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GRADUTE SCHOOL OF NATURAL AND APPLIED SCIENCES

TECHNO-ECONOMICAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN UZBEKISTAN

M.Sc. Thesis by

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Department of Energy Systems Engineering

July, 2025

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TECHNO-ECONOMICAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN UZBEKISTAN

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Abdulaziz MURTOZAEV

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THESIS EXAMINATION RESULT FORM

We have read the thesis entitled "TECHNO-ECONOMICAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN UZBEKISTAN" completed by **ABDULAZIZ MURTOZAEV** under the supervision of **Prof. Dr. BÜLENT YEŞILATA** and we certify that, in our opinion, it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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Date: July, 2025 **Abdulaziz MURTOZAEV**

TECHNO-ECONOMICAL ASSESSMENT OF GREEN HYDROGEN PRODUCTION IN UZBEKISTAN

ABSTRACT

The energy sector is the dominant source of greenhouse gas emissions in the world, and it needs to be totally transformed into the renewable, clean, and climate-friendly types of energy sources. The renewable energy has grown very rapidly for the last 25 years especially on solar, wind, hydropower, geothermal, and biomass. However, these sectors have some disadvantages such as initial cost (IC), unavailability round the clock – which means renewable energy (RE) is strongly dependent on the weather conditions, and lastly, the low efficiencies of renewable energy technologies. This requires us to create more effective and accessible new sources of energy. Green hydrogen is an emerging renewable energy carrier that has huge global potential due to its decarbonization promises.

Uzbekistan is used as a case study in this research work, being the presiding country with a growing population and high energy demands in Central Asia. The country's energy sector relies primarily on the burning of fossil fuels, especially natural gas and coal. Furthermore, due to the use of low-efficient energy technologies, Uzbekistan is struggling to meet its energy demand and is increasing its greenhouse gas emissions annually. Another obstacle to the development of Uzbekistan’s energy sector is the combination of low energy tariffs and a high level of state subsidies. Uzbekistan possesses significant potential in wind energy development, so this study aims to use wind energy for potential green hydrogen production.

On this purpose, we use Open Plan Tool to create techno-economic model and scenarios for the production of green hydrogen using wind energy in Uzbekistan, specifically in the Karakalpakstan region where the largest wind power farms are projected to be established within the next 3-5 years. A nominal installed capacity of 100 MW for wind plant is considered in the Karakalpakstan region. This tool is used to evaluate techno-economic performance and operational characteristics of green hydrogen integration. Certain attention is given to the role of capital expenditure (CAPEX) in discover of levelized cost of hydrogen (LCOH), and the reasons behind its corresponding high share are analyzed. The results of green hydrogen production

and utilization are discussed with a focus on their techno-economic implications.

The result of this study indicates that green hydrogen production from wind energy in Uzbekistan holds notable potential to enhance energy security, promote environmental sustainability, and stimulate economic development in Uzbekistan. This study demonstrates the technical feasibility and economic viability of green hydrogen production which can help Uzbekistan to reduce greenhouse emissions and address climate change issues. Overall, this study contributes to research on green hydrogen production potentials in Uzbekistan and provides valuable insights for policymakers, stakeholders, and researchers working toward a sustainable energy future.

Keywords: Green hydrogen, Renewable energy, Wind energy, CAPEX, OPEX, LCOH, Energy economics.

ÖZBEKİSTAN'DA YEŞİL HİDROJEN ÜRETİMİNİN TEKNO-EKONOMİK DEĞERLENDİRMESİ

ÖZET

Enerji sektörü dünyada sera gazı emisyonlarının baskın kaynağıdır ve tamamen yenilenebilir, temiz ve iklim dostu enerji kaynaklarına dönüştürülmesi gerekmektedir. Yenilenebilir enerji son 25 yıldır özellikle güneş, rüzgar, hidroelektrik, jeotermal ve biyokütle üzerinde çok hızlı bir şekilde büyümüştür. Ancak bu sektörlerin başlangıç maliyeti (IC), günün her saati erişilememesi - yani yenilenebilir enerjinin (RE) hava koşullarına güçlü bir şekilde bağımlı olması ve son olarak yenilenebilir enerji teknolojilerinin düşük verimliliği gibi bazı dezavantajları vardır. Bu, daha etkili ve erişilebilir yeni enerji kaynakları yaratmamızı gerektirir. Yeşil hidrojen, karbonsuzlaştırma vaatleri nedeniyle büyük küresel potansiyele sahip, ortaya çıkan bir yenilenebilir enerji taşıyıcısıdır.

Bu araştırma çalışmasında, büyüyen bir nüfusa ve Orta Asya'da yüksek enerji taleplerine sahip olan başkanlık ülkesi olan Özbekistan bir vaka çalışması olarak kullanılmıştır. Ülkenin enerji sektörü, özellikle doğal gaz ve kömür olmak üzere, öncelikle fosil yakıtların yakılmasına dayanmaktadır. Ayrıca, düşük verimli enerji teknolojilerinin kullanımı nedeniyle Özbekistan enerji talebini karşılamakta zorlanmakta ve sera gazı emisyonlarını yıllık olarak artırmaktadır. Özbekistan'ın enerji sektörünün gelişmesinin önündeki bir diğer engel ise düşük enerji tarifeleri ile yüksek düzeydeki devlet sübvansiyonlarının birleşimidir. Özbekistan, rüzgar enerjisi geliştirme konusunda önemli bir potansiyele sahiptir, bu nedenle bu çalışma potansiyel yeşil hidrojen üretimi için rüzgar enerjisini kullanmayı amaçlamaktadır.

Bu amaçla, özellikle önümüzdeki 3-5 yıl içinde en büyük rüzgar enerjisi çiftliklerinin kurulmasının öngörüldüğü Karakalpakstan bölgesinde, rüzgar enerjisi kullanılarak yeşil hidrojen üretimi için tekno-ekonomik model ve senaryolar oluşturmak için Open Plan Tool'ı kullanıyoruz. Karakalpakstan bölgesinde rüzgar santrali için nominal 100 MW kurulu güç düşünülmektedir. Bu araç, yeşil hidrojen entegrasyonunun tekno-ekonomik performansını ve operasyonel özelliklerini değerlendirmek için kullanılır. Hidrojenin seviyelendirilmiş maliyetinin (LCOH) keşfedilmesinde sermaye harcamasının (CAPEX) rolüne belirli bir dikkat gösterilir ve buna karşılık gelen

yüksek payının arkasındaki nedenler analiz edilir. Yeşil hidrojen üretimi ve kullanımının sonuçları, tekno-ekonomik etkilerine odaklanılarak tartışılmaktadır.

Bu çalışmanın sonucu, Özbekistan'da rüzgar enerjisinden yeşil hidrojen üretiminin enerji güvenliğini artırma, çevresel sürdürülebilirliği teşvik etme ve Özbekistan'da ekonomik kalkınmayı canlandırma açısından önemli bir potansiyele sahip olduğunu göstermektedir. Bu çalışma, Özbekistan'ın sera gazı emisyonlarını azaltmasına ve iklim değişikliği sorunlarını ele almasına yardımcı olabilecek yeşil hidrojen üretiminin teknik uygulanabilirliğini ve ekonomik uygulanabilirliğini göstermektedir. Genel olarak, bu çalışma Özbekistan'daki yeşil hidrojen üretim potansiyelleri üzerine yapılan araştırmalara katkıda bulunmakta ve sürdürülebilir bir enerji geleceği için çalışan politika yapıcılar, paydaşlar ve araştırmacılar için değerli içgörüler sunmaktadır.

