ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

COST ANALYSIS OF POTENTIAL WIND FARMS LOCATED AT DIFFERENT REGIONS IN CASPIAN SEA

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

HAZAR DENİZİNİN FARKLI BÖLGELERİNDE POTANSİYEL RÜZGAR ENERJİSİ ÇİFTLİKLERİNİN MALİYET HESABI ANALİZLERİ

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__To Mammad Amin Rasulzadeh,__

FOREWORD

First of all, I would like to say thanks to my advisor. Mrs. Deniz did not only help me with my thesis. She also did her best to foster my education in a good way. When I decided to give up, she always gave me a stimulus to continue my work

I can not forget my family's support. Without their help and prayings, I would never achieve my goal.

And finally, dear Farida, you taught me again that people can help each other without even knowing each other. Thank you for everything.

June 2020 Mahammad AHMADOV
(Offshore Engineer)

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ABBREVIATIONS

LCOE	: Levelized Cost of Energy
CF	: Capacity Factor
AEP	: Annual Energy Production
AEP_{fc}	: Annual Energy Production With Full Capacity
IRENA	: International Renewable Energy Agency
WACC	: Weighted Average Cost of Capital
USA	: United States of America
USD	: United States Dollar
PV	: Photovoltatics
CAPEX	: Capital Expenditures
OPEX	: Operation and Maintenance Expenditures
CBAR	: Central Bank of Azerbaijan Republic
OECD	: Organisation for Economic Co-operation and Development
N	: North
N.W	: North-West
S.E	: South-East

SYMBOLS

v	: Velocity of wind
A	: Area
A_1, A_2, A_3	: Areas of triangles in the square, regular hexagonal and regular octagonal layouts respectively
π	: Ratio of the circumference of a circle to its diameter
r	: Radius of the circle
D	: Diameter
t	: Time
ρ	: Air density
km	: Kilometer
m	: Meter
sm	: Santimeter
mm	: Millimeter
E	: Energy
GW	: Gigawatt
MW	: Megawatt
KW	: Kilowatt
s	: Second
h	: Height
h_{ref}	: Reference height
V	: Volt
rpm	: Revolutions per minute
z_0	: Roughness height
kcal	: Kilocalori
°C	: Celsius
Ω	: Ground resistance
C_p	: Power coefficient
P_w	: Total power contained in the wind resource
P_t	: Power extracted by the turbine

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COST ANALYSIS OF POTENTIAL WIND FARMS LOCATED AT DIFFERENT REGIONS IN CASPIAN SEA

SUMMARY

In this study, considering the Wind Energy Potential of the Caspian Sea, the Levelized Costs of Energy and Capacity Factors have been investigated for potential wind farms near the Absheron Peninsula, Olya site, Atyrau site, and finally for Sulak City's shoreline.

Before LCOE analysis, Simple Feasibility Study has been done for the Absheron Project.

Economical aspects of wind energy, today and the future of the wind power industry and its advantages and disadvantages have been investigated.

Capital Expenditures, Operation, and Maintenance Expenditures of the offshore wind farms have been checked.

Azerbaijan's wind energy potential has been checked. In the shoreline of the Absheron Peninsula, two different wind farms have been planned and designed and their Levelized Costs of Energy have been analyzed.

Besides, other regions of the Caspian Sea basin have been investigated and potential wind farms in certain areas have been designed and their LCOE and Capacity Factor results have been compared. All projects' layouts have been selected. Preliminary calculations have conducted for all projects.

For these projects, chosen regions' bathymetric maps, their hydrometrological features have been analyzed. Sea borders and shipping roads of the regions have been checked. Wind speeds of certain areas have been extrapolated by the help of power law.

In order to have better results, several wind turbine factories' products have been checked. Their power curves have been analyzed and the most efficient one has been chosen for this research.

Projects' Annual Energy Productions, their Capacity Factors, and finally, their LCOE have been calculated.

In the project Absheron, two different discount rates have been used and its results have been compared with the projects of the other regions of the Caspian Sea. Besides, the results of the Absheron Project have been compared to the Azerbaijani Government's energy policy.

Besides, the results of this research, have been compared to the results of the international offshore wind farms' average Capacity Factors and LCOE results.

Regions' metrological features and their impacts on the planned projects have been mentioned in the end.

To do that, researches and publications about the Caspian Sea basin have been checked and analyzed. To make a better comparison, their results have been compared to the results of this research.

HAZAR DENİZİNİN FARKLI BÖLGELERİNDE POTANSİYEL RÜZGAR ENERJİSİ ÇİFTLİKLERİNİN MALİYET HESABI ANALİZLERİ

ÖZET

Bu çalışmada, Hazar Denizi Havzasının rüzgar enerjisi potansiyeli göz önünde bulundurularak, Abşeron Yarımadasında, Olya bölgesi ve Atyrau bölgesinde, Sulak şehrinin deniz sahili açıklarında potansiyel, olası rüzgar çiftliklerinin Kapasite Faktörleri ve onların Seviyelendirilmiş Enerji Maliyetleri araştırılmıştır.

Seviyelendirilmiş Enerji Maliyeti hesabından önce, Abşeron Projesi için Basit Fizibilite Çalışması yapılmıştır.

Rüzgar enerjisinin ekonomik açıdan getirileri, rüzgar enerji santrallerinin bu günü ve yarını, bu sektörün avantajları ve dezavantajları incelenmiştir.

Açık Denizdeki rüzgar çiftliklerinin Sermaye Harcamaları, Operasyon ve Tamir Harcamaları incelenmiştir.

Azerbaycanın rüzgar enerjisi potansiyeli araştırılmış, Abşeron Yarımadasının iki farklı bölgesinde ayrı ayrı olmakla rüzgar çiftlikleri tasarlanmış ve onların Seviyelendirilmiş Elektrik Maliyeti hesapları irdelenmiştir.

Buna ek olarak, Hazar Denizi Havzasının farklı bölgeleri incelenmiş, adı geçen bölgelerde de potansiyel rüzgar çiftlikleri tasarlanmış ve onların Seviyelendirilmiş Enerji Maliyeti hesapları ve Kapasite Faktörleri mukayese edilmiştir. Bütün projelerin yerleşim düzeni seçilmiş, projelerin ön hesaplamaları yürütülmüştür.

Bu proje için seçili bölgelerin batimetrik haritaları, gemi taşımacılığının esas yolları, kıyı ülkelerin Hazar Denizi Havzası üzerindeki sınırları ve seçili arazilerin hidrometeorolojik özellikleri incelenmiştir. Seçili arazilerin rüzgar hızlarının ekstrapolasyonu Güç Yasası yardımı ile hayata geçirilmiştir.

Bu araştırma için birkaç farklı rüzgar türbini üreten firmaların rüzgar türbini ürünleri incelenmiş, bu türbinlerin güç eğrileri araştırılmış ve bölgenin şartlarına en uygun ve en verimli olan türbin seçilmiştir.

Planlanmış projelerin Yıllık Elektrik Enerjisi Üretimleri, çiftliklerin Kapasite Faktörleri ve son olarakta Seviyelendirilmiş Elektrik Maliyeti analiz edilmiştir.

Abşeron projesinde iki farklı İskonto Oranı İndirgenmiş Maliyet Hesabı için kullanılmış, çıkan sonuçlar Hazar Denizinde olası diğer projelerin Seviyelendirilmiş Enerji Maliyeti Hesaplarının sonuçları ile karşılaştırılmıştır. Buna ek olarak Abşeron Projesinin sonuçları Azerbaycan Hükümetinin elektrik enerjisinin satış maliyeti üzerine olan politikarı ile karşılaştırılmıştır.

İlaveten, bu çalışmadan çıkan sonuçlar, dünyadaki diğer açık denizlerde yapılmış rüzgar çiftliklerinin ortalama Kapasite Faktörleri ve Seviyelendirilmiş Enerji Maliyeti hesapları sonuçları ile kıyaslanmıştır.

Seçili bölgelerin meteorolojik özellikleri ve bu özelliklerin planlanlanmış projeler üzerinde yarattığı etkilere değinilmiştir.

Bu araştırmayı yürütebilmek için Hazar Denizi Havzasına ait çalışma örnekleri ve yayınlar kontrol edilmiş ve onların analizleri yapılmıştır.

Daha iyi sonuçlar elde ede bilmek için, bu tez araştırmasının sonuçları, diğer yayınların ve araştırmaların sonuçları ile de kıyaslanmıştır.

1. INTRODUCTION

Though the Caspian Sea Basin has got great importance for the energy industry, researches about its hydrometrological features, there are very few investigations. More than a hundred years, the Caspian Sea is the main resource for the oil and natural gas industry in the Caucasus and the middle of Euroasia. Nevertheless, as has been written before, investigations about its climate are very few. But, due to climate change and taking positions against it, the world has become more aware. New, green, and hurtless energy resources have been being investigated such as wind energy. Suitable regions are being checked. The Caspian Sea is one of the windy regions all over the world [1-2]. In this thesis work, the wind energy potential of the Caspian Sea Basin has been evaluated. To do that, some researches and publications about the Basin have been reviewed.

The most comprehensive researches about the Caspian Sea have been published by the "Azerbaijan National Academy of Science, H.A. Aliyev Institue of Geography". In 2003, the institute published a book named "Hydro Metrology of the Caspian Sea" [1]. Book gives comprehensive information about the Basin. In 2014, the institute published the "Hydrometeorological Atlas of the Caspian Sea" [2]. Atlas has got special maps about Basin's wind distribution, surface waters and air temperatures, solar radiation and, etc. In this thesis work, these two publications have been taken into consideration as the main resources.

Another research about the Basin has been done by R. Kerimov, Z. Ismailova and N. R. Rahmanov and named as "Modelling of Wind Power Producing in Caspian Sea Conditions"[3].

Also, there are some other investigations about the Basin too by foreign researches. Most of the works about the evaluation of the wind energy potential of the Caspian Sea have been done by Florin Onea and Eugen Rusu [4-7]. In 2012 they published an article named "Evaluation of the wind and wave energy along the Caspian Sea" [4]. In 2015, Onea, Rusu, and Alina Beatrice Raileanu have published their second article about the Basin which named as "Evaluation of the Wind Energy Potential in the Coastal Environment of Two Enclosed Seas" [5]. In this publication, they analyzed either Caspian and Black seas respectively. Another research of Onea and Rusu's about the Caspian Sea has been published in 2016 and named as "Efficiency Assessments for Some State of the Art Wind Turbines in the Coastal Environments of the Black and the Caspian Seas" [6]. The last investigation of Eugen Rusu and Florin Onea has been done and published in 2019 and named "An Assessment of Wind Energy Potential in the Caspian Sea" [7]. As it is clear, most of the researches have been conducted by Onea and Rusu. Meanwhile, they got different results every time. In this work, to make a better comparison, their last work's results have been compared to the results of this investigation.

For comprehensive research, other investigations about the Caspian Sea, such as the potential of wave energy in the Basin, have been checked too [8-11].

Besides, wind energy potential investigations and research for other regions rather than the Caspian Sea, have been used for this work too [12-20].

1.1 Purpose of Thesis

Offshore Wind Energy's fame increases day by day. Companies and countries are going deeper waters and further regions from the coast. Turbine manufacturers produce more efficient and durable turbines. Increased swept area, more efficient power-producing, strong structures make the turbines more appealing. Besides, climate change and its impact on economies of the world, make renewables inevitable [21].

The purpose of this research is, to evaluate the Caspian Sea Basin's wind energy potential. As the main target, the Absheron Peninsula's shorelines have been chosen. Another regions of the Basin have been analyzed too. The reason for this work is, to evaluate their Levelized Costs of Energy. Recently, coastal countries, especially Azerbaijan Republic, started to evaluate Basin's wind energy potential in its sea borders.

Hopefully, this work could be supportive of a better, peaceful, and green world.

2. ECONOMICAL ASPECTS OF WIND ENERGY

The importance of renewable energy increases day by day. Climate change, depletion of resources, and other reasons make renewable energy resources indispensable. Countries and private companies' investments in alternative energy resources making this market competitive. Meanwhile, countries invest in renewable energy, they also start to restrict conventional energy production such as coal firing based electricity production. For example, the United Kingdom will no longer invest in coal-fired power plants [22], Norges Bank Investment Management excludes 4 Canadian and some other non-Canadian oil companies because of the carbon emissions [23].

Not only oil, natural gas, and coal, also nuclear power will go down in history. Germany plans to shut down all its nuclear power stations by 2022 [24], and the Saudi Arabian private company ACWA Power is going to expand its footprint in Azerbaijan for wind energy production with 200 mln dollars. The capacity of the project has been planned for 240 MW [25].

As additional information, the coronavirus outbreak which started in China in 2019 and spread out all world, made an impact on the electricity production industry. Because of the outbreak, most of the countries decided to make lockdown and shut most of the industrial facilities down. Due to pandemic and global lockdown, electricity demand fell and it affected the whole energy industry. Interestingly, coal lost demand, wind, and solar energy, on the contrary, they gained popularity [26]. According to the Independent, the United Kingdom hit its record. The country did not use coal-fired electricity production at least for 18 days [27]. Of course, this is temporary. After the lockdown, demand for coal will rise again but it will never recover its previous prestige anymore. Also, this pandemic showed the society that the country can go on without coal.

In China, due to the pandemic, electricity demand declined by 7.8% during January and February. Nevertheless, electricity generation through renewables increased. Generation through wind increased by 1% and electricity generation through solar systems increased by 12% [26].

Fatih Birol, the International Energy Agency's executive director, said: "The plunge in demand for nearly all major fuels is staggering, especially for coal, oil, and gas. Only renewables are holding up during the previously unheard of slump in electricity use."[28]

These examples show that the market for renewables is becoming more beneficial and competitive. Here, the wind energy economy will be investigated. But, before the renewable energy market economy, it would be better to analyze the conventional energy economy. The diagram which is shown below gives brief information about the economical losses of conventional electricity production methods such as coal-fired power plants:

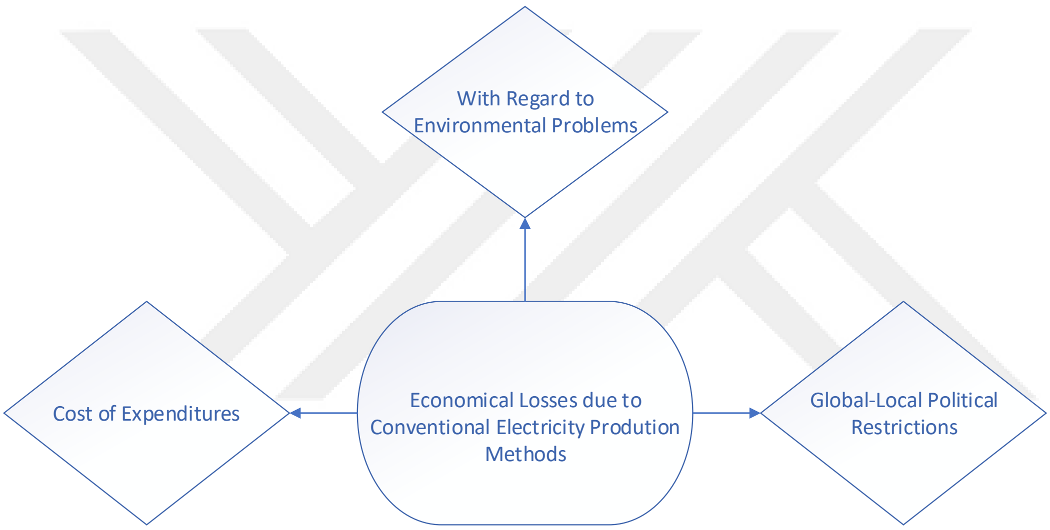

Figure 2.1 : Economical losses on conventional electricity production methods

Chapter number 2.1 is going to be about the disadvantages of conventional energy production in terms of either economic, environmental, or socio-political.

2.1 Disadvantages of Conventional Energy Production Methods

None can deny climate change disasters anymore. Australian bushfires, Venice's floods, storms, tornados, extreme cold, and hot weather problems are increasing day by day. Australian bushfires are going to cost more than 3 billion dollars [29]. And Venice lost more than 1.1 billion dollars due to flooding [30]. People can not breathe in New Delhi and Mongolia [31-32]. Furthermore, because of exploration and production drillings, seismic activity in the Caspian Sea becomes higher [1]. Oil, natural gas, and coal production cause soil contamination and it makes lands, which useful for agriculture, useless and dangerous for health and country economy. Oil and gas exploration and production activities in the Caspian Sea affect the Sturgeon fishes which the majority of them live in that sea all over the world [1]. Despite all conspiracy theories, the coronavirus outbreak is the result of destroying wild life's living borders which is the impact of conventional energy production and lifestyle. All these casualties are the results of conventional energy production methods. Because of climate change, many species are becoming extinct. This queue can be enlarged. But these examples are quite enough to explain climate change's effects on the world's economy and human health. The world's leading countries are not planning to invest in conventional coal power plants, quite the contrary, they are investing in renewables such as wind energy. Besides, the conventional energy market faces negative public opinion. A new coal-fired power plant with 600 MW capacity can cost 2 billion dollars [33]. A wind farm with the same capacity would cost even less than 1 billion.

2.2 Rising Trend of Wind Energy

This chapter is going to be about the wind energy market-economy. As it has been said, renewables' market enhancing itself day by day, year by year. Costs are decreasing and earnings, such as Capacity Factor, Annual Energy Production, etc. are increasing [21]. Either through economical or sociopolitical aspects, renewables, also wind energy becomes unavoidable. Features, such as no harm against nature, no fuel usage, and low expenditures, of wind energy, making it very feasible. According to the International Renewable Energy Agency (IRENA), the Levelized Cost of Energy values of wind energy gets down every year [21]. Governments are making so many opportunities for wind energy producers. Grants, tax exemption, governments' guarantees, etc. increase the potential of the wind energy market. Below, the diagram explains the benefits of wind energy:

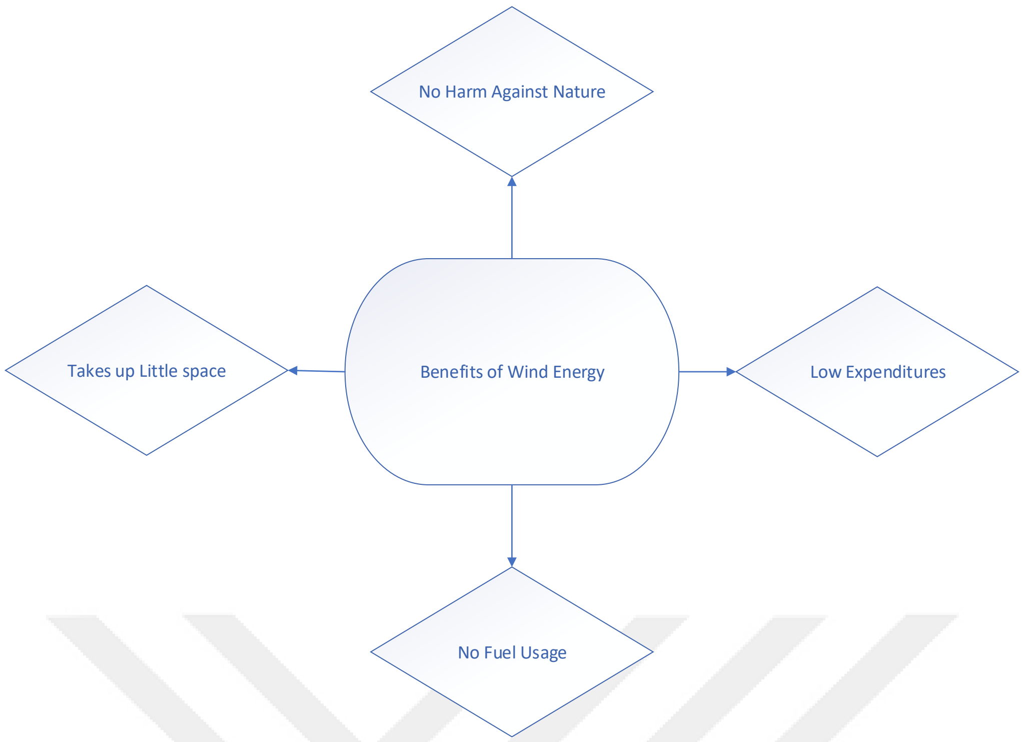

Figure 2.2 : Benefits of wind energy

Unfortunately, there are some disadvantages to wind energy too. The biggest and challenging drawback of this energy-producing method is, it depends on weather conditions. One of the challenges of this method is sound pollution due to turbine rotation. It can affect people's life quality. As has been written above, the most challenging problem of this green method is, it depends on the climate. If there is no wind, the turbine becomes useless. That is why, during the project phase, planning and project engineers must be very careful about calculations, estimation, and planning. For example, the article published July 1 in 2019, written by Florin Onea and Eugen Rusu [7], says that the highest winds in the Caspian sea flow in the northern part of the Caspian Sea. To build a wind farm, just higher wind speeds are not enough. It is a relevant need to have a stable wind distribution. This is true that the highest winds flow on the northern part but the distribution of them is not quite for building a wind farm in the northern part of the sea [1-2].

