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BY

Ahmed Soheyb BENABADJI

Feasibility study of offshore utility-scale wind farms implementation in Tunisia

Supervisor : Faten Attig Bahar	Dr.	University of Carthage, Tunisia Polytechnic School, Tunisia
Chair : Noara Kebir	Ms.	TU Berlin, Germany
External Examiner : Ancha Venkata Ramayya	Prof.	Jimma University., Ethiopia
Internal Examiner : Kerboua Abdelfetah	Dr.	ESSA, Algeria

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ACCEPTANCE LETTER

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Author(s): *Faten ATTIG BAHAR, Ahmed Soheyb Benabadji, Melik Sahraoui*

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Prof.Maher CHAABENE
Email : info@irec-conference.com

Kesraoui Mohamed <kesraoui_m@yahoo.fr>
to herrmann@ifes.uni-hannover.de, ali.j.mahdi@uokerbala.edu.iq, me, lotfi.saidi@essths.u-sousse.tn, Maher, Fernando

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Acronyms

CAPEX	Capital Expenditures
COP21	The 21st Conference of the Parties
EPT	The Energy Transition Fund
ETF	The Environment Tunisian Fund
EU	European Union
FIT	Tunisian Investment Fund
GW	Giga Watt
Kw	Kilo Watt
LASMAP	Structural And Applied Mechanics Research Laboratory of Tunisia
LCC	Life Cycle Cost
LCOE	Levelized Cost Of Energy
MDT	Million Tunisian Dinars
MV/HV	Medium Voltage/High Voltage
MW	Megawatt
MWh	Megawatt/hour
O&M	Operation and Maintenance
OPEX	Operational Expenditures
PAU	Pan African University
PAUWES	Pan African University of Water and Energy Sciences Including Climate Change
PPA	Power Purchase Agreement
PV	Photo-Voltaic
RETs	Renewable Energy Technologies
SAM	System Advisor Model

STEG	Tunisian Agency of natural Gas and Electricity
ACER	The Agency for Cooperation of Energy Regulators
TSO	Transmission System Operator
UK	United Kingdom
VAT	Value Added Tax

STATEMENT OF THE AUTHOR

I, Ahmed Soheyb BENABADJI, hereby declare that this thesis represents my original work and has not been submitted to another institution for the award of a degree, diploma, or certificate. I also declare that all words and ideas from other works presented in this thesis have been duly cited and referenced in accordance with the academic rules and regulations.

STUDENT:

Name: Ahmed Soheyb BENABADJI Signature:

Date: 24/11/2021

Academic Unit: Energy (Policy Track)

PAU Institute: PAUWES

SUPERVISOR:

Name: Dr. Faten ATTIG BAHAR Signature:

Affiliation: The University of Carthage, Tunisia Polytechnic School

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All thanks go to the staff of the Pan African university, the institute of water and energy sciences who allowed this thesis to be born and who provided all the necessary ingredients for it, to the LASMAP laboratory staff who had the hospitality and the warm welcome for the conclusion and the completion of the very beneficial practical training for this study, and finally, to the very competent and caring supervisor Dr. Faten Attig BAHAR.

Abstract

Climate change is one of the most pressing challenges of our society due to its adverse impact on the earth ecosystem and on the world economy. Improving energy system efficiencies and the massive expansion of renewable energy have become exceedingly important for climate protection.

With its 11.7 Mio inhabitants and its positively growing economy Tunisia has started to diversify its energy mix and to devise ambitious renewable energy plans to meet its growing energy demand in the future while contributing to climate protection. Wind energy, as a component of the green transition, has been given a lot of attention since 2000 in Tunisia.

Offshore wind power has the potential to play a key role for Tunisia in achieving the future renewable energy targets due to the country's favorable geographic location and coastline. Hence; the purpose of this study, is to investigate the potential of offshore wind energy in Tunisia and study the feasibility of a Utility-scale offshore wind farm in terms of prospecting for favorable sites, energy production, CAPEX (capital expenditures), OPEX (operational expenditures) and LCOE (levelized cost of energy).

The case of an offshore windfarm of 30 MW located off the Gulf of Gabes has been studied, the wind potential assessment and power production were determined by simulation using WindPro software, and the capital and operating costs as well as the price of the produced electricity were calculated by modeling the LCOE. Conclusions and recommendations on the feasibility of an offshore wind energy project in Tunisia were presented at the end of the study.

Introduction of the project context and the host institutions

The present work is the first step of a research program aimed at studying the possible implementation and distribution of Onshore and Offshore wind farms in Tunisia and was initiated by the Energy group at the research laboratory of Applied Mechanics and Systems Research (LASMAP) and lead by Dr. Faten Attig Bahar. It is devoted to developing ideas and solutions leading to improve the performance and the cost effectiveness of this technology implementation. Moreover, the work carried out was supported by the Pan African University PAU through its institute PAUWES (Pan African University of Water and Energy Sciences including Climate Change) hosted at University Abou Bekr Belkaid of Tlemcen –Algeria.

The Pan African University Institute of Water and Energy Science (PAUWES)

The Pan African University (PAU) is the culmination of continental initiatives of the Commission of the African Union to revitalize higher education and research in Africa, under the Second Decade of Education for Africa and the consolidated Plan of Action of Science and Technology for Africa. It will exemplify excellence, enhance the attractiveness and global competitiveness of African higher education and research and establish the African University at the core of Africa’s development.