Anahtar Kelimeler: Yeşil hidrojen, Yenilenebilir enerji, Rüzgar enerjisi, CAPEX, OPEX, LCOH, Enerji ekonomisi.

CONTENTS

THESIS EXAMINATION RESULT FORM III
ETHICAL DECLARATION IV
ACKNOWLEDGMENTS V
ABSTRACT VI
ÖZET VIII
NOMENCLATURE XII
LIST OF TABLES XIV
LIST OF FIGURES XV

CHAPTER 1 INTRODUCTION 1
1.1. OVERVIEW OF ENERGY SECTOR OF UZBEKISTAN 3
1.2. HYDROGEN PRODUCTION METHODS, TECHNOLOGIES, AND IT'S COST IN THE WORLD 5
1.3. Policy and technical base for green hydrogen production in Uzbekistan . 8

CHAPTER 2 LITERATURE REVIEW 10

CHAPTER 3 METHODOLOGY 15
3.1. RESEARCH OBJECTIVE 15
3.2. MODELING APPROACH 16
3.3. CALCULATION METHODOLOGY AND KEY FORMULAS 16
3.3.1. LCOH formula 17
3.3.2. Electrolyzer energy efficiency 17
3.4. SYSTEM CONFIGURATION AND ASSUMPTIONS 18

CHAPTER 4 RESULTS AND DISCUSSIONS 20
4.1. MODELING RESULTS 20
4.1.1. Wind power results 20
4.1.2. Hyrodgen production results 21
4.1.3. LCOH calculation and resultss 22
4.2. DISCUSSIONS 24

CHAPTER 5 CONCLUSIONS AND FUTURE WORK 26

5.1. CONCLUSIONS 26
5.2. FUTURE WORK AND SUGGESTIONS 26

REFERENCES 28

CIRRICULUM VITAE 32

NOMENCLATURE

Roman Letter Symbols

ADB	Asian Development Bank
AEM	Anion exchange membrane
AIIB	Asian Infrastructure Investment Bank
ALK	Alkaline
BESS	Battery energy storage system
CAPEX	Capital expenditure
CAREC	Central Asia Regional Economic Cooperation Program
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CRF	Capital recovery factor
DSO	Distribution system operators
EE	Energy efficiency
EU	European Union
GHG	Greenhouse gases
H_2	Hydrogen
HHV	High heating value
IC	Initial cost
IEA	International energy agency
IRENA	International renewable energy agency
JSC	Joint stock company
KW	Kilowatt
LAT/LONG	Latitude and Longitude
LCEE	Levelized costs of electricity equivalent
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
LHV	Lower heating value
MJ	Megajoules
MOU	Memorandum of understanding
MW	Megawatt
NDC	Nationally determined contribution

O	Oxygen
O&M	Operation and maintenance
OPEX	Operating expenditure
ORC	Organic Rankine cycle
PEM	Proton exchange membrane
PV	Photovoltaic
RES	Renewable energy sources
SMR	Steam methane reforming
USD	United States Dollars

LIST OF TABLES

Table 1. Various methods and costs for producing H_2……...7

LIST OF FIGURES

Figure 1.1 Global electricity production from renewable and nonrenewable sources….....1

Figure 2.1 Electricity generation from hydrogen fuel cell …….....2

Figure 3.1 Energy capacity growth in Uzbekistan for 2019-2030 years……....4

Figure 4.1 Methods of hydrogen production……...6

Figure 5.1 Energy system topology designed in Open Plan Tool ……19

Figure 6.1 Monthly wind capacity factor for Nukus city, Karakalpakstan.....20

Figure 6.2 Hourly power generation of 100 MW wind plant in Nukus, Karakalpakstan.....20

Figure 6.3 Hourly green hydrogen producton throughout the year.....22

Figure 7.1 LCOH cost breakdown per 1 kg of H_2.....24

CHAPTER 1

INTRODUCTION

As the world's population is growing rapidly, there is a huge increase in the demand for energy with the widespread use of technology. An increase in demand creates the common use of new, economical and ecologically sustainable, effective and safe types of energy. Global electricity demand is expected to rise at a faster rate over the next three years, growing by an average of 3.4% annually through 2026 [1].

It is globally considered that GHG emissions are being produced more year by year, and the energy sector is the main cause of GHG emissions and global warming. Despite ratifications of “Kyoto Protocol” in 1992, and “Paris Agreement” in 2015, world still producing GHG and energy transition to RE is marked as slow according to the goals of protocol and agreement accepted globally. On the other hand, transition to RE is requiring more economic support for low-income countries and communities as the initial cost of solar, wind, and hydropower is still high. However, there are still some alternative options which could be considered more sustainable and economically stable if we consider for long-term goals.

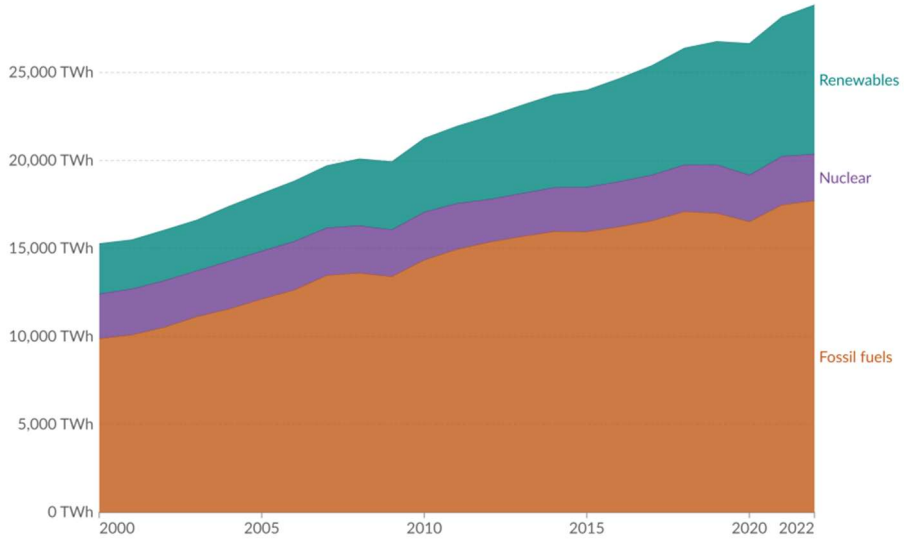


Figure 1.1 Global electricity production from renewable and nonrenewable sources [2]

As can be seen from Fig. 1, the share of renewable energy in electricity production is increasing rapidly between 2000-2022 years. At the same time energy production from fossil fuels is also increasing significantly due to high energy demand in the world. To achieve net zero emission by 2050 according to the Paris agreement world needs environmentally and economically affordable types of energy. For this purpose, countries are presenting their NDCs at every 5 years to illustrate their roadmap to achieve carbon neutral world by 2050.

