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SUSTAINABLE SOLUTIONS IN THE TRANSITION TO GREEN ENERGY: ECONOMIC AND ENVIRONMENTAL PERSPECTIVES

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By
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THESIS ACCEPTANCE

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ABSTRACT

Transitioning to green energy - becomes important every year. The world and humanity are developing fast. More emissions releasing to atmosphere and harming the environment. And conventional energy sources will end one day. That's why countries aim to integrate into renewable energy sources sooner. This research studies the sustainable steps for integration to clean energy. In addition, regions need strong transmission lines to move clean energy. So, thesis also focuses on HVDC.

Azerbaijan's location between Europe and Asia is very strategic. The new interconnection model was proposed and simulated. The new Central Asia → Azerbaijan → Türkiye → Europe interconnection between regions. The 2030 situation model was simulated for four regions. A 5 GW HVDC line was tested and estimated losses using typical HVDC values were calculated.

The results of this model show that Central Asia has extra renewable power. Which can be transferred through South Caucasus by corridor to Europe. Also results show the HVDC losses are very low. And Corridor technically worked at full capacity with benefits.

To sum up, the new interconnection model shows that the idea is technically possible. This corridor can support clean energy goals in the region. Additionally, corridor can be expanded in future. And this study is useful base for more detailed studies.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
CO_2	Carbon Dioxide
HVDC	High Voltage Direct Current
COP29	Conference of the Parties
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
CSC	Current Source Converter
VSC	Voltage Source Converter

CHAPTER ONE

INTRODUCTION

"The creation of green energy and the transportation of green energy to world markets are currently the priorities of our energy policy" - President of Azerbaijan Ilham Aliyev.

Without energy, it is impossible to imagine our life in the modern world. Almost every aspect of life - from households to various industries - heavily relies on energy. But conventional energy sources are not useful for our planet. Using the fusel foils seriously impacts the environment and human lives. Moreover, when burning these fossil fuels for energy production, tons of harmful emissions such as - CO_2. When they are released into the environment, which leads to climate change [1]. However, the use of fossil fuels also creates problems such as air pollution, acid rain, and ecosystem destruction [2].

1.1 Background of Study

Statistics from (IEA) journal show that [3], last decade usage of the conventional fuel sources decreased from 82% to 80% in 2023 (see Figure 1.0). During this period, the demand for energy also increased; however, it was met by renewable energy sources. Additionally, this graph clearly shows how the demand for oil, coal, and gas has also decreased. In parallel, as the demand for coal decreases, it is expected to be overtaken by natural gas in global energy demand by 2030. Between 2023 and 2035 years with this progress, clean energy is expected to rise by the total energy demand. By the mid-2030s, green energy is expected to become the largest source of energy worldwide.

As well as that, this change in energy demand shows how countries tend to clean energy, focusing on reducing carbon emissions. In fact, many countries nowadays, including Azerbaijan, are making investments for technologies for such as solar, wind, and hydropower. The incerase in this sector shows growing importance of transitioning to cleaner energy system.

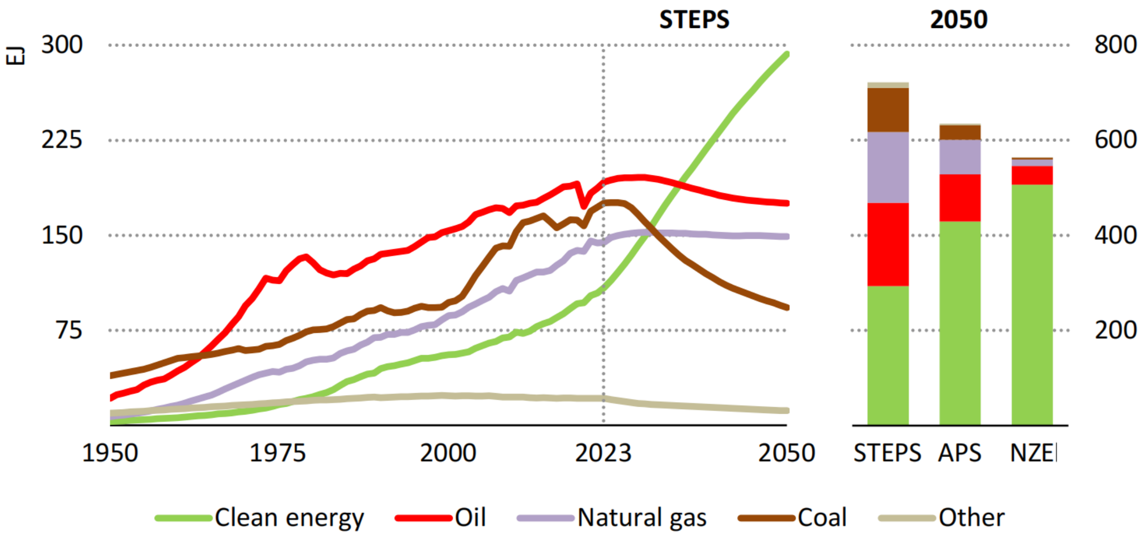

Figure 1.0 - Global energy mix

It is not possible for not considering CO_2 when the fossil fuels and energy demand mentioned. Nowadays when humanity heavily depends on transport, power generation and industrial production and mainly for energizing all of these, the large amounts of CO_2 releasing into the atmosphere. According to Our World in Data, [4], carbon dioxide emissions have increased significantly since the 1900s and reached their historical peak in 2023. (see Figure 1.2). Looking at the graph, we see that China is currently the largest emitter of carbon dioxide. But the developed countries such as USA and UK have great progress in reducing CO_2. This contributes to sustainable development.

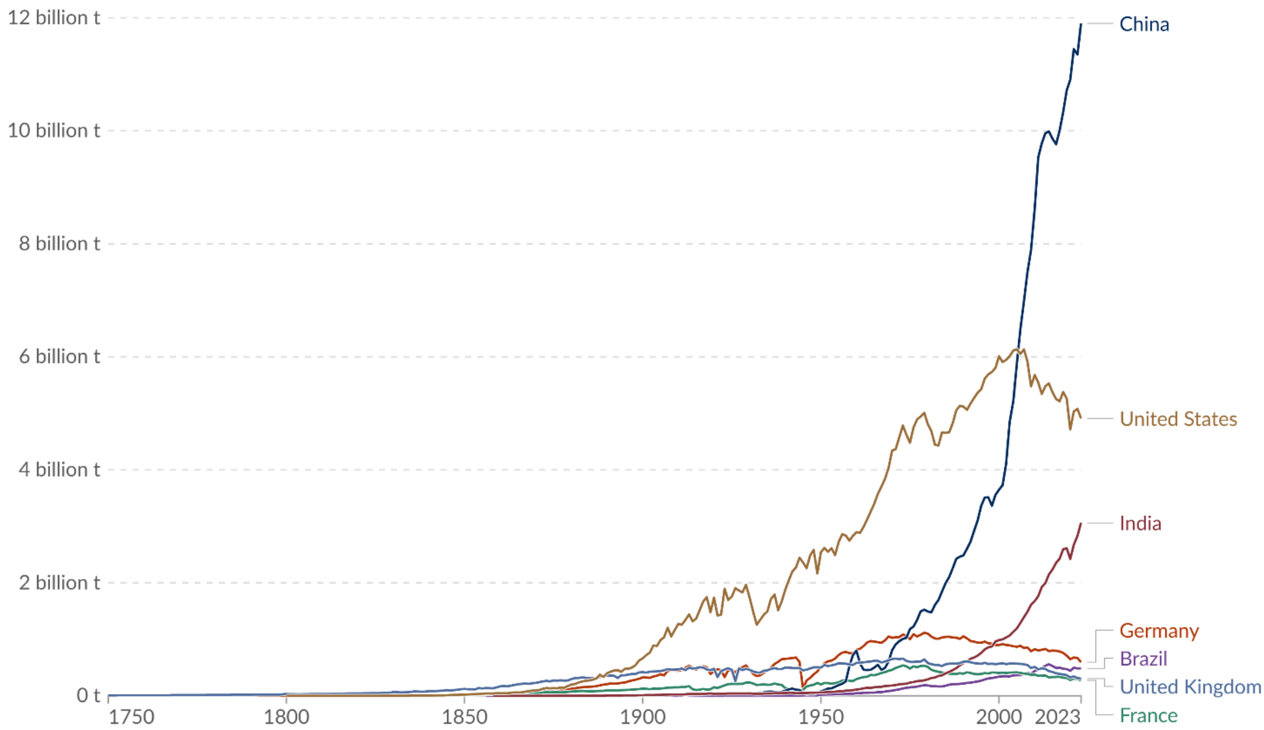

Figure 1.1 - Annual CO_2 emissions per country

1.2 Problem Statement

In the 21st century, the transition to green energy is taking place worldwide; however, progress is not equal across all countries. When looking at global CO_2 emissions, it becomes clear that mainly developed countries have achieved decreasing the numbers in greenhouse gas emissions. As indicated by the Climate Action Network in October 2024 [5], not a single country is doing enough to achieve fully clean, accessible, and affordable energy. In fact, recent research shows that almost all countries are falling behind in reaching the goal of achieving 100% renewable energy by 2050, even developed ones.