The Pan African University Institute of Water and Energy Science (PAUWES) was created in 2014 by the African Union Commission, in the framework of the Pan African University (PAU), it is hosted by the Abou Bakr Belkaïd University of Tlemcen, and it is seeking a new generation of highly educated, well-trained students who are committed to working as changemakers in the field of sustainable water and energy.

The research laboratory Applied Mechanics and Systems Research (LASMAP)

The LASMAP is a research and technological development laboratory of the Tunisian Ministry of Higher Education and Scientific Research, attached to the Polytechnic School of Tunisia (EPT), University of Carthage. Its expertise is the Development of numerical tools to simulate the behaviors of solids, structures and systems, Multiscale and multiphysical analysis of systems and structures, and Linear and nonlinear dynamics of structures and systems. Some of the laboratory applications are Micro and Nanosystems, Structures, Renewable energy systems, Biomechanics, Smart materials and dynamic systems

General introduction

Wind energy is the world's fastest-growing energy source, and the offshore wind energy business has clearly overtaken all other development options, creating a large number of new jobs. Onshore wind farms currently harvest the vast majority of wind energy. However, the paucity of affordable land near major population centers and the visual impact caused by enormous wind turbines are limiting their development. Offshore wind is a good alternative to onshore wind, with less restrictions and far more attractive performance; at sea, winds are often stronger and more stable, leading in significantly higher production per installed unit, and because it is easier to carry very large turbine components by sea, wind turbines can be larger than on land, opening up vast expanses for the building of massive wind farms.

The Tunisian government has, for the past few years, adopted concrete and carefully considered measures to promote the development of renewable energy and attract foreign and local investment to achieve its objectives in renewable energy share and the aim to get out of the dependence on hydrocarbons. Wind energy, as a component of the green transition, has been given a lot of attention since 2009 in Tunisia. Offshore wind power has the potential to play a key role for Tunisia in achieving the future renewable energy targets due to the country's favorable geographic location and coastline. However, there are currently no offshore wind farm projects, nor experiences in Tunisia.

The presented project explores offshore wind farm feasibility in Tunisia by providing an LCOE model according to the specifications of the energy market in Tunisia. The LCOE model takes into account the legal context; taxes, aids and impositions applied by the Tunisian government, and all expenses related to the purchase of equipment, installation, connection to the public grid, commissioning.

This thesis is divided in three distinct chapters, the first one presents the necessary generalities of the treated field, a state of the art of the wind energy in general and the offshore wind energy with more details as well as a literature review, treating all the aspects and parts of this study. The second chapter concerns the method followed during this research work, it is explained with precision the steps followed during this research and the choice of tools used, with a conclusion explaining the relevance of the methods followed and expected results.

The third chapter is devoted to the presentation of the results followed by the discussion of these results, where each outcome is analyzed and the results are assembled to arrive at an overall result, to finally conclude with a critique and recommendations for the Tunisian government and its energy policy.

CHAPTER ONE

1. INTRODUCTION

Offshore wind energy is a rapidly developing technology in the world, with important technological advances. In Africa, offshore wind energy is still at the experimental stage despite a great natural potential.

In this chapter, all the questions related to the implementation of an offshore wind farm in Tunisia will be formulated, as well as the questions of the adaptability of offshore wind energy to Africa with all its specificities will be raised.

1.1. Main research question

Recognizing the modernity of offshore wind technology, and the inexperience of Tunisia in this field, how feasible is the implementation of an offshore wind project in Tunisia, and what are the determining criteria for assessing the feasibility of such a project.

1.2. Specific research question

- Do the natural wind resources of Tunisia allow the implementation of offshore wind energy?
- Are there suitable sites for the implementation of an offshore windfarm? What are the criteria for site selection?

- Do the existing infrastructures in Tunisia allow the implementation of offshore wind energy?
- Since there has never been any previous experience in offshore wind in Tunisia, does the Tunisian regulatory framework ensure a defined status of offshore wind energy? Does it allow its implementation? Does it bring support mechanisms? Is it sufficient?
- What will be the costs and expenses for such a project? At what price would be set the energy produced by an offshore wind farm in Tunisia?
- What are the environmental risks that an offshore windfarm can represent for the chosen site?

1.3. Research Objectives

- Determine the potential of offshore wind energy to meet the Tunisian government's commitments to achieve 30% RE integration in 2030
- Present the key points for the implementation of an offshore wind farm

1.4. Significance of the study

- This study represents a novelty in the Tunisian context but also in Africa, since the continent has no experience in offshore wind energy.
- The particularity of this study, is to try to estimate the compatibility of the Tunisian legal framework to the offshore wind technology, which has particularities foreign to the previous energy policies set up in Tunisia.

1.5. Scope of the study

- The scope of this study is defined by the objective of reaching 30% of renewable energy share by 2030 only using photo-voltaic and wind energy with a regulatory framework that only considers onshore wind in the details of its laws.

CHAPTER TWO:

LITERATURE REVIEW

1. INTRODUCTION

Offshore wind power has the potential to play a key role in Tunisia to achieve the future renewable energy targets due to the country's favorable geographic location and coastline. However, there are currently no offshore wind farm projects.

This chapter focuses on offshore wind farms and the most important parts of a wind farm and its design will be presented and explained, and also the most determining elements of the location and dimensioning of a wind farm project is presented. Literature survey on the wind farms experiences in north Africa, with focus on offshore is detailed.