Above it is written that wind energy market enhancing. Today, most of the European countries trying to meet their electricity needs throughout the renewables also from wind energy. By the end of 2018, the world's total wind energy capacity became 591 GW [34]. But unfortunately, this number still does not subsume total electricity production and consumption of the world. In 2018, 5% of the electricity production came from the wind [35]. But this percentage is going to get higher and higher. The statistic of the installed capacity of wind turbine-capacity makes us sure to say this [21]. Below, the statistic can be seen:

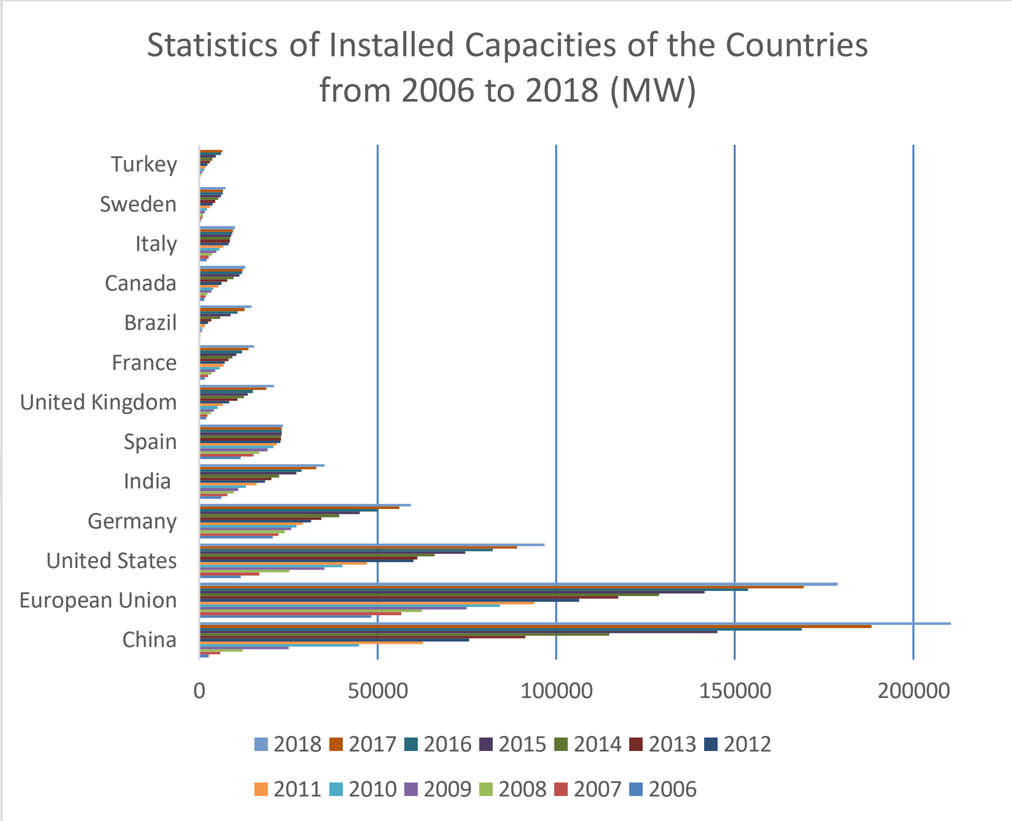

Figure 2.3 : Statistic of installed capacities of the countries

It can be easily seen that the way of the development of wind energy keeps growing trend. In 2017, Denmark met 43% of its electricity need throughout the wind. Though, in 2018 it dropped to 41%, in 2019 it hit its record by 47% [36].

2.3 Today and the Future of Wind Energy Industry

According to the International Renewable Energy Agency's (IRENA) 2018 report, solar PV and onshore wind farms are going to produce cheaper and clean energy than conventional ones. At the beginning of 2018, IRENA predicted that the weighted-average cost of wind energy will be 0,049 USD/kW in 2020. Just a year later, the value became lower than they predicted. Onshore wind energy prices dropped to 0,045 USD/kW. And it allows being confident about the trend of getting lower prices will be continued in the next coming years. Because of the new, innovative, and cheaper turbine technologies, the costs of onshore wind energy get down year by year. Higher hub heights, larger swept areas, and increased capacity factors drop down the prices and increase the efficiency of wind energy. Although, a sharp decrease in prices does not seem in the offshore industry, the costs of offshore wind energy decreasing too. In 2018, 4.5 GW of capacity has been installed and its average LCOE value is 0.127 USD/kW. The price difference between 2017 and 2018 was 1% lower. In the next coming years, the expectations of LCOE of offshore wind energy is 0.108 USD/kW [21].

2.3.1 Onshore wind energy market

In 2010, the global weighted-average of LCOE for onshore wind energy was 0.085 USD/kW. In 2018, it dropped to 0.056 USD/kW by 35%. Countries from all over the world are enhancing their onshore wind energy capacity. But two countries, China and the USA are leading them. The USA increased its onshore wind energy capacity to 6.8 GW. China's development is almost three times higher than its competitor. 18.5 GW. While years are passing, prices of wind turbines and their installation costs get down. The global weighted-average installation cost of the onshore wind turbine in 2017 was 1600 USD/kW. After a year the price became 1500 USD/kW. And decreasing continues. Besides, onshore turbine prices are also decreasing year by year. In 2018, the average onshore turbine price was changing between 790-900 USD/kW [21].

2.3.2 Offshore wind energy market

In the global offshore wind market, the total installed capacity of offshore wind energy became 4.5 GW in 2018. And the difference in price between 2017-2018 was 1%. The global weighted-average LCOE was 0.127 USD/kW. China leaded this trend. 40% of 4.5 GW has been installed by China. But the difference between 2010 and 2018 is more striking. It was 20% lower in 2018 compared by 2010. The price dropped from 0.159 to 0.127 USD/kW. And the difference in the costs of total installations between these years was 5%. Even though the process continues slowly but prices are decreasing. Getting farther deeper waters increases installation costs but stable wind conditions and higher wind speeds also new technologies counterbalancing it. Besides, the offshore wind industry still needs agile improvement. In Europe, between 2010 and 2018, the LCOE for offshore wind energy dropped from 0.156 to 0.134 USD/kW. The main reason for higher LCOE in Europe is they are going farther into the deeper waters and it increases the installation and maintenance costs. Global weighted installation costs also decreased in the offshore industry between 2010 and 2018. From 4572 USD/kW to 4353 USD/kW [21].

2.4 Wind Energy Potential of Azerbaijan

Azerbaijan also tries to increase its wind energy production. Approximately 90% of electricity generation, is being made by thermal power plants in Azerbaijan [37]. Thermal power stations are using oil, natural gas, biomass, and mostly coal as the main raw material, to produce electricity. Due to Azerbaijan's great potential for oil and natural gas reserves, the country mostly uses oil and natural gas resources for electricity generation. It gives either electricity or heating for getting homes warm. The first thermal power station was built in 1962 at Shirvan city in Azerbaijan [38].

As it has been said before, thermal power stations are mostly using coal as a main raw material. The world's main raw material rate shows that the majority belongs to coal. 60% of the main raw material part belongs to coal, 28% of part belongs to natural gas, 12% of part belongs to fuel-oil (diesel). But Azerbaijan does not use solid materials for its thermal power stations. 80-87% of part belongs to natural gas, 13-20% of part belongs to fuel-oil [39].

Azerbaijan's geographical circumstance is quite complicated. 60% of the country is mountainous. Greater Caucasus and Lesser Caucasus mountain ranges are making barriers and these barriers do not let the wind to get into the country. The Greater Caucasus mountain range is located in the northern part of Azerbaijan and the Lesser Caucasus range is located in the western part of Azerbaijan. That is why the annual wind speed of the Zagatala region is 1,2 m/s, and the annual wind speed of the Absheron Peninsula is 8,6 m/s. According to recent investigations, the best regions for wind energy is the shoreline of Azerbaijan. From the northern borders to Kura Island. The average wind speed of these areas is more than 4 m/s. This potential gets the highest rate at the Absheron Peninsula and its shoreline. In 1999, TOMEN Company

(Japan) made some experiments with 2 towers. The first one's height was 30 meters and the other one was 40 meters. After the investigations company got that annual wind speed of region, which located in Gobustan, is changing between 7,9-8,1 m/s. For now, just a little potential of the area is being used in Gobustan with 2,7 MW/h capacity but the government planned to increase its capacity potential to 30 MW/h [40].

Below inside the table, it can be seen the major wind power stations of Azerbaijan [41]:

Table 2.1 : Main wind power stations of Azerbaijan and their capacities

Wind Farm	Capacity (MW)
Gobustan	2.7
Yeni Yashma-1	50
Yeni Yashma-2	1.7
Sitalchay	8
Hokmeli	3.6

Figure 2.4 : Yeni Yashma wind power station

Also, the energy potential of the Caspian Sea is more than the onshore potential. Especially the region nearby shoreline has huge energy potential. That is why, for the next coming years, Azerbaijan plans to build offshore wind structures in the Caspian Sea. The Wind Island – 1, is the new project for wind energy in the Caspian Sea. Its capacity will be 200 MW/h [41].

Figure 2.5 : Wind Island – 1

To be realistic, this project has got so many unanswered questions. Because of being inexperienced, project makers made it so utopic. But still, it gives hope that the country tries to increase its wind energy potential. Either onshore or offshore. Also, the government guarantees that electricity tariffs for wind energy will be competitive for companies to improve their capacities. In Azerbaijan, the price of electricity changes between 0.041 – 0.065 USD/kW. From 0 to 300 kW, the price of the electricity which is selling to the citizens is 0.042 USD/kW. Above it, the calculation is being held with 0.065 USD/kW. Azerbaijanian government promises to wind energy producers that the country will buy their electricity with 0.0325 USD/kW price [42].

Another pivotal agreement on wind energy has been signed by the government of Azerbaijan and the Saudi Arabian company of ACWA Power in 2020 in January. The agreement has been done on wind energy production. The capacity has been planned for 240 MW and the investment planned to be 200 million USD. Due to coronavirus pandemic, the process became more longer but works still go on [25].

Besides, the Ministry of Energy of Azerbaijan Republic started to research the wind energy potential of the Caspian Sea. In the next coming years, new projects in the sea will be constructed [43].

"The Stone Age didn't end for lack of stone, and the oil age will end long before the world runs out of oil.." (Ahmad Zaki Yamani, former Minister of Oil of Saudi Arabia for more than twenty years)

3. METHODOLOGY

It has been told that, before building a wind farm, calculations must be held very carefully. Wind speed and its distribution in a year, turbine's height and its features such as Power Curve and Annual Energy Production, Capacity Factor of wind turbine and entire farms, Capital Expenditures (CAPEX) and Operation and Maintenance Expenditures (OPEX) and finally, Levelized Cost of Energy (LCOE) must be calculated very attentively [44-46]. In the next coming chapters, each feature will be mentioned.

Before the Levelized Cost of Energy Analysis, there is another simple feasibility study for analyzing the wind energy efficiency of certain regions.

3.1 Simple Feasibility Analysis

To estimate the probable kinetic energy that can be taken from the turbine, simple but meanwhile useful method should be taken into consideration. Before the project and feasibility analysis, this method is being used.

Conjectural kinetic energy amount is being calculated by the help of certain formula [47]:

$$E=1/2*\rho*v^3*A \tag{3.1}$$

Where ρ is the air density (1.225 kg/m^3), v is the velocity of the wind, A is the rotor swept area (A= π r ^{2}). Also, there is another component of the formula that has a relevant role. It is Power Coefficient. According to the Massachusetts Institute of Technology, the power coefficient is: "Power Coefficient, Cp, is the ratio of power extracted by the turbine to the total contained in the wind resource Cp = P_T/P_W". And according to Albert Betz, only 59% of the energy can be taken from the wind. After the adding of power coefficient, the formula becomes [47]:

$$E=1/2*\rho*v^3*A*C_p \tag{3.2}$$

Or:

$$E=1/2*\rho*v^3*A*0.59 \tag{3.3}$$

In chapter **5.1**, a simple feasibility study will be held before the real Levelized Cost of Energy Analysis.

3.2 Power Curve of a Turbine and Annual Energy Production (AEP)

Danish Wind Industry Association expresses the power curve of the turbines with this explanation: "The power curve of a wind turbine is a graph that indicates how large the electrical power output will be for the turbine at different wind speeds" [48].

All turbine manufacturers share their turbines' power curve information. The power curve gives a chance to calculate the probable amount of kinetic energy that can be extracted from the wind. Each turbine has its Cut-in Wind Speed where the turbine starts to produce electricity. This is the beginning speed of production. As the wind speed increases, the amount of kinetic energy follows it too. When the turbine's capacity gets its peak point, the turbine starts to generate the amount of power which is being called Rated Power. And the appropriate wind speed is being called Rated Wind Speed. After this limit, the turbine does not produce more energy but production continues until its predetermined wind speed which called Cut-out Wind Spee. When the turbine hits that point, the rotation of the turbine stops by manually or automatically. From this point, production could be very dangerous and the company waits until wind speed gets back to the normal – productive limit [44-46].

But meanwhile, the power curve should not be the only measurement for research. There are certain things (for example air density) that can have a pivotal role in generating electricity. Maybe the wind speed of a certain area is quite acceptable but the air density is lower than the turbine needs. These kinds of circumstances are having a bad impact on electricity production. Mostly this situation happens in the mountainous regions. Although strong winds blow mostly on mountains, the air density is usually challenging against the wind industry.

With the help of Power Curves, approximate Annual Energy Production (AEP) can be easily calculated and it is very helpful and relevant to analyze the wind farm's efficiency and feasibility study.

The AEP can be calculated by the turbine's rated power limit. With the help of the power curve, the amount of kinetic energy that is appropriated by the wind speed of the chosen site can be calculated. For example, the turbine's rated power is 1.2 MW and Rated Wind Speed is 8 m/s. It means that the turbine is going to produce approximately 10.5 GW in a year and the AEP of the turbine with 8 m/s wind speed is

10.5 GW [48]. But this is almost impossible. Because wind speed is not being stable all the time. Sometimes it gets down, but sometimes, quite the contrary, it gets high. That is why the distribution of the wind speed must be evaluated.

In this research, due to lack of complete data, wind speed has been conjectured stable and 250 days of the year wind blows all the time. The wind speed data and features of the regions have been taken from the book [1] and the atlas [2].

3.3 Capacity Factor

According to the Danish Wind Industry Association, an explanation of the Capacity Factor is: "Capacity factor means its actual annual energy output divided by the theoretical maximum output if the machine were running at its rated (maximum) power during all of the 8766 hours of the year" [48].

One of the main components of wind energy is the capacity factor. The capacity factor depends on either the annual wind speed of the site or the power generation capacity of the turbine. With the help of these two elements, feasibility study, and LCOE Analysis being calculated. To calculate the capacity factor, we are using a special formula:

$$CF = \frac{AEP}{AEP_{fc}} \tag{3.4}$$

Where AEP is the Annual Energy Production of the wind turbine with appropriated wind speed distribution, AEPfc is the Annual Energy Production of the turbine with rated speed and power or simply AEP with the full capacity of the turbine. For example, there is a turbine with 1.5 MW capacity and annual average wind speed is 7 m/s and appropriated AEP is 1.1 MW. Then the Capacity Factor:

$$CF = \frac{AEP}{AEP_{fc}} = 1.1 * 24 * 365/1.5x24 * 365 = 0.73\ (73\%) \tag{3.5}$$

The result means that our capacity factor is 73%. It is quite big but, meanwhile, unfortunately, it is also hard to get. For now, this result seems impossible but the future of the turbine technology gives hope to believe that it is impossible just for now. According to the IRENA, for onshore and offshore turbines, the Capacity Factors changing between 30-50% [21].

Figure 3.1 : Capacity Factor for commissioned offshore wind projects and global weighted average, 2000-2018 (IRENA)

3.4 Capital, Operational and Maintenance Expenditures

According to The National Renewable Energy Laboratory (NREL), the meaning of Capital Expenditure is: "Capital expenditures (CAPEX) are expenditures required to achieve commercial operation in a given year" [49].

NREL divides these capital expenditures into the three main branches. The first one is the turbine itself. The second component is the Balance of System. It includes a turbine and its substructures' installation, site preparation such as making access roads, buildings for operations and maintenance, etc. electrical supplies such as tranformators, switchgear, etc, and finally project-related indirect costs. The third and the last component of the triple is financial costs such as owners' costs, onsite electrical equipment, etc [49].

"An operating expense, operating expenditure, operational expense, operational expenditure, or simply OPEX is an ongoing cost for running a product, business, or system" [50].

OPEX may include accounting expenses, license fees, maintenance and repairs, such as snow removal, trash removal, janitorial service, pest control, and lawn care, etc.

advertising, office expenses, supplies, attorney fees, and legal fees, utilities, such as telephone, insurance, property management, including a resident manager, property taxes, travel, and vehicle expenses, etc. leasing commissions, salary and wages [50].

Before building a wind farm, during the planning phase, Capital Expenditures (CAPEX) and Operational and Maintenance Expenditures (OPEX) must be evaluated. Companies are not investing in these kinds of projects just because of to produce electricity, they also do it to get benefits. That is why CAPEX and OPEX calculations have got a huge impact on projects. These two components also affect the LCOE (Levelized Cost of Energy) value. In the beginning, CAPEX and OPEX values of offshore wind energy were very high. But after the new technologies, these values also follow a decreasing trend. Companies are working on their technologies, to get down their turbines' failure probabilities [21].

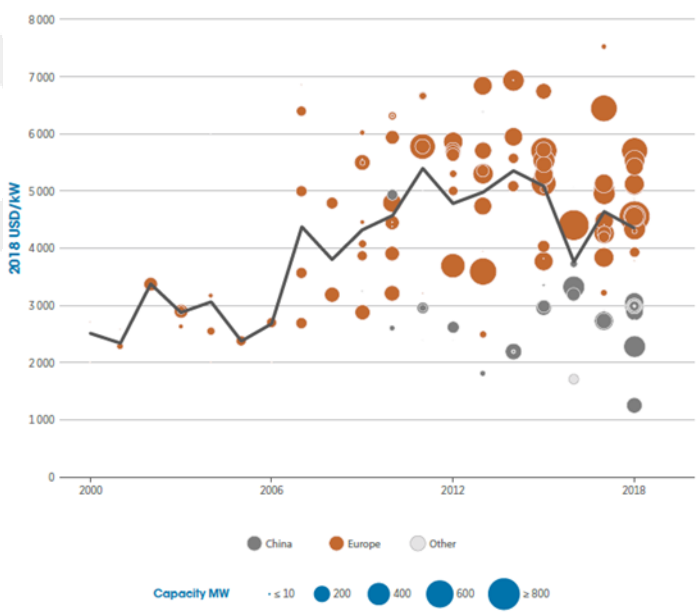

Figure 3.2 : Total installed costs for commissioned offshore wind projects and global weighted average, 2000-2018 (IRENA)

They are making stronger and more efficient turbines. That is why, OPEX values, such as maintenance expenditures are decreasing. As the request for wind energy expands, companies are building more efficient and cheaper turbines. They enlarge their turbines' capacity factors, meanwhile, they decrease the prices of turbines. According to the International Renewable Energy Agency, average wind turbine prices in China are approximately 500 USD/kW and 855 USD/kW in elsewhere. Total installation values for offshore projects were 2500 USD/kW at the beginning of 2000, after ten years, during 2011-2014, it became 5400 USD/kW. Because companies started to build new farms in deeper waters. And during 2018, this value became 4350 USD/kW. All these values have been taken from the 2018 report of IRENA [21].

4. OFFSHORE WIND FARM DESIGN IN THE SHORELINES OF ABSHERON PENINSULA

In this chapter, the wind farm design of the two chosen areas will be investigated. The first area is located nearby Sumgait city in the Northern part of the Absheron Peninsula. And the second one is located in nearby Pirallahi Island, in the Eastern part of the peninsula. Each area will be investigated separately. Areas' salinity, ice motion, waves, average yearly air temperature, humidity, precipitation, yearly average wind speeds, ship traffics, water depths, distances from the shoreline, foundations of the turbines, layouts of the farms, etc. features will be mentioned.

4.1 Common Features of the Sumgait Site and the Pirallahi Island Site

Although both sides have been checked separately, there are some similar characteristic features between two sites.

In the middle of the Caspian Sea, icing is being seen very rarely. During only extreme winters, ice motions can be seen in this part of the sea. Icing generally shows itself during the December-January period but sometimes, it can bee seen in February too. After the first part of February, defrosting starts [1-2].

Western shores of the Middle Caspian Sea, most especially the Absheron Peninsula's shoreline has got so little precipitation quantity during the year. The amount of precipitation is only 220 mm/year [1-2].