Several factors affect this issue. Especially for energy-exporting countries. And one of them is Azerbaijan which heavily depends on fossil fuels making it difficult to shift quickly from conventional grids to renewable systems. As noted by Marco Kopinke, M.Sc. (2025) [6], countries such as Saudi Arabia, Iraq, Nigeria, Kuwait, Bahrain, Yemen, and the Democratic Republic of Congo are making slow progress in transitioning to green energy due to various internal factors. For example, despite the enormous potential of solar energy and plan of producing 50% of energy from renewables, statistics show that in 2023, only 1.4% of their electricity came from renewable sources, showing slow progress.

In Azerbaijan, the traditional energy grid relies primarily on oil and gas production. With conventional grid systems it is hard to make transition to a renewable energy system. In most studies discussing the general transition but do not give specific solution. That is why countries are still struggling to make transition. Therefore, one of the goals of this study, to investigate these problems and help for integrating clean energy global and regionally.

UNEP's 2022 findings show that [7] at the global pandemic (Covid-19) anticipated that the world will focus more on developing to the clean energy. However, the 2022 Global Renewable Energy Status Report shows that that did not happen. The post-pandemic recovery even ended with 4% increase in energy demand. Which mostly were met by fossil fuels.

In addition, the war in Ukraine has worsened the situation and has become one of the main factors driving up global energy prices. Despite record investments of $366 billion in renewable energy, the transition continued to be delayed. Currently, renewable energy sources account for just over 10% of global electricity production.

1.3 Research Objectives and Questions

The key aim of this work is to look at issues related to is to analyze the problems of transitioning from conventional energy sources to renewable ones and to identify the key barriers, especially on a local focus on Azerbaijan. Considering that Azerbaijan has great potential for producing green energy - even more than its own domestic demand - this research also aims to provide innovative suggestions for its utilization. Data published from the national agency responsible for renewable energy in Azerbaijan indicates potential renewable power sources of country is roughly 135 gigawatts on land nearly 157 gigawatts offshore [8].

For achieving these goals, study consists of these objectives:

1. Analyzing current energy situation in Azerbaijan. Also research the renewable potential.

2. To study the main problems which slow down the transition to green energy.

3. To study main government policies and strategies related to green energy development.

4. To suggest practical recommendations for speeding up the transition process to green energy in Azerbaijan.

Following these objectives, this study also seeks to answer several research questions, such as:

1. What is the Azerbaijan's current energy situation in and its renewable capacity?

2. By taking which actions Azerbaijan can improve plans for quick transition to clean energy?

3. Which polices and technological solutions can help to achieve these goals and contribute for Azerbaijan 2030 project?

1.4 Significance of Study

This study plays a key role by helping to investigate the steps how Azerbaijan could move toward a cleaner energy future. As the current energy situation depends on oil and gas production, this research aims to effective ways to develop alternative energy sources. Additionally, this study is supporting the national project "Azerbaijan 2030". This project is national plan for making Azerbaijan as clean energy producer country.

1.5 Structure of the Thesis

The plan of this thesis contains five key chapters:

Chapter 1 - Introduces research topic. It also explains main problem plus objective. And topic of study.

Chapter 2 - covers the literature review. Additionally, it focuses for global and local renewable energy transition, problems, and suggestions.

Chapter 3 - explains the research method, including how the data was collected. Also, analysis techniques, and study design.

Chapter 4 presents and discusses the main results. Shows the key findings about Azerbaijan's energy transition and comparing them with global trends.

In the end, **Chapter 5** closes the study by outlining the key outcomes and giving suggestions and possible areas to explore next.

CHAPTER TWO

REVIEW OF THE LITERATURE

2.1 Introduction to Literature Review

Green energy - trend topic which is discussed in modern world. If the world will not act in time, the future energy situation of energy may be under the serious problem. However, there is good news. Recent reports show the global energy sector is changing. Countries reducing carbon emissions and increasing the usage of renewable sources. According to IRENA (2023) [9], the transition is not only about adding more renewable sources. But many things. For instance, modern technologies help sending electricity over long distances.

The International Energy Agency (2022) [10] reports that technologies such as HVDC are very important. It helps to connect the producer and demand centers. This system is very advantageous, which will be discussed in detail in next chapters. Sovacool (2021) explains that the energy transition brings economic and environmental benefits. He also notes that it helps support more sustainable long-term development. And one main goals of the energy transition are to reduce the harmful effects of conventional energy sources. [11]

2.2 Global Perspective on Energy Transition

Data from IRENA (2023) [8] says that the world should focus on how power everything, otherwise things could face environmental consequences. In addition, new steps should be taken in order to handle growing energy demand for next 30 years. The new system which will also emit less CO_2. And keeping economies running without harming the planet

During COP29 in Baku - held in November 2024 - developed countries promised yearly aid topping $300 billion from now till 2035. The goal- is helping to fight climate change for poor countries. [12]. The financial support is very important, because it helps in shifting toward greener power worldwide.

Also, during the COP29 conference, it was noted that energy storage upgrades plus wider grids play a big role in shifting toward greener power worldwide. It was also noted how necessary investments are in these areas.

Similarly, Azerbaijan planning to increase renewable energy production to 30% by 2030. And also, to reduce its dependence on fossil fuels [13]. As a developing country and a major fossil fuel producer, Azerbaijan is taking significant steps toward this transitionю. Also being a strong example for other fossil fuel-dependent nations.

According to the IEA (2023) [3] and IRENA (2023) [8], the demand in energy likely will grow by the end of 2030 due to economic growth. Several reasons affecting this such as the development of smart cities, and the electrification of transport and industry. As noted by Sovacool (2021) [10], to meet demand in global power, the process should be accelerated.

Based on information published from journal (IEA) [3] in 2023, the capacity of renewable energy sources exceeded 3,000 GW globally. Besides, their contribution to electricity generation is increasing year after year. However, conventional energy sources are still dominating the energy sector. They supply over 60% of the world's electricity.

Environmental factors also play important role besides economic and policy aspects. In fact, several studies prove this statement. The transition of renewables directly contributes planet. As greenhouse gas emissions are reducing, parallelly overall air quality improves. As pointed out by the IPCC (2022) [14] and UNEP (2023) [7] that accelerating to achieve the Paris Agreement's 1.5°C target.

2.3 HVDC Technology and Its Role in Renewable Integration

During the transition to green energy several systems are being used. When the energy transfers from renewable sources to demand center, it is challenging to do without modern efficient systems. One of these systems is HVDC (High Voltage Direct Current). IRENA (2022) notes that HVDC is important for linking areas that produce renewable energy with places where electricity demand is high. This system is used for transferring large amounts of electricity over long distances efficiently. It is very beneficial compared to AC systems because DC transmission offers several advantages - such as lower power losses during long-distance transmission, the ability to interconnect asynchronous networks, and better control of power flow at different frequencies [16]. Several studies note that HVDC is considered a base technology for future networks based on renewable energy sources.

The main components and power flow of an HVDC transmission system showed in Figure 1.3.

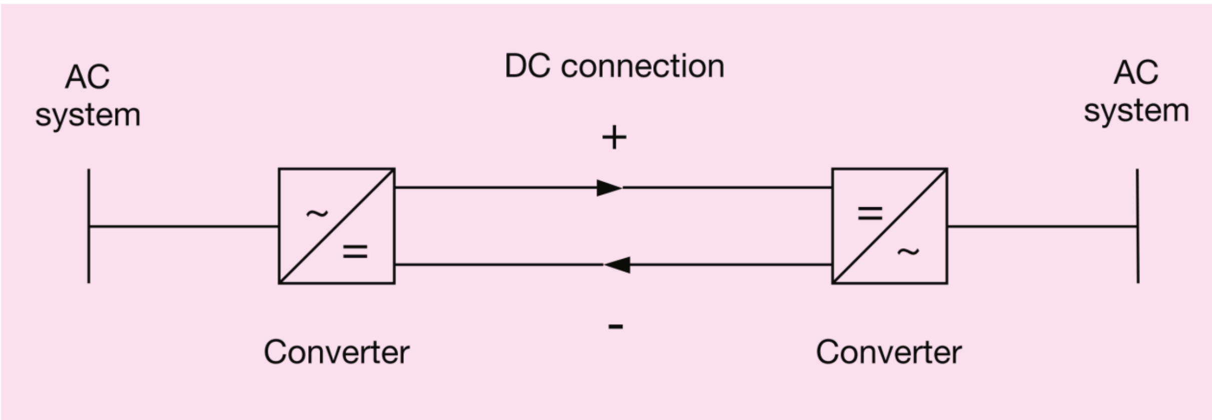

Figure 2.1 - HVDC system's Scheme

From this figure, it can be seen the from the left part of scheme acting as a rectifier, the converter at the sending terminal changes the power from AC to DC. At the receiving end, the converter operates as an inverter, making Direct Current electricity to the Alternating Current. Converters are linked to either transmission lines, by cables, or sometimes by using both together.

