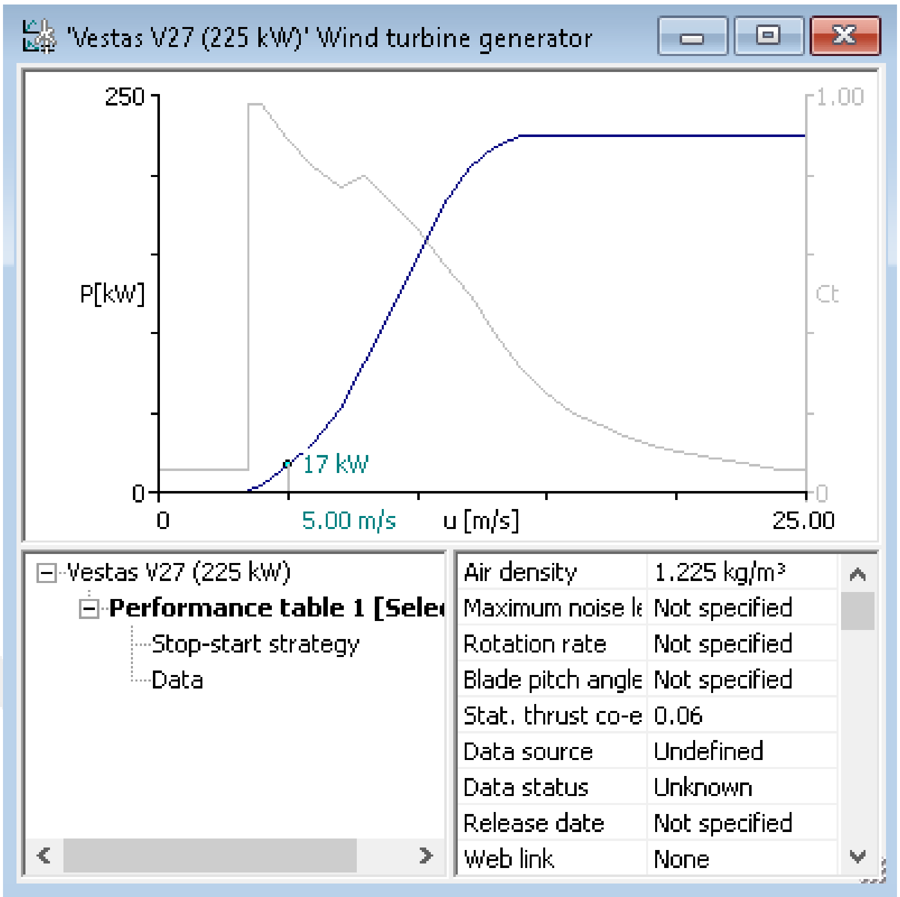
Elevation a.s.l. 11.0 m

☑ Require and use a map location

Figure 3.9 : Determination of the wind measurement station coordinates in the WAsP program.

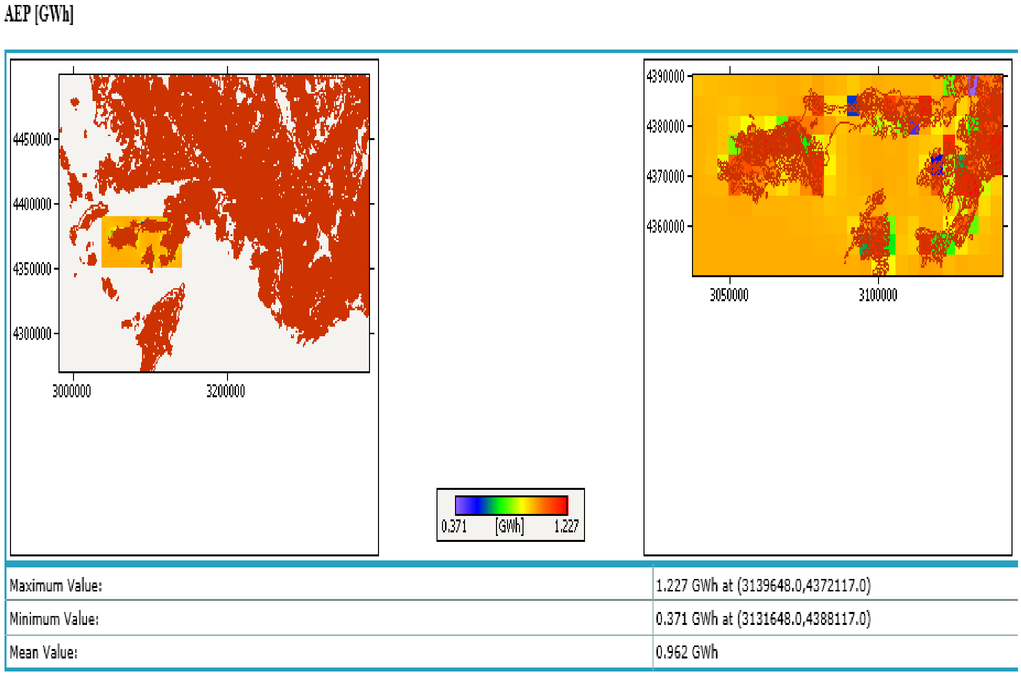
3.4.3 Calculation of annual energy production of 225 kW Vestas turbine

Figure 3.10 shows the wind speed - power curve of Vestas brand 225 kW. As can be seen from Figure 3.11, the maximum value of annual energy production from V27, 225 kW wind turbine is calculated as 1.227 GWh.



Air density	1.225 kg/m³
Maximum noise le	Not specified
Rotation rate	Not specified
Blade pitch angle	Not specified
Stat. thrust co-e	0.06
Data source	Undefined
Data status	Unknown
Release date	Not specified
Web link	None

Figure 3.10 : Demonstration of wind speed and power curve of Vestas brand 225 kW wind turbine.

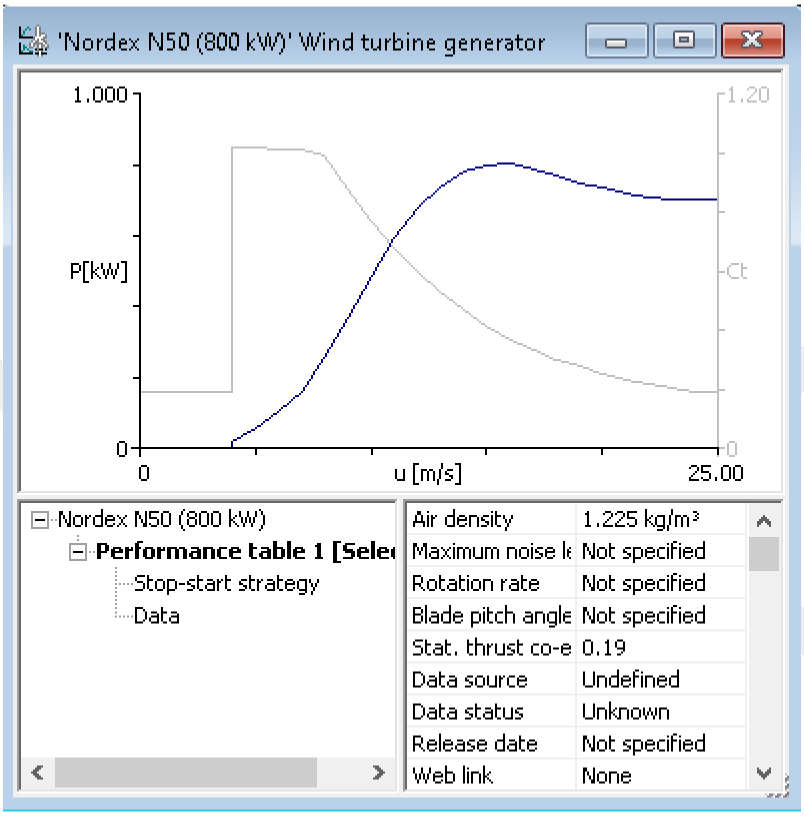


Maximum Value:	1.227 GWh at (3139648.0,4372117.0)
Minimum Value:	0.371 GWh at (3131648.0,4388117.0)
Mean Value:	0.962 GWh

Figure 3.11 : Annual energy production of Vestas brand 225 kW wind turbine.