Offshore wind turbine's foundation is another main component of projects. According to the Caspian Sea's bathymetric map which has been shown in Appendix A, both sites' water depths are not exceeding 30 meters. There are some foundation types for offshore wind turbines. These types changes in accordance with water depth [51]. Next figure shows some of them:

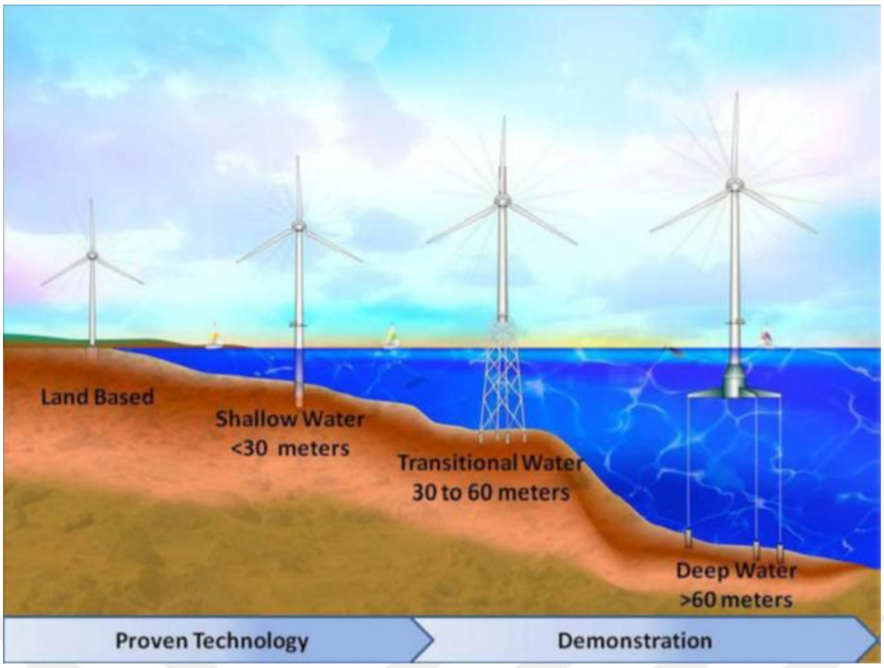

Figure 4.1 : Offshore wind turbine foundations

As it has been written that water depths do not exceed 30 meters, that is why, in both sites, the monopile wind turbine foundation is going to be used for this project.

Sea bed inclination in both sites does not exceed 10° (Appendix K). The tallest waves are propagating in the Western part of the Middle Caspian Sea, in the shoreline of the Absheron Peninsula. During storms, the height of the waves can reach 7.5-8 meters. In the extreme storms, the wave height can reach 9-10 meter. But yearly average wave height in the sea is 3 meters.

In the middle part, the lowest water surface temperature occurs in February with 5-6° C. The highest temperature occurs in August with 25-26° C.

During the year, winds from the north are dominant on the sea. The probability of the north winds is 41% during a year. But in the summer, it becomes 48.7%. The southern winds' probability is 35,9% [1-2].

Sea borders with other countries can also make some troubles for the wind farm designers.

Though border conflict among the coastal countries continues, for now, simulation map shows that there will not be border problem due to wind farm in the shorelines of Absheron [52]:

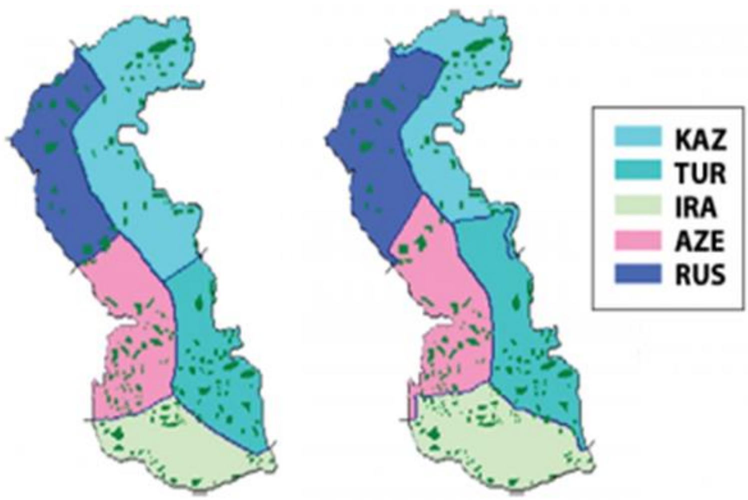

Figure 4.2 : Sea borders of the Caspian Sea

4.1.1 Features of the chosen wind turbine

The wind speeds of both sites are similar. Even their average yearly values are the same [1-2]. The turbine which is going to be used for this work is going to be the same for both sites too. The turbine's name is GE 87/1500 which has been built by GOLDWIND AMERICAS [53].

The turbine designed for onshore projects but it can be also used offshore too. The differences between onshore and offshore turbines are not very big. Even until recently, they were not separated. Below the turbine's power curve is shared:

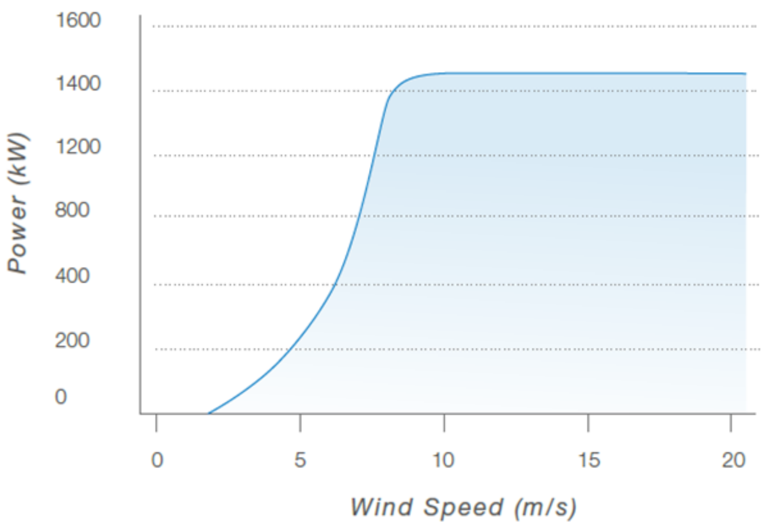

Figure 4.3 : The power curve of the GE 87/1500

Inside the table, more information can be found about the turbine:

Table 4.1 : Technical data of GE 87/1500 wind turbine

Definition	Feature	Definition	Feature
Rated Power (kW)	1500	Converter Type	Full Power Conversion
Cut-in Wind Speed (m/s)	3	Rated Output Voltage	620/690
Rated Wind Speed (m/s)	9.9	Aerodynamic Brake System	Blade Pitch Triple-Redundant
Cut-out Wind Speed(m/s)	22	Mechanical Brake System	Hydraulic Drive/Four Planetary Stages for Speed Reduction
Designed Service Life (year)	20	Yaw System-Type/Design	Motor Drive/Four Planetary Stages for Speed Reduction
Operating Temperature Range (°C)	-30°C to +40°C	Yaw Brake	Hydraulic Brake
Survival Temperature Range (°C)	-40°C to +50°C	Control System and Lightning Protection-Type	PLC Control System
Nominated Rotor Diameter (m)	87	Lightning Protection Standart	Complying with IEC 61400-24:2010 and IEC 62305:2006, and in conformance with GL Standards for the Certification of Wind Turbines
Rotor Swept Area (m^2)	5909	Ground Resistance (Ω)	≤4
Generator Type	Permanent Magnet Synchronous Generator (PMSG)	Tower Type	Conical Steel Tower
Rated Voltage (V)	720	Max Hub Height (m)	85
Rated Rotation Speed	16.6/17.3 (rpm)	Min Hub Height (m)	75

4.1.2 Layouts of the wind farms in the shoreline of Absheron Peninsula

Another important element of the wind farm project is the project's layout. To gain the maximum kinetic energy from the wind, turbines should not intercept each other. To make this circumstance, during the planning phase, designers should pay more attention to layouts.

There are three types of layouts. Square layout, hexagonal layout, and the last one, the octagonal layout [54]:

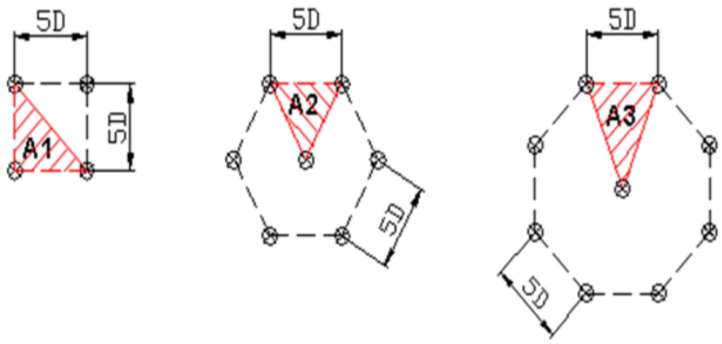

Figure 4.4 : Types of layouts

Where A1, A2**,** and A3 are the areas of triangles in the square, regular hexagonal and regular octagonal layouts respectively and D is the diameter of the wind turbine's rotor. Obviously, it can be seen that the distance between 2 turbines should not be less than 5*D**.** In this project, the square layout type will be used for both sides and the calculations will be held in the next coming pages. To make the wind turbines' adaptation to this type, a special formula is being used which is shown below:

$$A = \frac{1}{2} * 25 * D^2 \tag{4.1}$$

. In both sites, 360, seperately180 wind turbines will be installed and LCOE Analysis will be calculated on these numbers for Absheron projects. Like a bird's eye view, both farms will be rectangular. Taller part of the farm will subsume 30 turbines and the shorter part will consist of 6 turbines.

4.2 Sumgait Project

As has been written before, the first area is located in the Northern part of the Absheron Peninsula near Sumgait city [55].

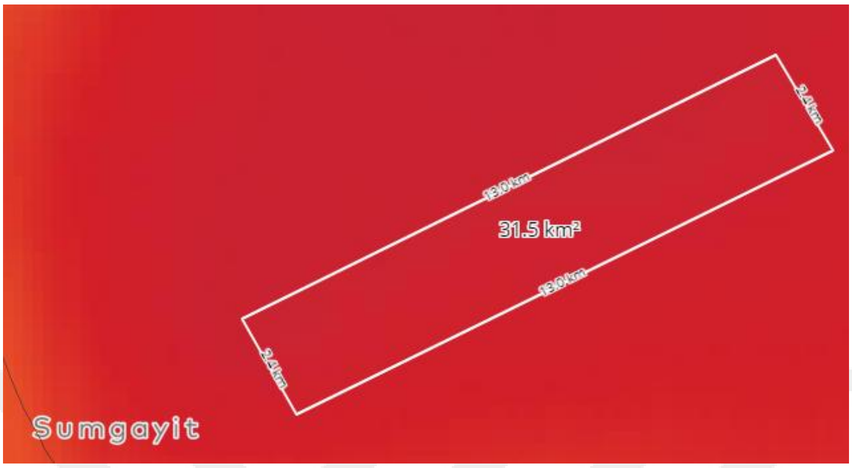

Figure 4.5 : Sumgait project

The distance between the nearest shoreline and the area is 10.68 km and the distance between the Sumgait city and the area is 16.10 km. The planned total occupied area is 31.7 km^2 but after the calculations, the occupied total area can be changed [56].

Figure 4.6 : Distances between the project and the shorelines

During the planning phase of an offshore wind farm, marine traffic must be also taken into consideration. According to the marine traffic map [57], there is no problem with the Northern Project. In Eastern Project, shipping roads across the chosen point but the density of the traffic is not that much and it is being considered that this farm will not be harmful to the shipping traffics. The map shows the first area's shipping traffic density:

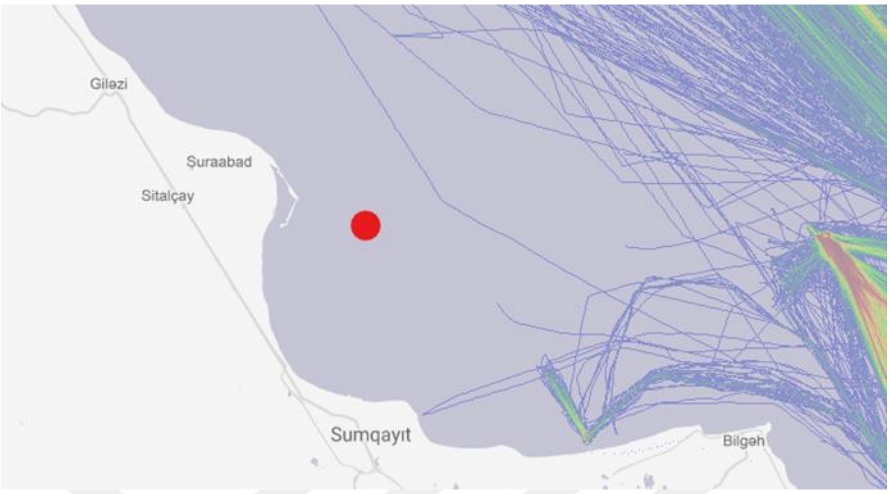

Figure 4.7 : Shipping roads (The red dot represents the wind farm)

Below, the table gives more specific information about the area [1-2]:

Table 4.2 : Additional information about the Sumgait Site

Average surface water's temperature	Salinity percentage of the surface waters	Average weather temperature	Yearly average absolute humidity	Yearly average relative humidity	Yearly average cloudiness	Yearly average heat of evaporation
14.1° C/year	11.9 %/year	13.7° C/year	10.5	80.18%	5.4	50.6 $kcal/sm^2$

Below, it can be seen the wind data of the Northern Part of the Peninsula. The wind speed data has been taken from the book and from the atlas [1-2]. The wind speed parameters conjectured at 10-meter height. All calculations will be investigated on 10-meter height's wind speed.. Inside the next table, monthly and average wind speed of the Northern Part of the Absheron Peninsula's shoreline nearby Sumgait City at 10-meter height has been shared:

Table 4.3 : Monthly wind speeds (Average wind speed of the year at 10 m height is 6.4 m/s)

Month	Wind Speed
January	6.9 m/s
February	6.5 m/s
March	6.6 m/s
April	6.5 m/s
May	5.9 m/s
June	5.3 m/s
July	5.6 m/s
August	6.3 m/s
September	6.5 m/s
October	6.9m/s
November	6.9 m/s
December	6.7 m/s

The chosen wind turbine is "Goldwind GW 87/1500". Here the wind speed of the area will be extrapolated from 10 meters to 85 meters. The turbine's maximum hub height is 85 meters. To extrapolate our wind speed, the special formula is being used which has been written below [51]:

$$V = V(h_{ref}) \times \left(\frac{ln\left(\frac{h}{z_0}\right)}{ln\left(\frac{h_{ref}}{z_0}\right)} \right) \tag{4.2}$$

Where h_{ref} is the reference height (10 meters), Z_0 is the roughness height. Most commonly Z_0 is changing between 0.03-0.25 m at land. For the sea environment, Z_0 is approximately 0.0002 m.

After the extrapolation process, the wind speeds at 85-meter height are becoming higher. The results can be seen in the next table:

Table 4.4 : Monthly wind speeds at 85-meter height (yearly average wind speed is 7.68 m/s)

Month	Wind Speed
January	8.26 m/s
February	7.78 m/s
March	7.9 m/s
April	7.78 m/s
May	7.06 m/s
June	6.34 m/s
July	6.34 m/s
August	7.54 m/s
September	7.78 m/s
October	8.26 m/s
November	8.26 m/s
December	8.02 m/s

Below, the picture shows the wind farm and the yearly main wind directions. The tallest arrow represents north-west winds which have got high probabilityn [1-2]:

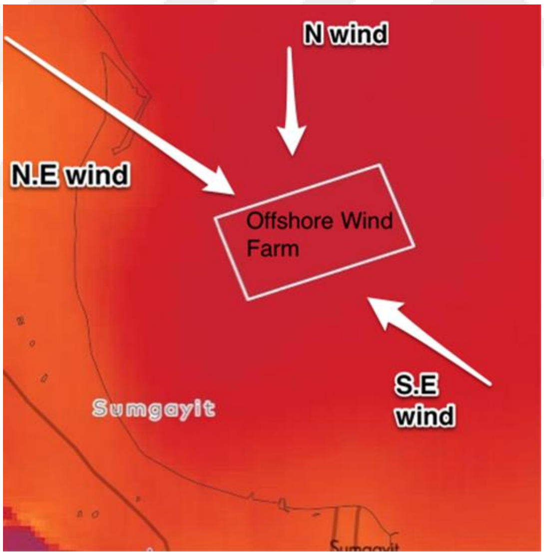

Figure 4.8 : Dominant wind directions of the site

4.3 Pirallahi Island Project

The second area is located on the shoreline of the Absheron Peninsula too, nearby Pirallahi Island in the North-East part of the Peninsula [55].

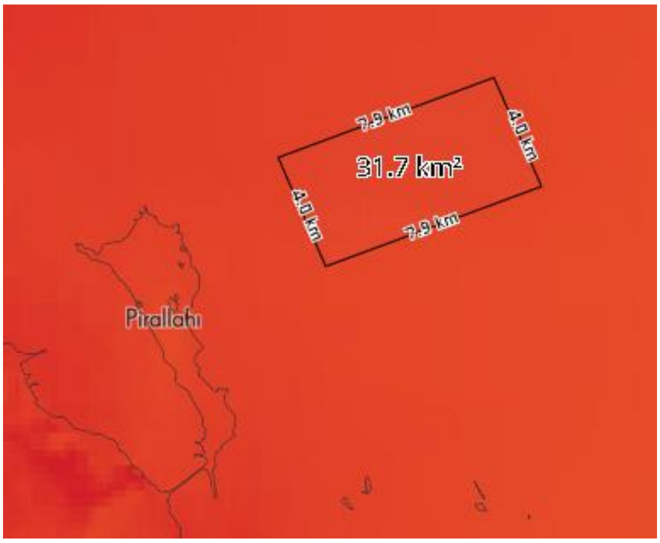

Figure 4.9 : Pirallahi project

The distance between the island and the farm is 4.45 km and the distance between the farm and mainland Azerbaijan is 11.89 km [56].

Figure 4.10 : Distances between the farm and the shorelines

Next, the map shows the shipping roads located on the farm's location. It can be seen that our wind farm located on the position which does not have a big importance for shipping. The impact on shipping must be very low:

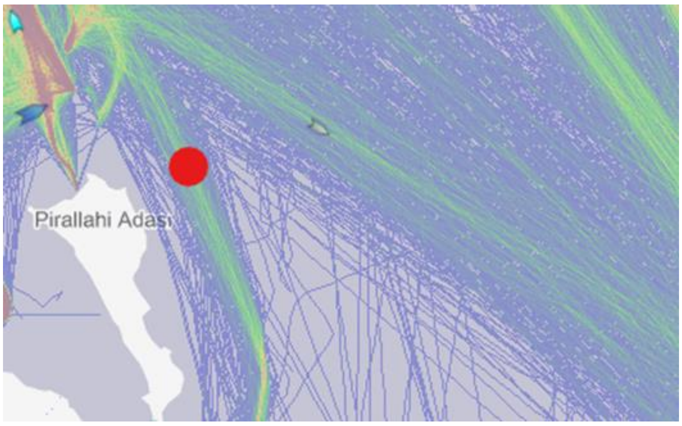

Figure 4.11: Shipping roads (The red dot represents wind farm)

In the next table, some additional but meanwhile substantial information can be seen about the North East Project. These pieces of information are very important. During the planning phase, they must be taken into consideration [1-2]:

Table 4.5 : Additional information about the Pirallahi Island Site

Average surface water's temperature	Salinity percentage of the surface waters	Average weather temperature	Yearly average absolute humidity	Yearly average relative humidity	Yearly average cloudiness	Yearly average heat of evaporation
14.3° C/year	12.59 %/year	14.3° C/year	10.8	82.02%	5.1	48.1 kcal/sm^2

The next coming pages are going to be about the wind speeds of the second project. In this area, the wind speeds have been extrapolated from 10 meters to 85 meters too.