1.1. Utility scale wind farms

Utility-scale turbines are usually defined as turbines that exceed 100 kilowatts in size [1]. Utility-scale wind turbines are typically installed in large, multi-turbine wind farms connected to the nation's transmission system.

1.1.1. Onshore wind industry

In the 1980s, the first wind farms were built in California[1]. By the end of the 1990s, wind energy had re-emerged as one of the most important sustainable energy resources. Today, it is the leading source of renewable electricity, and it has become an international business sector, spreading beyond its original markets in a few European countries, India and the United States. The major manufacturers and project developers now operate across five continents. Over 80 countries around the world now contribute to the global total energy production from wind energy [2].

1.1.2. Offshore wind industry

In 1991, at Vindeby in Denmark and at a distance of 2.5 km offshore, the first large commercial offshore wind farm was constructed, having a rated power of 4.95 MW and consisted of 11 Bonus wind turbines of 450 kW each. The water depths at that site are from 2.5 to 5 m and the annual energy production is equal to 12 GWh/year. In 1995, Denmark constructed its second offshore wind farm at Tuno Knob. Currently, the world has 162 offshore wind farms producing electricity, with the UK being the biggest offshore wind market with 10.4 GW of total capacity[3].

Figure 1: Offshore wind farm [4]

1.2. Wind resource assessment

Wind is globally available, and in order to make the choice of potential project sites an affordable and manageable process, some indications on the relative size of the 'wind resource' across an area is very useful. The wind resource is usually expressed as a wind speed or energy density, and typically there will be a cut-off value below which the energy that can be extracted is insufficient to merit a wind farm development.

1.2.1. On-site measurement:

The most accurate indication of the wind resource at a site is through on-site measurement, using an anemometer and wind vane. This is, however, a fairly costly and time-consuming process.

1.2.2. Computer modeling

On a broader scale, wind speeds can be modeled using computer programs which describe the effects on the wind of parameters such as elevation, topography and ground surface cover. These models must be primed with some values at a known location, and usually this role is fulfilled by local meteorological station measurements or other weather-related recorded data, or data extracted from numerical weather prediction models, such as those used by national weather services.

1.2.3. Wind Atlases

Wind Atlas employs meteorological data from a selection of monitoring stations, and shows the distribution of wind speeds on a broad scale. It has been used extensively by developers and governments in estimating the resource and regional variations. It is possible to map wind speeds at a higher resolution, using, for instance, more detailed topographical data and a larger sample size of meteorological data, in order to show more local variations in wind speed. This can be used by developers looking for sites in a particular country

1.3. Local Wind Resource Assessment and Energy Analysis

For the majority of prospective wind farms, the developer must undertake a wind resource measurement and analysis program. This must provide a robust prediction of the expected energy production over its lifetime.

Wind energy has the attractive attribute that the fuel is free and that this will remain the case for the project lifetime and beyond. The economics of a project are thus crucially dependent on the site wind resource.

1.3.1. The annual variability of the speed

A 'wind rose' is the term given to the way in which the joint wind speed and direction distribution is defined. The duration for which the wind comes from this sector is shown by the length of the spoke and the speed is shown by the thickness of the spoke. The design of a wind farm is sensitive to the shape of the wind rose for the site.

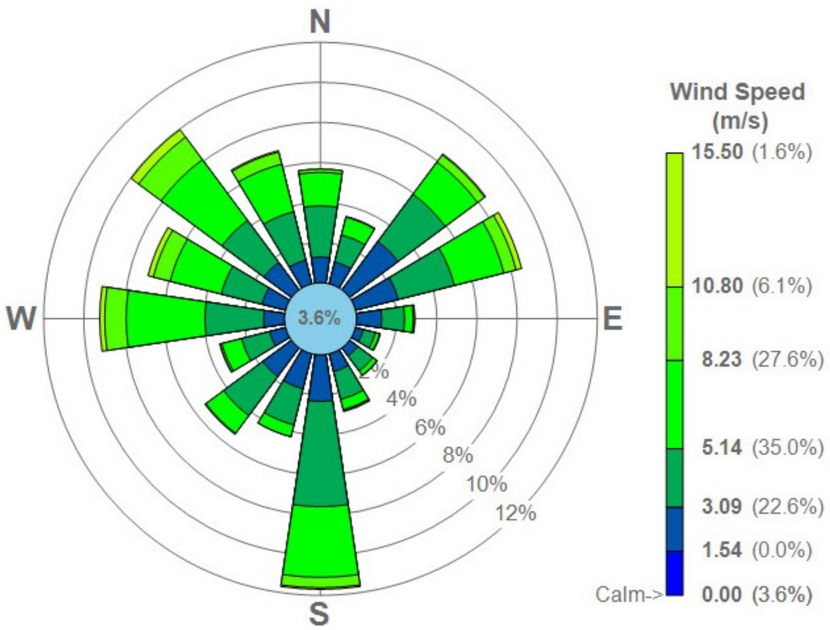


Figure 2: Wind rose

1.3.2. Analytical methods for the prediction of the long-term wind regime at a site:

The key element of the energy production assessment of a proposed wind farm site, is the prediction of the long-term wind regime at the site. The outcome of the variability of one-year period analysis and the variability of three years period analyses is a long-term wind speed distribution, together with the wind rose. Other meteorological inputs to the energy production analysis are the long-term site air density and site turbulence intensity, a measurement of the 'gustiness' of the wind. These, while still important, are of secondary influence to the energy production of the wind farm, and therefore their derivation is not considered in detail here. It should be noted, however, that the turbulence intensity is very important in determining the loading on a wind turbine, and hence its life expectancy.