3.4.4 Calculation of annual energy production of 800 kW Nordex turbine

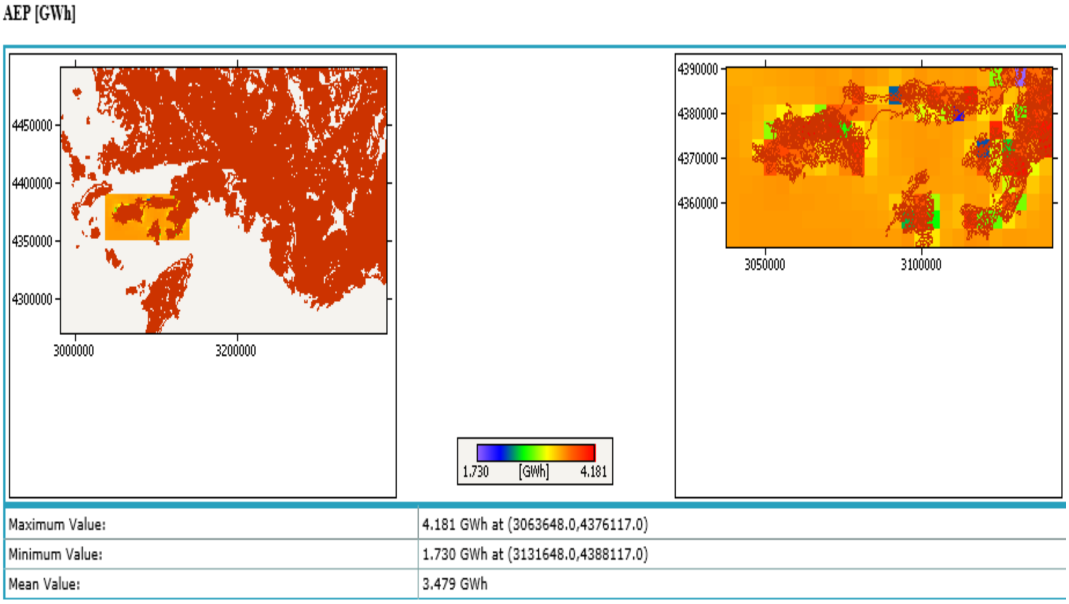
Figure 3.12 shows the wind speed and power curve of Nordex brand 800 kW. As can be seen from Figure 3.13, the maximum value of annual energy production from N50, 800 kW wind turbine is calculated as 4.181 GWh.



Nordex N50 (800 kW)
  Performance table 1 [Selec
    Stop-start strategy
    Data

Air density	1.225 kg/m³
Maximum noise le	Not specified
Rotation rate	Not specified
Blade pitch angle	Not specified
Stat. thrust co-e	0.19
Data source	Undefined
Data status	Unknown
Release date	Not specified
Web link	None

Figure 3.12 : Demonstration of wind speed and power curve of Nordex brand 800 kW wind turbine.

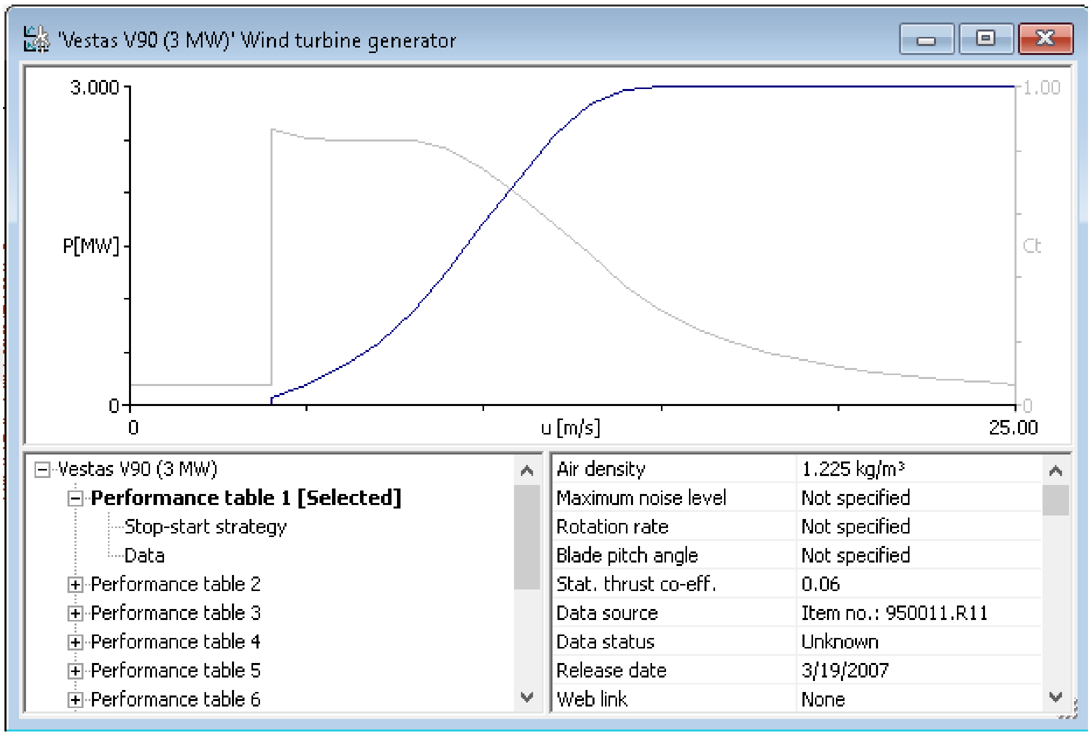


Maximum Value:	4.181 GWh at (3063648.0,4376117.0)
Minimum Value:	1.730 GWh at (3131648.0,4388117.0)
Mean Value:	3.479 GWh

Figure 3.13 : Annual energy production of Nordex brand 800 kW wind turbine.

3.4.5 Calculation of annual energy production of 3 MW Vestas turbine

Figure 3.14 shows the wind speed and power curve of Vestas brand 3 MW. As can be seen from Figure 3.15, the maximum value of annual energy production from V90, 3 MW wind turbine is calculated as 16.592 GWh.

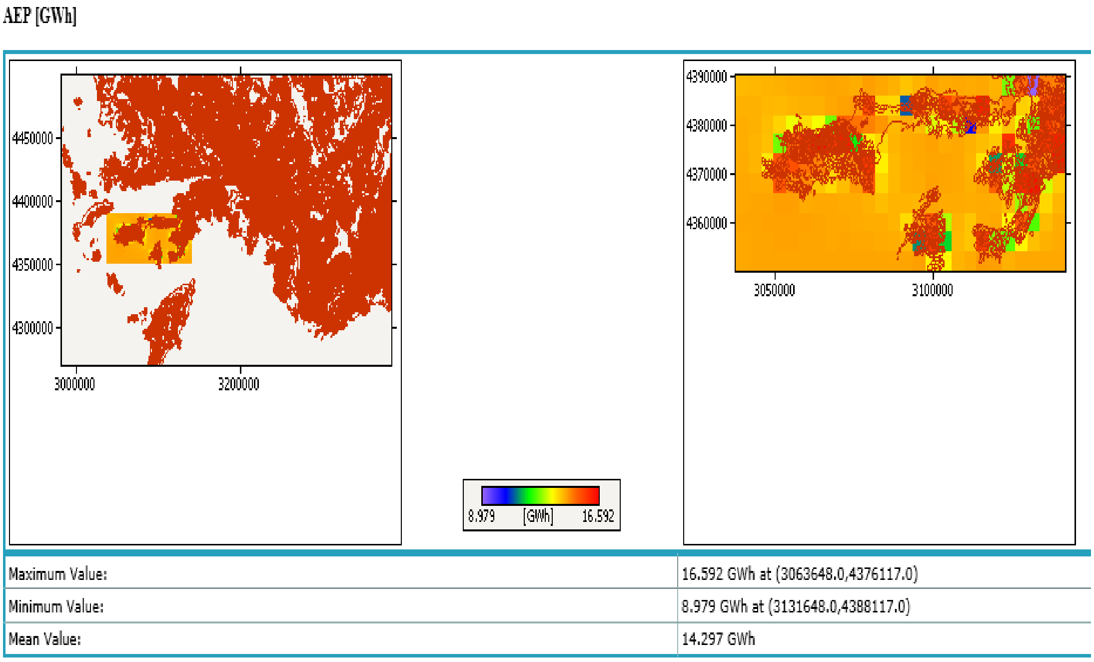


'Vestas V90 (3 MW)' Wind turbine generator

Vestas V90 (3 MW)
  Performance table 1 [Selected]
    Stop-start strategy
    Data
  Performance table 2
  Performance table 3
  Performance table 4
  Performance table 5
  Performance table 6

Air density	1.225 kg/m³
Maximum noise level	Not specified
Rotation rate	Not specified
Blade pitch angle	Not specified
Stat. thrust co-eff.	0.06
Data source	Item no.: 950011.R11
Data status	Unknown
Release date	3/19/2007
Web link	None

Figure 3.14 : Demonstration of wind speed and power curve of Vestas brand 3 MW wind turbine.