Table 4.6 : Monthly wind speeds (Average wind speed of the year at 10 m height is 6.4 m/s)

Month	Wind Speed
January	7 m/s
February	6.8 m/s
March	6.7 m/s
April	5.7 m/s
May	5.3 m/s
June	5.8 m/s
July	6.4 m/s
August	6.2 m/s
September	6.8 m/s
October	6.7 m/s
November	6.8 m/s
December	6.8 m/s

As can be seen, almost all wind speeds, also average yearly wind speeds are similar to the first area. Here, the power-law also used to extrapolate wind speeds. Below, extrapolated wind speed result has been shared (4.2):

Table 4.7 : Monthly wind speeds at 85-meter height (yearly average wind speed is 7.68 m/s)

Month	Wind Speed
January	8.38 m/s
February	8.14 m/s
March	8.02 m/s
April	6.82 m/s
May	6.34 m/s
June	6.94 m/s
July	7.66 m/s
August	7.42 m/s
September	8.14 m/s
October	8.02 m/s
November	8.14 m/s
December	8.14 m/s

Next figure demonstrates the main wind directions on wind farm [1-2]:

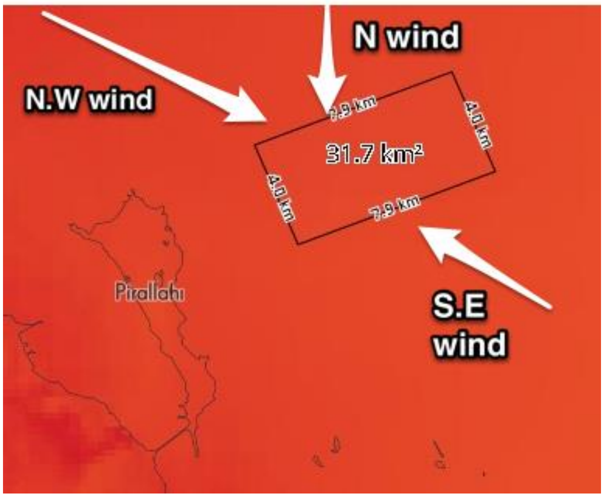

Figure 4.12: Dominant wind directions of the site

5. LEVELIZED COST OF ENERGY

What is LCOE? Most simply, the price of electricity per kW or MW which the farm is going to sell. To gain back all the investments and get benefits, the LCOE calculation gives the minimum price result. The LCOE calculation decides the price of electricity. Although, there are some examples and formulas to calculate it, the best way for the renewable energy sector is, IRENA's LCOE formula [21]. International Renewable Energy Agency developed more simple and the finest formula which it has been using by companies:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (5.1)$$

Where:

LCOE: The average lifetime levelized cost of electricity generation (USD/kW);

I_t: investment expenditures in the year **t** (USD);

M_t: Operations and maintenance expenditures in the year **t** (USD);

F_t: fuel expenditures in the year **t** (USD) (for the renewables the value of F_t is zero);

E_t: Electricity generation in the year **t** (kW/year);

r: Discount rate (%);

n: Economic life of the system (year);

t: number of years.

The table which has been taken from the IRENA's 2018 report, is about the average LCOE values for renewable energy resources also for onshore and offshore wind energy from all over the world [21]:

Table 5.1 : Global electricity costs in 2018 (IRENA)

Renewable Energy Type	Global Weighted Average Cost of Electricity (USD/kW) 2018	Cost of Electricity: 5th and 95th Percentiles (USD/kW) 2018	Change in the Cost of Electricity 2017-2018
Bioenergy	0.062	0.048-0.243	-14%
Geothermal	0.072	0.060-0.143	-1%
Hydro	0.047	0.30-0.136	-11%
Solar Photovoltatics	0.085	0.058-0.219	-13%
Concentrating Solar Power	0.185	0.109-0.272	-26%
Offshore Wind	0.127	0.102-0.198	-1%
Onshore Wind	0.056	0.044-0.100	-13%

5.1 Preliminary Calculations

In this part, some relevant calculations will be held. These calculations have a huge impact on LCOE Analysis. Before LCOE Analysis, Annual Energy Production, Capacity Factor will be investigated, CAPEX, and OPEX data, which has been taken from the IRENA, will be taken into consideration. After all, LCOE Analysis will be evaluated in the next coming pages. The results will be compared with IRENA's 2018 annual report's results.

First of all, AEP should be calculated. Before the investigation, because of both annual average wind speeds are the same in both sites and the same wind turbine and foundation are going to be used for both projects, calculations will be held as one.

Now the calculation of Annual Energy Production and Capacity Factor can be done with the help of taking into consideration wind data and wind turbine technical parameters. It has been calculated that the wind speed at 85-meter height is 7.68 m/s in both sites. According to the wind turbine's power curve, 1200 kW/h (1.2 MW/h) kinetic energy can be extracted from the wind with 7.68 m/s wind speed. Considering "Hydrometeorology of the Caspian Sea" [1] book and "Hydrometrological Atlas of the Caspian Sea" [2], 250 days of the year in the Caspian sea are windy. It has been conjectured that wind speed is stable all the time and it does not change. Now the calculation of the Annual Energy Production can be evaluated:

$$\text{AEP} = 1.2 \times 24 \times 250 = 7200\ MW \quad (5.2)$$

Where 1.2 MW is hourly kinetic energy from the turbine with 7.64 m/s wind speed, 24 is the hours of the day and 250 is the windy days of the year. It means, 7200 MW (7.2 GW) kinetic energy from the turbine can be extracted in a year. Now, the Capacity Factor must be calculated. CF is one of the key factors of wind energy parameters. Before the wind farm building process, CF must be taken into consideration during the project phase. To calculate CF, a special formula is being used (3.4).

$$CF = \frac{1.2\times24\times250}{1.5\times24\times365} = 0.547 \approx 0.55\ (55\%) \quad (5.3)$$

The result shows that with these parameters, an offshore wind farm in the chosen areas of the Caspian Sea will be profitable.

In the previous pages, layouts of the wind farms have been written. The distance between two turbines must be at least 5×D. The chosen turbine's diameter is 87 meters. Thus, the minimum distance between two turbines must be at least 435 meters. With the help of this information, the total occupied area can be easily calculated.

$$5 \times 87 \times 5 = 2175\ meter\ (shorter\ part\ of\ the\ rectangular) \quad (5.4)$$

$$5 \times 87 \times 29 = 12615\ meter\ (taller\ part\ of\ the\ rectangular) \quad (5.5)$$

$$S = a \times b = 2175 \times 12615 = 27.43\ km^2 \quad (5.6)$$

For both sites, the planned total occupied area will be 27.43 km^2.

After the Preliminary Calculations, a Simple Feasibility study should be analyzed. To that, certain components, such as air density, wind speed at a certain height, rotor's swept area, and then finally power coefficient or Betz Limit must be taken into consideration. The formula (3.3) which has been written before is going to be used for calculation.

Where "ρ" is air density (1.225 kg/m^3), "v" is the wind velocity, "A" is the rotor's swept area (5909 m^2) and the "C_p" is the power coefficient or Betz Limit (59%).

Now, a simple feasibility study can be analyzed. Before, it has been calculated that at the 85 m height, the wind speed is 7.68 m/s. Then:

$$E=1/2*1.225*7.68^3*5909*0.59 \quad (5.8)$$

Then:

$$E=967\ kW/h$$

The simple feasibility study shows that the maximum amount of kinetic energy that can be gained throughout the wind is 967 kW/h. And the Capacity Factor will be:

$$CF = \frac{967\times24\times250}{1500\times24\times365} = 0.44\ (44\%) \quad (5.9)$$

During LCOE Analysis and after, only the first calculations will be taken into consideration.

5.2 Calculation of Levelized Cost of Energy

In this part, LCOE will be calculated and in the end, results will be compared with IRENA's results and Azerbaijanian government's energy policy.

Here, all values have been taken from the IRENA's 2018 annual report and all of them are reliable. The turbine price has been taken as an average between the cheapest and the expensive ones. The cheapest's price is 500 USD/kW and expensive ones are 855 USD/kW [21]. The average value is 677.5 USD/kW. Our turbine's capacity is 1.5 MW/h. Then, the turbine's price becomes 1016250 USD. The total number of turbines is 360. Then the total price of the turbines is 365850000 USD.

According to the IRENA, the installation process' price for shallow waters is 2500 USD/kW [21]. Thus, for both projects, the total installation expenditures will be 1350000000 USD. These two prices constitute the project's investment or capital expenditures – CAPEX.

According to the IRENA, operation, and maintenance costs for offshore wind farms is 0.02 USD/kW for a year [21]. Thus, for a year, the turbine's operation and maintenance cost, taking into consideration of turbines' AEP capacity, it becomes 10800 USD/year.

The discount rate is 7.5% for OECD countries and China. For the rest of the world, it is 10%. To get a more acceptable result, the discount rate has been taken as 10% [21]. Also, to make a more realistic comparison, another calculation will be held where Azerbaijan's Central Bank's discount rate and the inflation rate will be taken into consideration. Both calculations' inflation rates have been taken the same. The discount rate will be calculated differently.

In 2019, the Central Bank of the Azerbaijan Republic (CBAR) has been reported that the inflation rate of the year is 2.5% and the discount rate has been reported as 8.75% for 2019 [58].

The lifetimes of the farms have been taken for 25 years [21]. But the beginning year has been taken as a construction year. This year, wind farms are being built but do not produce electricity. That is why, in total, the lifetime of the project and the construction year have been taken as 26 years.

Inside the next table, all components of the LCOE Analysis can be seen as more clear:

Table 5.2 : Inputs of the LCOE

CAPEX I_t	OPEX M_t	The discount rate of IRENA r	The discount rate of the CBAR	Fuel expenditures F_t	The lifetime of the farms n	AEP of turbine E_t	The inflation rate of the Azerbaijan Republic
1715250000 USD	10800 USD	10%	8.75%	0 USD	25 year	7200000 kW/h	2.5%

Now LCOE Analysis can be calculated. As it has been mentioned before, two different calculations will be held. One of them will be evaluated with the values of IRENA, where the discount rate is 10%, in the second calculation discount rate will be taken as 8.75% according to the CBAR. Both calculations' inflation rates have been taken 2.5% for accurate comparison.

To calculate LCOE, special formulas have been being used. But here, only IRENA's LCOE Analysis Formula (5.1) will be taken into consideration.

The formula has been adapted to the Excell Program to make calculations easier. In Appendix B, the Excell sheet demonstrates the first calculation's result of the analysis with the values of IRENA.

The result of the first calculation is 0,073684 USD/kW.

Now the second analysis will be calculated. Here also the Excell Program will be used for evaluation. The second analysis has been evaluated with the values of CBAR. The discount rate has been taken as 8.75% and the inflation rate has been taken as 2.5 % and stable. The result can be seen in Appendix C.

The second calculation's result is 0,066858 USD/kW. The result with the values of CBAR is lower than the values of the IRENA.

The LCOE result indicates that with the values of the CBAR, project in the shoreline of the Absheron Peninsula is highly acceptable. The main comparison of the LCOE results and Capacity Factors will be held in chapter **7**.

6. WIND ENERGY POTENTIAL IN OTHER REGIONS OF THE CASPIAN SEA

What if, building a wind farm in other regions of the Caspian Sea rather than shorelines of the Absheron Peninsula? Would it be a great idea? The article about wind power potential of the Caspian Sea [7] claims that building farms in the northern part, most especially in the shoreline of Atyrau and the shoreline of the Olya would be better than building a farm in the shoreline of the Absheron Peninsula. To learn the truth, it would be better to make projects in both sites like it has been done for the Absheron Peninsula in the previous pages. In the next coming pages, two projects for those two sites will be analyzed respectively and their LCOE analysis also will be held.

Though authors' have got some other investigations and different results [4-7] about the wind energy potential of the Caspian Sea, their latest article has been published in 2019 [7] and the projects will be built on their last research.

Besides, the windiest area's wind energy potential in the Caspian Sea [2], will be evaluated too.

To get a better comparison, layouts of the projects will be considered as the same as Absheron's project. Square layout type will be chosen for all farms.

Here also the first years of the projects have been taken as construction years. It has been conjectured that the first year wind farms do not generate electricity.

In the end, results will be compared. For getting a better comparison, all data will be taken from the same book and the atlas. Turbines and their sizes also will be the same and the windy days in these areas also conjectured 250 days in a year.

6.1 Wind Farm Design in the Shoreline of the Atyrau

As it has been written before, the first area in the northern part will be on the shoreline of the Atyrau city, inside the sea borders of the Kazakistan Republic [55].

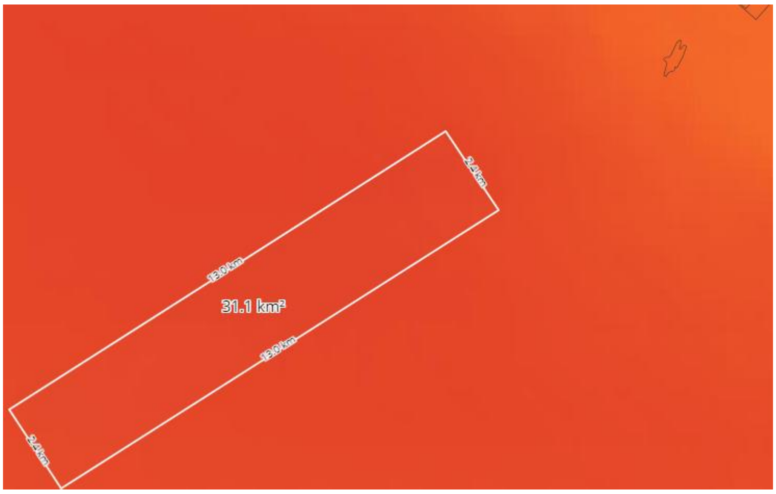

Figure 6.1 : Atyrau project

The distance between the farm and the shore will be approximately 12 km [57].

Figure 6.2 : The distance between the farm and the shoreline

Though, the farm's position located in front of the Ural River, nevertheless it can be easily seen that it does not affect main ship roads:

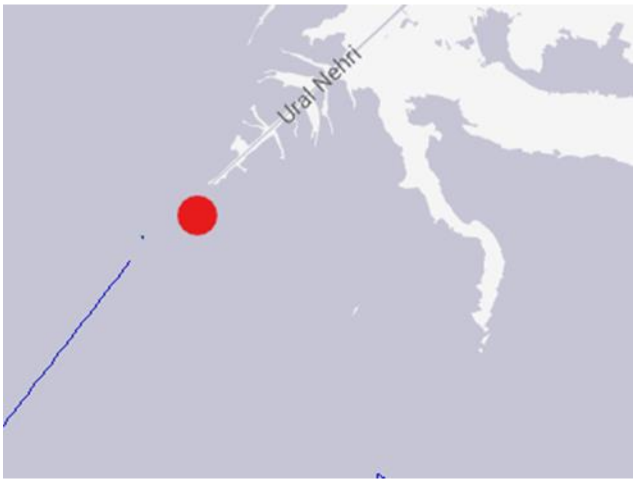

Figure 6.3 : The main shipping roads map (Red dot represents wind farm)

Inside the next table, additional information can be found about the site [2]:

Table 6.1 : Additional information about the Atyrau site

Average surface water's temperature	Salinity percentage of the surface waters	Average weather temperature	Yearly average absolute humidity	Yearly average relative humidity	Yearly average cloudiness	Yearly average heat of evaporation
11.4° C/year	3.95 %/year	9° C/year	8.4	79.59%	4.8	56.3 kcal/sm^2

Inside the next table, monthly and yearly wind speed data can be found. As it has been done before, here, the wind speeds will be extrapolated from 10 m to 85 m (4.2):

Table 6.2 : Monthly wind speeds (Average wind speed of the year at 10 m height is 5.5 m/s)

Month	Wind Speed
January	6.1 m/s
February	6.3 m/s
March	6 m/s
April	4.2 m/s
May	5.4 m/s
June	5.1 m/s
July	4.7 m/s
August	5 m/s
September	5.4 m/s
October	5.9 m/s
November	6.3 m/s
December	6.1 m/s

Now, wind speeds should be extrapolated from 10 m to 85 m which is the heigh of the chosen turbine:

Table 6.3 : Monthly wind speeds at 85-meter height (yearly average wind speed is 6.58 m/s)

Month	Wind Speed
January	7.3 m/s
February	7.54 m/s
March	7.18 m/s
April	5.03 m/s
May	6.46 m/s
June	6.1 m/s
July	5.62 m/s
August	5.98 m/s
September	6.46 m/s
October	7.06 m/s
November	7.54 m/s
December	7.3 m/s

In the next picture, the dominant wind directions of the chosen site can be seen. As it is clear, the longest arrow represents predominant North-West winds [1-2]:

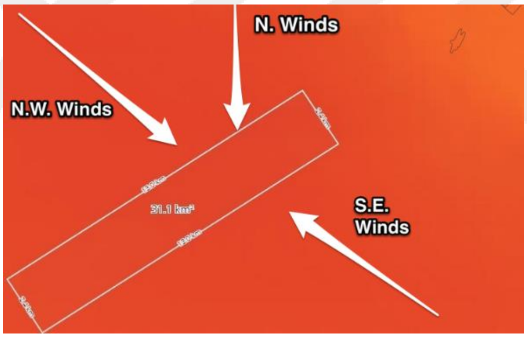

Figure 6.4 : Dominant wind directions of the site

In Appendix A, a bathymetric map of the Caspian Sea shows that the water depth of the chosen region does not exceed 30 meters. It changes around 5-meter water depth. That is why the monopile wind turbine foundation type would be the best match for the project.

6.2 Preliminary Calculations and LCOE Analysis of Atyrau Site

In the previous pages, it has been investigated that the average wind speed of the site is 6.58 m/s. In order to get a more accurate result, the windy days of the year in all sites will be taken the same as the Absheron site. 250 days in a year, winds blow steadily and the wind speed does not change.

According to the power curve of the turbine, with that wind speed, the highest extracted power from the turbine's blades will be 610 kW/h.

Now the capacity factor of the site can be calculated. To do that, the formula (3.4) which has been used for the Absheron site will be taken into consideration again:

Before that, AEP of the turbine with 6.58 m/s wind speed must be calculated:

$$AEP = 610 \times 24 \times 250 = 3660\ MW \quad (6.1)$$

Where 610 is the power of the turbine which has been extracted with 6.58 m/s wind speed, 24 is the hours of a day and 250 is the windy days of the year in the Caspian Sea.

The capacity factor has been found at 28%. Obviously, the capacity factor of the Atyrau site is lower than the Absheron Peninsula's site.

To have a better comparison of the sites' LCOE results, the turbines' size and the layouts will be the same. In the Absheron Peninsula, 360 wind turbines have been used. Here in the Atyrau project, the turbine size will be the same. 360 wind turbine is going to be used for the project. That is why the annual energy production of the farm is going to be 1317600 MW/year.

To calculate the project's occupied area, the same formulas as used for Absheron projects will be taken into consideration (5.6). Then, the total occupied area for the Atyrau project will be approximately 61.12 km^2.

Here, in the Atyrau project, Exell Program also used for LCOE calculations. The discount rate of the project has been taken as 10%. The inflation rate is 2.5%.

The comparison of the Caspian Sea Projects will be held in the next coming pages but to have an accurate comparison, as a first, analysis of the results will be taken into the consideration with their IRENA's discount rate values. Others have been used for more advantages.

In Appendix D, the calculation of the LCOE can be found for project Atyrau.

The LCOE result of the Atyrau site is higher than the Absheron site. 0,144952 USD/kW permits to say building a wind farm in the Atyrau site is not reasonable. Meanwhile, during the winter season, the sea is always freezing and makes thick ices on the sea surface. The freezing process always creates troubles for the operation and maintenance process and these troubles cause higher LCOE values inevitable.

6.3 Wind Farm Design in the Shoreline of the Olya City

Florin Onea and Eugen Rusu [7] state that building wind farms in the shorelines of Atyrau and Olya would be beneficial. Atyrau project has been evaluated and the result was not quite acceptable. In this part, the wind energy potential of the Olya site will be analyzed.

The chosen area located on the shoreline of the Olya City where belongs to the Russian Federation [55]:

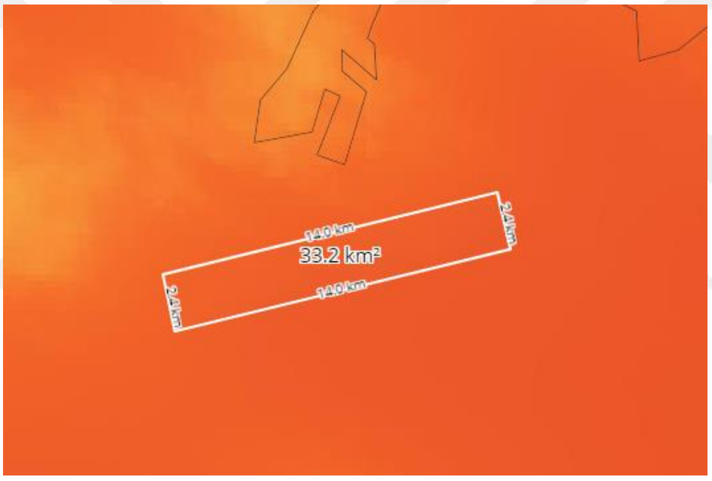

Figure 6.5 : Olya project

The distance between the site and the nearest shoreline is approximately 8.4 km [56].