1.3.3. The prediction of the energy production of a wind farm

In order to predict the energy production of the wind farm, it is necessary to predict the variation in the long-term wind speed over the site at the hub height of the machines, based on the long-term wind speeds at the mast locations; predict the wake losses that arise as a result of one turbine operating behind another, in other words in its wake; and calculate or estimate the other losses.

2. OFFSHORE WIND FARMS

Offshore wind turbines were first commissioned first in 2000. Since then, this technology has been continuously developed for technical and practical reasons. One advantage of this technology is that the wind resource is higher at the coast and the roughness length z0 is significantly smaller than at land. Another aspect that supports the development of offshore wind technology is that wind projects usually occupy a large area which often conflicts with high density population regions.

Figure 3: Offshore wind turbine development for deep water [6]

Designing an offshore wind farm is a staged process involving, data-gathering; preliminary design and feasibility study, site investigation, concept development and selection, value engineering, specification and detailed design [1]. There are generally five main stages in the lifecycle of an offshore wind farm, for each stage different actors are involved as shown in Figure 2.

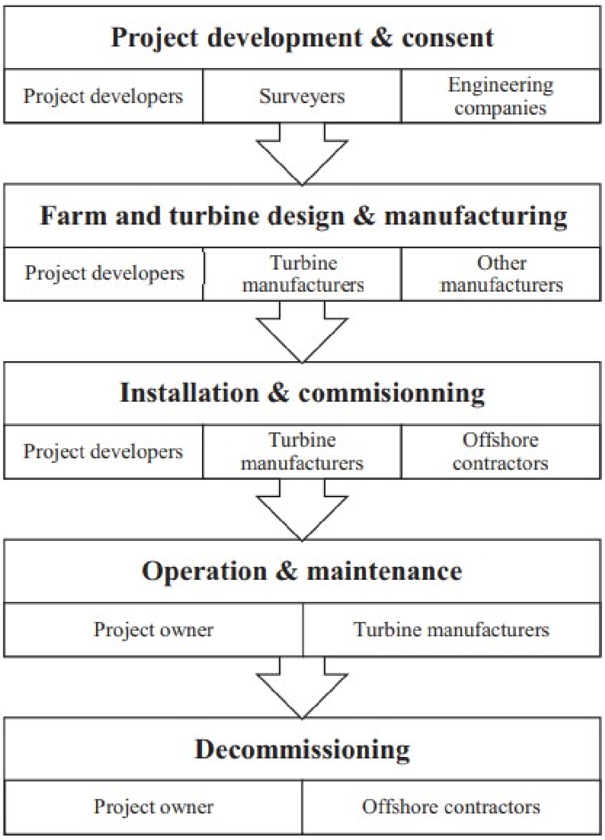


Figure 4: Offshore wind farm life cycle and main actors [5].

Close interaction throughout the design process is required, including interaction about the grid connection arrangements and constraints introduced through the consenting process. Key aspects of the design, and the process of arriving at that design, are described in the following sections. The capital cost of offshore projects differs markedly from those onshore, with nearly 50 per cent of the capital cost being due to non-turbine elements, compared to less than 25 per cent in onshore projects.

Before any fieldwork is undertaken, it is important to determine and measure the wind potential at a given site, and there are several ways of doing this which differ according to the means and purpose of the assessment.

2.1. Wind Resource Assessment for Offshore

Onshore, topographic effects are one of the main driving forces of the wind regime. With no topographic effects offshore, other factors dominate the variation in wind speed with height. The low surface roughness also results in low turbulence intensity. This serves to reduce mechanical loads. It also may increase the energy capture compared to an identical wind turbine at an onshore location with identical mean wind speed.

A further factor influencing offshore winds can be the tide level in areas with a high tidal range. The rise and fall of the sea level effectively shift the location of the turbine in the boundary layer. This can have impacts in variation of mean wind speed within a period of approximately 12 hours, and also on the variation in mean winds across the turbine rotor itself. Temperature-driven flows due to the thermal inertia of the sea initiate localized winds around the coastal area. Compared to the land, the sea temperature is more constant over the day. During the day, as the land heats up, the warmer air rises and is replaced by cooler air from over the sea. This creates an onshore wind. The reverse effect can happen during the night, resulting in an offshore wind. The strength and direction of the resulting wind is influenced by the existing high-level gradient wind, and in some situations the gradient wind can be canceled out by the sea breeze, leaving an area with no wind. Finally, as all sailors are aware, close to the coast there are 'backing' and 'veering' effects.

2.2. Site Selection and Factors Affecting Turbine Location

The fundamental aim to optimize the site selection and the turbine's distribution is to maximize energy production, minimize capital cost and operating costs, and stay within the constraints imposed by the site.

The factors affecting the wind farm location are the following:

- maximum installed capacity (due to grid connection or power purchase agreement terms);
- site boundary and distances from roads, dwellings, overhead lines, ownership boundaries and so on;
- environmental constraints;
- location of noise-sensitive dwellings, if any, and assessment criteria;
- location of visually-sensitive viewpoints, if any, and assessment criteria;
- location of dwellings that may be affected by 'shadow flicker' (flickering shadows cast by rotating blades) when the sun is in particular directions, and assessment criteria;
- turbine minimum spacings, as defined by the turbine supplier (these are affected by turbulence, in particular); and
- constraints associated with communications signals, for example microwave link corridors or radar.