Two principal converter technologies are commonly used by HVDC setups: the CSC type and the VSC type. In many HVDC installations, the CSC design is the one most used. A Figure 1.4 gives an example of how a CSC converter is arranged electrically [17].

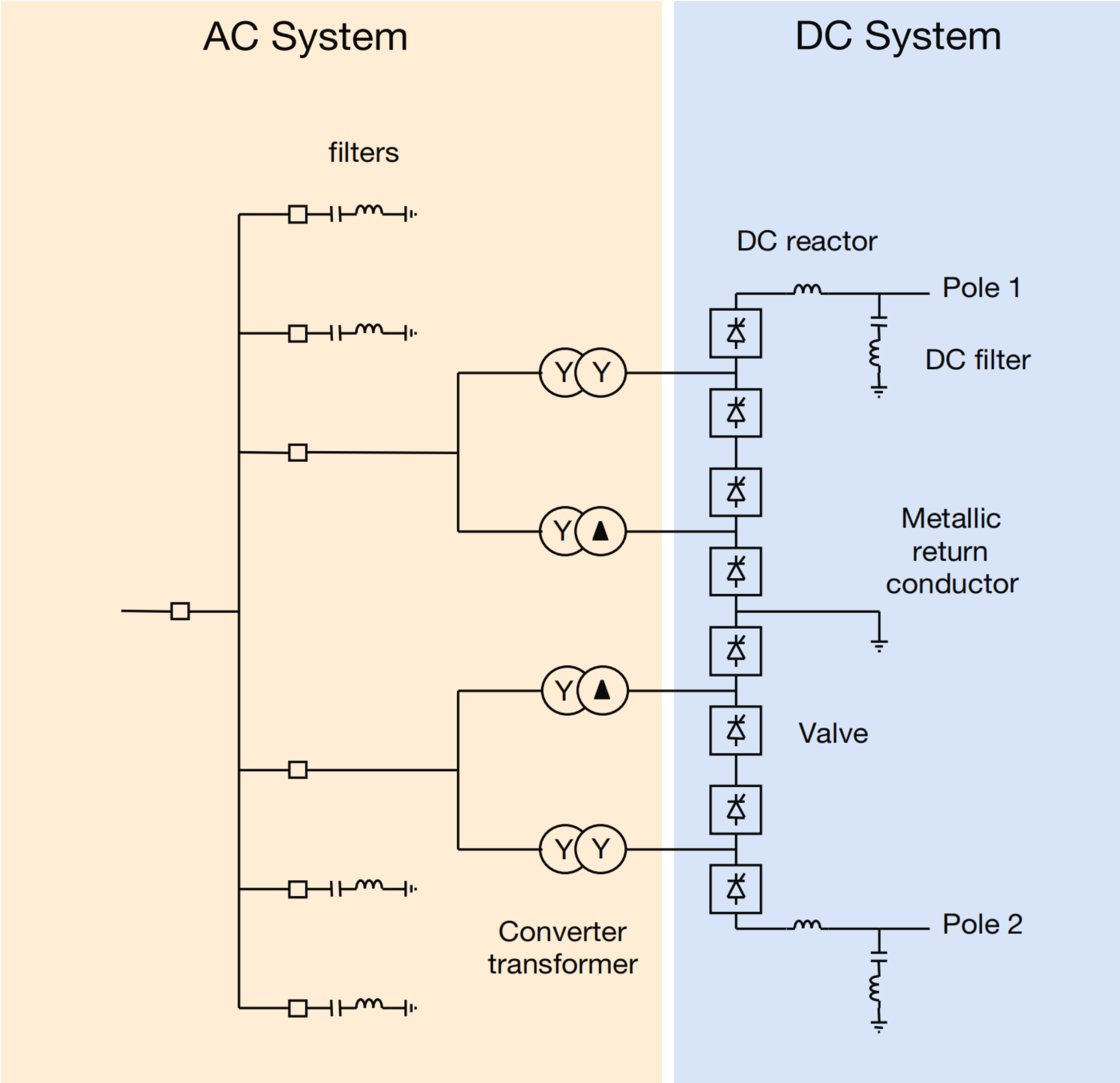

Figure 2.2 - Current source converter (CSC) diagram

When we look at the schematic – the power is changed from AC to DC as part of the process. However, on the AC network, the converter draws reactive power and produces harmonic currents. Harmonic filters on the AC side help to provide the reactive power for the converter and to keep the harmonic currents in check.

In addition, HVDC system is very beneficial for providing more control over how electricity is transferred across different areas of the grid, including asynchronous parts. With modern converter technologies, HVDC can regulate both the direction and the amount of power transferred, while also improving grid stability [17].

One of the global examples of HVDC system is the NordLink project. It connects Germany and Norway. That interconnection is a 623-kilometre subsea cable with a transmission capacity of 1,400 MW. This system demonstrates how HVDC systems can effectively balance renewable energy sources between regions. It helps to enable the exchange of surplus wind power from Germany and hydropower from Norway. [18]. All these advantages make HVDC a suitable system that could be applied in Azerbaijan's Green Energy Corridors which will be discussed in detail in the next chapters.

2.4 Regional Energy Corridors and Interconnections

In recent years, regional energy interconnections have become a very important element of the global energy transition. Especially in places that have strong renewable energy potential. They allow countries to exchange renewable electricity. In addition, this cooperation between countries helps for better integrating clean energy and supports decarbonization goals. As indicated by IRENA (2022) [19], regional energy interconnections and electricity corridors are strategic tools for achieving global sustainability goals.

Based on the global context, regional initiatives have also begun to develop and gain more importance. As it was mentioned in previous chapters, Azerbaijan has very great renewable generation. There are several new regional green energy corridor projects. This regional interconnection will link Azerbaijan neighboring countries. So, one of the main projects is 'Caspian - Black Sea Green Energy Corridor,' which is connects Azerbaijan and Europe.

The plan of this project is to transmit around 1,000 MW of renewable electricity, mostly from wind and solar sources in the Caspian region. The HVDC line which is expected to be approximately 1,195 km that reaches depths of up to 2,200 meters beneath the Black Sea [20]. The Black Sea Submarine Cable shows Azerbaijan's strategic plan to become a renewable electricity exporter, contributing to both regional energy development and Europe's decarbonization goals [21] (see Figure 2.3).

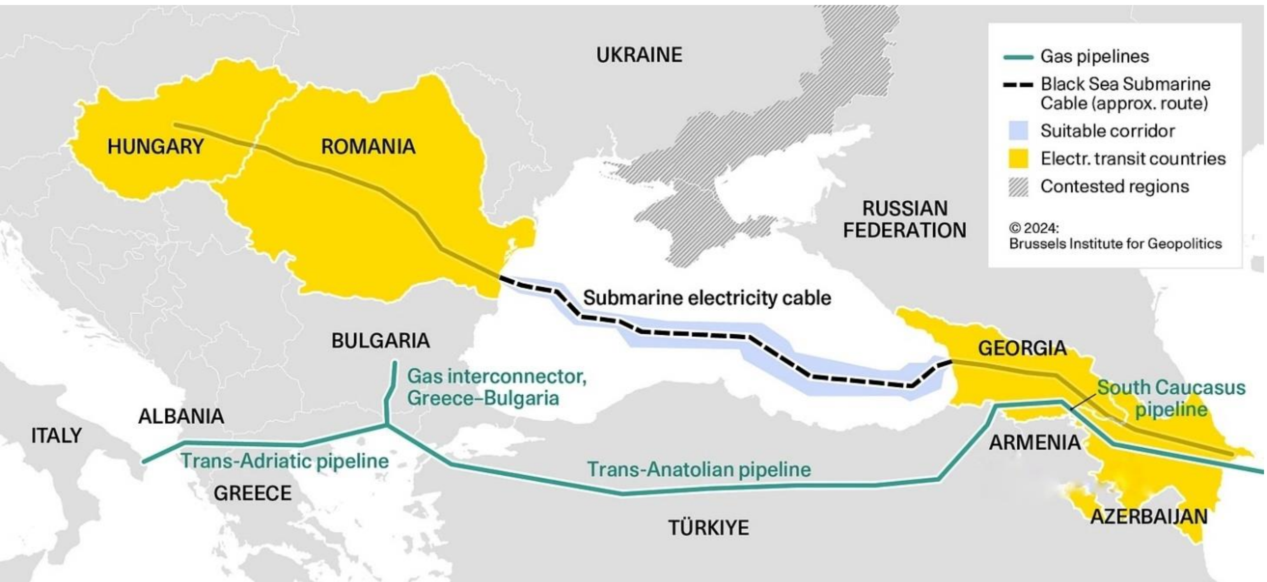

Figure 2.3 - Overview EU-South Caucasus Corridor

Based on information published by a study by the Georgian State Electrosystem, the cable will operate on a bipolar ±500 kV configuration with electrodes, capable of transmitting up to 1.3 GW of energy. And, estimated price of this plan is between €3.1 and €3.6 billion, with an additional €70-90 million. In addition, operation forecasts show that the system will run at nearly 90% of the capacity. Because seasonal shifts in demand and available supply mean that electricity moves toward the EU for most of the time (about 78%). Also, only about 10% of the time the flow goes the other way [22].