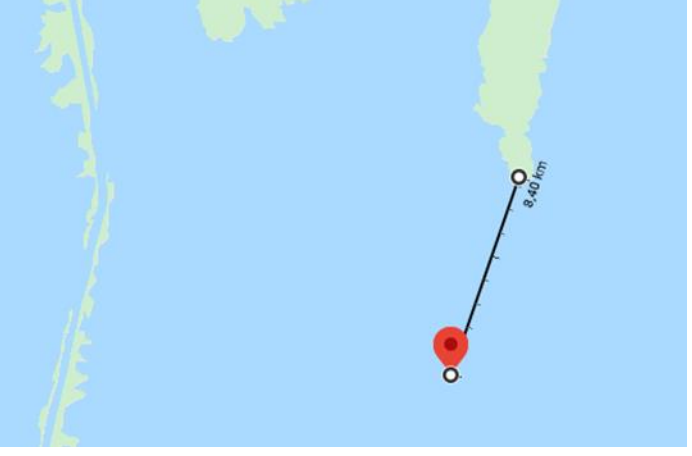

Figure 6.6 : The distance between the farm and the shoreline

The density map of the shipping traffic is clearly showing that the impact of the farm on shipping road will not be heavy in the site:

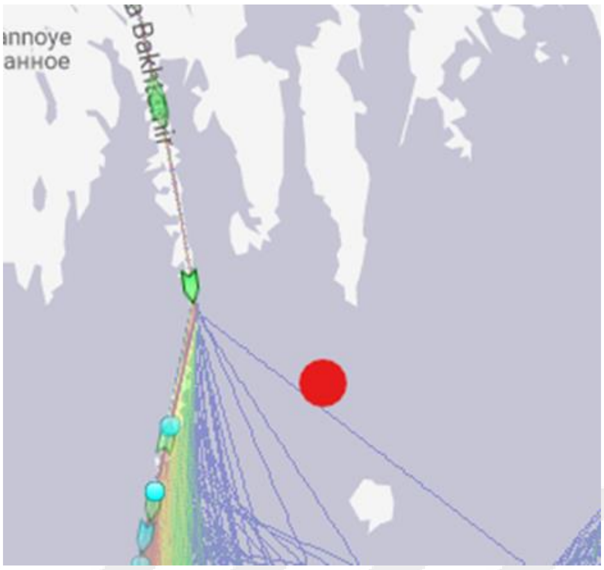

Figure 6.7 : The main shipping roads map (Red dot represents wind farm)

Below inside the table, additional information can be found about the site Olya:

Table 6.4 : Additional information about the Olya site

Average surface water's temperature	Salinity percentage of the surface waters	Average weather temperature	Yearly average absolute humidity	Yearly average relative humidity	Yearly average cloudiness	Yearly average heat of evaporation
10.1° C/year	0.40 %/year	10° C/year	8.8	80.63%	5.5	60.4 kcal/sm^2

Now monthly wind speeds and average yearly wind speed must be extrapolated from 10 meters to 85 meters (4.2). Below, monthly and yearly wind speeds at 10-meter height have been shared:

Table 6.5 : Monthly wind speeds (Average wind speed of the year at 10 m height is 6.2 m/s)

Month	Wind Speed
January	6.3 m/s
February	6 m/s
March	6 m/s
April	6.9 m/s
May	6.2 m/s
June	5.5 m/s
July	5.3 m/s
August	5.8 m/s
September	6.4 m/s
October	6.5 m/s
November	6.6 m/s
December	7 m/s

Table 6.6 : Monthly wind speeds (Average wind speed of the year at 85 m height is 7.42 m/s)

Month	Wind Speed
January	7.54 m/s
February	7.18 m/s
March	7.18 m/s
April	8.26 m/s
May	7.42 m/s
June	6.58 m/s
July	6.34 m/s
August	6.94 m/s
September	7.66 m/s
October	7.78 m/s
November	7.9 m/s
December	8.38 m/s

Next figure shows dominant wind directions on the project's location:

Figure 6.8 : Dominant wind directions of the site

According to the bathymetric map (Appendix A), water depth does not exceed 30-meter.

6.4 Preliminary Calculations and LCOE Analysis of Olya Site

In project Olya, the windy days of the year have been taken as 250 days as it has been conjectured for either Absheron or Atyrau projects. Wind speed does not change and the wind blows steadily.

Now preliminary calculations can be held. First of all, the AEP of the turbine must be calculated. According to the power curve of the turbine, with 7.42 m/s average wind speed, a wind turbine in the Olya site can produce 1105 kW/h. Then, the turbine's AEP in the Olya site will be 6630 MW. And the capacity factor of the turbine will be 51%.

In the Olya site, 360 wind turbines will be installed. Then, total electricity production in a year will be 2386800 MW.

The total occupied area will be as same as the Atyrau project. 61.12 km^2 will be the total area (5.6).

Now LCOE analysis of the Olya site can be executed (5.1). Before that, the discount rate must be taken into consideration as 10% and the yearly average inflation rate must be taken at 2.5%. The calculation process of the Olya project can be found in Appendix E.

0.080019 USD/kW is quite acceptable result for a wind farm in offshore. The result shows that the project in the Olya site would be more beneficial than in the Atyrau site. Nevertheless, the LCOE result of the Olya site is still higher than the Absheron site's result.

6.5 Wind Farm Design in the Shoreline of the Sulak City

In this part, another project will be designed and its LCOE analysis will be evaluated.

The site has been chosen from the "Hydrometrological Atlas of the Caspian Sea"[2]. According to this atlas, the windiest area in the Caspian Sea located in the shoreline of the Sulak city where belongs to the Dagestan Republic (Russian Federation) [55].

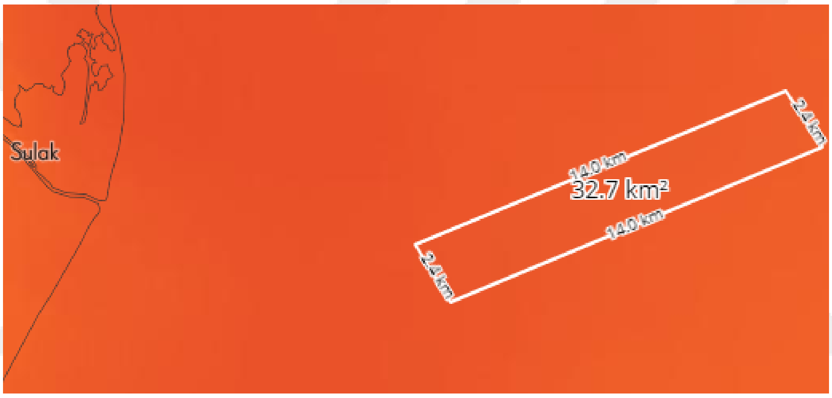

Figure 6.9 : Sulak project

Distance between the farm and the shoreline is 18.64 km [56].

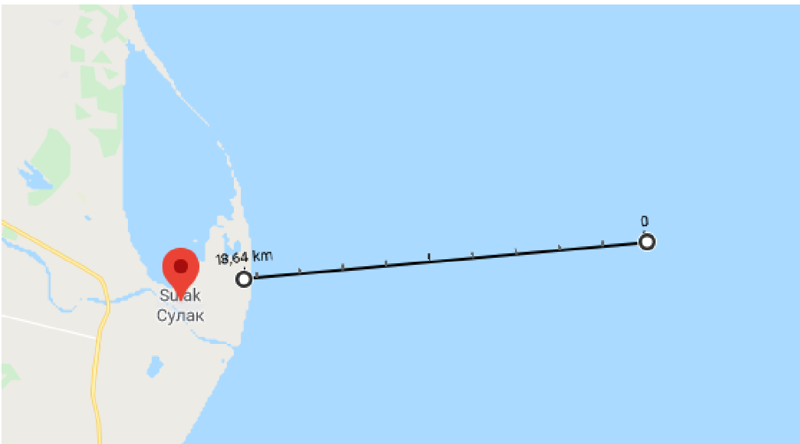

Figure 6.10 : The distance between the farm and the shoreline

According to the marine traffic map, the farm will not be located on the main shipping roads. The map which has been added below demonstrates the wind farm's location:

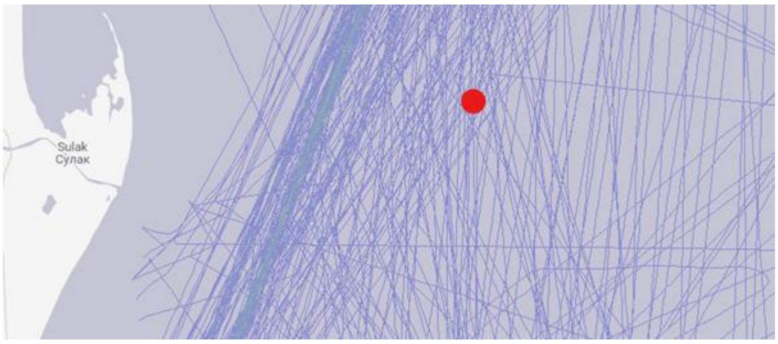

Figure 6.11 : The main shipping roads map (Red dot represents wind farm)

Below, additional information can be found in the table about the Sulak site:

Table 6.7 : Additional information about the Sulak site

Average surface water's temperature	Salinity percentage of the surface waters	Average weather temperature	Yearly average absolute humidity	Yearly average relative humidity	Yearly average cloudiness	Yearly average heat of evaporation
12.7° C/year	10.49 %/year	12.2° C/year	9.8	80.21%	5.9	50.8 kcal/sm^2

Now, monthly wind speeds and yearly average wind speed of the site must be extrapolated from 10 meters to 85 meters.

Table 6.8 : Monthly wind speeds (Average wind speed of the year at 10 m height is 6.7 m/s)

Month	Wind Speed
January	7 m/s
February	6.7 m/s
March	6.7 m/s
April	7 m/s
May	6.5 m/s
June	6 m/s
July	6.1 m/s
August	6.2 m/s
September	6.9 m/s
October	7.3 m/s
November	7.4 m/s
December	7.3 m/s

Inside the next table, extrapolated version of the wind speeds can be found:

Table 6.9 : Monthly wind speeds (Average wind speed of the year at 85 m height is 8.02 m/s)

Month	Wind Speed
January	8.38 m/s
February	8.02 m/s
March	8.02 m/s
April	8.38 m/s
May	7.7 m/s
June	7.18 m/s
July	7.3 m/s
August	7.42 m/s
September	8.26 m/s
October	8.74 m/s
November	8.86 m/s
December	8.74 m/s

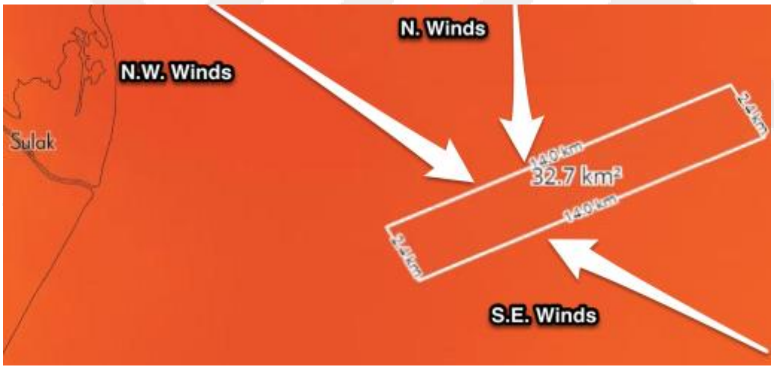

Figure 6.12 : Dominant wind directions of the site

The longest arrow indicates dominant winds that blow from the North-West regions.

In the Sulak region, water depth is lower than 30 meters (Appendix A). That is why the monopile wind turbine foundation would be enough for the project.

6.6 Preliminary Calculations and LCOE Analysis of Sulak Site

Now, the LCOE analysis of the Sulak site can be evaluated. Before that, some preliminary calculations should be analyzed. First, the AEP of the site is going to be evaluated.

According to the power curve of the turbine, with 8.02 m/s average wind speed, a wind turbine in the Sulak site can produce approximately 1370 kW/h. Turbine's AEP has been found 8220 MW. Then, the turbine's capacity factor will be approximately 63%.

Here, in the Sulak site, 360 turbines will be installed too to get an accurate comparison among projects in the Caspian Sea. Then, the total annual energy production of the farm will be approximately 2959200 MW.

At last, the LCOE analysis of the Sulak site can be evaluated (5.1). As it has been done before for other regions' LCOE analysis, here also Excell program is going to be used for calculation and similar to what was done before for other projects, the discount rate has been taken as 10% and the inflation rate has been accepted as 2.5%. In Appendix F, the calculation of LCOE for Sulak region can be found.

The result is quite acceptable and beneficial. 0.064541 USD/kW is a competitive price for the wind energy industry.

7. COMPARISON OF THE CAPACITY FACTORS AND THE LCOE RESULTS

In this section, the comparison of the capacity factors and the LCOE results will be analyzed. The base rates for either CF and LCOE results have been taken from IRENA’s 2018 report [21]. As it has been written in the previous pages, according to the International Renewable Energy Agency, the maximum capacity factor for offshore wind energy is around 50%. This rate has been recorded in Europe. And LCOE for the offshore wind energy is approximately 0.127 USD/kW. These two results are going to be base rates for CF and LCOE results of the projects.

Besides, Eugen Rusu and Florin Onea’s project results [7] will be also compared with the results of this research.

First of all, the capacity factors of certain projects must be evaluated, and then their LCOE results can be analyzed respectively. Below, the graphic shows the results of the capacity factors. As it has been written, the base rate has been chosen as IRENA’s result.

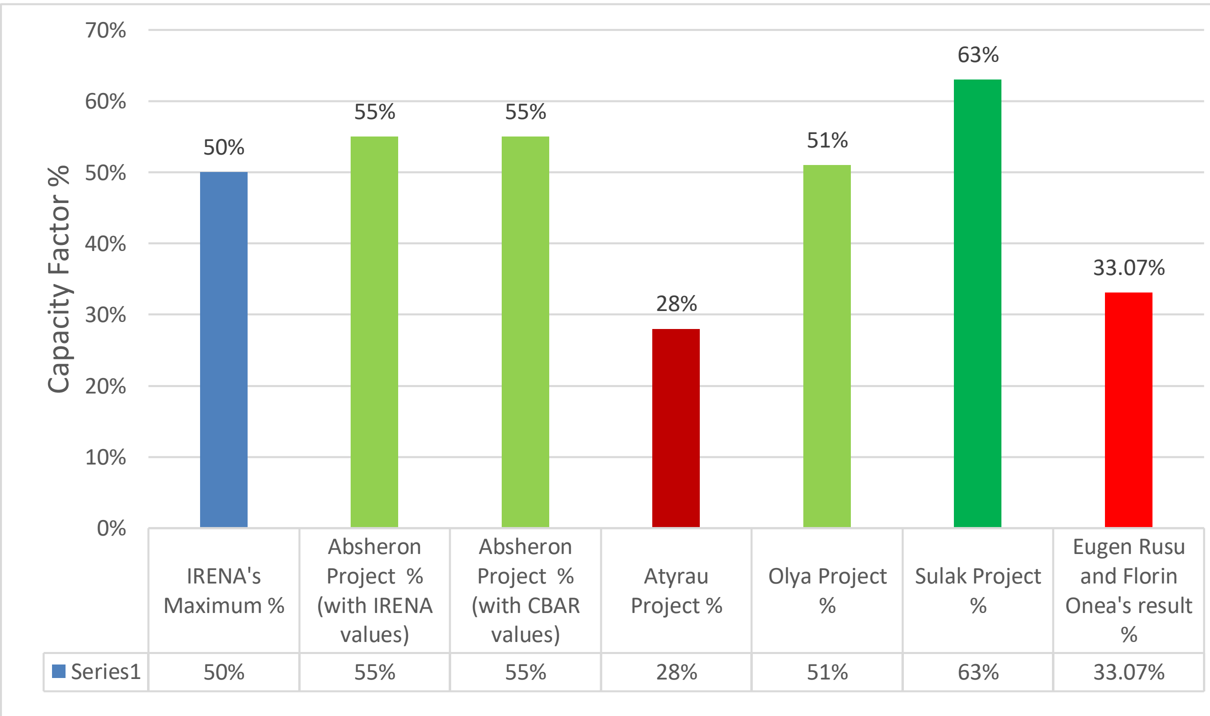

Figure 7.1 : Comparison of the capacity factors

The first result shows IRENA's CF rate and the last one with light red color represents Florin Onea and Eugen Rusu's project's result which has been published in 2019. Though their article is trying to prove that the best regions for a wind farm in the Caspian Sea are located in the northern part of the sea, this graph demonstrates quite a different result. Besides, all other projects' CF results are higher than the IRENA's result except Project Atyrau.

Though this research's main target was the potential of the Absheron regions, Sulak Project surprisingly demonstrated excellent results. The capacity factor of the Sulak region is higher than the other regions and even higher than IRENA's.

The second graph shows the differences between LCOE results of the projects and here also the result of Eugen Rusu and Florin Onea's research and the IRENA's result have been added for better comparison. In addition, the LCOE result for the Absheron projects with the values of the Central Bank of the Azerbaijan Republic has been added too:

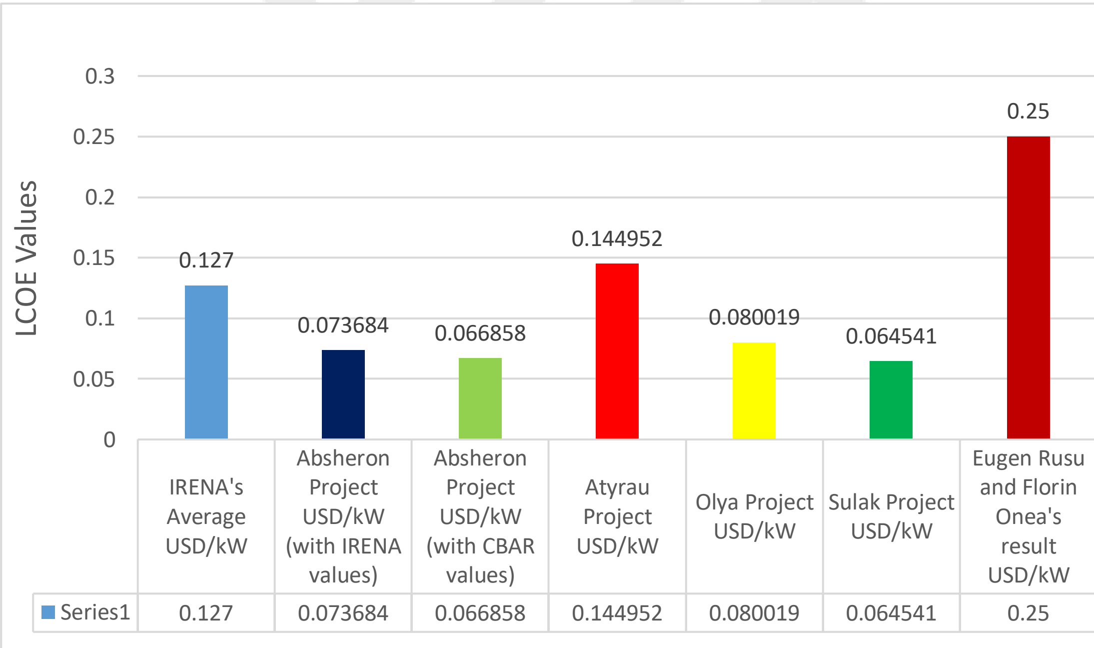

Figure 7.2 : Comparison of the LCOE results

As a first, a comparison of the projects should be conducted with the IRENA's discount rate. As can be seen, the best result among the projects belongs to Sulak Project. Its capacity factor is higher than the others but quite the contrary its LCOE result is lower than the others. Even IRENA's average LCOE rate and LCOE result of the Absheron projects with CBAR values are higher than Sulak Project.

Meanwhile, Eugen Rusu and Florin Onea's result is not acceptable. It is higher than IRENA's average LCOE rate. But it should not be forgotten that Rusu and Onea have been conducted their project with different wind turbines and has been achieved their maximum Capacity Factor with the turbine which its capacity is 4.2 MW. That is why the difference between capacity factors can be highly different.

Quite the contrary, in this research, projects have been conducted with the turbine which its capacity is 1.5 MW and even with low wind speeds, the turbine gives excellent efficiency

Also during the planning phase, it should not be forgotten that the water depths of the northern area are extremely suitable. But meanwhile, the winter season in this region passes very hard. According to the book [1] and atlas [2], the northern part freezes every year and during extreme winters, thermometers show -19° C and -20° C degree. But shorelines of the Absheron Peninsula freezes only in extreme winters. During January and February, the surface waters' temperature becomes 0° C in Olya and Atyrau regions. During March, Atyrau's surface water temperature becomes 0.9° C and in the Olya site, it becomes a 2° C degree. In January, February, and March, air temperatures in the Atyrau region become -8.3° C, -8.2° C, and -2.3° C degree respectively. During December, air temperature becomes -3.7° C degree. Also in the Olya site, winter makes troubles. Air temperature in December January and February become -1.5° C, -5° C, and -4.4° C degree respectively. Also, in the Sulak region, air temperature hits under 0 in winter. In January and February, thermometers show a -0.6° C degree. As has been written before, water depths of these regions can be suitable but the water and the air temperatures can make big troubles for operation and maintenance. And inevitably these troubles will have a bad impact on the LCOE result.