The potential for offshore wind is enormous in Europe and elsewhere, but the technical challenges are also great. The capital costs, the project sizes are more important than in the case of onshore wind farms.

3. LITERATURE REVIEW

3.1. Offshore experiences in Europe and Africa

Both in Europe and worldwide, wind power is being developed rapidly. In 2008, more wind power capacity was installed in Europe. Between 2005 and 2010, the EU wind energy industry has created more than 60,000 new jobs. The wind energy sector in Europe is generating new employment for 33 new people every day, 7 days a week over this period[7].

3.1.1. Offshore wind farms development and localization and

Projects localization

Wind energy is a fastest-growing energy worldwide and this energy has become an important energy source in the world's energy markets, with a market size 36.5 billion. The wind now generates more than 1.5% of the world's electricity by 2019. The wind industry also creates many new jobs; over 400,000 people in 2010.

In the EU, onshore wind energy will continue to be the largest contributor to employment through the next few years. Offshore wind energy sector has also been the fastest in its development compared to other energy sources.

At present, the vast majority of wind power is generated from onshore wind farms. However, their growth is limited by the lack of inexpensive land near major population centers and the visual pollution caused by large wind turbines[7], [8] .

Development

Development of new wind farms requires large ocean space. Therefore, there is a need for an efficient spatial planning process. Due to technical nature, the useful surface area at depths of less than 50 meters is required for offshore wind farms

The geophysical characteristics of the area is the primary reason for low feasibility of offshore wind technology and the inclusion of environmental factors and marine activities reduced the overall integrated feasibility and space availability for wind farms. [8], [9].

Offshore wind energy in Europe began in shallow waters of the North Sea where the abundance of sites and higher wind resources are more favorable by comparison with Europe’s land-based alternatives. The first installation was in Sweden with a single 300-KW turbine in 1990 and the industry has grown slowly over the past 15 years. Offshore wind currently accounts for a small amount of the total installed wind power capacity in the world. Nine countries have operating offshore wind farms: Belgium, Denmark, Finland, Germany, Ireland, Italy, the Netherlands, Sweden and the UK. By the end of 2008, 1473 MW of wind turbines were in operation offshore, more than 99% of it in Europe, representing slightly more than 1% of the total installed wind turbine capacity. 366 MW were added offshore in 2008 (compared to 8111 MW onshore), equaling a growth rate of 30%. The development of offshore wind has mainly been in northern European countries, around the North Sea and the Baltic Sea[7].

Development of offshore wind energy in the Nordic countries has been remarkable. This can be attributed to two factors, the geophysical characteristics of the North and Baltic Seas and also the support that the National governments are giving this technology. But the development and diffusion of offshore wind energy can be shaped by the barriers of cost, project risk and complexity, capital requirements, and multidisciplinary and the lack of energy policies that create stable regulatory framework for renewable energies and that guarantee the return of investments over the life of the facility [5], [9].

The growing European demand for clean electricity has provided the North African countries with the opportunity for foreign investments in RETs, capacity building and knowledge transfer[10].

In Africa, the coast of Western Africa at the Equator possesses a fair wind resource potential, followed by Angola and Southern Africa west coast with a good resource potential, while the northern and south-eastern coasts recorded an excellent wind resource for diversified energy mix and developing economy[11]. Currently, there are no offshore wind farms in Africa, but exploration and measurement studies of the wind potential in Africa are increasing and are proving to be very promising.

Advantages

There are many advantages of offshore wind energy, compared to its onshore counterpart. Offshore wind power is more complex and costly to install and maintain but also has several key advantages. Winds are typically stronger and more stable at sea, resulting in significantly higher production per unit installed. Wind turbines can also be bigger than on land because it is easier to transport very large turbine components by sea. Installing wind turbines sufficiently far from the shore can nearly eliminate the issues of visual impact and noise. This makes it possible to use different designs for the turbines, improving their efficiency. This also makes huge areas available for the installation of large wind farms. As transportation and erection are made at sea, there is virtually no limit on the size of the turbines that can be installed, as opposed to limits imposed by road restrictions onshore. Also, offshore wind farms can be installed close to major urban centers, requiring shorter transmission lines to bring this clean energy to these high energy cost markets [7].

3.1.2. Legal framework

Mapping of the legal framework in Europe

In Europe, it is suggested that policy makers can affect the cost and profitability of an offshore wind project in many ways. At a continental level, the EU has enforced legislation on the European electricity and gas markets called the “Third Package”. The aim of the Third Package was to further liberalize European energy markets by

2014 to provide an integrated European electricity market. The Agency for Cooperation of Energy Regulators (ACER) was set up in 2011 to further progress the completion of the internal energy market for both electricity and natural gas by ensuring that market integration and harmonization of regulatory frameworks are done in respect of the EU's energy policy objectives. The decrease in project costs coupled with an increase in offshore wind subsidies should see offshore wind becoming a critical renewable source of electricity and the feed-in tariff policy reduces the energy price and increases wind farms profitability [12], and a feed-in tariff higher than the breakeven point, would attract private sectors to invest on this type of energy system [13].

If the project developer is responsible for the grid connection, the costs are allocated to the investment costs of the project. In fact, in France, the UK, Ireland and Sweden the project developer is required to supply the grid connection, while in Denmark and Germany the transmission system operator (TSO) supplies the grid connection [12]. However, if the TSO is responsible, the costs are excluded from the project costs.