Green hydrogen stands out as an outstanding option among other sources of energy. Green hydrogen and its derivatives are the keys to the last mile of net-zero emissions reduction – which should be completed by mid-century at the latest [3]. Using RES to produce green hydrogen using electrolysis is sustainable, cost effective, and secure way to get hydrogen gas. Once green hydrogen is produced it can be consumed in two different ways: a) transformed into electricity; b) synthetic gas. Fig. 1.2 illustrates the working principle of a PEM fuel cell where hydrogen enters from anode side, electrons are navigated via an external circuit to produce power, meantime protons pass via the membrane and combine with oxygen at the cathode to create water.

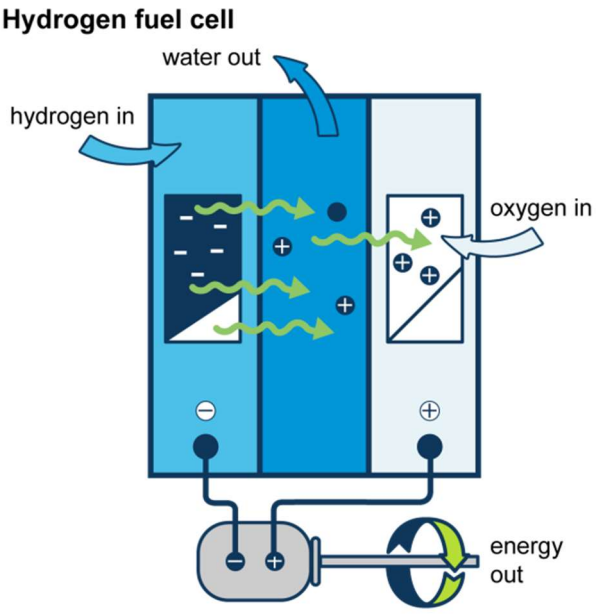


Figure 2.1 Electricity generation from hydrogen fuel cell [4]

In this study Karakalpakstan region of Uzbekistan is taken as study case. Uzbekistan is located in the middle of Central Asia, where half of the population of the region lives, and in turn, it is the main consumer of energy sources in the Central Asia.

1.1. Overview of energy sector of Uzbekistan

The energy sector of Uzbekistan is based on outdated and non-renewable resources. The main energy sources for power plants are natural gas and coal. Almost all power plants were built during the Soviet Union era. The efficiency of old the power plants are low and the main share of greenhouse gases of Uzbekistan are caused by these power plants. At the same time, another factor that hinders the development of the energy sector of Uzbekistan is the low energy tariffs and the high share of state subsidies to cover expenses and minimize cost shares for consumers. The low tariffs and government subsidies prevent the industry from developing and growing based on competitive market principles.Increasing tariffs for the energy would influence to effective use of energy and achieving low carbon targets faster. The Ministry of Energy of Uzbekistan has introduced a revised electricity tariff structure that varies according to monthly consumption of consumers. On January 23, Regional Electric Networks management held a press conference to address the upcoming electricity tariff increase scheduled for April 2025, as per a government decision made in April 2024. According to the representative, electricity tariffs had not been raised since 2018, but the prices of fuel and oil products have been rising annually due to market conditions. According to the approved plan, starting from April 1, 2025, for other domestic consumers, the price for 1 kWh of electricity will be as follows:

For up to 200 kWh, the price will rise from 450 UZS to 600 UZS (0.035$ - 0.047$); for consumption between 201 kWh and 1000 kWh, the price will increase to 1000 UZS (0.078$); for consumption between 1000 kWh and 5000 kWh, the price will rise to 1500 UZS (0.12$); for consumption between 5000 kWh and 10,000 kWh, the price will be 1750 UZS (0.14$); for consumption over 10,000 kWh, the price will be 2000 UZS (0.16$).

On November 4, 2024, President Shavkat Mirziyoyev emphasized that 2025 would be the year of energy efficiency for the energy sector [5]. The total installed capacity is

16 000 MW and electricity generation is 80 000 GWh where the main source is natural gas 70% and coal 22% as of 2020 year. In May 2020, the Ministry of Energy announced a goal to source 25% of powerfrom renewables by 2030, which would require an estimated 5 GW of solar, 3.8 GW of hydropower, and 3 GW of wind which is illustrated in the Fig. 3 below. In order to develop renewable energy sources and hydrogen energy in Uzbekistan, the National Research Institute of Renewable Energy Sources was established under the Ministry of Energy of the Republic of Uzbekistan. These national targets are aligned with global efforts to address climate issues and reduction of GHG emissions which support Paris Agreement where Uzbekistan is a part of it. Uzbekistan's growing energy demand coupled with dependency on fossil fuels, shows up importance of advancing energy transition to more sustainable energy sources. In this regard, green hydrogen represents crucial solution for the decarbonization of hard-to-abate sectors enhance long-term energy security and sustainability. The government of Uzbekistan has clearly outlined extensive roadmap for a carbon-neutral electricity sector, which shows that it is technically and economically achievable for Uzbekistan to reach an early peak in energy sector GHG emissions and secure carbon neutrality by 2050 year.



Figure 3.1 Energy capacity growth in Uzbekistan for 2019-2030 years [6]

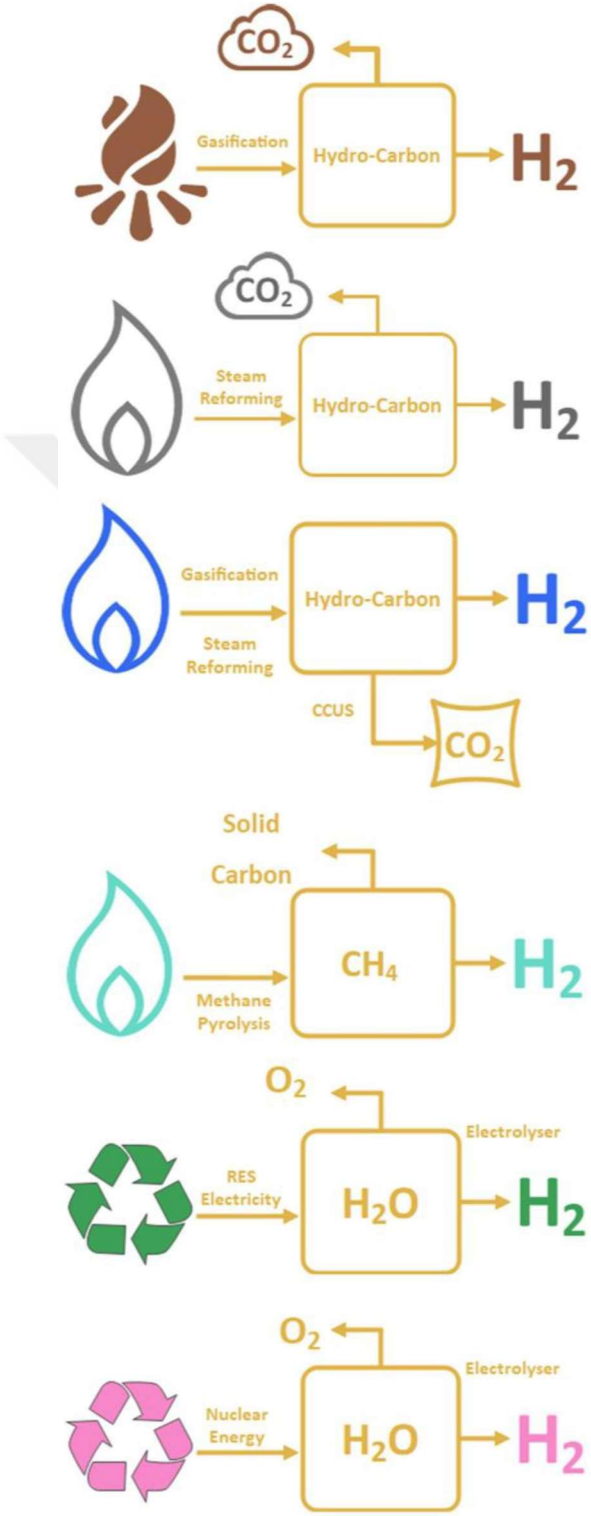
1.2. Hydrogen production methods, technologies, and it's cost in the world