Now, the LCOE results of the Absheron region should be compared with the government of Azerbaijan's electric tariffs. As it has been written in the early pages of this research, the government of Azerbaijan guarantees wind energy companies that will buy their electricity for 0.0325 USD/kW. Research showed that with the values of the CBAR, these farms' LCOE results can be a minimum 0.066858 USD/kW. Under this price, wind farms can sell their electricity at a loss. But meanwhile, the government sells electricity to its citizens for 0.065 USD/kW when their consumption hits above 300 kW/month. Policymakers of government on energy can stabilize their price policy. With the values of IRENA, most probably building a wind farm in the

Absheron Peninsula's shorelines, can be inefficient and unacceptable. But with the values of CBAR and policy changing on the price of electricity, these farms might be efficient. Despite everything, all LCOE results are still lower than most of the offshore wind farms all over the world except the Atyrau project.

In addition, in Pirallahı island, there is an electric cable structure that has been being used for years. That is why there will not be a need to build a new structure for the farms. Thus, it will have a good impact on the LCOE result.

8. RESULT AND CONCLUSION

For this research, Goldwind Americas' GE 87/1500 with 1.5 MW capacity wind turbine has been chosen. Different regions with different water depths and wind speeds in the Caspian Sea have been evaluated and their wind energy potentials have been analyzed. To remind, in all regions, windy days of the year have been conjectured as 250/365, and the wind blows 24 hours in all these 250 days of the year. In all regions, the same wind turbine has been used. The inflation rate has been taken at 2.5%. The turbine price has been conjectured 1016250 USD or 677.5 USD/kW. In total, for 360 turbines, the price has been found 365850000 USD. Installation expenditures have been taken 2500 USD/kW. Total CAPEX has been found 1350000000 USD for a farm with 360 wind turbines. OPEX has been taken 0.02 USD/kW for a year. Total, 10800 USD/year has been conjectured for 360 turbines as a first-year price. Working time of all projects have been chosen as 25 years. Total projects' lifetime is 26 years. First-year conjectured as building and installation year. This year there is no power generation in all regions.

In this section, the numeric results will be discussed and conclusions will be analyzed respectively. Only projects in the shorelines of the Absheron Peninsula have been accepted as one. Due to all parameters of these projects are the same, result evaluation process will be held together.

According to the "Hydrometrological Atlas of the Caspian Sea", yearly average wind speed at 85 meters has been found as 7.68 m/s in both regions of the Absheron Peninsula. And with that speed, the chosen turbine produces approximately 1.2 MW/h, and annual energy production per turbine is 7200 MW/year. Totally 360 wind turbines have been planned to be built for both regions. Thus, the total AEP of the farms is 2592 TW/year. The water depth of both regions does not exceed 30 meters. And the capacity factor has been found as 55%. In the Absheron project, two different discount rates have been taken into consideration. The first one is 10% and belongs to IRENA, and the second Weighted Average Cost of Capital (discount rate) is 8.75% and belongs to the Central Bank of Azerbaijan Republic (CBAR). With the first value, the LCOE result became 0.073684 USD/kW. And with the second discount rate, the LCOE result became lower, 0.066858 USD/kW.

In Atyrau site, yearly average wind speed at 85-meter height has been found 6.58 m/s. With that wind speed, the turbine produces 610 kW/h. Annual energy production becomes 3660 MW/year per turbine. The total AEP of the farm is 1317.6 GW/year. Capacity Factor of the farm has been found 28%. And the water depth of the region is lower than 30 meters. With these parameters, LCOE of the Atyrau farm has been found 0.144952 USD/kW which is the highest rate among the projects. LCOE calculation conducted with the values of IRENA.

Olya site's yearly average wind speed at 85-meter turbine height has been found 7.42 m/s. Electricity production corresponding to this wind speed is 1105 kW/h. AEP of one turbine is 6630 MW/year and wind farm's total AEP is 2386.8 GW/year. The water depth of the chosen region has been found that does not exceed even 10 meters. The capacity factor of the farm has been found at 51%. Corresponding LCOE rate found as 0.080019 USD/kW.

The last project has been planned in the area where the wind blows faster. Sulak region's yearly average wind speed, according to the "Hydrometrological Atlas of the Caspian Sea", has been found 8.02 m/s. Corresponding electricity generation has been found 1370 kW/h or 1.3 MW/h. AEP of the turbine has been found 8220 MW/year and the farm's total AEP is 2959200 MW/year. The region's water depth does not exceed 30 meters. According to all these parameters, Capacity Factor has been found 63% and the corresponding LCOE rate has been found 0.064541 USD/kW.

After all investigations and research, LCOE results showed that the Caspian Sea has a huge potential for wind energy. Though this research has been planned mainly for the Absheron Peninsula projects, the Sulak project surprisingly demonstrated a more beneficial result. Nevertheless, the results of the Absheron projects have been found quite acceptable and beneficial. With the values of CBAR, the LCOE result became more competitive and suitable to build wind farms in certain areas. Unlike Eugen Rusu and Florin Onea's conclusion, the Atyrau region where belongs to the northern part of the Caspian Sea, has showed the highest LCOE value among these projects. Meanwhile, the Olya site's result was quite competitive but still higher than Absheron projects. As it has been written before, surprisingly Sulak region showed the highest CF but the lowest LCOE values.

While the Caspian Sea has got great importance for the energy industry, unfortunately, there are very little researches about its wind energy potential. That is why, there is some unanswered question, in other words, unsolved issues about its climate. According to the book and the atlas, 250 days of storm winds blow here in a year. But unfortunately, there is no access to daily wind records. Because of that, Weibull distribution is a challenging minus point of this research. And this missing point affects the capacity factors of the farms and their LCOE rates. Distribution of Weibull could have a good impact on CF and LCOE rates. Because 115 days of the year have been conjectured as off days of the turbines. In other words, turbines do not work. Or quite the contrary could have a bad impact. That is why Weibull distribution should be investigated. For future works, permanent or mobile meteorology stations can be built in certain areas where these areas give the best performance estimations. Also, one turbine can be installed there too and then the results of these two different components can be compared and the final decision can be made.

The Caspian Sea is a seismically active basin and there are so many mud volcanos in the sea. These are major challenges against offshore structures and must be evaluated for the feasibility study. Besides, underwater riches such as its flora and faunas, oil and natural gas resources, etc should be analyzed. Azerbaijan is one of the oil-producing countries and it has oil and natural gas wells in the Caspian Sea. Because of that, it has great potential for building offshore structures and their installations. These features should be investigated and inevitably it will have an impact on the feasibility study. For better feasibility investigations, the wind turbine’s real price and its transportation expenditures must be evaluated. Impact on tourism, historic or cultural texture, and fishing activities should be analyzed too. And finally, legal procedures for wind energy must be taken into consideration.

As has been written above, there are very little researches about the wind energy potential of the Caspian Sea. So, it would be better, if this study is considered as the first step in this way.

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APPENDICES

APPENDIX A: Bathymetric Map of the Caspian Sea

APPENDIX B: LCOE Calculations of the projects

APPENDIX C: Wind roses above the Caspian Sea in different months

APPENDIX D: Map of the inclination angles of the bottom surface

APPENDIX E: Chart of flows of surface waters of the Caspian Sea

APPENDIX F: Annual mean height of surface waves of the Caspian Sea – with points

APPENDIX G: Annual mean temperature over the surface of the Caspian Sea

APPENDIX H: Annual mean temperature of surface waters of the Caspian Sea

APPENDIX I: Annual mean salinity of surface waters of the Caspian Sea

APPENDIX J: Average annual absolute humidity above the Caspian Sea

APPENDIX K: Annual mean relative humidity (%) above the Caspian Sea

APPENDIX A

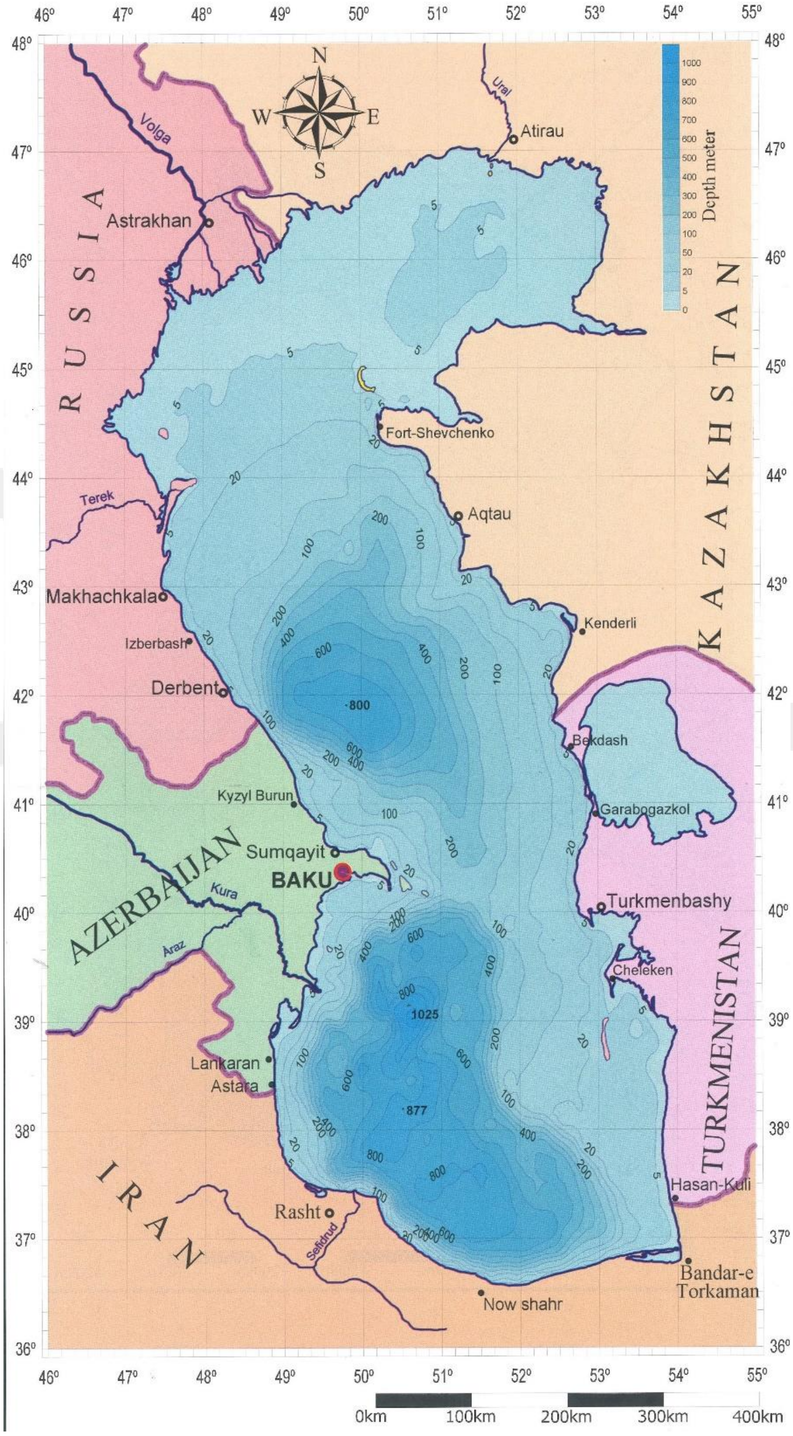

Figure A.1 : Bathymetric map of the Caspian Sea

APPENDIX B

t	I	M	F	E	r	(It+Mt+Ft)/((1+r)^t)	Et/((1+r)^t)		
1	1,716E+09	10800	0	0	0,1	1559873455	0		
2	0	11070	0	2,592E+09	0,1	9148,760331	2,142E+09		
3	0	11346,75	0	2,592E+09	0,1	8524,981217	1,947E+09		
4	0	11.630	0	2,592E+09	0,1	7943,731986	1,77E+09		
5	0	11.921	0	2,592E+09	0,1	7402,113616	1,609E+09		
6	0	12.219	0	2,592E+09	0,1	6897,423797	1,463E+09		
7	0	12524,69	0	2,592E+09	0,1	6427,144812	1,33E+09		
8	0	12837,8	0	2,592E+09	0,1	5988,930312	1,209E+09		
9	0	13158,75	0	2,592E+09	0,1	5580,594112	1,099E+09		
10	0	13487,72	0	2,592E+09	0,1	5200,098779	999328206		
11	0	13824,91	0	2,592E+09	0,1	4845,546265	908480187		
12	0	14170,53	0	2,592E+09	0,1	4515,16788	825891080		
13	0	14524,79	0	2,592E+09	0,1	4207,315445	750810072		
14	0	14887,91	0	2,592E+09	0,1	3920,452804	682554611		
15	0	15260,11	0	2,592E+09	0,1	3653,149006	620504192		
16	0	15641,61	0	2,592E+09	0,1	3404,070502	564094720		
17	0	16032,65	0	2,592E+09	0,1	3171,974727	512813382		
18	0	16433,47	0	2,592E+09	0,1	2955,703668	466193983	LCOE	0,07368
19	0	16844,3	0	2,592E+09	0,1	2754,178304	423812712		
20	0	17265,41	0	2,592E+09	0,1	2566,39333	385284284		
21	0	17697,05	0	2,592E+09	0,1	2391,41193	350258440		
22	0	18139,47	0	2,592E+09	0,1	2228,361098	318416764		
23	0	18592,96	0	2,592E+09	0,1	2076,427297	289469785		
24	0	19057,78	0	2,592E+09	0,1	1934,852612	263154350		
25	0	19534,23	0	2,592E+09	0,1	1802,930795	239231227		
26	0	20022,58	0	2,592E+09	0,1	1680,003643	217482934		

Table B.1 : LCOE calculation of the project Absheron with IRENA values

APPENDIX B

t	I	M	F	E	r	(It+Mt+Ft)/((1+r)^t)	Et/((1+r)^t)		
1	1715850000	10800	0	0	0,0875	1577803034	0		
2	0	11070	0	2592000000	0,0875	9360,285375	2191676576		
3	0	11346,75	0	2592000000	0,0875	8822,337939	2015334782		
4	0	11.630	0	2592000000	0,0875	8315,306487	1853181409		
5	0	11.921	0	2592000000	0,0875	7837,415014	1704074859		
6	0	12.219	0	2592000000	0,0875	7386,988591	1566965387		
7	0	12524,687	0	2592000000	0,0875	6962,44892	1440887712		
8	0	12837,804	0	2592000000	0,0875	6562,308088	1324954218		
9	0	13158,749	0	2592000000	0,0875	6185,163898	1218348707		
10	0	13487,717	0	2592000000	0,0875	5829,694395	1120320650		
11	0	13824,909	0	2592000000	0,0875	5494,65412	1030179908		
12	0	14170,531	0	2592000000	0,0875	5178,869135	947291869		
13	0	14524,794	0	2592000000	0,0875	4881,232886	871072983		
14	0	14887,913	0	2592000000	0,0875	4600,701997	800986651		
15	0	15260,11	0	2592000000	0,0875	4336,293602	736539449		
16	0	15641,612	0	2592000000	0,0875	4087,08113	677277655		
17	0	16032,652	0	2592000000	0,0875	3852,191338	622784050		
18	0	16433,468	0	2592000000	0,0875	3630,800965	572674989	LCOE	0,066858
19	0	16844,304	0	2592000000	0,0875	3422,134101	526597691		
20	0	17265,411	0	2592000000	0,0875	3225,459615	484227762		
21	0	17697,046	0	2592000000	0,0875	3040,088325	445266907		
22	0	18139,472	0	2592000000	0,0875	2865,370582	409440834		
23	0	18592,958	0	2592000000	0,0875	2700,693995	376497319		
24	0	19057,781	0	2592000000	0,0875	2545,48157	346204431		
25	0	19534,225	0	2592000000	0,0875	2399,189461	318348902		
26	0	20022,58	0	2592000000	0,0875	2261,304939	292734623		

Table B.2 : LCOE calculation of the project Absheron with CBAR values

APPENDIX B

t	I	M	F	E	r	(It+Mt+Ft)/((1+r)^t)	Et/((1+r)^t)		
1	1715850000	10800	0	0	0,1	1559873455	0		
2	0	11070	0	1317600000	0,1	9148,760331	1088925620		
3	0	11346,75	0	1317600000	0,1	8524,981217	989932382		
4	0	11.630	0	1317600000	0,1	7943,731986	899938529		
5	0	11.921	0	1317600000	0,1	7402,113616	818125935		
6	0	12.219	0	1317600000	0,1	6897,423797	743750850		
7	0	12524,687	0	1317600000	0,1	6427,144812	676137137		
8	0	12837,804	0	1317600000	0,1	5988,930312	614670124		
9	0	13158,749	0	1317600000	0,1	5580,594112	558791022		
10	0	13487,717	0	1317600000	0,1	5200,098779	507991838		
11	0	13824,909	0	1317600000	0,1	4845,546265	461810762		
12	0	14170,531	0	1317600000	0,1	4515,16788	419827965		
13	0	14524,794	0	1317600000	0,1	4207,315445	381661787		
14	0	14887,913	0	1317600000	0,1	3920,452804	346965261		
15	0	15260,11	0	1317600000	0,1	3653,149006	315422964		
16	0	15641,612	0	1317600000	0,1	3404,070502	286748149		
17	0	16032,652	0	1317600000	0,1	3171,974727	260680136		
18	0	16433,468	0	1317600000	0,1	2955,703668	236981942	LCOE	0,144952
19	0	16844,304	0	1317600000	0,1	2754,178304	215438129		
20	0	17265,411	0	1317600000	0,1	2566,39333	195852844		
21	0	17697,046	0	1317600000	0,1	2391,41193	178048040		
22	0	18139,472	0	1317600000	0,1	2228,361098	161861855		
23	0	18592,958	0	1317600000	0,1	2076,427297	147147141		
24	0	19057,781	0	1317600000	0,1	1934,852612	133770128		
25	0	19534,225	0	1317600000	0,1	1802,930795	121609207		
26	0	20022,58	0	1317600000	0,1	1680,003643	110553825		

Table B.3 : LCOE calculation of the project Atyrau with IRENA values

APPENDIX B

t	I	M	F	E	r	(It+Mt+Ft)/((1+r)^t)	Et/((1+r)^t)		
1	1715850000	10800	0	0	0,1	1559873455	0		
2	0	11070	0	2386800000	0,1	9148,760331	1972561983		
3	0	11346,75	0	2386800000	0,1	8524,981217	1793238167		
4	0	11.630	0	2386800000	0,1	7943,731986	1630216515		
5	0	11.921	0	2386800000	0,1	7402,113616	1482015014		
6	0	12.219	0	2386800000	0,1	6897,423797	1347286376		
7	0	12524,687	0	2386800000	0,1	6427,144812	1224805797		
8	0	12837,804	0	2386800000	0,1	5988,930312	1113459815		
9	0	13158,749	0	2386800000	0,1	5580,594112	1012236196		
10	0	13487,717	0	2386800000	0,1	5200,098779	920214723		
11	0	13824,909	0	2386800000	0,1	4845,546265	836558839		
12	0	14170,531	0	2386800000	0,1	4515,16788	760508036		
13	0	14524,794	0	2386800000	0,1	4207,315445	691370942		
14	0	14887,913	0	2386800000	0,1	3920,452804	628519038		
15	0	15260,11	0	2386800000	0,1	3653,149006	571380943		
16	0	15641,612	0	2386800000	0,1	3404,070502	519437221		
17	0	16032,652	0	2386800000	0,1	3171,974727	472215656		
18	0	16433,468	0	2386800000	0,1	2955,703668	429286960	LCOE	0,080019
19	0	16844,304	0	2386800000	0,1	2754,178304	390260873		
20	0	17265,411	0	2386800000	0,1	2566,39333	354782611		
21	0	17697,046	0	2386800000	0,1	2391,41193	322529647		
22	0	18139,472	0	2386800000	0,1	2228,361098	293208770		
23	0	18592,958	0	2386800000	0,1	2076,427297	266553427		
24	0	19057,781	0	2386800000	0,1	1934,852612	242321297		
25	0	19534,225	0	2386800000	0,1	1802,930795	220292088		
26	0	20022,58	0	2386800000	0,1	1680,003643	200265535		