Therefore, energy policy makers can have a direct impact on the capital costs of an offshore wind project. Governments and other public actors are crucial to offshore wind, leading the planning process for offshore wind farms and providing support mechanisms to offshore wind. Among the most common support mechanisms:

Table 1: Examples of support mechanisms in energy policy and countries using those support mechanisms (information source [14]–[16]**)**

Feed in tariffs	It offers long-term contracts to renewable energy producers and cost-based compensation to renewable energy producers, providing price certainty. It provide also guaranteed grid access, long-term contracts and cost-based purchase prices[14].	As of 2019, feed-in tariff policies had been enacted in over 50 countries, including Algeria, c, Denmark, Estonia, France, Germany, Greece, Hungary, Iran, Republic of Ireland[15]
Green Certificates	A green certificate is a tradable asset which proves that electricity has been generated by a renewable (green) energy source. It is also referred to as Renewable Energy Certificate (REC), Renewable Obligation Certificate (ROC) or more generally a Guarantee of Origin (GO or GoO) from a renewable energy source. Through Green Certificates, governmental policies require suppliers to have a certain percentage of renewable production in their supply portfolio.	Poland, Sweden, UK, Italy, Belgium…
PPAs	A Power Purchase Agreement (PPA) is a long-term contract for the delivery of electricity between two parties, usually a generator and a buyer of electricity (consumer or trader). The PPA details all the terms and conditions of the sale of electricity (the quantity of electricity to be delivered, the negotiated prices, the accounting method and the penalties for non-compliance).	The use of PPAs has been increasing around the world and they are commonly used in Europe, the U.S., and in Latin America [16].

The policy makers can also affect offshore wind projects through financial support schemes (e.g. Feed in tariffs or green certificates), total remuneration levels, regulatory framework and the geographic conditions (water depth and distances to shore) of offshore wind zones. A government's ability to affect the profitability of an offshore wind farm through changes to the electricity markets directly impacts the wholesale cost of electricity therefore any changes to the electricity markets requires careful consideration [12].

Mapping of the legal framework in North Africa

In Africa, Morocco and Tunisia have worked on the inclusion of green economic strategies in their national planning and strategies,

Table 2 – Renewable energy legal framework in Tunisia and Morocco (Information sources[17]–[19])

Tunisia RE framework		Morocco RE framework	
2008	Announcement of the National Energy efficiency program.	2009	(Law 13.09): Establishment of core regulation mechanisms for the production and commercialization of renewable energies.
2009	Announcement of the Tunisian Solar plan 2010/2016.	2009	Creation of the Moroccan Agency for Solar Energy "MASEN" (Law 57.09):
2012	Preparation of new regulatory framework for RE (Electricity production)	2008	Law of self-generation of power (Law 16.08): self-generation by industrial sites from 10MW to 50MW.
2012	New constitution states the climate must be protected. Under Article N°. 44 of the new constitution, the state shall “Provide the means necessary to guarantee a healthy and balanced environment and contribute to climate integrity.”	2009	Creation of the Agency for the Development of Renewable Energy and Energy Efficiency (Law 16-09)
2014	Law N°. 12: Electricity production from Renewable energy.	2009	Law 47-09 on Energy Efficiency Includes a range of measures (mandatory energy audits, minimum energy performances standards for appliances and preferential tariffs (known as «super-peak” tariffs) for industries that voluntarily shift their energy consumption away from peak periods
2015	Decree N°.1123: Definition of conditions and procedures for implementing RE projects.	2010	Morocco Renewable Power Tenders (MASEN)

2016	Call for projects for 210 MW in May 2017. Official document on the technical requirements for connection and evacuation of energy produced from RE installations connected to the low voltage grid	2015	Morocco Net-Metering legislation (Law n°58-15): Net-metering scheme for solar PV and onshore wind plants and only power plants connected to the high-voltage grid may participate.
2017	Call for projects for 210 MW in May 2017. Publication of the official document on the technical requirements for connection and evacuation of energy produced from renewable energy installations connected to the low voltage grid (all regimes).	2015	Morocco Renewable Energy Target 2030 The 2009 National Energy Strategy set out an ambition for 42% of the total installed power capacity to come from renewable energy in 2020. Plan for an energy mix of 52% of the total by 2030 (20% solar, 20% wind, 12% hydro).
2018	Authority acceleration plan for renewable energy implementation	2016	Morocco ratified and signed the Paris agreement
2019	Revision of the PPA and the MoP for the authorization regime and auto-production regime.		

3.2. The cost of offshore wind energy

Offshore wind turbines are still around 50% more expensive than onshore wind turbines [2]. The higher offshore capital costs are due to the larger structures and complex logistics of installing the towers. The costs of offshore foundations, construction, installations and grid connection are significantly higher than onshore. The main differences in the cost structure between onshore and offshore turbines are linked to three issues: foundations are considerably more expensive for offshore turbines. Transformer stations and sea transmission cables increase costs. Installation cost increase both due to increasing distance to the coast and water depth [7].

2.1. LCC (Life Cycle Cost)

LCC (Life Cycle Cost) describes the entire costs of a project over its entire service lifetime. A comprehensive consideration of all costs incurred and the calculation of the LCC are essential to predict the profitability of a project as well as to compare alternative investments and make decisions regarding their use[20]. The basis for life cycle cost analysis is development and consenting, production and acquisition (Substructures, Mooring and Grid connection), installation and commissioning, total capital expenditures, operation and maintenance and decommissioning [21].