The second project is the "Central Asia - Azerbaijan Energy Corridor," which is planned to create an interconnection between Azerbaijan, Uzbekistan, and Kazakhstan through the Caspian Sea (see Figure 2.3). This interconnection could also enable the export of Central Asian renewable and hydropower electricity to the South Caucasus and Europe. The corridor supports Azerbaijan's national strategy to reach about 40% renewables in its energy mix by 2030 [23].

Figure 2.4 - *Existing and potential green energy corridors*

According to Ember (2024), the Central Asia and South Caucasus can generate more than 1,000 GW of renewable energy potential. Kazakhstan having around 650 GW (mostly onshore wind and solar). Uzbekistan about 300 GW (mainly solar). These two countries contribute most of the wind and solar resources, while Azerbaijan has 135 GW of onshore wind and solar potential, along with roughly 157 GW of offshore capacity available in the Caspian Sea. Currently, conventional grid, which was built during the Soviet era, operates at only 6-7 GW capacity. The planned Trans-Caspian corridor is expected to have 1-2 GW of green power transfer from Kazakhstan and Uzbekistan to Azerbaijan, with future expansion to 5 GW by 2035. The corridor's total length is expected to be about 1,200 km, including a submarine HVDC line across the Caspian Sea. With this corridor, yearly CO_2 emissions in the region could drop by up to 25 million tons [23].

The third project is the "Azerbaijan - Türkiye Europe Corridor" (see Figure 2.3). In this project planned to transfer renewable electricity from Azerbaijan through Türkiye into the European energy system. Currently, it uses the existing 400 kV infrastructure. Also, it is expected to have an HVDC upgrade in the future. Additionally, this project supports the "Azerbaijan 2030: National Priorities for Socio-Economic Development" project. This corridor will connect several countries and bring the energy stability. Additionally, it aims to synchronize regional energy systems with the European ENTSO-E network. [25].

Overall, the new interconnection system shows Azerbaijan's geographically in very strategic location. Having great potential for renewables, it also is a bridge. And very strategic. The projects in South Caucasus which connect Central Asia and Europe are supported by several global programs. For example - European Commission, the Worldwide Banking, ADB and etc.

2.5 Azerbaijan's Energy Transition Policies

Currently Azerbaijan has set up the new policy for green world. The national plan is to become a clean-energy producer. The 'Azerbaijan 2030' national plan. It was signed by a country's president in 2021. And this project consists of several main goals.

- Reducing the carbon emissions
- To boost how much renewable power will be used for production about 30–40% by 2030.
- Modernizing the energy infrastructure
- Attracting foreign investors
- digital transformation, human capital, green growth, and social welfare [26].

Several companies invested in major renewable projects. For example, Masdar (UAE). Masdar made an agreement for 230 MW solar plant. Expected around 500 million kWh of power per year. This amount can power above 110k homes and drop emissions by nearly 200k tons annually. [27]. And this plan comes with its benefits for region, creating new jobs and supporting national plan.

Another investor is investor is ACWA Power (Saudi Arabia). ACWA Power has partnered with the country's' national energy authority and SOCAR for performing a a 240-megawatt wind project. The plan features 1 GW of onshore wind, 1.5 GW of offshore wind, and an integrated battery storage system [28].

2.6 Summary of Literature Review

In overall, this chapter reviews the main studies, reports and policy documents. Also was explained how these projects support Azerbaijan's national plans. The literature shows that the renewable energy is important for both economic development and environmental aspects. Especially for countries which want to reduce carbon emissions. And join the green world. Modern technologies, such as HVDC is key for transferring large amounts of renewable electricity over long distances. This chapter also highlights three major regional corridors. These corridors show how Azerbaijan located between energy rich Asia and energy demanding Europe. In overall, Azerbaijan’s national plan, green-energy goals and all investments supporting for this transition. The next chapter explains the research methods and analytical approach used to study these issues in detail.

METHODOLOGY AND RESEARCH APPROACH

3.1 Introduction to the Methodology

For this chapter plan to explains framework and procedures for transition to green energy, focusing on Azerbaijan. As the country has great potential for renewable generation and addressing the HVDC system and its technical optimization. Since the energy corridors are part of national plans, this thesis analyzes the technical configuration that can maximize renewable integration efficiency and minimize transmission losses.

The research method was chosen to include both the engineering and sustainability aspects of the topic. For this research the mixed-method approach was used. As in this study focuses at technical side on HVDC systems plus their economic and environmental benefits. By combining qualitative and quantitative methods, this research connects both technical analysis and policy aspects.

In the following chapters will be discussed about the structure of research, the data sources and modelling tools which were used to achieve the objectives of study.

3.2 Research Design and Approach

This research consists of mixed approaches, by using conceptual and analytical methods. The qualitive part. The qualitative part which focuses on policy and strategy review. And the quantitative part, focusing on MATLAB technical analysis. The conceptual part focuses on Azerbaijan's national projects, regional cooperation and the idea of creating green corridors with HVDC lines. However, the quantitative part focuses on the technical side, using MATLAB to assess HVDC capacity, efficiency, and power losses.

The chapter studies HVDC systems in three ways:

- Technical: to study operational performance and understand the advantages of HVDC systems in long-distance power transmission.

- Economic: to estimate potential cost efficiency, investment needs, and long-term financial benefits.

- Environmental: to analyze how HVDC systems contribute to reducing carbon emissions.

The MATLAB is used for running simulation for the quantitative part. There are several steps, such as calculating HVDC losses, corridor efficiency and etc.

Also, study reviews several policy documents for the qualitative part. For instance, reports from Azerenergy LLC IRENA, the IEA, The World Bank and etc.

Using both methods, the research studies HVDC from technical and economic aspects.

3.3 Data Collection and Preparation

For this research several data types are used from different local and global databases. Data covers simulation and corridor values, HVDC characteristics etc. Also, from Azerenergy the electricity production and demand values. This data will be used in MATLAB simulation for new interconnection proposal. Only reliable datasheets and reports were used. The information basically from recent years.

However, there are also some limits to the data. Some reports give different numbers, and some corridor plans are still being developed, so the values may change. The same situation is with HVDC data, because different sources sometimes show slightly different technical details.

3.4 Analytical and Calculation Approach

The general approach that studies this section is done in several steps. First, renewable capacity is checked. For both global and regional. Then, the main growth trends are checked from reliable sources. Also, the corridors distances ad possible transfer numbers. And then, the national renewable goals are connected with the capacity of each corridor. All of this is done by using information from reports and statistics

For the qualitative part small datasets are prepared and entered to MATLAB. The aim is to calculate approximate values - such as corridor efficiency, renewable energy transfer rate, and how the regions can be connected by HVDC. As these projects are still planned, only simple numerical calculations are used, not advanced modelling.

As currently there is green corridor, different global examples are looked for getting close numbers. The national renewable targets are also investigated with the possible corridor limits. And the numbers are checked to see if they support Azerbaijan's export potential. Overall, the overall approach is a mix of basic numerical steps and simple qualitative review, and the goal is to understand if the plans are generally possible.

3.5 Scope, Assumptions, and Limitations

This research examines the plan for transition to cleaner energy. Regionally and for Azerbaijan. The main idea is long-term HVDC corridor. The plan is that by 2040- or 2050-year Azerbaijan could act as central HVDC link between Europe and Asia. In this one line the Europe South Caucasus and Central Asia will be linked. The study only uses secondary data from reports and datasheets. There is no field work, measurements, or interviews. The goal is to see if HVDC corridors are realistic and useful for Azerbaijan's green transition.

For simple modelling of interconnection corridors a few assumptions are needed.

1. The simulated model of corridor will follow the current published values.
2. HVDC efficiency will be close for the numbers which were released in datasheets and reports.
3. Azerbaijan will continue its energy policies.
4. Project values also will stay similar to official plans.
5. International cooperation on energy trade will continue

However, there are some limitations. At the moment, these is no green corridor in Azerbaijan. Because of this, HVDC values from IRENA and IEA are used and adapted for the region. The study relies heavily on external reports and available data. The results are approximate and not exact.