Industrial production of hydrogen began in the very early 20th century, mostly for ammonia synthesis in the Haber-Bosch process. After that, different production pathways were used depending on resource availability and technological evolution. Currently, several methods of hydrogen production exist from various sources of energy as shown in the Fig. 4 below. Among them green hydrogen is considered as clean, environmentally-friendly, and most importantly net zero emissions supportive. Hydrogen can be produced through various processes, often categorized into a color group: green, blue, gray, white, pink, yellow, turquoise, brown and black as illustrated in the Fig. 4 below. The color codes are used to differentiate how the hydrogen is produced and the emissions associated with production. The three main types are grey, blue and green hydrogen, illustrated in Fig. 4.

We can see from Fig. 4 that in both grey and blue hydrogen production we also produce CO_2 and it is still harmful to the environment. However, IC of green hydrogen is twice expensive then grey and blue due to RES technology costs. Green hydrogen can be produced from various sources of renewable energy and in our case, it is onshore wind power plant which is in the construction stage in Karakalpakstan region of Uzbekistan republic. As Karakalpakstan region is considered one of the most water-stressed regions in the Central Asia, water supply in this region needs to be developed for green hydrogen production.

Generally green hydrogen is produced by implementing electrolysis, a process where water molecules (H_2O) are spilt into hydrogen (H_2) and oxygen (O) by applying electric current taken from renewable source of energy. This process is clearly illustrated in the Fig. 2. Electrolysis is the technique used to produce hydrogen that consists of "breaking" the water molecules using an electric current in an electrolyzer in order to extract the dihydrogen H_2. According to Lazard's report on Levelized cost of energy LCOE electrolyzer with the capacity of 20MW has the efficiency of 58% where the unsubsidized levelized cost of 1 kg of hydrogen is 7.37 $ [7]. This cost includes CAPEX and OPEX, and the cost of electricity taken from renewable source.

Electrolysis is considered to be the most important part to achieve net zero emissions as it is taking huge role on hydrogen and nuclear production.



Brown Hydrogen:
The production of hydrogen from coal gasification generates large amounts of GHG emissions.

Grey Hydrogen:
The use of natural gas reforming to produce hydrogen, including SMR method, also generates GHG emissions,

Blue Hydrogen:
Hydrogen production from a fossil energy combination CCUS to reduce emissions.

Turquoise Hydrogen:
Produced by methane pyrolysis, generates solid carbon residues and achieves CO_2 neutral.

Green Hydrogen:
Producing clean hydrogen with no carbon emissions through electrolysis of water from RES energy sources

Pink Hydrogen:
Coupling a nuclear reactor with a thermochemical cycle hydrogen production unit to produce hydrogen.

Figure 4.1 Methods of hydrogen production [8]

However, electrolysis is one of the main economic costs in green hydrogen production. Electrolysis capacity for dedicated hydrogen production has been growing in the past few years, but the place slowed down in 2022 with about 130 MW of new capacity entering operation, 45% less than previous year. However, electrolyzer manufacturing capacity increased by more than 25% since last year, reaching nearly 11 GW per year in 2022. The realization of all projects in the pipeline could lead to an installed electrolyzer capacity 170-365 GW by 2030 [9]. The one of the main costs in hydrogen production is electricity cost which is taken from RES in green hydrogen production and it also depends on what type of RES used to produce electricity and location of it depending on weather conditions.

Table 1. Various methods and costs for producing H_2 [10]

Methods	Cost of Production (USD per kg)	Source
Photo-catalytic H2OH2O splitting	5.0	Solar
Steam reforming	0.75	Methane
Centralized biomass gasification	1.2 to 2.4	Biomass
Gasification without CO2CO2 sequestration	0.92	Coal
Electrolysis	2.6 to 3.0	Nuclear
H2OH2O splitting	1.4 to 2.3	Nuclear

Hydrogen production costs vary notably depending on the technology used in the production process. Depending on the Table. 1 above the costly method of hydrogen production is photo-catalytic water splitting which costs 5 USD/kg of hydrogen. While

the most economic method is SRM which costs 0.75 USD/kg of hydrogen. SRM remains the most widely used method to produce hydrogen due to its high efficiency and low cost. However, this method is a carbon-intensive action that produces remarkable CO_2 emissions, making it ecologically unsustainable without carbon capture technologies.

1.3. Policy and technical base for green hydrogen production in Uzbekistan

On April 9, 2021, the President of the Republic of Uzbekistan Shavkat Mirziyoyev signed the decision "On measures to develop renewable and hydrogen energy in the Republic of Uzbekistan" [11]. This policy aims to boost the development of hydrogen energy by building research centers and a laboratory for testing and certification processes of hydrogen energy technologies. In line with policy, significant agreement was signed between the Ministry, ACWA Power (Saudi Arabia) and Air Products (USA) on the development of renewable and hydrogen energy in Uzbekistan. ACWA Power will build wind power stations in Karakalpakstan and Bukhara regions with a total capacity of 2600 MW + 300 MW BESS - battery energy storage system.

Within these wind power stations foundations center will be established for green hydrogen production. The project is planned to be in two phases:

Phase 1: A pilot project which will produce 3,000 tons of green hydrogen ammonia is already underway.

Phase 2: Once second phase is complete, 2.4 GW of wind energy will power the production of 500,000 tons of green ammonia per year [12].

In 5th April 2025, Baku, Azerbaijan - The Asian Development Bank (ADB), the Asian Infrastructure Investment Bank (AIIB), and the energy ministries of Azerbaijan, Kazakhstan, and Uzbekistan today signed a Memorandum of Understanding (MOU) to support the Feasibility Study for the Caspian Green Energy Corridor Project. The initiative is part of ADB’s regional technical assistance for the project. The MOU establishes a high-level framework for cooperation, focusing on the development of a robust institutional and legal framework to facilitate cross-border electricity trade among Azerbaijan, Kazakhstan, and Uzbekistan. The Caspian Green Energy Corridor

project aims to bolster regional energy cooperation and promote green energy trade among most of the Central Asia Regional Economic Cooperation Program (CAREC) member countries [13].

These policy measures and technical base will significantly help to forward Uzbekistan energy strategy and climate related issues. Furthermore, regional cooperation ambition, such as the Caspian Green Energy Corridor, bolster the institutional framework for international green energy integration, which would open the door for the trading of green hydrogen. Uzbekistan has also initiated the progress of technical standards and pilot projects to evaluate possibility of integrating hydrogen into existing and planned renewable energy systems. Uzbekistan's hydrogen policy is also closely tied to its NDCs under the Paris Agreement, putting a focus on clean technology development and decarbonization goals.