2.2. LCOE (Levelized Cost of Energy)

The financial attractiveness of an offshore wind farm project is defined by the LCOE amount. The costs of different generation technologies (wind versus photovoltaics) or the costs of different designs of a generation technology (fixed versus floating foundation) can be compared with one another using the LCOE method. The LCOE describes the costs that are required to generate 1 kW hour of electricity and it considers the initial capital expenditures (CAPEX) as well as all annual operating expenditures (OPEX) and the annual generated electricity (EPNET) incurred over the total project lifetime[20].

The most widely used indicator to compare electricity costs is the levelized cost of energy (LCOE), which gives the present average unit cost of electricity for a certain generation technology. The current LCOE estimates for offshore wind fluctuates between 120 and 340 US $/MWh. By comparison, the current range for conventional fossil fuel technologies of the LCOE studies is 38–140 US$/MWh [5].

Different LCOE models

Several LCOE models currently exist and are used to determine prices for wind energy. NREL (National Renewable Energy Laboratory) uses SAM (System Advisor Model) to compute the LCOE using wind farm data for PPAs (power purchase agreement). Equation (1) is the LCOE model used in SAM

$$LCOE = \frac{\sum_{i=0}^{n} \quad \frac{CPE_i}{(1+r)^i}}{\sum_{i=0}^{n} \quad \frac{E_i}{(1+r)^i}} \qquad Equation\ (1)$$

where CPEi is the cost to produce energy in year i and each parameter is given in the *i*th year. In the SAM model, the LCOE is calculated based on expected cash flows for O&M and capital expenditures. Although cash flow is important for determining the actual money spent and costs involved in a wind farm project, SAM does not recognize the implementation of penalties or tax credits in its wind LCOE model. The SAM model does calculate a PPA price within its financial model that does not include tax credits, but the PPA price is only a discounted value from the calculated LCOE and does not capture the impact of penalties [16].

Similar to SAM, most conventional LCOE models do not include tax credits, production losses, or penalties. Some LCOE models, such as Equation (2) consider a more detailed break-down of parameters

$$LCOE = \frac{\sum_{i=0}^{n} \quad \frac{I_i+OM_i+F_i-PTC_i-D_i-T_i+R_i}{(1+r)^i}}{\sum_{i=1}^{n} \quad \frac{E_i}{(1+r)^i}} \quad \text{Equation (2)}$$

Equation (5) explicitly includes the following costs: fuel cost (F), production tax credit (PTC), depreciation (D), tax levy (T), and royalties (R)[3]. Equation (2) includes fuel cost and royalties that are not relevant (equal to zero) for wind, however, they are included in the proposed model for generality. Unlike Equation (1), Equation (2) recognizes that the tax credits reduce the total cost, but it does not recognize PPA penalties as a cost [16].

Other models have also been used, such as:

$$LCOE = \frac{CRF}{E}(I + OM) \qquad \text{Equation (3)}$$

where CRF is the capital recovery factor. Equation (6) considers the LCOE as a direct project cost and not the sum of the TLCC (Total life-cycle cost) of wind farms, which should include tax credits and PPA penalty costs in the TLCC. PPAs typically consider tax credits as a part of LCOE and explicitly in Equation (5). Tax credits are a mechanism used to reduce the cost of producing energy. In the case of renewable energy technologies, tax credits reduce the LCOE by creating another source of revenue, thus allowing them to compete in the market against other energy sources such as coal and oil. The extra revenue generated by tax credits is included in the LCOE equation and is then incorporated into the PPA price [16].

3.3. Renewable and wind energy in Tunisia

Tunisia is endowed with an enormous potential in renewable energy resources (availability of sunshine and existence of very windy regions) due to its geographical position, and the availability of a long coastline on the Mediterranean Sea, which allows the installation of offshore wind farms.

Looking at the installed capacities, it becomes obvious that the need for new power plant capacity in Tunisia is substantial as Tunisia needs to meet the 30% renewable electricity in the energy mix by 2030 [22].

3.3.1. Legal framework renewable energy

The increasing interest of the country to develop renewable energy is clearly displayed through the careful elaboration of laws and decrees. Indeed, in 2009 the renewable legal framework introduced the concept in law N°2009-7 text. Then the ministry developed the **Grid Code in 2011** to specify the condition of connection from Renewable to the National Grid. To cover all the aspects of renewable **in 2015, the Law for renewable N°2015-12** is submitted. At the moment, the Tunisian's legal framework now has a turning point, with the approbation of the application **decree** of the Law N°2015-12 **in August 2016**, finalizing the legal framework of Tunisia regarding Renewable Energy to support and promote renewable energy projects[23].

For the acquisition of the right to install a renewable energy power source, the owner must apply for three different permits;

Environmental permit of which the environmental assessment study done beforehand by consultants and experts must be included,

Grid connection permit provides the project the permission to connect new installations to the network, making the subscriber responsible for the connection fee, and the cost will be determined by the STEG, after an analysis of technical specifications.

Land permit where the producer must negotiate a concession agreement[24].