CASE STUDY AND RESULTS: MODELLING THE EUROPE-SOUTH CAUCASUS-ASIA HVDC CORRIDOR

4.1. Corridor concept and scenarios

In the recent years Azerbaijan is getting attention for its strategic location and having great renewable potential. The country is located between energy rich regions in Asia and demand centers Europe. Additionally, both Europe and Central Asia are looking for new clean energy sources. Because of these factors, there is an opportunity to propose a new HVDC interconnection. This new proposed interconnection will link Central Asia - Azerbaijan - Türkiye - Europe into one long corridor.

The chapter’s goal is to understand how this corridor could work in practice. The analysis focuses on a simplified four-node system and shows how power could move across regions. Also, how much renewable surplus can be transferred and what losses appear along the HVDC line. (see Figure 4.3) The aim is not to build a full power-flow model, but to give a clear demonstration of the technical behavior of the proposed corridor and to show how it supports long-term clean energy exchange.

The corridor in this study follows these nodes:

- **Node 1 - Central Asia**
  Region with high renewable potential and expected future surplus.

- **Node 2 - Azerbaijan / South Caucasus**
  Transit point and regional hub linking east and west.

- **Node 3 - Türkiye**
  Large and fast-growing electricity market with both demand and renewable expansion.

- **Node 4 - Europe**
  Final demand region with long-term interest in clean imports.

This chapter uses MATLAB to model the basic energy balance between these nodes and estimate the amount of electricity that can be transferred through the proposed HVDC system. The MATLAB model calculates renewable energy generation, demand, net surplus or deficit, and the amount of electricity transferred from one region to another.

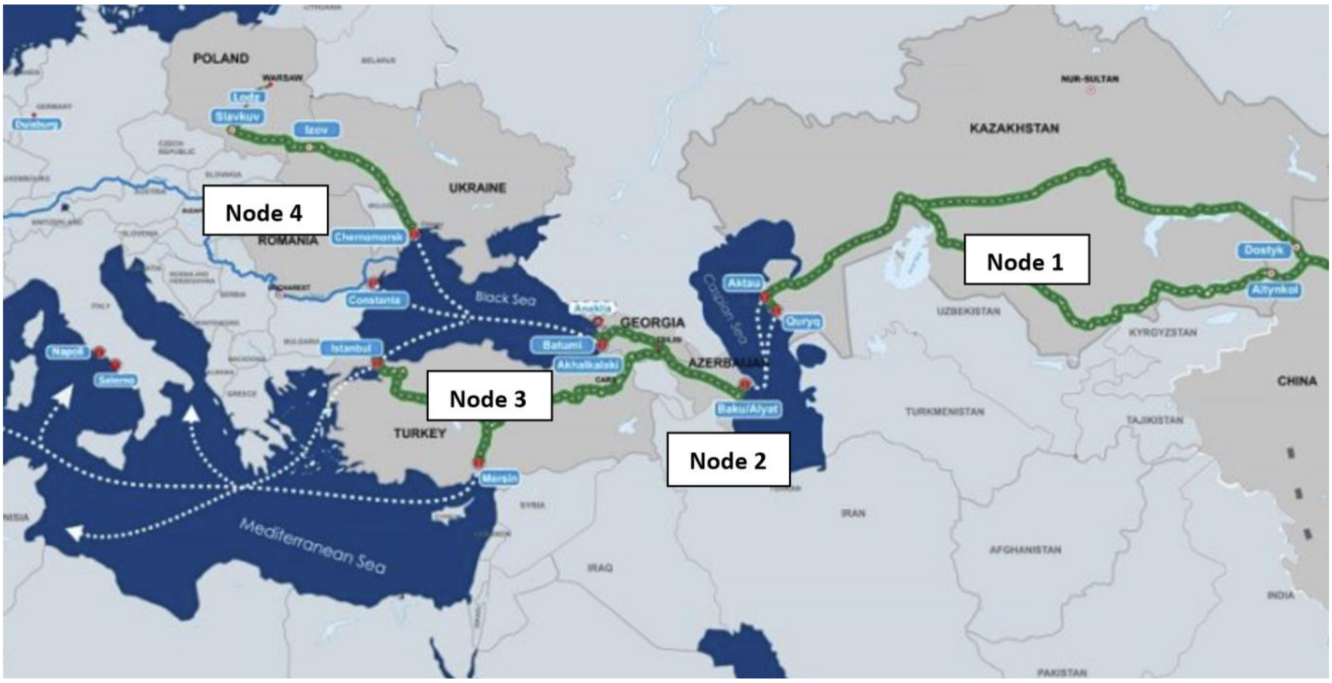

Figure 4.1 - Proposed Europe-Caucasus-Asia HVDC corridor with modelling nodes

4.2. Input Data and Assumptions

This part shows what data and assumptions were used in the MATLAB model. For each node, the assumed numbers were taken based on the region's generation and demand potential. Also, typical HVDC loss values of about 3-5% per segment, depending on the converter substations and line distance, are given to demonstrate realistic performance. These assumed values will be used for further analysis. The aim is to build a consistent 2030-year-old example that can show how the proposed corridor could work in practice.

The plan is:

- estimate renewable generation and electricity demand for each node (in GW),
- calculate the surplus or deficit of power in each region,
- simulate power transfers along the HVDC corridor through Azerbaijan,
- estimate how much power can realistically be delivered to downstream regions,
- calculate the HVDC transmission losses and comment on corridor efficiency.

4.2.1 System boundary and nodes

The model includes four nodes that represent wider regions:

- **Central Asia (Node 1)** - export-oriented region with large renewable potential.
- **Azerbaijan / South Caucasus (Node 2)** - hub and transit region between east and west.
- **Türkiye (Node 3)** - large and growing power system with rising demand.
- **Europe (Node 4)** - final

- demand region with long-term interest in clean imports.

The corridor is modelled only between these four nodes. Internal grids inside each region are not included. Each node is represented by total renewable generation (GW) and total electricity demand (GW).

4.2.2 Renewable generation and demand in 2030

Table 4.2 shows the assumed renewable generation capacity and electricity demand for the four nodes in 2030. The values are chosen to explore a situation where Central Asia already has some surplus renewable power, Azerbaijan is close to balance, and Türkiye and Europe still rely on imports.

Region	Year	Renewable generation (GW)	Demand (GW)	Net balance (GW)
Central Asia	2030	30	22	+8
Azerbaijan	2030	6	7	-1
Türkiye	2030	20	32	-12
Europe	2030	30	80	-50

Table 4.2 - Assumed renewable generation and demand in 2030.

For this 2030 case, Central Asia shows a moderate surplus. Azerbaijan is slightly in deficit. But Türkiye and Europe have larger deficits and would benefit from additional imports. This supports the idea that a corridor from east to west can help use surplus renewable power instead of curtailing it.

4.2.3 HVDC corridor parameters

The proposed corridor is modelled as three HVDC links in series:

Central Asia → Azerbaijan
Azerbaijan → Türkiye
Türkiye → Europe

For simplicity, each link is given the same transfer capacity and typical loss values. The exact route and length are not fixed in this thesis, but the distances are chosen in a realistic range for long-distance HVDC.

Link	Approx. length (km)	Rated capacity (GW)	Voltage level (kV DC)	Loss assumption (%)
Central Asia → Azerbaijan	~1500	5	±525	4%
Azerbaijan → Türkiye	~700	5	±525	3%
Türkiye → Europe	~800	5	±525	3%

Table 4.3 - Assumed HVDC corridor parameters.

The loss assumptions show typical values for modern HVDC systems. Depending on voltage and design, the converter stations usually have around 2-3% loss. But the long lines add roughly 1-3% per 1,000 km. For this reason, an overall loss of around 3-5% per segment is reasonable for a regional corridor.

4.2.4 Simplifications and limitations

The following simplifications have been made:

- Each region is represented as a separate node with one value for renewable generation and one value for demand.
- Only renewable generation is enabled. Other sources of generation are not shown, as the focus is on clean energy flows.
- The HVDC corridor has a fixed capacity of 5 GW on each segment. Possible subsequent upgrades are discussed only qualitatively.
- The model uses stationary power balances (GW) and does not consider hourly fluctuations or dynamic stability.

These assumptions make the model simple enough to implement in MATLAB, while providing useful information on how the proposed corridor can provide long-range clean energy exchange in 2030.

4.3 MATLAB Model Setup

To analyze the proposed model of the Europe - Caucasus - Asia HVDC corridor, a simple four-node model was created in MATLAB. Each node displays renewable generation (GW) and electricity demand (GW) in the regions. In addition, the model calculates the net balance of each region and simulates the movement of excess energy along the HVDC corridor from east to west.