Maximum Value:	16.592 GWh at (3063648.0,4376117.0)
Minimum Value:	8.979 GWh at (3131648.0,4388117.0)
Mean Value:	14.297 GWh

Figure 3.15 : Annual energy production of Vestas brand 3 MW wind turbine.

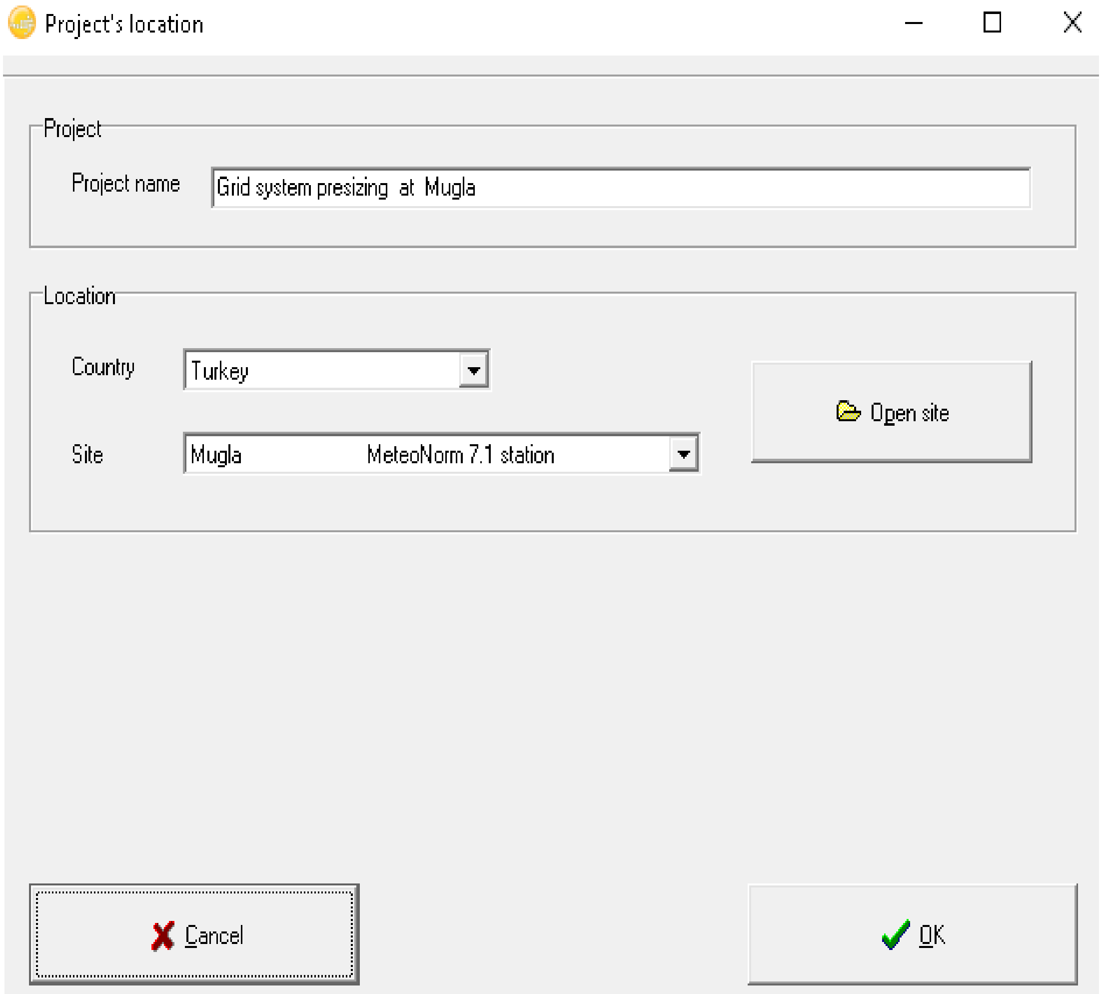
3.5 Calculation of 1 Year Energy to Be Produced by Solar Panels with PVSyst Software

Muğla, MeteoNorm 7.1 station’s data is used for solar measurement which is located at 37.20 °N latitude and 28.35 °E longitude (Massachusetts Institute of Technology, 2019). The system is designed on-grid.

Standard is selected as module type and polycrystalline technology is selected as technology.

Also system is designed to be ground based and free standing.

3.5.1 System design with PVSyst program

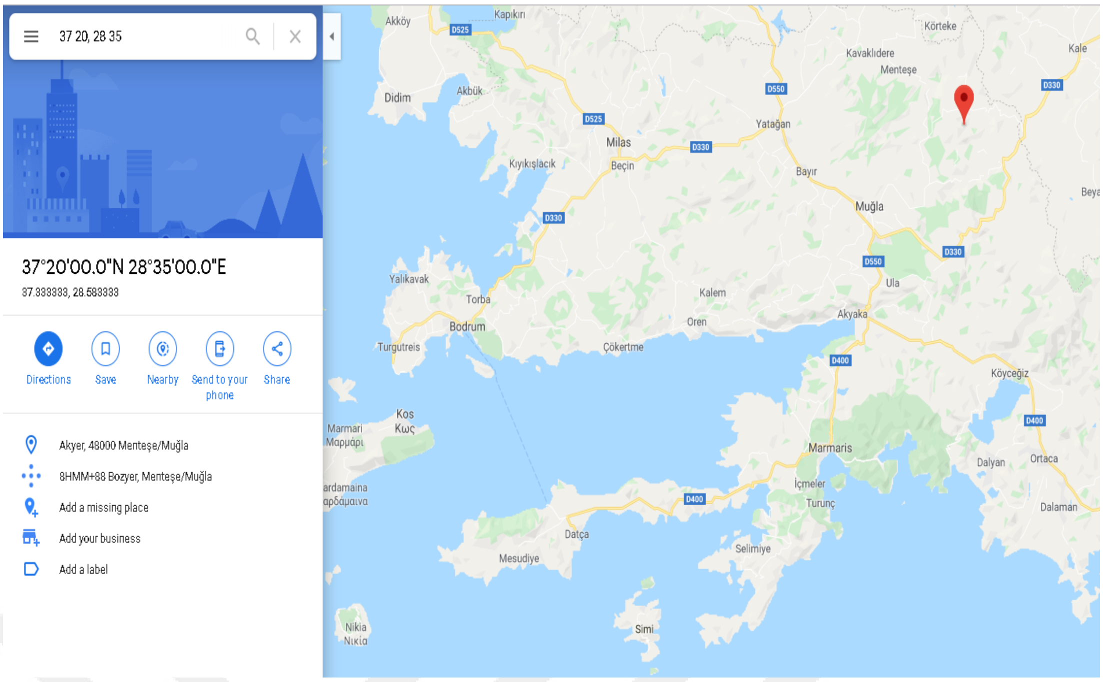


Project name: Grid system presizing at Mugla

Country: Turkey

Site: Mugla MeteoNorm 7.1 station

Figure 3.16 : Determination of solar measuring station with PVSyst program.