Table B.4 : LCOE calculation of the project Olya with IRENA values

APPENDIX B

t	I	M	F	E	r	(It+Mt+Ft)/((1+r)^t)	Et/((1+r)^t)		
1	1715850000	10800	0	0	0,1	1559873455	0		
2	0	11070	0	2959200000	0,1	9148,760331	2445619835		
3	0	11346,75	0	2959200000	0,1	8524,981217	2223290759		
4	0	11.630	0	2959200000	0,1	7943,731986	2021173417		
5	0	11.921	0	2959200000	0,1	7402,113616	1837430379		
6	0	12.219	0	2959200000	0,1	6897,423797	1670391254		
7	0	12524,687	0	2959200000	0,1	6427,144812	1518537503		
8	0	12837,804	0	2959200000	0,1	5988,930312	1380488640		
9	0	13158,749	0	2959200000	0,1	5580,594112	1254989672		
10	0	13487,717	0	2959200000	0,1	5200,098779	1140899702		
11	0	13824,909	0	2959200000	0,1	4845,546265	1037181547		
12	0	14170,531	0	2959200000	0,1	4515,16788	942892316		
13	0	14524,794	0	2959200000	0,1	4207,315445	857174833		
14	0	14887,913	0	2959200000	0,1	3920,452804	779249848		
15	0	15260,11	0	2959200000	0,1	3653,149006	708408952		
16	0	15641,612	0	2959200000	0,1	3404,070502	644008139		
17	0	16032,652	0	2959200000	0,1	3171,974727	585461944		
18	0	16433,468	0	2959200000	0,1	2955,703668	532238131	LCOE	0,064541
19	0	16844,304	0	2959200000	0,1	2754,178304	483852846		
20	0	17265,411	0	2959200000	0,1	2566,39333	439866224		
21	0	17697,046	0	2959200000	0,1	2391,41193	399878385		
22	0	18139,472	0	2959200000	0,1	2228,361098	363525805		
23	0	18592,958	0	2959200000	0,1	2076,427297	330478005		
24	0	19057,781	0	2959200000	0,1	1934,852612	300434550		
25	0	19534,225	0	2959200000	0,1	1802,930795	273122318		
26	0	20022,58	0	2959200000	0,1	1680,003643	248293016		