Additionally, water availability is another critical factor for green hydrogen production via electrolyzers in the region as Karakalpakstan region is the most water-stressed region in the whole Central Asia. It is very crucial that hydrogen production development plans should include sustainable water supply system strategies for the region. Using treated wastewater or investment into small-scale water desalination plants could reduce the demand for freshwater demand in the region. National hydrogen policy should line up with Uzbekistan's water strategy to secure resource-efficient and environmentally friendly hydrogen development in the country.

CHAPTER 2

LITERATURE REVIEW

Hankwon Lim published scientific research paper with subject study on an overview of water electrolysis technologies for green hydrogen production. In this research Hankwon Lim compares these technologies: Alkaline water electrolysis, AEM water electrolysis, PEM water electrolysis and Solid oxide water electrolysis to obtain green hydrogen. In the study 4 different water electrolysis technologies are well compared to each other and tested to ensure which electrolysis has highest efficiency [14].

B.E. Lebrouhi and T. Kousksou has research paper on topic: Global hydrogen development – A technological and geopolitical overview. In this research topic technical and technological aspects of hydrogen production, purification, compression, transportation and use hydrogen are discussed and summarized. Research results show that the development of green hydrogen requires massive factories of electrolysis, storage, sustainable transportation, and lastly but most importantly the availability of fresh water resources [15].

Shree Om Bade and his friends have study on the topic: Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: A review. This study shows that US produces over 10 million metric tons of H_2 annually but, only 1% of it produced by water electrolysis technologies. However, study says that as green hydrogen is new technology to be implemented, society members have some barriers such as: lack of knowledge, fear of technology, cost of energy, and lack of understanding. Shree Om Bade and his friends believe that these barriers could be solved through: training and awareness, conducting social programs, and providing incentives and state subsidies [16].

Marek Jaszczur and his friends have research study on topic: Renewable energy-to-green hydrogen: A review of main resources routes, processes and evaluation. In this research green hydrogen production from different source of RES such as: solar, photovoltaic, wind, solar thermal, geothermal, biomass, and food waste to hydrogen

are discussed. Moreover, in this study two energy storage methods: a hydrogen fuel cell with electrolysis and a conventional battery storage system are compared for household energy system. Wind and solar energy are considered as potential future supply for electrolysis to produce green hydrogen in upcoming future [17].

Sumit Roy and his friends have research on Techno-economic analysis of large-scale green hydrogen production and storage topic. In this study 10 MW PEM electrolyzer model integrated with heat recovery system coupled with an ORC for mechanical compression of hydrogen. The results of this study show that by implementing waste heat recovery coupled with ORC efficiency of electrolyzer goes from 71.4% to 98% which shows that within this system we can get better efficiencies [18].

Alessandro Bianchini and his friends published research paper on Techno-economic analysis of wind-powered green hydrogen production to facilitate the decarbonization of hard-to-abate sectors: A case study on steelmaking topic. According to this study within the optimal case it is possible to reduce emission intensity associated with the steelmaking process to 235 kg of CO_2 per ton of finished steel, which is 88% less than the conventional method. The results of this study show that in a country which relies on fossil fuel power systems it is the one of the best ways using renewable energy systems to produce hydrogen and use it for the decarbonization of hard-to-abate processes like steel manufacturing [19].

Francisco Moraga and his friends have research paper on: Techno-economic analysis of the integrated of large-scale hydrogen production and hybrid CSP+PV plant in Northern Chile. 100 MW hybrid CSP-PV power plants which is located in Northern Chile is taken for this study to evaluate techno-economic analysis like storage and transportation for local and outside consumers. Within hybrid system LCOH is ranges between 3,59 – 3,99 USD/kgH_2 with ALK water electrolysis in 2021 year and is expected to be 1,91 – 2,07 USD/kgH_2 in 2030 year depending on price decrease of RES in upcoming years [20].

Abdulla Rahil and his friends have study on “Techno-economic assessment of dispatchable hydrogen production by multiple electrolyzers in Libya” topic. The study looks into how certain garage forecourts use on-site electrolysis to create hydrogen

only using off-peak electricity. Six garage forecourts are supposed to be located in Darnah, a tiny city on Libya's east coast, in a case study simulation. Results of this study show that within the long term 2030 scenario of hydrogen production cost per kg of H_2 decreases significantly thanks to cost decrease in renewable electricity. Researchers believe that governments and international institutions should continuously support the transition to renewable energy production to achieve better costs for hydrogen production in upcoming years [21].

Gour Chand Mazumder and his friends have done research on “Solar PV and PEM electrolyzer-based green hydrogen production cost for a selected location in Bangladesh” topic. As green hydrogen production cost is high, researchers believe that using solar PV electricity for membrane-based electrolysis can reduce production costs. They used HOMER Energy Software for PV electricity cost calculation. Moreover, according to this research another cause of high cost of hydrogen is availability of inexpensive and sustainable water resources [22].

Somtochukwu Godfrey Nnabuife and his friends have research paper on the topic: A comparative analysis of different hydrogen production methods and their environmental impact. This research highlights the growing significance of hydrogen as a sustainable source of energy. Paper compares different hydrogen production methods based on cost, scalability, and ecological effect, including GHG emissions, and water usage. According to the study SMR is efficient but carbon-intensive, meanwhile electrolysis offers more environmentally friendly substitutive utilization of RES [23].

Adel Mellit and his friends have research paper on the topic: Hydrogen production methods based on solar and wind energy: a review. This study shows up us how the cost of hydrogen is dependent on electricity source which is applied to the electrolysis unit. Study indicates that hydrogen production from renewable energy sources is still higher than hydrogen production from other source. However, current trend in the world is given preference to the green energy due to net zero emission targets. Furthermore, green hydrogen production depends on weather conditions as well. Study shows that hydrogen production from wind using PEM costs from 5 to 9.37 USD/kg [24].

Pierluigi Leone, Marco Cavana, and Jamshid Yakhshilikov have research paper on topic: A review of the energy system and transport sector in Uzbekistan in view of future hydrogen uptake. In this study potential of hydrogen on decarbonization of the transport sector considering various aspects of the Uzbekistan's energy system and final use in transportation sector. This study indicates that, in areas where railway lines are non-electrified, hydrogen-powered trains have potential to cut down carbon emissions up to 0.1 $kgCO_2eq/km$ of journey. The development of hydrogen technologies over Central Asia depends heavily on powerful cooperation among the nations in the region [25].

K.R. Allaev and N. R. Avezova have research paper on topic: Hydrogen – the future of power engineering for the world and Uzbekistan. In this paper importance of hydrogen for the world and Uzbekistan were discussed considering cost, production, transportation, storage and utilization factors. Study shows the significance of the following framework strategy roadmap and concept of the government of Uzbekistan in order to develop RES and hydrogen development: "Strategy for the Transition of the Republic of Uzbekistan to a Green Economy for the period of 2019–2030" (Strategy) and the "Concept of Providing the Republic of Uzbekistan with Electric Energy for 2020–2030" (Concept) [26].

Quliyev Maqsud has paper on topic: Green transition: the case of Turkey and Central Asia countries. This study shows the value of energy transition for Central Asian countries and Turkey as these regions will be mostly water stressed and effected by climate change outcomes by 2050 year. Research indicates that Uzbekistan has biggest potential of wind and solar power among Central Asian countries. Furthermore, social survey was applied in this study to evaluate the concerns of the population living in these countries. Meanwhile, Uzbek people believe that cause of climate change is considered "people", however, people living in Turkey, Azerbaijan, and Kazakhstan consider that industry is in charge of this damage [27].