37 20, 28 35

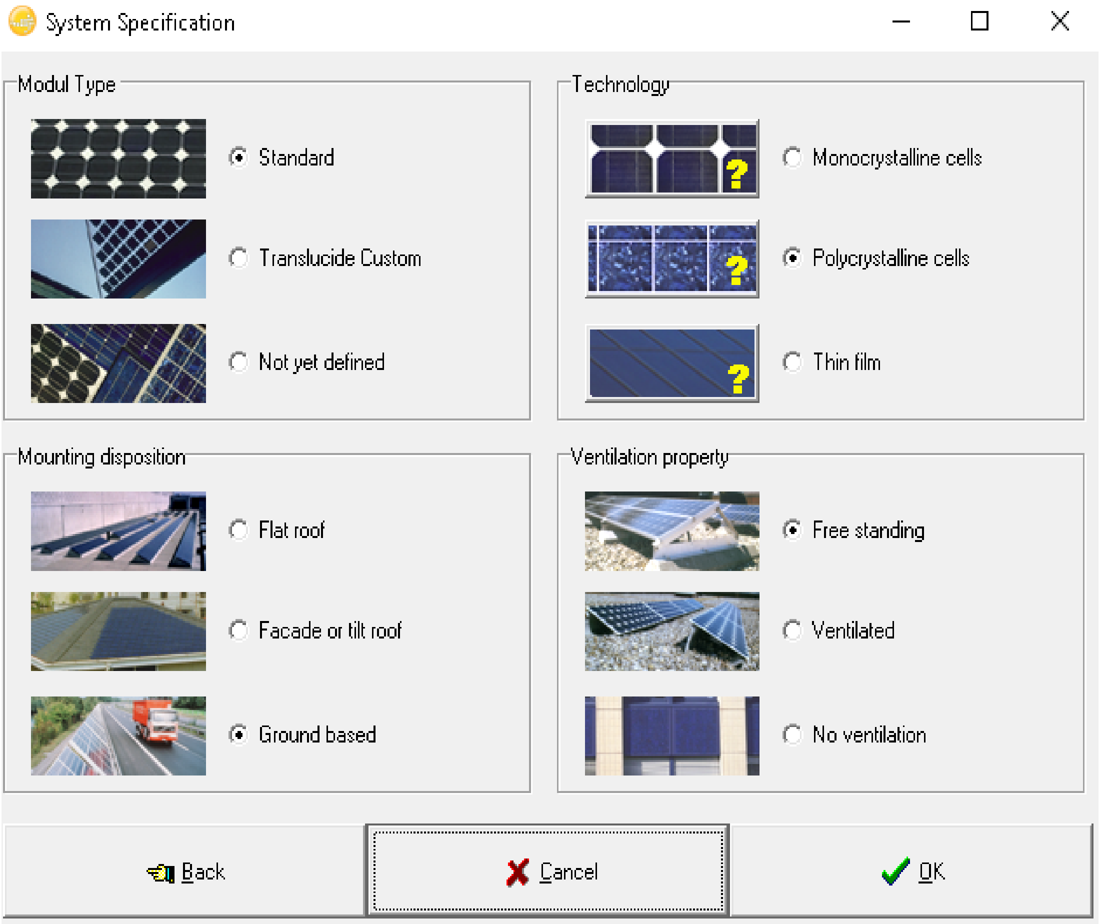
37°20'00.0"N 28°35'00.0"E

37.333333, 28.583333

Akyer, 48000 Menteşe/Muğla

8HMM+88 Bozyer, Menteşe/Muğla

Figure 3.17 : Demonstration of the location of the solar measuring station of Meteonorm in Muğla with Google Maps (Massachusetts Institute of Technology, 2019).



System Specification

Modul Type

● Standard

○ Translucide Custom

○ Not yet defined

Technology

○ Monocrystalline cells

● Polycrystalline cells

○ Thin film

Mounting disposition

○ Flat roof

○ Facade or tilt roof

● Ground based

Ventilation property

● Free standing

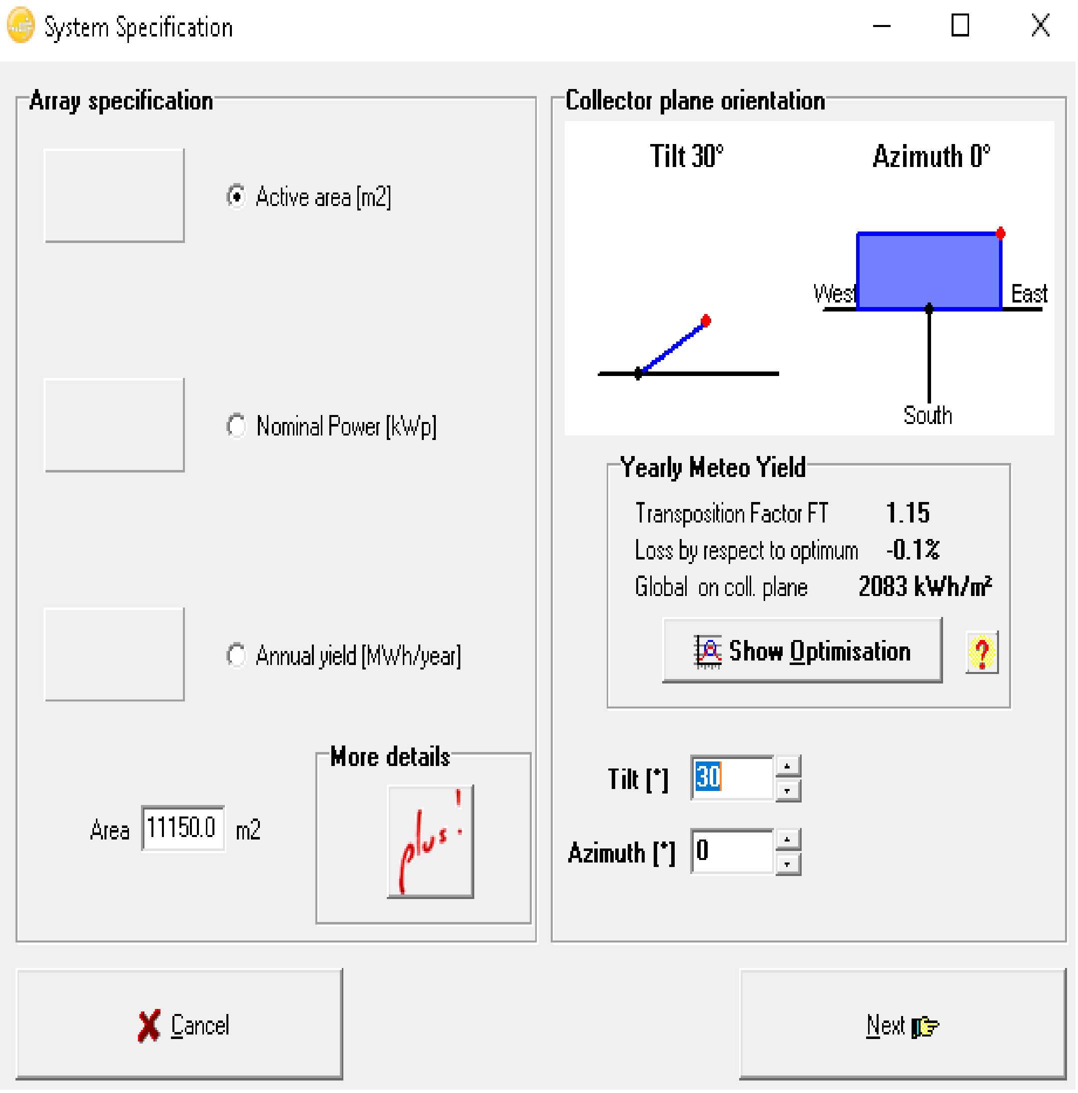
○ Ventilated

○ No ventilation

Figure 3.18 : Determination of modul type, technology, mounting disposition and ventilation property with PVSyst.