4.3.1 Model structure

The model uses the following four nodes:

- **Node 1 - Central Asia**
- **Node 2 - Azerbaijan / South Caucasus**
- **Node 3 - Türkiye**
- **Node 4 - Europe**

Each node has:

Gen_RES - renewable generation (GW)
Load - demand (GW)
Net - surplus or deficit (GW), calculated as:

$$Net = Gen\_RES - Load$$

Positive Net values indicate surplus renewable power available for export. Negative values indicate that the region needs imports.

4.3.2 HVDC corridor representation

The proposed corridor is modelled as three HVDC links:

1. Central Asia → Azerbaijan
2. Azerbaijan → Türkiye
3. Türkiye → Europe

Each link has:

- a transfer capacity (C*)*, assumed at 5 GW per segment.
- a loss percentage (*L*), representing converter + line losses.

The power received after each link is:

$$P_{received} = P_{sent} \times (1 - L)$$

The algorithm always sends power from the region with surplus to the next region in the corridor, up to the HVDC capacity limit.

4.3.3 MATLAB implementation

The MATLAB script contains three main parts:

1. **Input data:**
    - renewable generation and demand for 2030

- HVDC capacities
- HVDC loss values

2. **Power balance:**
in the model surplus/deficit will be calculated the for each node.

3. **Power flow calculation:**
Surplus from Central Asia is pushed through the corridor node by node, while applying capacity limits and losses.

In this script was included input data, HVDC parameters, and the power-flow calculation for MATLAB model. In the Figure 4.4 only the main part of the code is shown here, which includes the regional values and the corridor assumptions. This section shows how the nodes, renewable geenration and HVDC loses defined before running simulation. The complete version of the script is provided in the Appendix.

4.4 MATLAB Simulation Results

This section shows the results of the '2030 corridor's calculation. The MATLAB output shows the net renewable balance in each region. Additionally, how much electricity can move through the planned HVDC links. The results also include the power losses on the corridor.

4.4.1 Regional balance results

Model's first part output calculates the renewable surplus or deficit for each node in 2030:

```
Command Window
Net balance (GW) in 2030:
Central Asia: 8.0 GW
Azerbaijan: -1.0 GW
Turkiye: -12.0 GW
Europe: -50.0 GW
```

Figure 4.5 - MATLAB output showing regional net renewable balance in 2030

4.4.2 Corridor flow results

When calculating the flow in the corridor, a limit of 5 GW is used for each HVDC segment. MATLAB calculates how much surplus electricity from Central Asia can be transferred to the west and how much will be lost at each site. The results are:

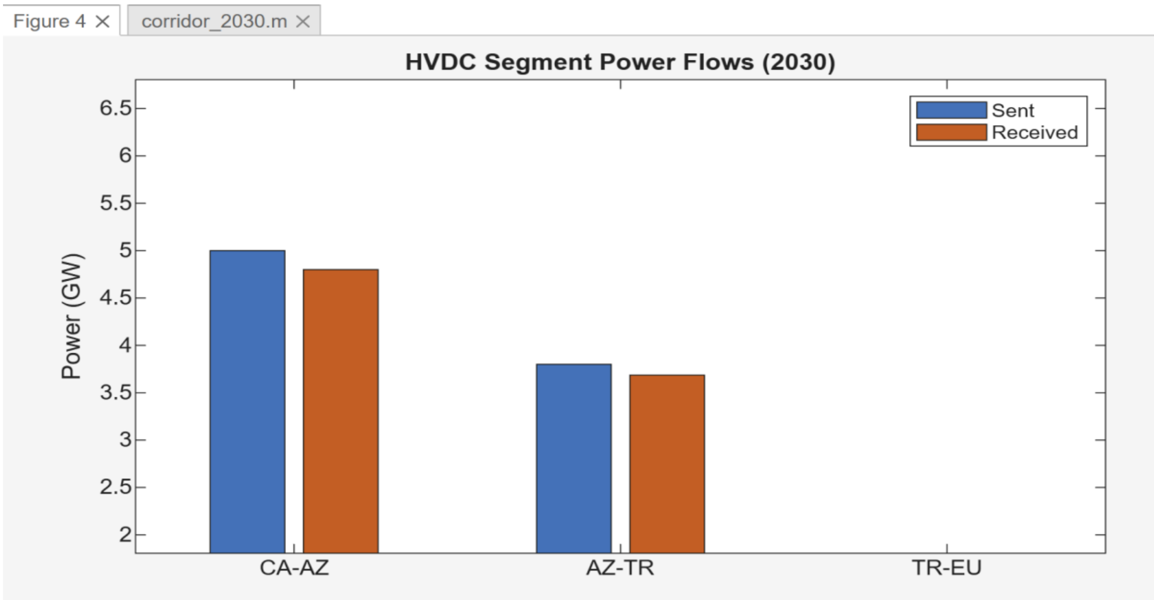

Figure 4.6 - Comparison of sent and received power across the Central Asia-Azerbaijan, Azerbaijan-Türkiye and Türkiye-Europe HVDC links (2030)

The results are:

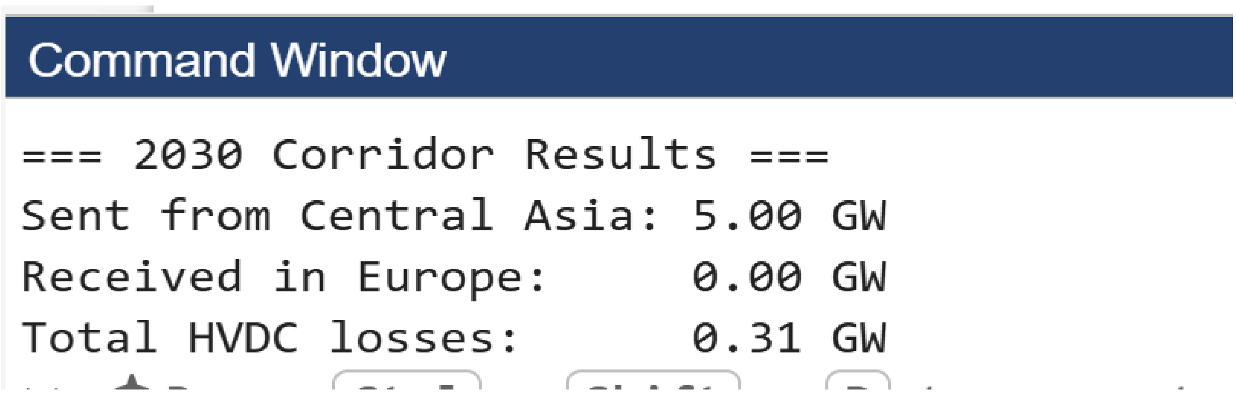

Figure 4.7 - MATLAB output showing HVDC segment flows and total losses (2030)

4.4.3 Interpretation of results

Modeling shows that the proposed corridor will start functioning as a balancing route as early as 2030. Central Asia will be able to export the maximum allowable capacity of 5 GW allowed by the first HVDC segment. After considering the losses, this capacity is supplied to Azerbaijan, and then further to Turkey.

Türkiye has a significant deficit of -12 GW. After getting the 3.69 GW from the corridor, the demand still did not cover. In this regard, there is no surplus left in 2030 that could continue to supply Europe. As a result, Europe gets 0 GW in this baseline scenario.

Although the corridor does not deliver power to Europe in the 2030 model, it still provides important technical benefits:

- It reduces Türkiye's deficit.
- It ensures that surplus renewable energy in Central Asia is not wasted.
- It strengthens Azerbaijan's position as a link between different regions.
- HVDC losses stay low (about 0.31 GW), showing that DC works efficiently over long distances.

These results show how corridor becomes important when renewable energy generation grows in Azerbaijan and Central Asia.

4.5 Technical, Economic, Social and Environmental Benefits

This section explains the wider technical, economic, as well as the environmental advantages suggested by the model results for 2030. The aim is to show how the interconnection supports long-term clean energy integration across the regions.

4.5.1 Technical Benefits

By proposing and simulating the new interconnection model, it becomes clear that it can bring several advantages. This section explains the main technical benefits of the new HVDC corridor. One of these benefits is the reduction of curtailment. In many cases the grid cannot accept the renewable energy that is produced. In this case, the part of the generation is wasted, and wind or solar plants are forced to shut down. However, with new corridor this situation changes. For instance, Central Asia has a surplus of around +8 GW. And this power can be sent to other regions that need it.