Vladislav Zavadskiy and Gita Revalde have research on topic: Upcoming water deficit in Central Asia rural regions and perspectives of green hydrogen production. In this study effects of climate crisis and water deficit are discussed and how it will influence the development of green hydrogen is reviewed. According to the study, water

resources are forecasted to decrease by 2035 in Aral Sea due to water policy of Afghanistan in the region. Study uses calculation methodology to evaluate necessary water for green hydrogen project of ACWA Power in Uzbekistan will need only 0.18 million tons of water which is not large amount. This study shows that to cover electric demand for green hydrogen production Central Asia has huge potential on wind and solar energy [28].

CHAPTER 3

METHODOLOGY

The process for evaluating the techno-economic viability of green hydrogen production and its integration to Uzbekistan's energy system is outlined in this chapter. The Open Plan Tool is used for modeling of diverse green hydrogen production scenarios powered by wind energy. The Open Plan Tool is based on the multi-vector simulator (MVS), which in turn is based on the oemof-solph python library, with which a problem is described by specifying an objective function to minimize annual energy supply costs, decision variables and limits and constraints. The Open Plan Tool project consortium is composed of the Reiner Lemoine Institute (RLI), German Solar Energy Society [Deutsche Gesellschaft für Sonnenenergie (DGS)] and the Potsdam Institute for Climate Impact Research. It is funded within the framework of the "Technology-oriented systems analysis" funding area of the BMWi's 7th Energy Research Programme "Innovation for the energy transition" [29]. This model admits multi-vector energy planning and is fit for analyzing renewable-based hydrogen production pathways. In this study we use Open Plan Tool to simulate green hydrogen production powered by wind energy and to evaluate LCOH and compare various system configurations.

3.1. Research Objective

The primary objective of this study is to evaluate the techno-economic feasibility of green hydrogen production in Uzbekistan, specifically utilizing wind energy resources in the Karakalpakstan region. The research uses modeling hydrogen production scenarios using the Open Plan Tool, focusing on key indicators such as LCOH and LCEE, GHG emission reduction potential. By simulating different production scales and operational suppositions, the research focuses on finding the most feasible circumstances for integration into national energy system. Furthermore, this study seeks to point out policy and infrastructural gap that may delay implementation and expansion of green hydrogen development aligned with Uzbekistan's energy goals.

This study will be strong base for the green hydrogen development in Uzbekistan where the government is focusing on green transition to achieve zero emission targets.

3.2. Modeling Approach

Energy system modeling is computational method to represent and optimization, generation, transportation, storage, and distribution of energy system. In this study, Open Plan Tool is used to obtain techno-economic modeling approach and analyses, also simulation of the integration of green hydrogen into Uzbekistan's energy systems. This study aims to model the power supply system of Uzbekistan within the combination of green hydrogen. Energy conversion technologies in the generation phase contain technical-economical specifications for every system component. The data for the generating and consumption sections are constructed with a one-year hourly temporal resolution. Based on hourly demand patterns, the hourly timescale enables the balancing of consumption and generation components, including variable RES. For a year, the model uses a time series with 8760 hourly time units. In order to meet the required power demand, the model elaborates hourly power generation outputs for each technology, optimizing both cost and capacity.

Several energy system modeling frameworks are being developed to provide insights, proposals, and recommendations for electricity transition paths. Energy system models are necessary for designing various energy generation component combinations to meet electricity demand. Models provide insights from a variety of viewpoints, including capacity configuration, carbon computation, cost optimization, and so on. In our case, a model framework is required to support decision-making-based operations (supply configurations to meet demand), investments (cost optimizations to satisfy sustainability), and scenarios (path considerations to reach targets). Based on the criteria, the Open Plan Tool is chosen for modeling this study.

3.3. Calculation Methodology and Key Formulas

In this study we used the core calculation methods to assess the technical and economic performance of green hydrogen production modeled using Open Plan Tool. The key metrics analyzed in this study included the LCOH, GHG emission reduction, and

energy conversion efficiency. These indicators are very crucial for then assessment of the technical and economic feasibility and impact of the climate of green hydrogen into Uzbekistan's energy system.

3.3.1. LCOH Formula

The LCOH is a broadly accpeted metric which acts for the average cost per kilogram of hydrogen produced during the lifetime of a project. It involves capital, operational, and maintanance costs, formalized by the total output of hydrogen.

$$LCOH = \frac{CAPEX \times CRF + OPEX}{H_{2\ annual}}$$

Where:

$CAPEX$: Capital expenditures (USD),

$OPEX$: Operating expenditures (USD),

$H_{2\ annual}$: Annual hydrogen production,

CRF: discount rate.

3.3.2. Electrolyzer Energy Efficiency

Electrolyzer efficiency is a crucial parameter for assessing the performance of the green hydrogen production system. It shows the ratio between the practical energy contained in the produced hydrogen and input required electrical power for the electrolyzer. The lower energy losses in the conversion process causes the higher efficiencies. The efficiency (η) is calculated through the following formula:

$$\eta = \frac{E_{H_2}}{E_{input}} \times 100\%$$

Where:

E_{H_2}: produced hydrogen at LHV=33.33 kWh/kg,

E_{input}: consumed electricity by the electrolyzer per kg of H_2 produced (kWh/kg).

In this study electrolyzer efficiency is presumed to range between 60% and 70% depending on the technology. Electrolysis systems are typically 60–65% efficient, meaning they convert 60–65% of the input electrical energy into chemical energy stored in hydrogen gas [30].

This study does not directly assess the calculation of CO_2 emission reduction, but it is globally admitted that green hydrogen is to result almost zero emissions comparison to traditional hydrogen production methods such as SMR. Therefore, transition to green hydrogen production from conventional production through sustainable sources plays significant role on GHG emissions reduction.

3.4. System Configuration and Assumptions

In this study we simulate a green hydrogen production system using Open Plan Tool integrated with 100 MW wind power plant located in the Karakalpakstan region of Uzbekistan. The system includes various energy elements such as generation of renewable electricity, electrolysis-based green hydrogen production, energy storage and grid nexus.

A 100 MW onshore wind power plant is modeled as the main renewable electricity source in this study. We used hourly wind data of 8760 hours for one year from renewables.ninja website. The investment cost of this wind power plant is supposed to be 1000 USD/kW with 20 years of lifetime.

A PEM electrolyzer used in our model on account of its prompt load-following capacity and closeness with inconstant renewable energy sources like wind energy. Our system is modeled with 60% of energy efficieny relying on LHV and assumed investment and operational costs based on IRENA and IEA benchmarks. Capacity of electrolyzer is 100 MW with 60% efficiency and 38000 USD/kVA investment cost. Lastly, lifetime of electrolyzer is 20 years.

A compressed hydrogen storage unit is considered in this model to absorb hourly inconsistency production and usage. Efficiency of this this storage system is assumed to be 98%.

A PEM fuel cell is involved in to reconvert stored green hydrogen into electricity when there will be a demand. Fuel cell capacity is considered to be 100 MW with 20 years of lifetime and 3000 USD/kVA investment cost.