3.5.1.1 Calculation of annual energy produced from the sun in an area of 11,150 m^2 in Muğla

As seen in Figure 3.21, the annual energy production from a solar power plant of 11,150 m^2 is 2,958 MWh, nominal power is 1,673 kW and the highest energy production is in July.


System Specification

Array specification

● Active area [m2]

○ Nominal Power [kWp]

○ Annual yield [MWh/year]

Area 11150.0 m2

Collector plane orientation

Tilt 30°

Azimuth 0°

Yearly Meteo Yield

Transposition Factor FT 1.15

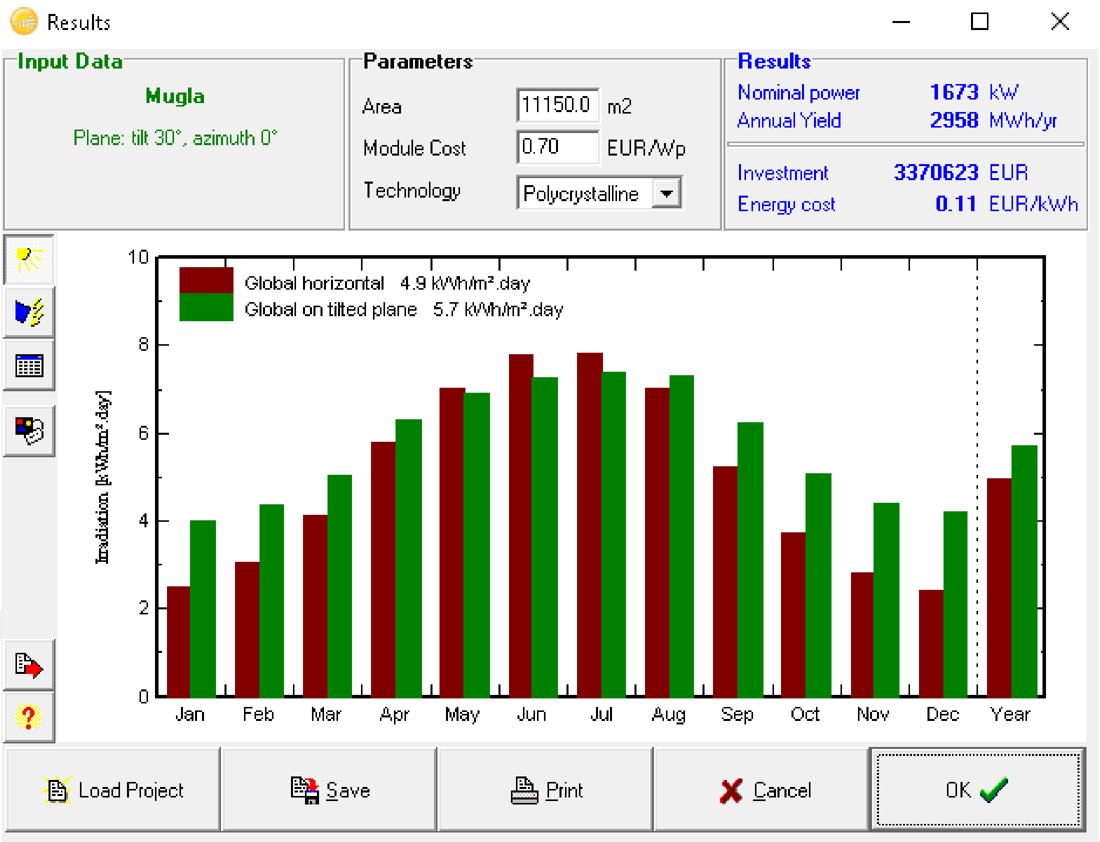
Loss by respect to optimum -0.1%

Global on coll. plane 2083 kWh/m²

Tilt [°] 30

Azimuth [°] 0

Figure 3.19 : Demonstration of system specification in PVSyst.


Results

Input Data

Mugla

Plane: tilt 30°, azimuth 0°

Parameters

Area 11150.0 m2

Module Cost 0.70 EUR/Wp

Technology Polycrystalline

Results

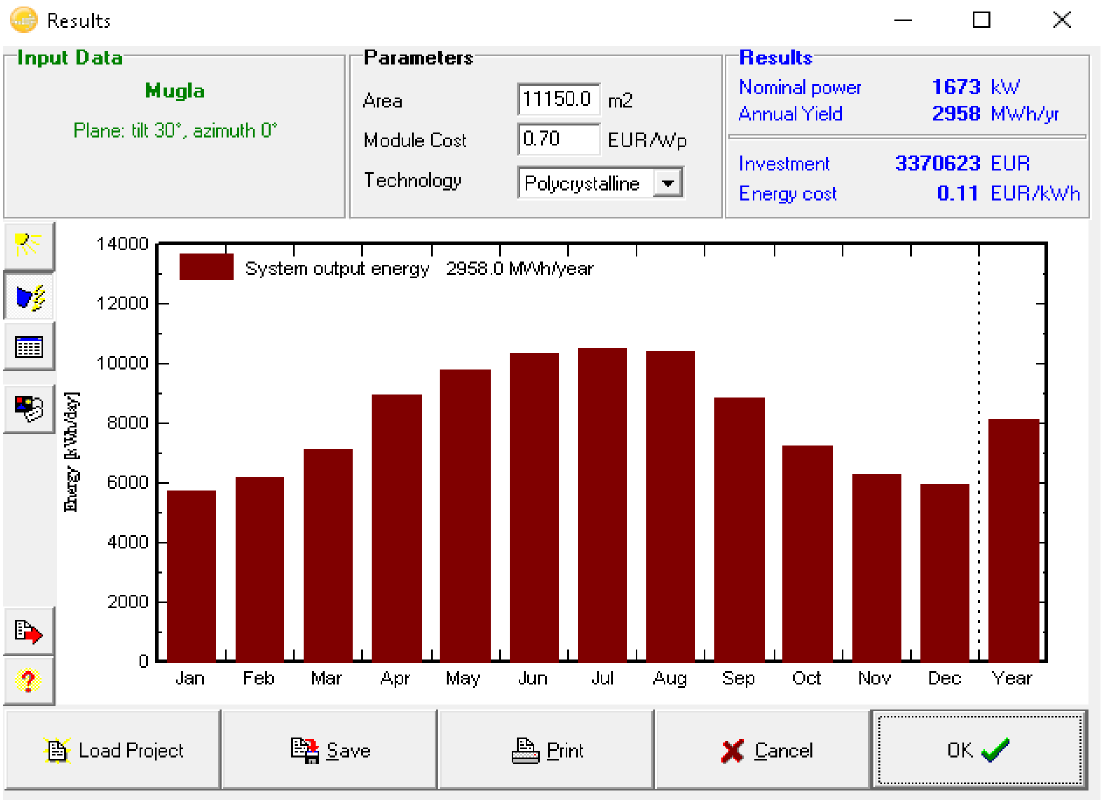
Nominal power **1673** kW

Annual Yield **2958** MWh/yr

Investment **3370623** EUR

Energy cost **0.11** EUR/kWh

Figure 3.20 : Distribution of irradiation on horizontal and tilted plane according to months.