Also, one of the benefits is better system Balancing. As the grid will be connected between regions. If one region has global shutdown the other can support, it. In many countries, however, the grid is still fully AC-based. For example, Azerbaijan. Which makes it hard to full integration. And this creates problems with stability. But with the HVDC system, regions will be able to support each other more easily. HVDC works well over long distances and has low losses. [29]

The results from MATLAB show that even 5 GW link improving the balance in region. New interconnection system makes it easier to use renewable potential of countries. Especially for Central Asia. Instead leaving it unused. In the 2030 case Türkiye's deficit was reduced with the imported renewable power. In the future, if the corridor capacity grows to 10-15 GW, then it becomes possible to send renewable power all the way to Europe.

4.5.2 Economic Benefits

Undoubtedly, the new interconnection system comes with clear economic benefits. Since Central Asia is exporting electricity, it can gain export revenue from selling its renewable power. Azerbaijan, acting as the hub between east and west, would also receive payments for hosting the HVDC lines and converter stations. Similar economic gains appear for Türkiye and Europe. Additionally, importing renewable electricity is cheaper. Renewable energy also has no fuel cos. The prices stay more stable over time. In general, investment of this scale brings activity to the local and regional economy, especially for Central Asia.

Another economic benefit of this new interconnection system is the improvement of communication between countries. The corridor opens the door to long-term contracts between countries. Especially for the countries in Central Asia, which are far away from Europe. And this is direct key for future investment and improvement of region. The new interconnection system will open new job positions for all local markets which will boost economy. Building HVDC lines creates demand for materials, services, and logistics. The new converter stations will need more engineers, technicians and maintenance teams

As the Europe and Türkiye currently import a lot of fossil fuels, new interconnection system will affect economically for the markets also. Because renewable electricity imports replace part of that spending. And, because of these reasons the countries will save money because renewable electricity prices don't change much. Less fossil imports mean better trade balance. Economy will improve more in the whole region.

4.5.3 Social Benefits

The new interconnection system also provides its social benefits. As the new HVDC systems require skilled workforce the new programs will be created. Training programs can develop new technical knowledge in each region. And because of this, universities and engineering communities will benefit from new technology. Also, countries can build stronger local expertise in modern energy systems.

Another benefit is stronger regional cooperation. The corridor connects Central Asia, Azerbaijan, Türkiye and Europe, which naturally brings these countries to work closer together. In addition, this kind supports political relations. Because partnerships give more long-term stability.

4.5.4 Environmental Benefits

It is not possible not to consider the environmental benefits. Because they are plenty. For instance - clean energy replacing conventional. And this helps to reduce pollution. Plus improves air quality. Better air quality - better environment for all livings. So, with the help of new interconnection system, regions will significantly decrease greenhouse gas emissions.

Additionally, Central Asia using the potential renewable energy sources is highly beneficial. More clean energy will go to grid. And less gas will be used for conventional stations. This also will decrease the gas prices. All of this leads to a lower overall carbon footprint. Better use of wind and solar projects also means less need for conventional power backup.

4.6 - Additional Technical Analysis

The MATLAB simulation of model showed that even with assumed numbers corridor will be in full beneficial run. After expanding its capacity, corridor prognosed to provide even more efficiency. By using reliable technical datasheets and reports, the approximate corridor length was used in order to calculate the HVDC losses. And the results showed that only about 0.31 GW is lost over the three segments. Additionally, HVDC system brings other benefits. Such as support during regional shortages, helping during outages. Or even during peak hours and seasonal changes. There are several examples where HVDC is used in great way. For instance, the North Sea HVDC links and the large HVDC corridors in India.

Seasonal changes also affect the generation. Central Asia has strong winter winds. More power can be exported during the cold period. Türkiye and Azerbaijan have strong summer solar. So, the balance changes in the warmer months. Europe’s demand is usually high in winter. So future exports will be more important in that season.

4.7 - Discussion

The simulated corridor model shows that the interconnection already works. Even using simple assumptions. For 2030 model, Türkiye can reduce the deficit. Europe, however, will receive low until 2030. After improving and expanding corridor that values will rise. In this case, the Central Asias additional clean energy is not wasted. The whole region benefits from it. And Azerbaijan will act as bridge between regions.

The new interconnection corridor also supports the regional strategies. The countries which are involved to this project will benefit. In recent years, Central Asia is planning to use its renewable potential. And Azerbaijan’s goal to become hub will be real. And benefit from it also. Türkiye is working on increasing renewable integration into its system. The EU wants clean imports in the long term. So, the proposed corridor supports all these policy directions inside one system.

4.8 - Limitations of the Study

There are some limits which are better to mention. The simulation uses only one simple flow calculation. Since the real corridor does not exist yet and exact data is not available, it is difficult to study hourly behavior or run a full-year simulation. No AC load flow or system stability analysis was done because conventional AC grid data was not accessible. There is also no detailed converter station model, again mainly because of missing information. So, the study focuses only on steady-state power balance.

The renewable data for 2030 is estimated. The numbers are assumed based on regional demand and available reports. The demand values are also generalized, not exact. As there is no current real model, the length values are approximate. Also. Other aspects are hard to examine. For example, the projects' general cost. In addition, there is no detailed cost-benefit calculation also. And the job creation is discussed also in a general way.

Only 2030 case model was simulated. The 2040–2050 cases mentioned generally but not simulated because of lack of data. After the 2030 the renewable growth actually can change the results. Even with these limitations, the results still show good results. The simulation results look technically beneficial. To sum up, this research is a good base for next studies.

4.9 - Summary of Chapter 4

This chapter focuses on proposed new interconnection system and on its simulation. The Europe-Caucasus-Asia 2030 model was simulated in MATLAB. The simulation showed that Central Asia has a plenty additional energy. And also showed how Türkiye absorbed most energy because of deficit. For 2030 model, Europe did not receive almost no power. This is normal for early phase of corridor. Simulation also confirmed that the HVDC losses are low. And the 5 GW link works at its full capacity. With future expansion, the Europe will receive more energy. Also, technical, economic, social and environmental benefits were discussed.

Chapter 5

CONCLUSION AND RECOMMENDATIONS

5.1 Purpose of the Study.

The main aim of the research examines how Azerbaijan and other countries could take steps for the integrating clean energy. Nowadays, many countries globally planning to change their energy sources from conventional to renewables. In addition, the clean energy needs efficient system for exporting over long distances. Because of that, a new interconnection idea was studied and tested in MATLAB. HVDC was chosen as the main technology since it works well for long-distance and efficient power transfer. Another reason of this study is the location of Azerbaijan. The strategic location of Azerbaijan makes it a future energy bridge between regions. Between located between energy-rich Central Asia and big demand centers such as Türkiye and Europe. At the moment, there is no study that connects Central Asia → Azerbaijan → Türkiye → Europe in one HVDC concept. So this work can be a useful base studying more in the future.

5.2 Summary of Main Findings

From simulated corridor model in MATLAB, several results were found. Central Asia has a clear renewable surplus of about +8 GW. Azerbaijan stays almost balanced with around -1 GW. Türkiye has a large deficit with -12 GW. And Europe has the biggest deficit with -50 GW. The 5 GW corridor works at full capacity under these conditions.

Additionally, the losses for HVDC lines also were simulated and calculated in model. By using common values from HVDC technical datasheets, results were obtained. The total losses are very low, around 0.31 GW over the three segments. So, this value proves that HVDC system very efficient for long distances. To sum up, the results support that the HVDC system is better choice for proposed interconnection corridor.

5.3 Contribution of This Thesis

The contribution of this study is the proposal of a new interconnection system and its possible benefits for the region. The idea of linking Central Asia → Azerbaijan → Türkiye → Europe offers advantages for every country involved. Until now, no previous study has combined these four regions into one HVDC corridor model. The MATLAB simulation also showed that even a simple 5 GW link can bring useful technical results and early benefits.

The benefits of the corridor are not limited only to energy transfer. The study also connects the idea to the national strategies of the countries, and shows how cooperation between them can become stronger. The corridor reduces renewable curtailment, supports system balancing, and can create new jobs in several sectors. In the end, the proposed system offers technical, economic, environmental and social benefits, which makes it a strong base for future planning.

5.4 Recommendations for Future Work

Since there is limited data and no real corridor in operation yet, this study had several restrictions. Future work can look at hourly or seasonal data instead of using only one steady-state case. A time-series simulation in MATLAB (8760 hours) would give more realistic results. With tools such as PowerFactory or PSSE, it would also be possible to add AC load-flow and stability analysis.

Corridor expansion scenarios can also be studied in more detail. This includes checking how a 10–15 GW system could work by 2040–2050. Additionally, Parallel HVDC lines or higher voltage levels (±600 kV or ±800 kV) can be part of future system. Scenarios where Europe starts to receive larger energy volumes will need more detailed modelling. When more data becomes available, future work can also calculate exact corridor costs, trading revenues, and possible payback periods.