In our case the system is connected to the local electricity distributor of “Regional power networks” JSC of Uzbekistan for electricity import/export. The normal tariff of the regional power networks is considered 0.07 USD/kWh and peak demand tariff is considered 0.12 USD/kWh.

The Open Plan Tool uses hourly resolution within one year which is equal of 8760 hours for the simulation of the model. It indicates the variability of the renewable sources and operational performance throughout the year.

In the Figure 5 is indicated the system topology modeled in Open Plan Tool.

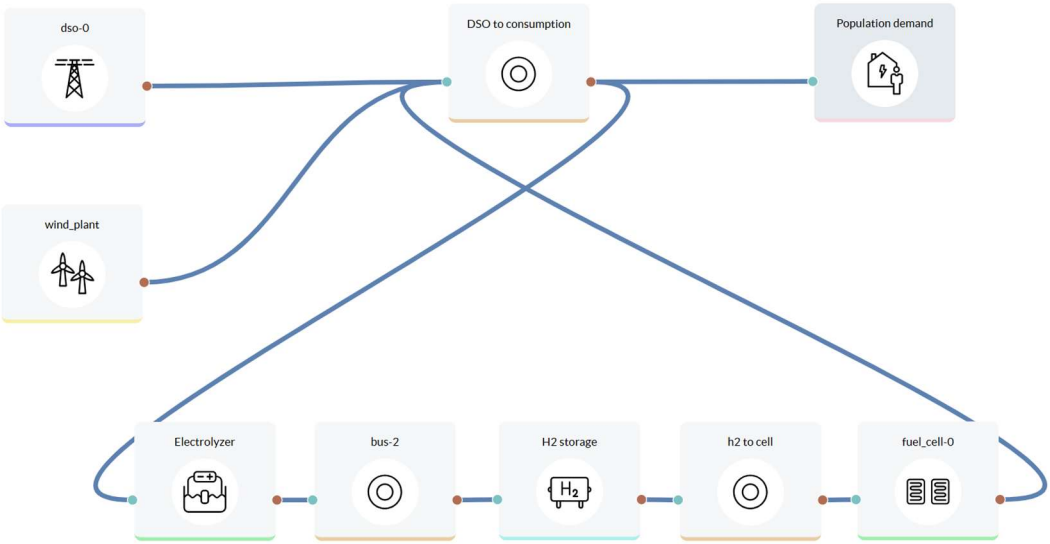


Figure 5.1 Energy system topology designed in Open Plan Tool

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1. Modeling Results

In this section we will review key results and outputs of the simulation from Open Plan Tool. Our model utilized one year hourly resolution which is 8760 hours relying on the resource data from renewables.ninja online tool for LAT: 43,084 and LONG: 58,824 Nukus city, Karakalpakstan region of Uzbekistan.

4.1.1. Wind Power Results

The wind power plant produced electricity source dependent on hourly capacity factors obtained from renewables.ninja online tool and illustrated in the Fig. 6 below. The average capacity factor of 38,6% was obtained for Nukus city over one year.

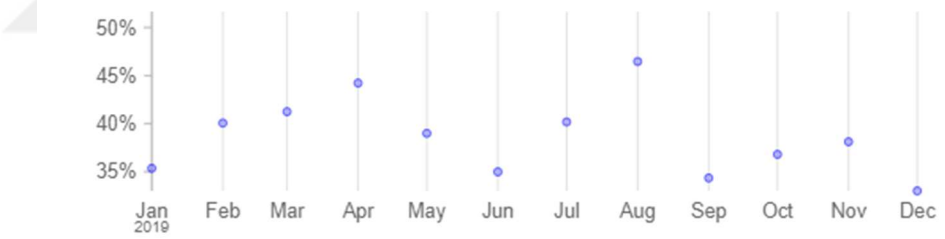


Figure 6.1 Monthly wind capacity factor for Nukus city, Karakalpakstan [31]

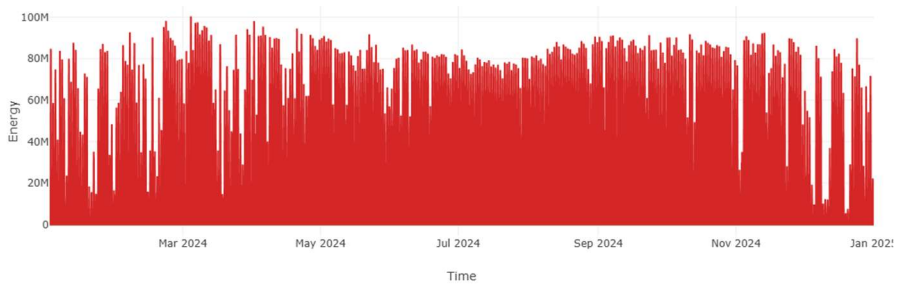


Figure 6.2 Hourly power generation of 100 MW wind plant in Nukus, Karakalpakstan

Fig. 7 highlights the hourly electricity generation from wind plant throughout the simulation year. For the proposed location in Nukus city of Karakalpakstan region we obtain 38.6% capacity factor which is very good result for onshore wind plants. As simulation utilizes 8760 hourly annual data our 100 MW wind plant generates 338.136 GWh through formula given below:

$$E_{annual} = P_{installed} \times T_{year} \times CF$$

Where:

$P_{installed}$: installed power capacity=100 MW

T_{year}: total number of hours annually=8760,

CF: average capacity factor=0.386.

4.1.2. Hyrodgen Production Results

By generating electricity from wind power plant with 100 MW capacity, green hydrogen was produced by operating PEM electrolyzer system with 100 MW capacity with 60% efficiency based on LHV. The annual green hydrogen production was calculated using the formula below:

$$H_{2\,annual} = \frac{P_{electrolyzer} \times t \times \eta}{E_{H_2}}$$

Where:

$P_{electrolyzer}$: power capacity of the electrolyzer=100 MW,

t: annual operating hours=3382,

η: efficiency of the electrolyzer=60%,

E_{H_2}: required energy to generate 1 kg of H_2 at LHV=33.3 kWh/kg.

The LHV of hydrogen is 120 MJ/kg or 33.3 kWh/kg and the HHV is 142 MJ/kg or 39.4 kWh/kg [32].

The effective working hours were calculated by multiplying wind power plant's average capacity factor of 0.386 to total of hours 8760 annually and we determine *t* is 3382 hours.

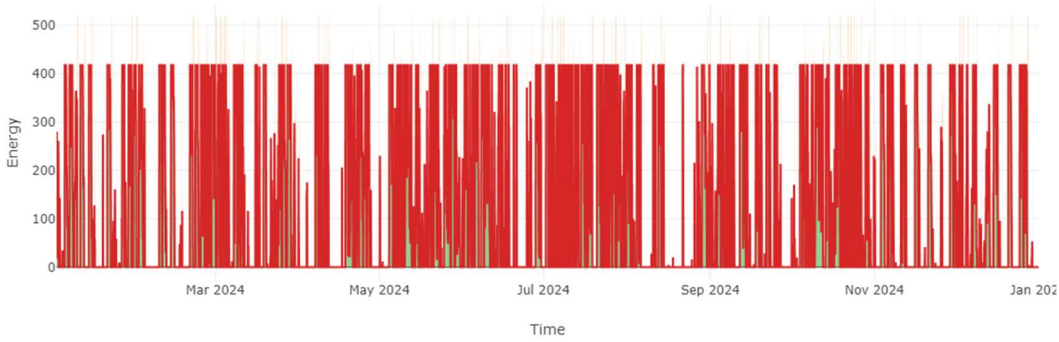


Figure 6.3 Hourly green hydrogen producton throughout the year

Fig. 8 illustrates the simulation of green hydrogen production and storage parameters based on hourly resolution. By using formula mentioned above we obtain the following:

$$H_{2\ annual} = \frac{100000 \times 3382 \times 0.6}{33.3} = 6.09$$

simulation calculates the total 6.09 million kg/year or 6091 metric tons/year of green hydrogen production annually.