Results

Input Data

Mugla

Plane: tilt 30°, azimuth 0°

Parameters

Area 11150.0 m2

Module Cost 0.70 EUR/Wp

Technology Polycrystalline

Results

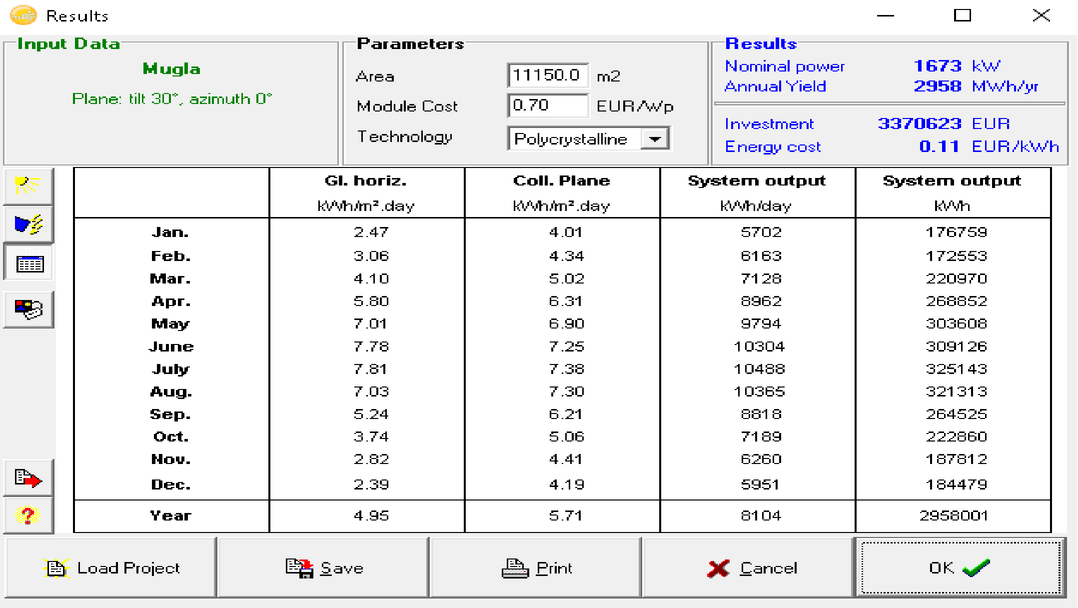
Nominal power **1673** kW

Annual Yield **2958** MWh/yr

Investment **3370623** EUR

Energy cost **0.11** EUR/kWh

Figure 3.21 : Distribution of energy produced by 11,150 m2 of solar field per month.



Input Data

Mugla

Plane: tilt 30°, azimuth 0°

Parameters

Area: 11150.0 m2
Module Cost: 0.70 EUR/Wp
Technology: Polycrystalline

Results

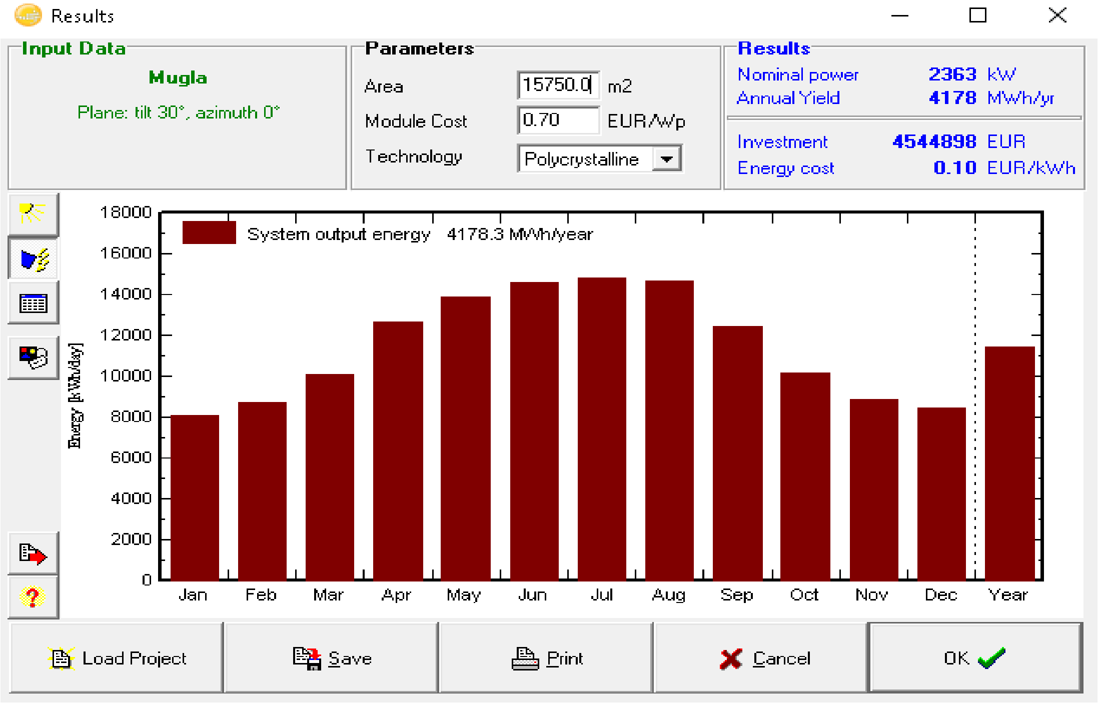
Nominal power: **1673** kW
Annual Yield: **2958** MWh/yr
Investment: **3370623** EUR
Energy cost: **0.11** EUR/kWh

	Gl. horiz. kWh/m².day	Coll. Plane kWh/m².day	System output kWh/day	System output kWh
Jan.	2.47	4.01	5702	176759
Feb.	3.06	4.34	6163	172553
Mar.	4.10	5.02	7128	220970
Apr.	5.80	6.31	8962	268852
May	7.01	6.90	9794	303608
June	7.78	7.25	10304	309126
July	7.81	7.38	10488	325143
Aug.	7.03	7.30	10365	321313
Sep.	5.24	6.21	8818	264525
Oct.	3.74	5.06	7189	222860
Nov.	2.82	4.41	6260	187812
Dec.	2.39	4.19	5951	184479
Year	4.95	5.71	8104	2958001

Figure 3.22 : Demonstration of global irradiation, collector plane irradiation and system energy output on monthly basis for 11,150 m2 of solar field.

3.5.1.2 Calculation of annual energy produced from the sun in an area of 15,750 m^2 in Muğla

As seen in Figure 3.23, the annual energy production from a solar power plant of 15,750 m^2 is 4,178 MWh, nominal power is 2,363 kW and the highest energy production is in July.



Input Data

Mugla

Plane: tilt 30°, azimuth 0°

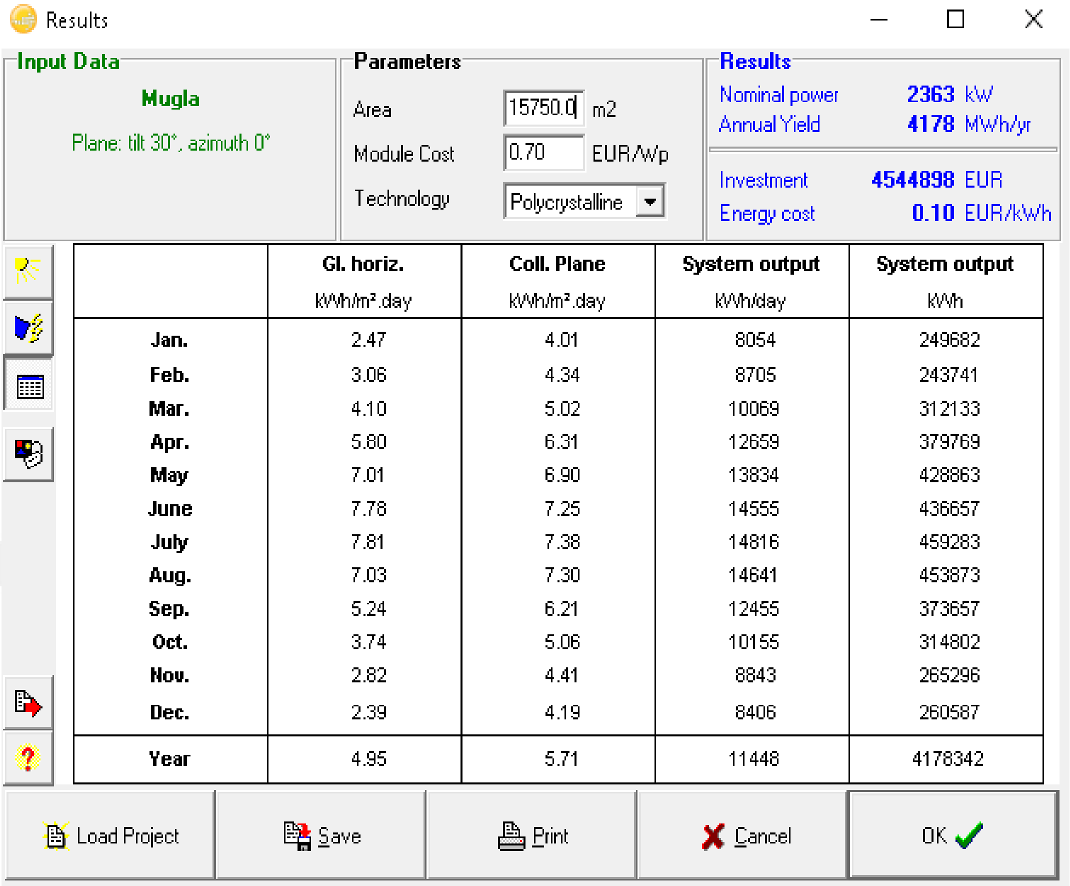
Parameters

Area: 15750.0 m2
Module Cost: 0.70 EUR/Wp
Technology: Polycrystalline

Results

Nominal power: **2363** kW
Annual Yield: **4178** MWh/yr
Investment: **4544898** EUR
Energy cost: **0.10** EUR/kWh

Figure 3.23 : Distribution of energy produced by 15,750 m2 of solar field per month.