Table B.5 : LCOE calculation of the project Sulak with IRENA values

APPENDIX C

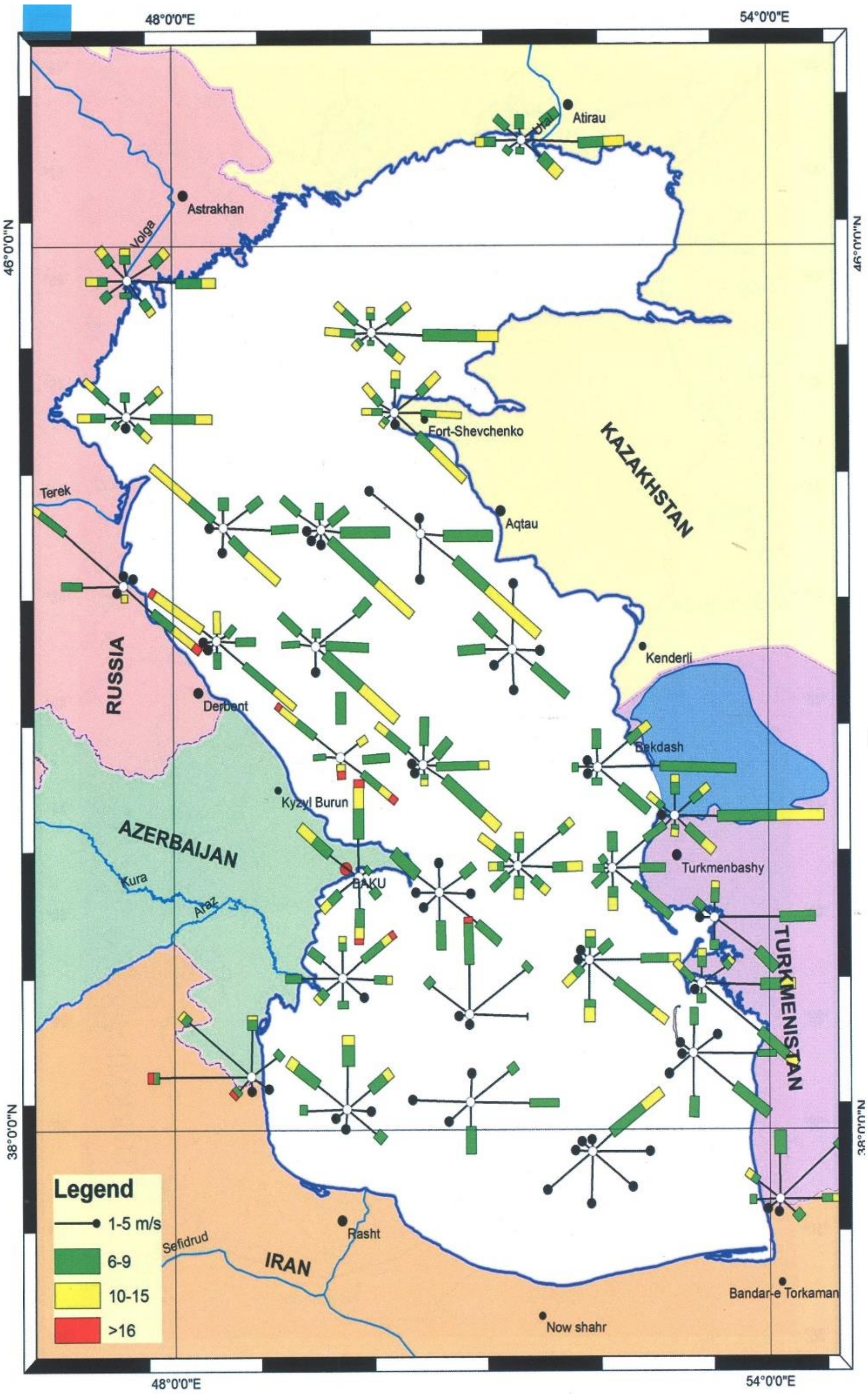

Figure C.1 : Wind roses above the Caspian Sea in January

APPENDIX C

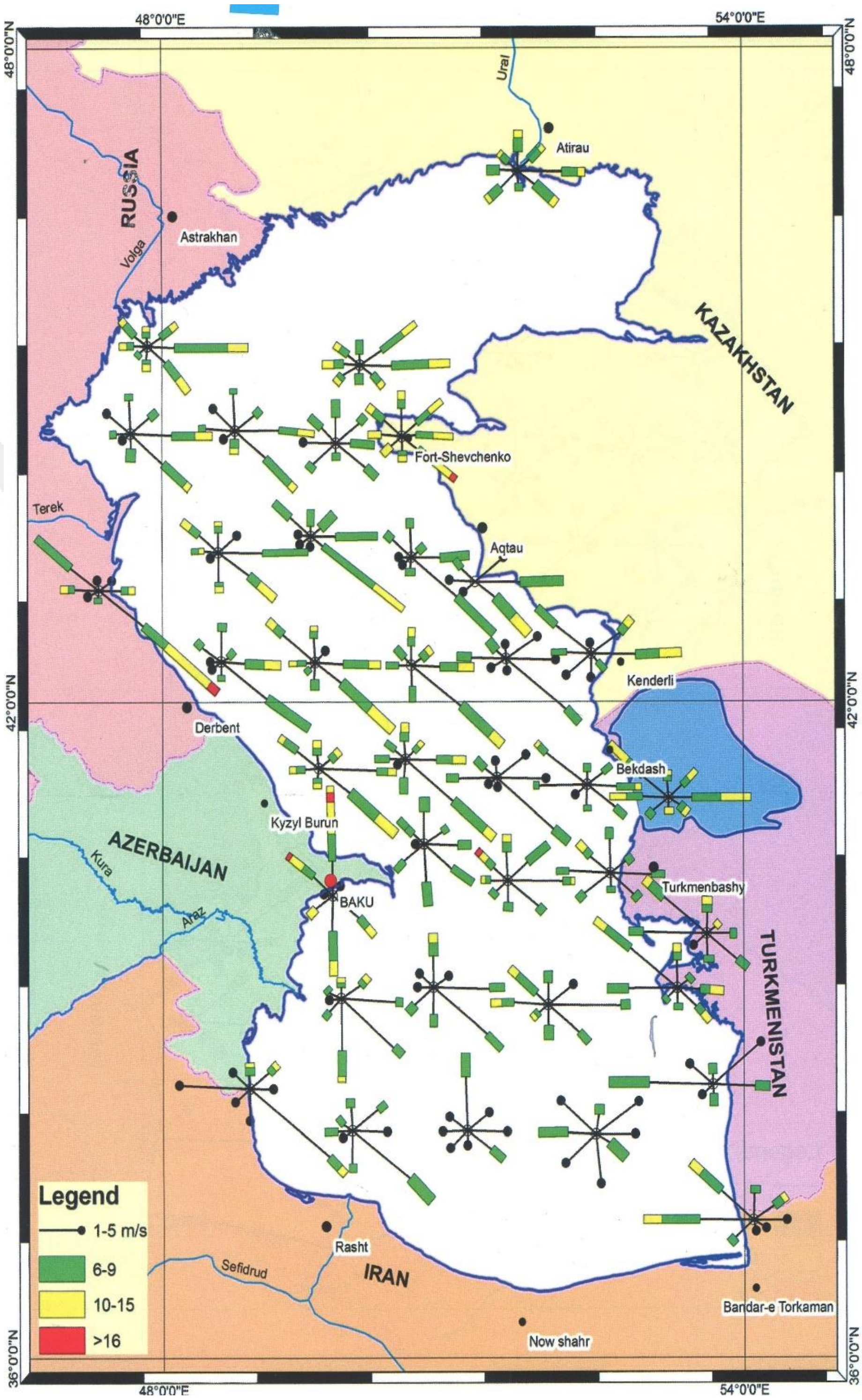

Figure C.2 : Wind roses above the Caspian Sea in April

APPENDIX C

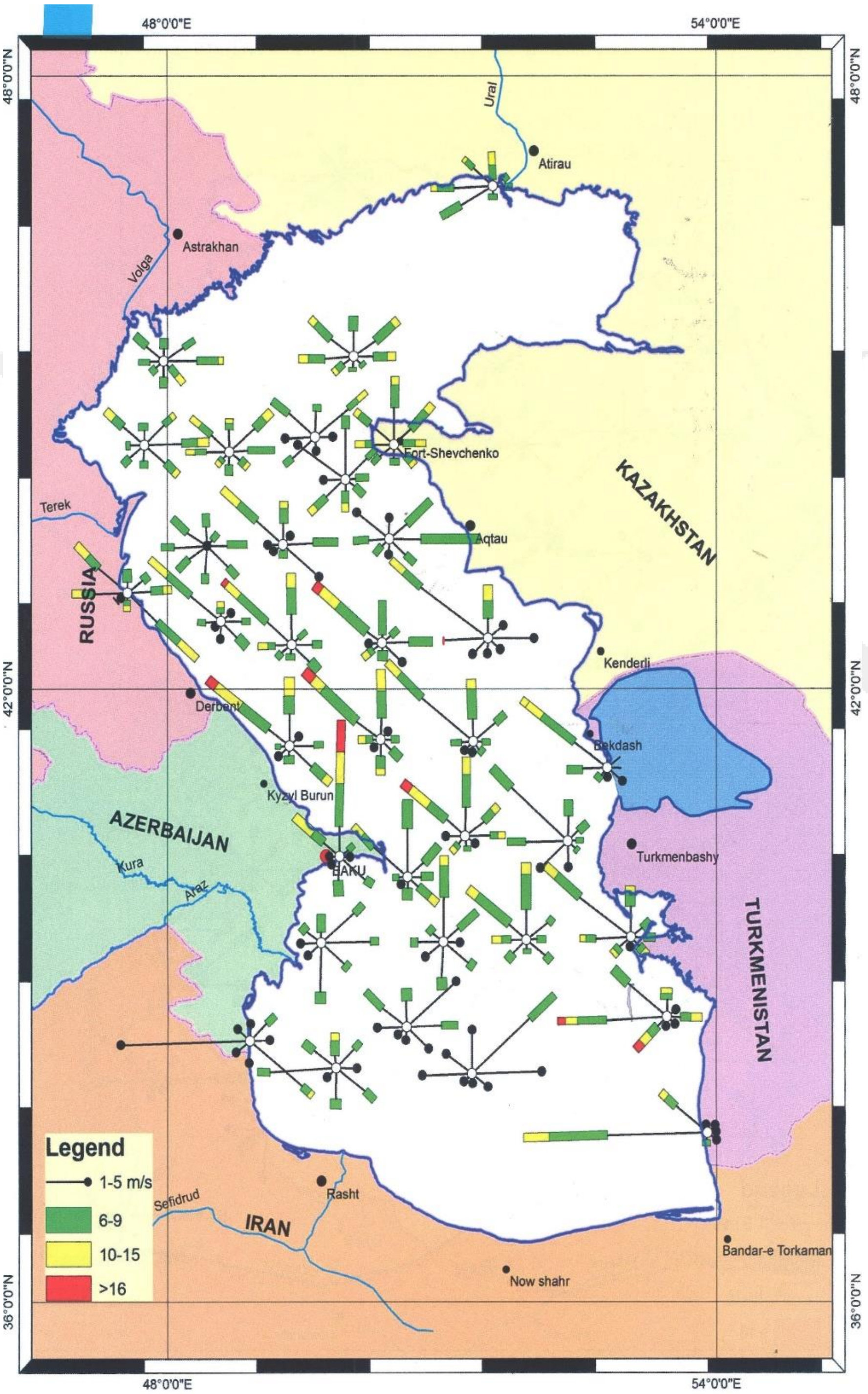

Figure C.3 : Wind roses above the Caspian Sea in July

APPENDIX C

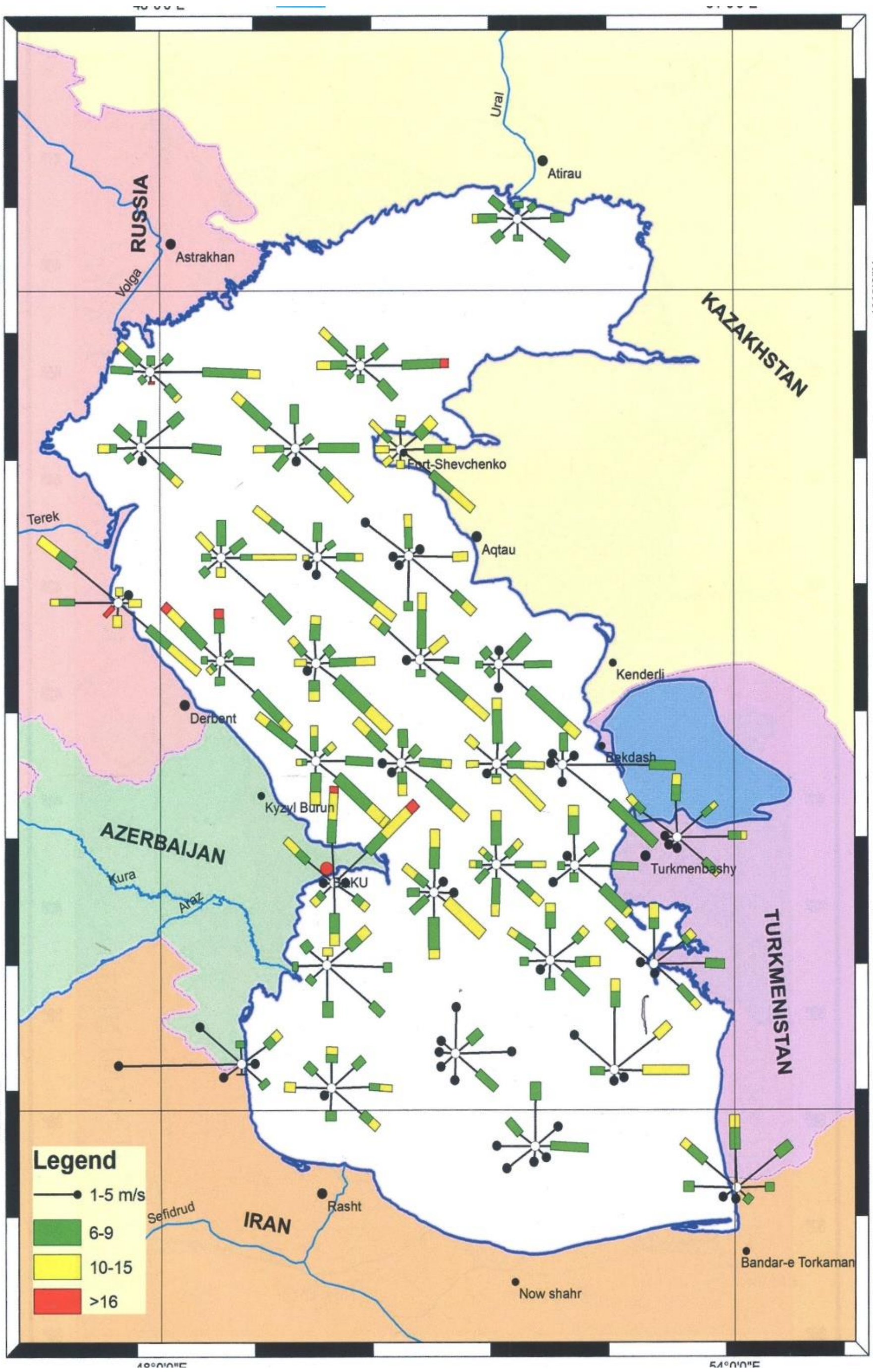

Figure C.4 : Wind roses above the Caspian Sea in October

APPENDIX D

Figure D.1 : Map of inclination angles of the bottom surface

APPENDIX E

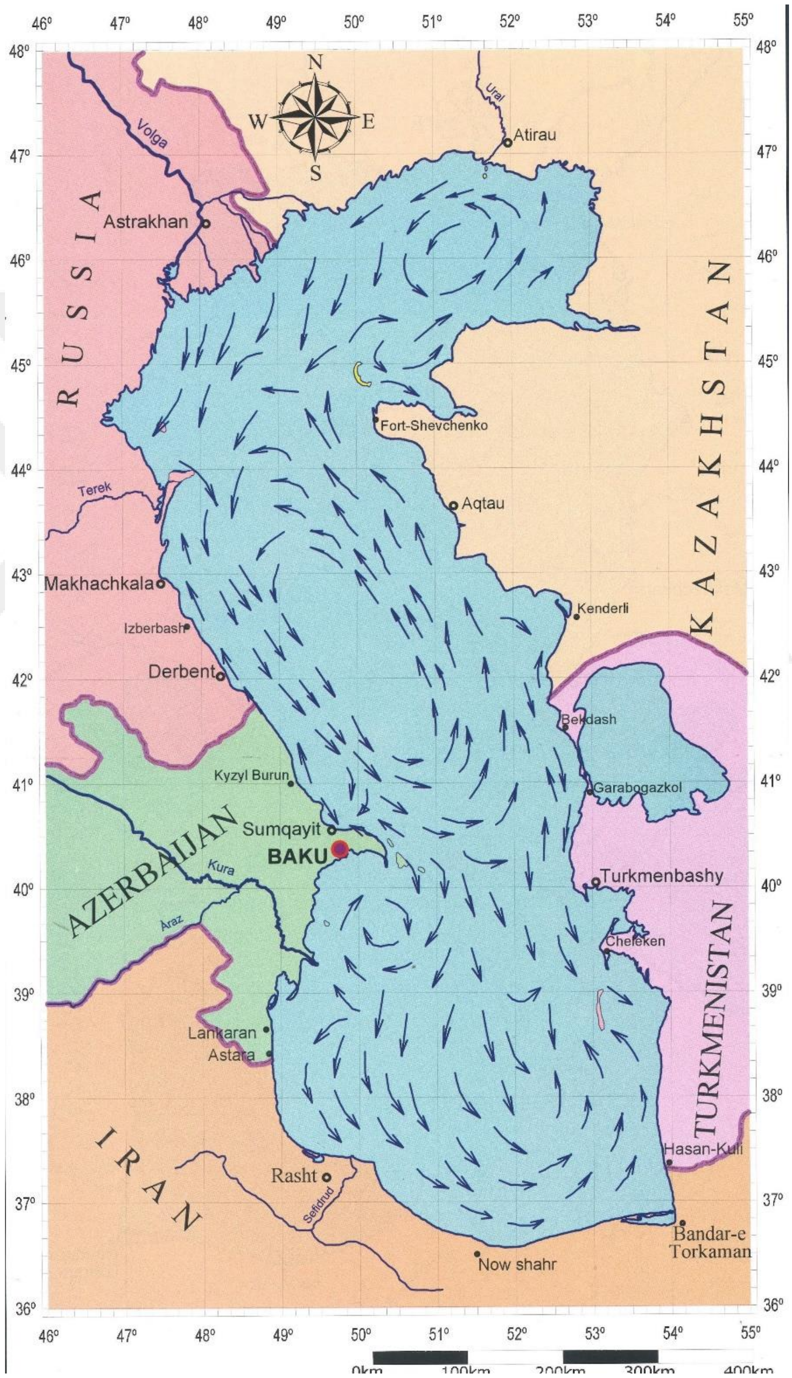

Figure E.1 : Chart of flows of surface waters of the Caspian Sea

APPENDIX F

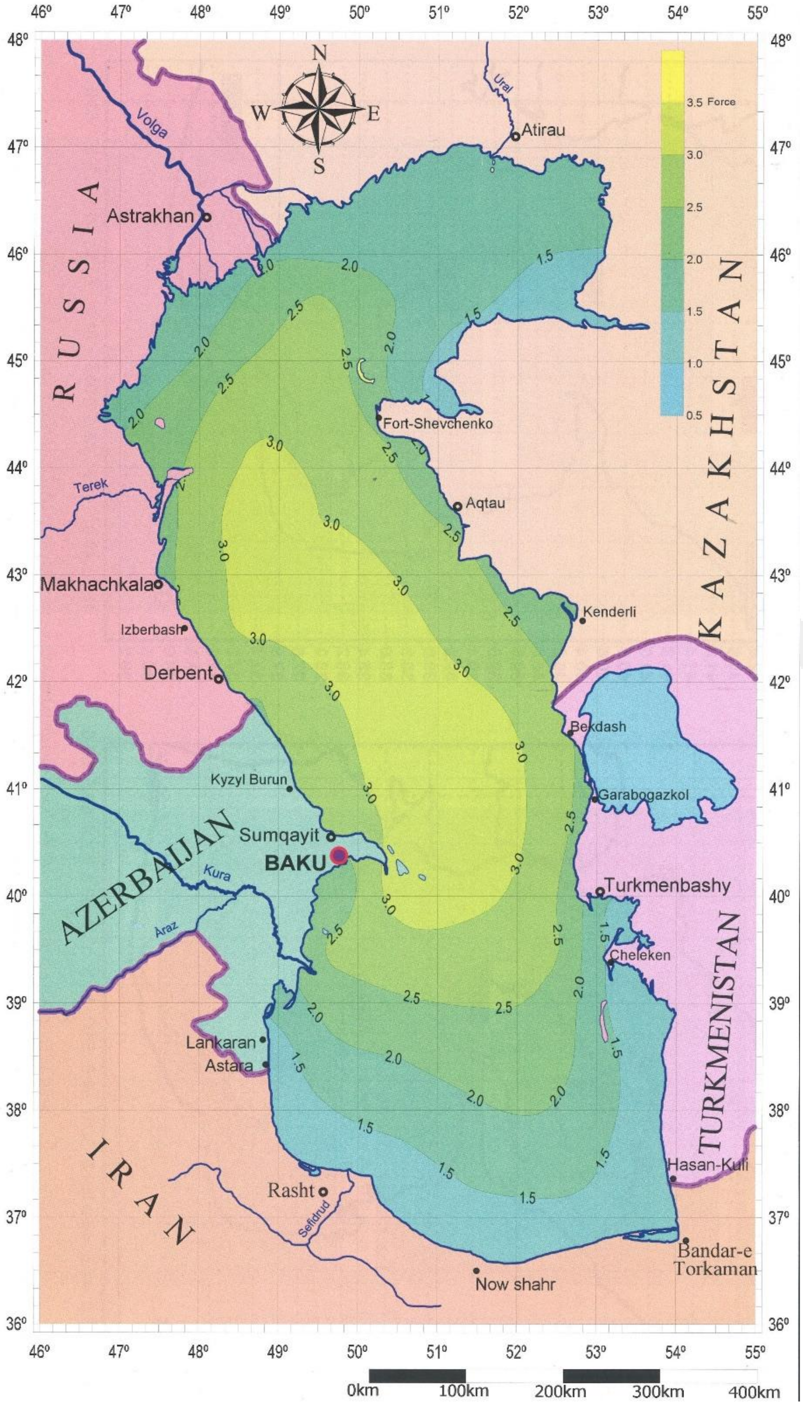

Figure F.1 : Annual mean height of surface waves of the Caspian Sea – with points

APPENDIX G

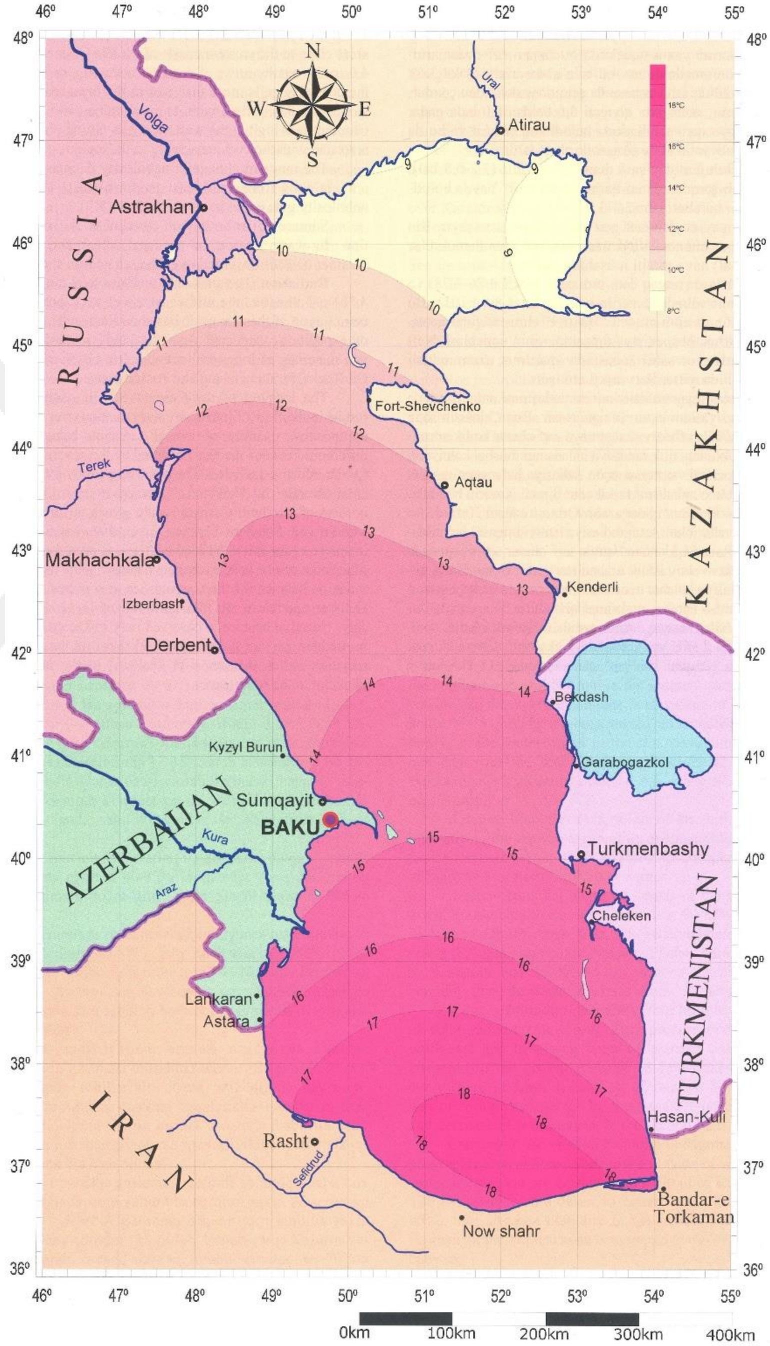

Figure G.1 : Annual mean temperature over the surface of the Caspian Sea

APPENDIX H

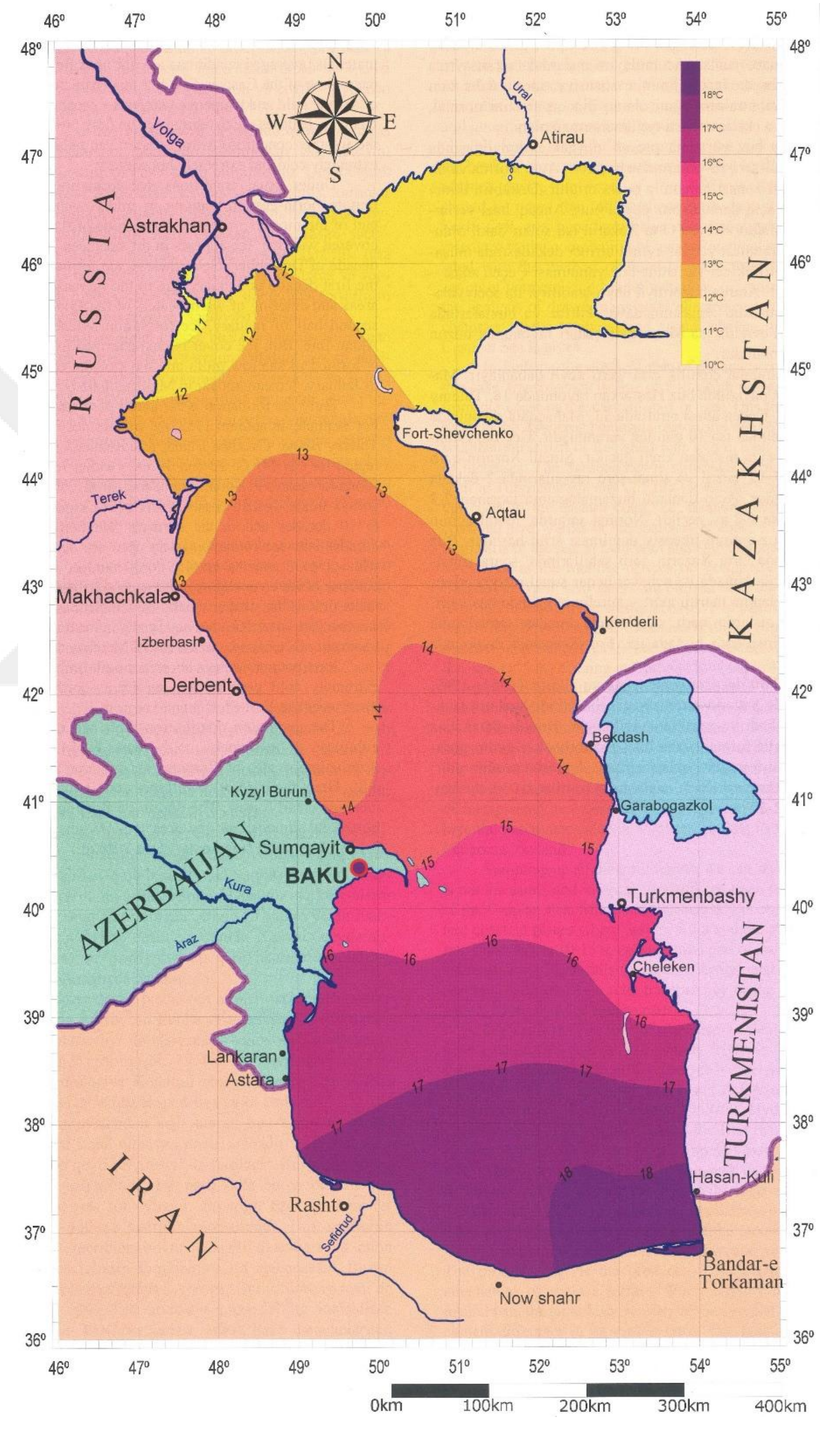

Figure H.1 : Annual mean temperature of surface waters of the Caspian Sea

APPENDIX I

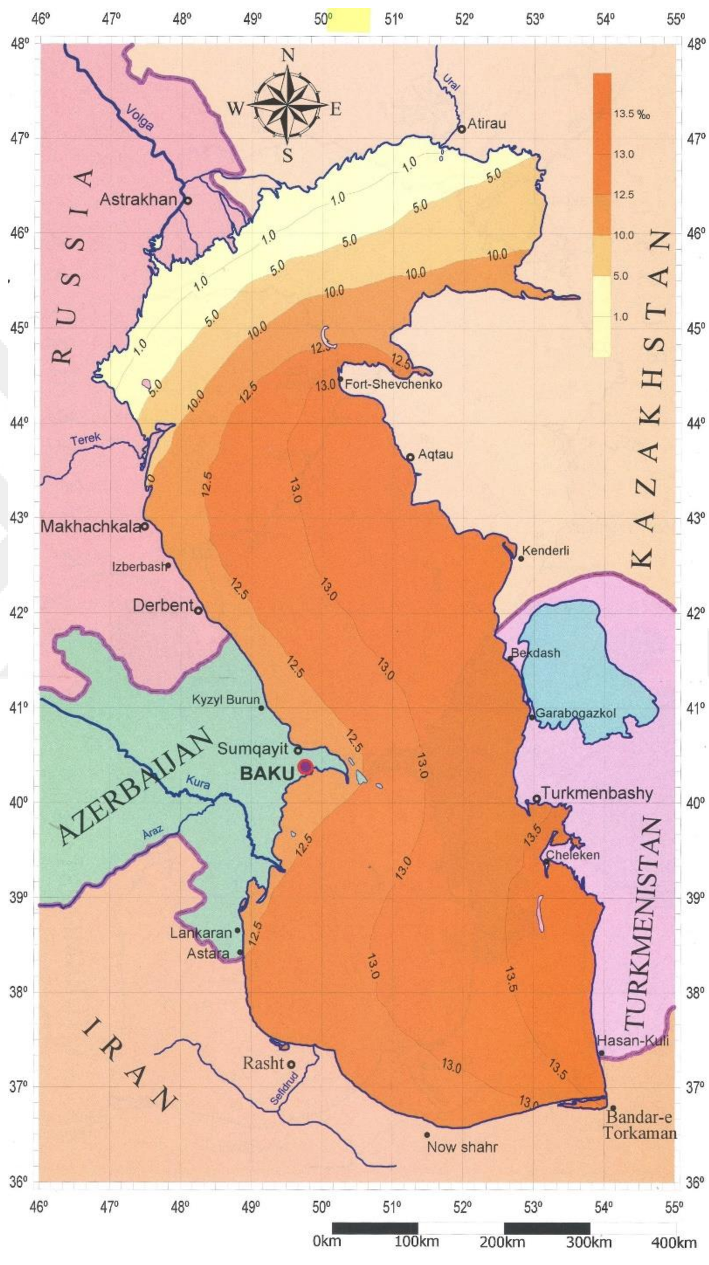

Figure I.1 : Annual mean salinity of surface waters of the Caspian Sea

APPENDIX J

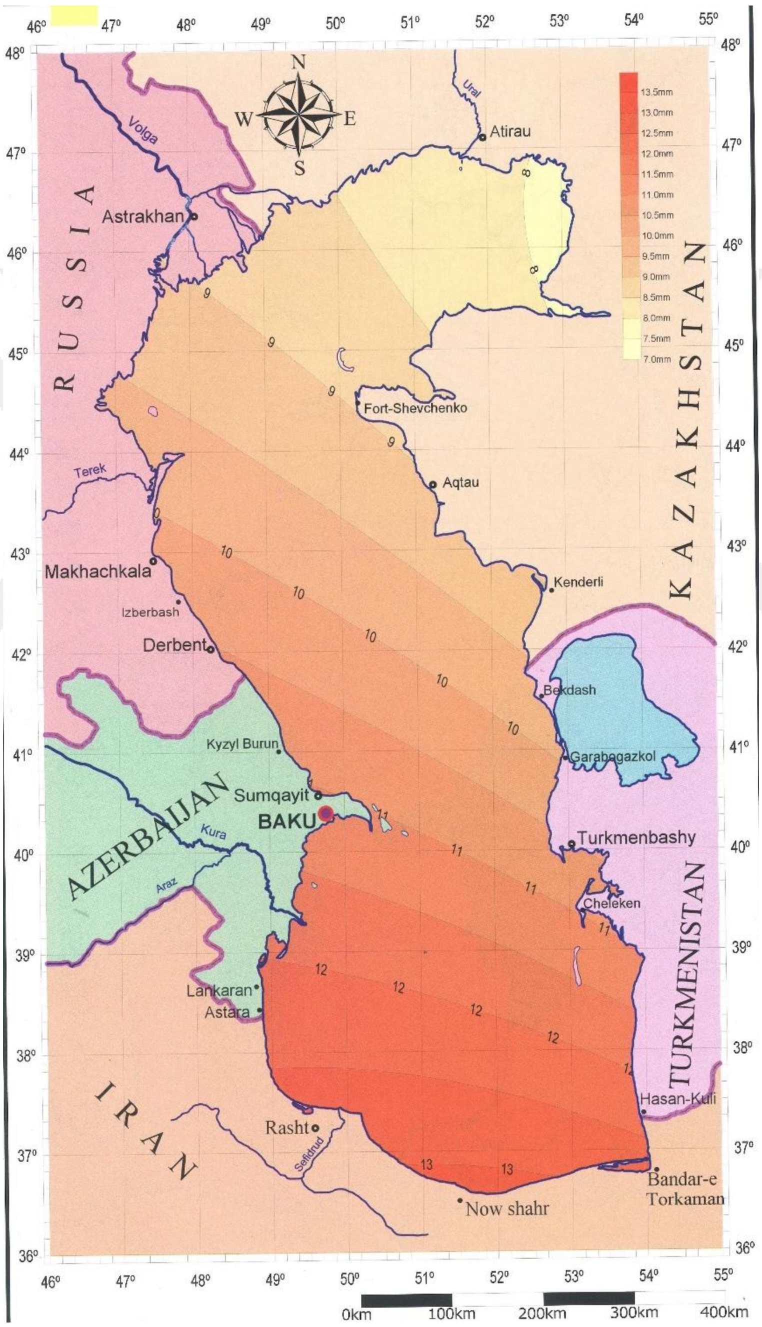

Figure J.1 : Average annual absolute humidity above the Caspian Sea

APPENDIX K

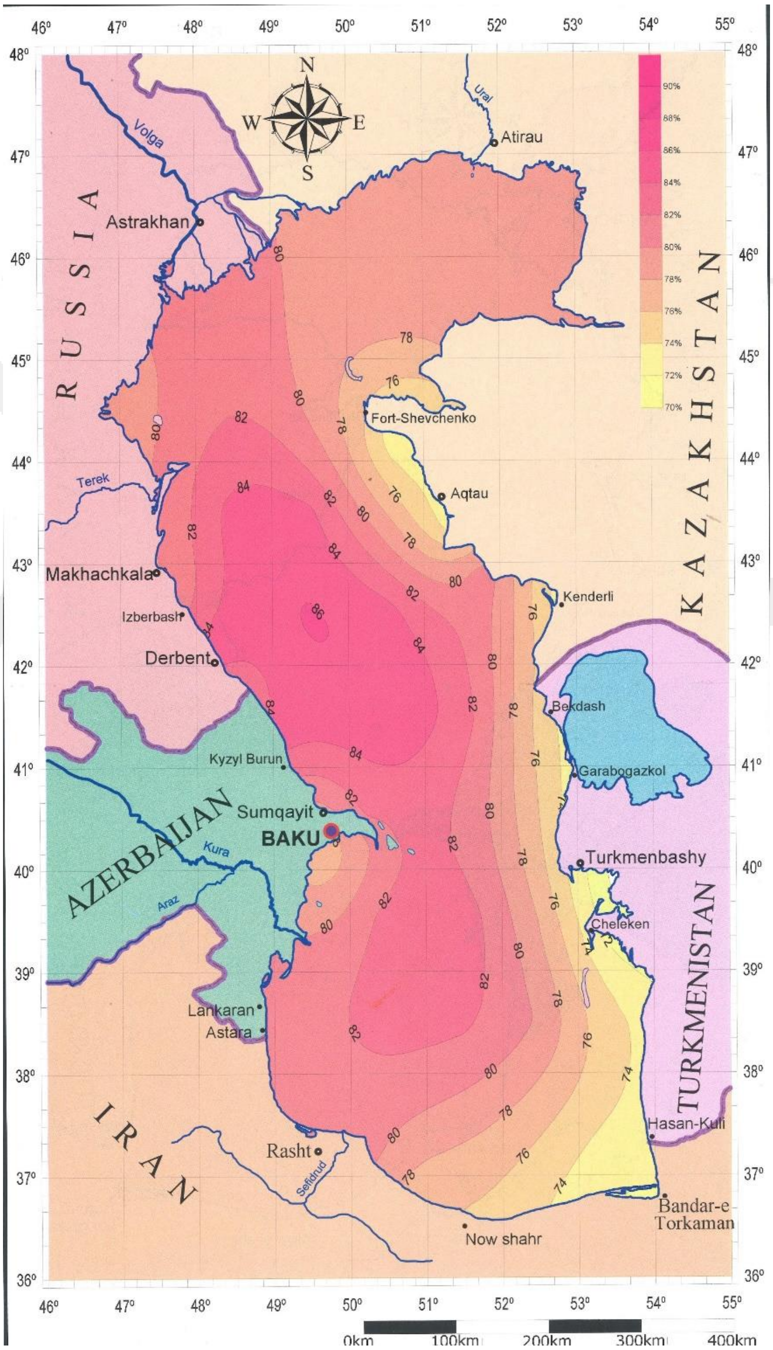

Figure K.1 : Annual mean relative humidity (%) above the Caspian Sea

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