4.1.3. LCOH Calculation and Resultss

The LCOH was calculated through using formula below, containing both CAPEX and OPEX within the lifetime of the system. The given equation is as follows:

$$LCOH = \frac{CAPEX \times CRF + OPEX}{H_{2\ annual}}$$

Where:

$CAPEX$: Capital expenditures (USD),

$OPEX$: Operating expenditures (USD),

$H_{2\ annual}$: Annual hydrogen production,

CRF: Capital recovery factor,

CRF is calculated by:

$$CRF = \frac{r(1+r)^n}{(1+r)^n - 1}$$

Where:

r: annual discount rate=5%≈0.05

n: system lifetime=20 years

In this study 5% discount rate was selected to calculate CRF based on international practice and methodological standards recommended by IEA which commonly uses a 5% discount rate for publicly financed or low-risk hydrogen projects [33]. By using formula above we obtain the following result for CRF:

$$CRF = \frac{0.05(1+0.05)^{20}}{(1+0.05)^{20} - 1} = 0.08024$$

With 5% discount rate with 20 years of project lifetime CRF was calculated to be 0.08024, defining that 8.024% of the total CAPEX is recovered yearly over the lifetime of the system.

With obtained CRF result we can now calculate LCOH as following:

$$LCOH = \frac{100000000 \times 0.08024 + 31570000}{6090909} \approx 6.5\ USD/kg$$

In this study LCOH is calculated based on the techno-economic modeling performed using Open Plan Tool and we obtained 6.5 USD/kg result for green hydrogen production in Karakalpakstan region. This result obtained from a 100 MW wind-powered PEM electrolyzer system with 60% efficiency, producing nearly 6.09 million

kilograms of green hydrogen annually. In the fig. 9 below we can see LCOH cost breakdown between CAPEX and OPEX.

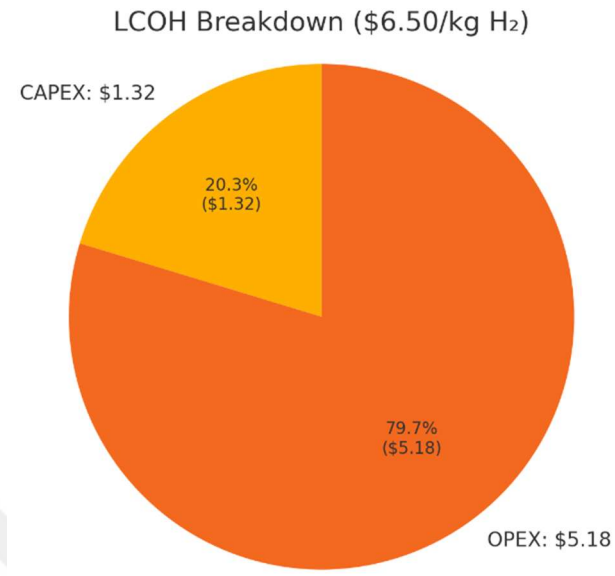


Figure 7.1. LCOH cost breakdown per 1 kg of H_2

Fig. 9 illustrates that CAPEX has 1.32$ which is 20.3% of LCOH cost share and OPEX has 5.18$ which is 79.7% cost share per kg of produced green hydrogen in this model.

4.2 Discussions

In this study simulation model obtained the following results: Based on the results obtained via modeling simulation from Open Plan Tool LCOH for a 100 MW wind-powered PEM electrolyzer system in Karakalpakstan was 6.5 USD/kg. This study also illustrates generation of 337.5 GWh/year wind power potential with 100 MW installed capacity of wind plant in Nukus city of Karakalpakstan region via simulation from Open Plan Tool. Capacity factor for the chosen area was 38.6% which is very good result for onshore wind plant comparing globally. This gives us potential to produce 6.09 million kg of green hydrogen annually using wind energy. Further, fig. 9 shows the contribution of CAPEX and OPEX in LCOH cost breakdown from what we can see the high share of OPEX due to operational costs of electricity powered by wind. This output mirrors the specific techno-economic parameters simulated in Open Plan

Tool including 5% discount rate and 20 years of project lifetime. The CRF of 8.024% was used to calculate annualized capital costs. These findings highlight that depletion of OPEX – particularly through access to low-cost renewable electricity will be main improvement for the competetiveness for green hydrogen production in Uzbekistan. Additionally, reductions in electrolyzer CAPEX are foreseen globally because of technological improvements and increase of production. However, cost refinements will be still dependent on policy frameworks support from government levels, transition to RE, and market integration of RE.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

This study presented the techno-economic feasibility of green hydrogen production using 100 MW wind-powered PEM electrolzer system in Karakalpakstan region of Uzbekistan. The main aim of this study was to determine technical feasibility which we obtaine 6.09 million kg of green hydrogen and economic parameter which is LCOH is 6.5 USD/kg under 5% discount rate and 20 years of project lifetime.

The outcome of this work shows that green hydrogen production in the chosen area is technically feasible, but in terms of economic competitiveness remains immensely sensitive to operating expenditures, mainly electricity costs. This study highlights the cost structure of green hydrogen production and show the importance of RE integration on cost cuttings. Moreover, green hydrogen production in Uzbekistan will significantly impact to achieve net zero targets. Latsly, but importantly, green hydrogen production in Uzbekistan will create new job opportunities for locals in Karakalpakstan region which is considered the most remote area of Uzbekistan. This will boost economic and social development in the country.

5.2. Future Work and Suggestions

In the future research work I will focus on cost-reduction pathways in order to make green hydrogen production economically viable in Uzbekistan. Meantime, cost reductions in LCOH could be achieved by reducing electricity tarrifs for electrolyzers, integrating hybrid renewable systems, and by improving the efficiency of electrolyzers via more advanced technologies. Localized manufacturing of electrolyzers, and optimization of O&M will also lower the CAPEX and OPEX share in LCOH.

Additionally, research is needed to evaluate the feasibility of exporting green hydrogen to EU either in compressed, liquid,or green ammonia and methanol forms of hydrogen.

This will including techno-economic feasibiltity study of potential pipeline corridors and port infastructure in Central Asia.

In the future research cost reduction can be achieved by obtaining energy from solar panels for green hydrogen production as solar energy has lower OPEX and CAPEX costs, LCOH will be in the lower rate. Furthermore, storage facilities for green hydrogen needs to be developed and this requires financial and policy support from the government and international funding organizations. Storage of green hydrogen will be promising option for Uzbekistan’s decarbonization plans.

This study is useful for research institutes, investment companies, and the relevant ministries of Uzbekistan when developing green hydrogen plant in Uzbekistan.

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