Input Data

Mugla

Plane: tilt 30°, azimuth 0°

Parameters

Area 15750.0 m2

Module Cost 0.70 EUR/Wp

Technology Polycrystalline

Results

Nominal power **2363** kW

Annual Yield **4178** MWh/yr

Investment **4544898** EUR

Energy cost **0.10** EUR/kWh

	Gl. horiz. kWh/m².day	Coll. Plane kWh/m².day	System output kWh/day	System output kWh
Jan.	2.47	4.01	8054	249682
Feb.	3.06	4.34	8705	243741
Mar.	4.10	5.02	10069	312133
Apr.	5.80	6.31	12659	379769
May	7.01	6.90	13834	428863
June	7.78	7.25	14555	436657
July	7.81	7.38	14816	459283
Aug.	7.03	7.30	14641	453873
Sep.	5.24	6.21	12455	373657
Oct.	3.74	5.06	10155	314802
Nov.	2.82	4.41	8843	265296
Dec.	2.39	4.19	8406	260587
Year	4.95	5.71	11448	4178342

Figure 3.24 : Demonstration of global irradiation, collector plane irradiation and system energy output on monthly basis for 15,750 m2 of solar field.

3.6 Optimization Calculations for Hybrid System

As seen in Table 3.4, tilt planes of solar panels are arranged according to the seasons and energy production of each month is calculated separately for the hybrid system where both solar and wind power plants are located.

For spring and autumn, the tilt plane is arranged as 36 degrees, 24 degrees for summer and 48 degrees for winter to increase monthly energy production. The electricity obtained from the 225 kW Vestas wind turbine was calculated separately for each month.

With the optimization of a hybrid system, 4,276,500,996 kWh of electricity was generated annually. Considering 4,185,000 kWh produced with a non-optimized hybrid system, we can generate 91,500,996 kWh more electricity with optimization.

Table 3.4 : Monthly optimization results for a hybrid system.

	Monthly Energy Produced by 225 kW Vestas Turbine	Montly Energy Produced by 11,150 m2 of Solar Field	Tilt Plane	Total
Months	[kWh]	[kWh]	[Degree]	[kWh]
January	96,611.014	198,863	48	295,474.014
February	73,823.726	184,926	48	258,749.726
March	91,885.397	223,500	36	315,385.397
April	117,926.630	266,053	36	383,979.630
May	122,260.877	294,503	36	416,763.877
June	109,707.452	319,252	24	428,959.452
July	124,419.781	334,734	24	459,153.781
August	141,030.740	324,675	24	465,705.740
September	93,186.904	265,680	36	358,866.904
October	96,271.835	228,767	36	325,038.835
November	70,536.493	196,566	36	267,102.493
December	89,369.147	211,972	48	301,341.147
Total	1,227,029.996	3,049,491		4,276,501.996

3.7 Calculation of 1 Year Total Fuel Need of the Public Transport Line Between Datça-Marmaris with Diesel Buses

The average fuel consumption of 12 meter of diesel buses in liters per 100 km is given in Table 3.5. The amount of diesel required by the public transportation line between Datça and Marmaris is calculated as follows:

Total km covered between Marmaris and Datça for 1 year = km = 927,368 km.

12 m Diesel bus average fuel consumption (l/100km) = 40.9 l/100 km.

The 1 year diesel fuel requirement of the buses for public transport line between Datça and Marmaris = 927,368 km x 40.9 l/100 km = 379,293.512 liters.

Table 3.5 : Fuel consumption of 12 m H2FC and diesel buses (Lozanovski, 2018).

	Average 12 m H_2FC Bus	Average 12 m Diesel Bus
Consumption [kg H_2/100 km]	9.0	-
Consumption [l Diesel equivalent/100 km]	30.1	40.9

3.8 Calculation of 1-year total emissions due to the use of diesel buses in the public transport line between Datça and Marmaris

Table 3.6 shows the emission rates per km of the 12-meter Diesel Euro V bus and fuel cell bus. As can be seen from the table 3.5, while fuel cell buses have zero emissions, diesel buses emit CO_2, NO_x, particulate matter and total hydrocarbon emissions 986, 11.29, 0.019, 0.004 grams per kilometer respectively.

Table 3.6 : Emissions of a 12 m diesel bus (Diesel Euro V) under London specific circumstances (Lozanovski, 2018).

Emission	Diesel Euro V SCR	H_2FC Bus
CO_2 [g/km]	986	0 (no local emission)
NO_x [g/km]	11.29	0 (no local emission)
PM [g/km]	0.019	0 (no local emission)
THC [g/km]	0.004	0 (no local emission)

Total km covered between Marmaris and Datça for 1 year = km = 927,368 km.

Calculation of the total annual carbon dioxide emissions released from the bus line between Marmaris and Datça: 927,368 km x 986 g/km = 914,384,848 g CO2. Calculation of the total annual NOx emissions released from the bus line between Marmaris and Datça: 927,368 km x 11.29 g/km =10,469,984.72 g NOx.

Calculation of the total annual particulate matter emissions released from the bus line between Marmaris and Datça: 927,368 km x 0.019 g/km = 17,619.992 g PM.

Calculation of the total annual total hydrocarbon emissions released from the bus line between Marmaris and Datça: 927,368 km x 0.004 g/km = 3,709.472 g THC.

4. CONCLUSION

Total length of the road covered on the public transport line between Datça and Marmaris was calculated as 332,852 km for the 3-month summer period and 594,516 km for the remaining 9 months, which corresponds to a total of 927,368 km for 1 year. The data given by Muğla Municipality was used in determining the number of buses. Google Maps application was used for calculating the round trip distance between Datça and Marmaris.

According to the information received from Datça Municipality, 12 meter diesel buses are currently being used. Our study recommends replacing these 12-meter diesel buses with 12-meter hydrogen-powered fuel cell buses in order to provide a healthier environment for the nature and human health and reduce dependence on foreign sources in terms of fossil fuels.

The average fuel consumption of buses with fuel cells may vary depending on the route in which they are used. While calculating the average fuel consumption of the buses to be used on Datça and Marmaris lines, the average fuel consumption of 9 kg H_2/100km was used, which is the average of 25 fuel cell buses (12-meter) currently used in Europe. By multiplying the amount of hydrogen to be burned by fuel cell buses per 100 km and the route covered in this line, the 1 year hydrogen need of the public transportation line between Datça and Marmaris was found to be 83,463.12 kg H_2.

The hydrogen demand for this line was provided by the electrolysis of water in our study so that no emission gas will be released to the outside while producing hydrogen. The system efficiency was calculated as 50 kWh/kg H_2, which is the 2011 status of U.S. Department of Energy. In addition, 2015 and 2020 targets of the U.S. Department of Energy were examined in our study. When calculating the electrical energy required to produce 1 year total hydrogen requirement for this line by electrolysis of water, the system efficiency of the Department of Energy in 2011 was multiplied by the 1 year total hydrogen requirement of the bus line and the total electrical energy requirement was calculated to be 4,173,156 kWh per year.