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APPENDIX

Appendix A - MATLAB Code and Simulation Outputs

A.1 MATLAB Code

corridor_2030.m

/MATLAB Drive/corridor_2030.m

```
function corridor_2030()
    % corridor_2030.m
    % Simplified model of Europe-Caucasus-Asia corridor in 2030

    clear; clc;

    % ---- 1. Regional data (2030) ----
    regions = ["Central Asia","Azerbaijan","Turkiye","Europe"];

    Gen_RES = [30, 6, 20, 30];   % Renewable generation (GW)
    Load    = [22, 7, 32, 80];   % Demand (GW)

    Net = Gen_RES - Load;        % Surplus (+) or deficit (-)

    disp('Net balance (GW) in 2030:')
    for i = 1:length(regions)
        fprintf('%s: %.1f GW\n', regions(i), Net(i));
    end

    % ---- 2. HVDC corridor parameters ----
    C_CA_AZ = 5;   % Capacity (GW)
    C_AZ_TR = 5;
    C_TR_EU = 5;

    L_CA_AZ = 0.04;   % Loss fractions
    L_AZ_TR = 0.03;
    L_TR_EU = 0.03;

    % ---- 3. Power flow simulation ----

    % Central Asia -> Azerbaijan
    surplus_CA = max(Net(1),0);
    P_CA_AZ_sent = min(surplus_CA, C_CA_AZ);
    P_CA_AZ_recv = P_CA_AZ_sent * (1 - L_CA_AZ);

    % Azerbaijan updated balance
    Net_AZ_after = Net(2) + P_CA_AZ_recv;
    surplus_AZ = max(Net_AZ_after, 0);

    % Azerbaijan -> Turkiye
    P_AZ_TR_sent = min(surplus_AZ, C_AZ_TR);
    P_AZ_TR_recv = P_AZ_TR_sent * (1 - L_AZ_TR);

    % Turkiye updated balance
    Net_TR_after = Net(3) + P_AZ_TR_recv;
    surplus_TR = max(Net_TR_after, 0);

    % Turkiye -> Europe
    P_TR_EU_sent = min(surplus_TR, C_TR_EU);
    P_TR_EU_recv = P_TR_EU_sent * (1 - L_TR_EU);

    % ---- 4. Results ----
    Total_losses = (P_CA_AZ_sent - P_CA_AZ_recv) + ...
                   (P_AZ_TR_sent - P_AZ_TR_recv) + ...
                   (P_TR_EU_sent - P_TR_EU_recv);

    disp(' ')
    disp('=== 2030 Corridor Results ===')
    fprintf('Sent from Central Asia: %.2f GW\n', P_CA_AZ_sent);
    fprintf('Received in Europe:     %.2f GW\n', P_TR_EU_recv);
    fprintf('Total HVDC losses:      %.2f GW\n', Total_losses);
end
```

Figure A.1- MATLAB Code Used for the 2030 Simulation (Full Script)

Screenshot of the MATLAB script used to calculate the 5 GW power flow and approximate HVDC losses for the proposed corridor.

A.2 Command Window Output

```
Command Window

Net balance (GW) in 2030:
Central Asia: 8.0 GW
Azerbaijan: -1.0 GW
Turkiye: -12.0 GW
Europe: -50.0 GW
```

Figure A.2 - MATLAB Command Window Output for the 2030 Case

Screenshot of the MATLAB command window showing the main results: regional balances, corridor flows, and approximate HVDC losses.

Appendix B - Additional Figures and Corridor Maps

B.1 Supply - Demand Comparison Chart

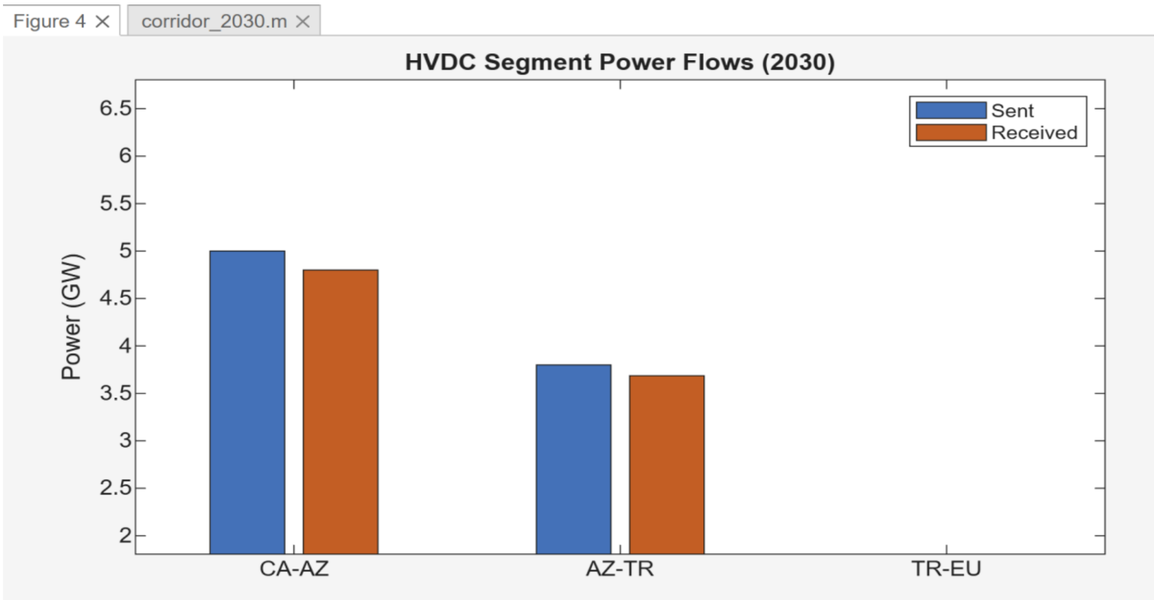

Figure B.1 - Renewable Generation and Demand Values for 2030

Bar chart comparing the assumed renewable generation and demand levels for the four regions in the 2030 case.

B.2 Corridor / Node Map

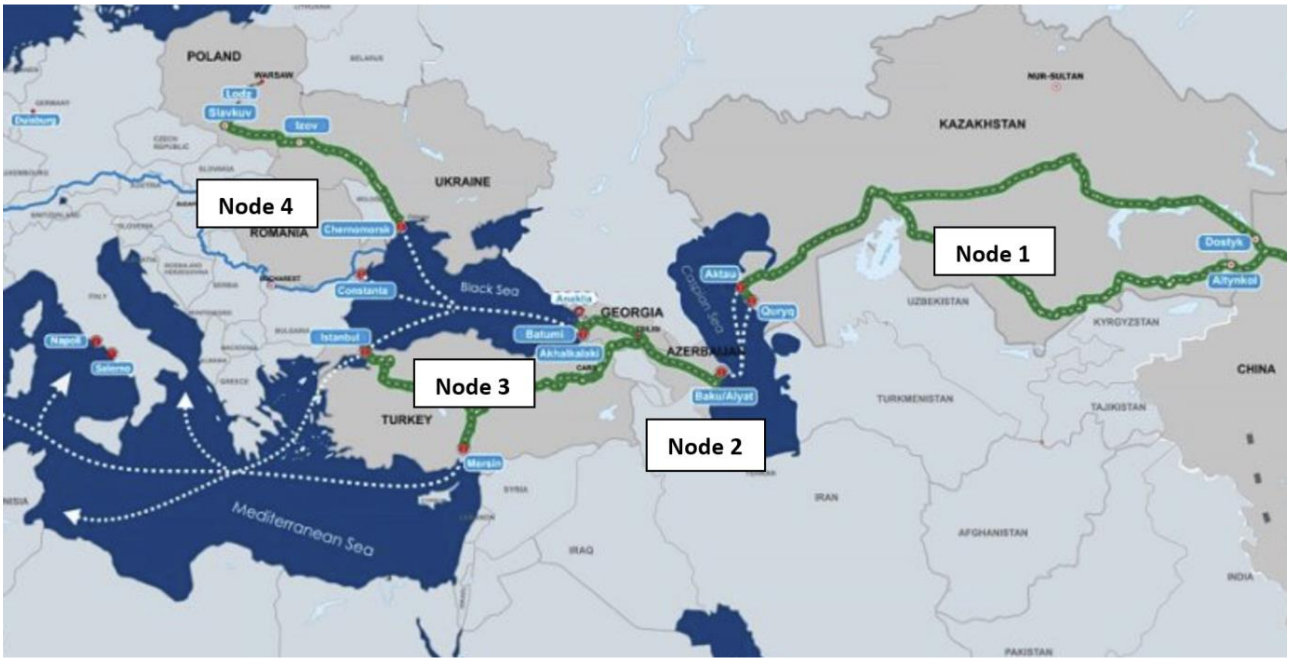

Figure B.2 - Proposed Four-Node Corridor Map

This figure shows the simplified layout of the proposed HVDC corridor connecting Central Asia, Azerbaijan, Türkiye and Europe. Each region is presented as a node in the model.