When the electrical energy required for the production of hydrogen is supplied from fossil fuels, emission gases are released to the outside, so if such methods are used, there will be no benefit to the environment and human health. For this reason, our study aims to provide the necessary electrical energy for the production of hydrogen from clean and renewable energy sources such as solar and wind.

In general, Turkey is a country that provides the electricity production from fossil fuels and natural gas. However, sources in Turkey in terms of fossil fuels and natural gas are not sufficient and these fuels are imported from other countries. Due to its geographical location, Turkey is a country that lives four seasons. Thus, especially in the south western region of Turkey is efficient in terms of the solar energy. In addition, due to its geographic shapes, Datça region of Turkey is efficient in terms of wind energy. Instead of using fossil resources, Turkey should be directed to clean energy sources and thus would have reduced the dependence on fossil fuels and also will have achieved an important step both for the environment and human health. For these reasons, the public transportation line between Datça and Marmaris was chosen for our study. In addition, while the annual energy production of wind energy were calculated from different wind turbines in the Datça area which is efficient in terms of installation of wind energy power plants, annual energy production was evaluated for the solar power plants in different sizes.

Annual energy production of 3 wind turbines with different power outputs were calculated to supply sufficient energy from wind turbines in order to generate the necessary hydrogen for this bus line. With three different scenarios, it is aimed to research whether the electrical energy required for the production of hydrogen is provided only by wind energy, the state of a hybrid system with solar energy or the supply of more than one public transport line with only wind energy. Calculations of annual enery production from wind were made with WAsP program. The system was designed to be on-grid. Wind measurement station of Turkish State Meteorological Service’s data in Datça was used. Wind speed and direction data were recorded per hour. Totally 1 year wind speed and direction data were used. With the OWC wizard, the data of the measuring station in Datça was optimized for the WAsP program. The vector map used in the WAsP program was created by the optimization of satellite images with the Global Mapper program.

Vestas and Nordex branded wind turbines with 3 different power outputs of 225 kW, 800 kW and 3 MW were used to calculate the annual energy production.

The electricity required to provide 1 year hydrogen demand of the public transportation line between Datça and Marmaris was calculated as 4,173,156 kWh. With the establishment of a 225 kW Vestas turbine in Datça, the annual energy production was calculated as 1,227,000 kWh. With this amount of production, only 29 percent of the energy required for the hydrogen production of this line can be provided, thus the 225 kW wind turbine will be used for the hybrid system considering the amount of energy to be obtained from the solar plants in the following discussion. With the establishment of a 800 kW Nordex turbine in Datça, the annual energy production was calculated as 4,181,000 kWh. With this amount of production, all the energy required for hydrogen production of this line can be provided and the remaining 7,844 kWh energy can be supplied to the grid. With the establishment of a 3 MW Vestas turbine in Datça, the annual energy production was calculated as 16,592,000 kWh. This amount corresponds to approximately 4 times the energy required for the hydrogen production of this line, so if a 3 MW wind turbine is used in Datça, hydrogen production can be provided for 3 more different bus lines on the same scale with the public transport line between Datça and Marmaris.

In order to provide the electrical energy required for the generation of the hydrogen demand of this line, solar power plants with 2 different size in Muğla were examined separately. PVSyst program was used to calculate the annual energy production from solar energy in Muğla. Muğla, MeteoNorm 7.1 station’s data was used for solar measurement which is located at 37.20 °N latitude and 28.35 °E longitude. The system was designed to be on-grid. Standard was selected as module type and polycrystalline technology is selected as technology. Also system was designed to be ground based and free standing. With the establishment of a 11,150 m^2 solar power plant in Muğla, the annual energy production was calculated as 2,958,000 kWh and nominal power was 1,673 kW. With this amount of production, only 71 percent of the energy required for the hydrogen production of this line can be provided, thus 11,150 m^2 solar panels will be used for the hybrid system considering the amount of energy to be obtained from 225 kW wind turbine in the following scenario.

With the establishment of a 15,750 m^2 solar power plant in Muğla, the annual energy production was calculated as 4,178,000 kWh and nominal power was 2,363 kW. With this amount of production, all the annual energy required for hydrogen production of this line can be provided and the remaining 4,844 kWh energy can be supplied to the grid.

In the case of a hybrid system that uses both solar and wind energy, a total of 4,185,000 kWh will be generated by the installation of a solar panel of 11,150 m^2 and the simultaneous use of a 225 kW wind turbine. In addition, the remaining 11,844 kWh energy can be supplied to the grid.

In the hybrid system, 4,276,500,996 kWh of electricity is produced annually by tilt plane optimization of solar panels according to the seasons. Considering 4,185,000 kWh produced with a non-optimized hybrid system, we can generate 91,500,996 kWh more electricity in the hybrid system with optimization.

The public transport line between Datça and Marmaris is currently using 12-meter diesel buses and these buses consume 40.9 liters diesel fuel per 100 kilometers. Considering that the total number of roads covered by this bus line is 927,368 km, the total amount of diesel that this bus line will consume was calculated as 379,293.512 liters.

Diesel-fueled buses emit harmful emission gases to the environment. In terms of both environmental and human health, the use of fuel cell buses on this line is proposed in our study. While fuel cell buses have zero emissions, diesel buses emit CO_2, NO_X, particulate matter and total hydrocarbon emissions 986, 11.29, 0.019, 0.004 grams per kilometer respectively. Considering the total distance covered by this bus line, the total annual carbon dioxide emissions released from the bus line between Marmaris and Datça was calculated as 914,384,848 g CO_2. The total annual NO_X emissions released from the bus line between Marmaris and Datça was calculated as 10,469,984.72 g NO_X. The total annual particulate matter emissions released from the bus line between Marmaris and Datça was calculated as 17,619.992 g PM. In addition, the total annual total hydrocarbon emissions released from the bus line between Marmaris and Datça was calculated as 3,709.472 g THC.

By promoting domestic production, renewable energy systems such as hydrogen, wind, and solar, which have a high initial investment costs, might become advantageous in the long term for countries dependent on foreign fossil fuels such as Turkey.

Except for the transport line between Datça and Marmaris, by examining which renewable energy resources the region has in various regions, similar systems can be established that are completely independent of fossil fuels and do not spread pollutants to the environment.

With the current and future studies, through increasing the efficiency of both renewable energy systems and fuel cell technology, hydrogen powered vehicles can reach the level of not only durability, also economic competitiveness with fossil fuels; therefore, they can be an alternative to the fossil fuel powered vehicles.

Table 4.1 : Examination of the use of diesel buses in public transport line between Datça and Marmaris.

Total km covered between Marmaris and Datça for 1 year [km]	927,368
The 1 year diesel fuel requirement of the buses for public transport line [liter]	379,293.512
Total annual CO2 emissions released from the bus line [gram]	914,384,848
Total annual NOx emissions released from the bus line [gram]	10,469,984.72
Total annual PM emissions released from the bus line [gram]	17,619.992
Total annual THC emissions released from the bus line [gram]	3,709.472

Table 4.2 : Summary of energy production scenarios

Annual amount of electrical energy required for hydrogen production [kWh]	4,173,156
The maximum value of annual energy production from 225 kW wind turbine [kWh]	1,227,000
The maximum value of annual energy production from 800 kW wind turbine [kWh]	4,181,000
The maximum value of annual energy production from 3 MW wind turbine [kWh]	16,592,000
The annual energy production from a solar power plant of 11,150 m^2 [kWh]	2,958,000
The annual energy production from a solar power plant of 15,750 m^2 [kWh]	4,178,000
The annual energy production of a hybrid system which contains 225 kW wind turbine and solar power plant of 11,150 m^2 [kWh]	4,185,000
The annual energy production of a hybrid system with optimization [kWh]	4,276,501

Table 4.3 : Examination of the use of fuel cell buses in public transport lines between Datça and Marmaris.

The 1 year hydrogen requirement of the fuel cell buses [kg]	83,463.12
Total annual CO2 emissions released from fuel cell buses[gram]	0
Total annual NOx emissions released from fuel cell buses [gram]	0
Total annual PM emissions released from fuel cell buses [gram]	0
Total annual THC emissions released from fuel cell buses [gram]	0

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