Table 3- The different RE project schemes in Tunisia[24]

AUTORISATION RÉGIME	Projects of exclusive and total sale of electricity to STEG for national needs: These are projects intended to meet the national consumption of electricity by exclusive and total sale of electricity to STEG. The maximum capacity of such projects is fixed by decree. They are subject to an authorization which is issued by the Minister in charge of energy (ME). Authorizations are granted in the form of a call for projects and in accordance with the annual opinion issued by the Ministry in charge of Energy.
CONCESSION REGIME	Projects of exclusive and total sale of electricity to STEG for national needs: These are projects intended to meet the national consumption of electricity by exclusive and total sale of electricity to STEG. Projects whose maximum power exceeds the threshold set by decree (10MW PV, 30MW wind) for the authorization regime, fall within the framework of concessions, the broad outlines of whose implementation are described in law 2015-12 and law n°1996-27 of 1 April 1996 and its implementing decree n°1996-1125. This framework provides in particular that the projects must be subject to a tender procedure by the State and that the various agreements relating to the concession of each project must be approved by a special committee in the Assembly of People's Representatives
MV/HV self-consumption regime:	Projects for self-consumption: Any local authority and any public or private establishment, connected to the national electricity network at Medium Voltage or High Voltage (MV/HV) and operating in the industrial, agricultural or tertiary sectors may decide to produce their own electricity from renewable energy sources. This is known as a self-consumption project [24].

Table 4 - Financing facilitation and incentives for investment in renewable energy in Tunisia[24]

The Investment Act 2016-71 of 30 September 2016 came into force on 1 April 2017,	the objective of this law is to promote investment and encourage the creation of companies and their development according to the priorities of the national economy, notably through increasing the added value, competitiveness and export capacity of the national economy and its technological resources skills, the achievement of an integrated and balanced regional development, and the achievement of a sustainable development.

Reforms and guarantees in relation to transfer and convertibility risk:	The freedom to transfer for current operations, the actual net proceeds, as well as the capital gain from the sale or liquidation of capital previously invested by means of an import of foreign currency. All other operations and commitments that result or may result in a transfer, as well as any offsetting of foreign debts, are subject to prior authorization. Movements of funds between Tunisia and a foreign country must be carried out through the Central Bank of Tunisia (BCT) or, on its behalf, through intermediaries approved by the Minister of Finance on the proposal of the Governor of the BCT.
The creation of guarantee funds:	The main objective of which is to support SMEs in their development by promoting access to bank financing through setting up guarantees. There are several funds, including - The SME Guarantee Fund (main fund, resources of 122.3 million Tunisian Dinars (MDT) in 2017) - The SME Guarantee Fund II (allocated envelope of 15 MDT)
Lines of credit granted to Tunisian banks by some development institutions:	Among the most important credit lines granted to Tunisian banks by the development funds; the French Development Agency (AFD) made available to some Tunisian bank's important resources via SUNREF credit lines dedicated to the green economy between 2017 and 2018. - The International Finance Corporation (IFC), a subsidiary of the World Bank, lent €40 million to Attijari Bank Tunisia. The loan agreement was concluded in October 2018. - FADES line in the profile of the bank BFPME (1.5 million Dinar) - maturity up to 10 years - QFF line in the profile of the BFPME bank (1.25 million Dinar) - maturity up to 10 years - GGF (Green for Growth Fund) line in the profile of Tunisia Leasing & Factoring (TLF) - EUR 10 million - Under negotiation: EIB line for BNA bank (EUR 150 million - covering several sectors: agriculture, 150m - covering several sectors: agriculture, SMEs, renewable energy and energy efficiency) - maturity up to 10 years, ceiling of 12.5m per project.

Schemes for « Projects of National Interest »	According to Law 2016-71, Art.20 & Decree 2017-389, Title V, Projects of national interest are subject to facilitation and encouragement by the Tunisian government, for a project to be defined as a project of national interest, the Investment cost of the project must exceed 50 million dinars OR create at least 500 jobs over a period of three years from the date of effective operation. The "national interest" character must also be validated by the Higher Investment Council, the project benefits from a deduction of the profits from the corporate tax base within the limit of ten years, an investment premium within the limit of a third of the investment cost including the expenses of the intramural infrastructure works with a ceiling of 30 million Dinars, and the participation of the State in the coverage of the expenses of the infrastructure works.
The Tunisian Investment Fund (FTI)	The resources of the fund are made up of State resources, loans and donations granted from within and outside the country and any other resources made available to it. Its interventions include the release of premiums for the realization of direct investment operations in priority sectors, including the production of renewable energies, and the participation in the capital.
The Energy Transition Fund (ETF)	The Energy Transition Fund (ETF) is governed by Decree 2017-983 of 26 July 2017 and is intended to accompany Tunisia's energy transition. Its purpose is to provide integrated solutions for financing solutions for investments in the field of renewable energies, namely subsidy premiums, subsidized credits, subsidized credits, subsidized commercial credits and equity financing.
Incentives for the import of components in the field of renewable energy	According to decree n° 2018-234 of 12 March 2018 & Decree n° 2017-191 of 25 January 2017, raw materials, semi-finished products and equipment used in the field of renewable energy ("RE components” in the following) benefit from tax advantages when they are acquired on the local market or when they are imported. These advantages consist of the application of minimum customs duties (at10%) and the minimum VAT rate (at 6%) for "RE components" that do not have similar products manufactured locally[24].

3.3.2. Renewable energy market structure in Tunisia:

The renewable energy market in Tunisia only allows producers in their different regimes to produce electricity from renewable energy and sell it entirely to STEG (Société Tunisienne de l'Electricité et du Gas, Tunisian Electricity and Gas Company). The transmission and distribution of this produced electricity is handled by STEG, and the sale of this electricity is governed by a PPA (Power Purchase Agreement) at the end of which the different parties agree on the terms of the sale and the price of the energy as shown in Figure 3:

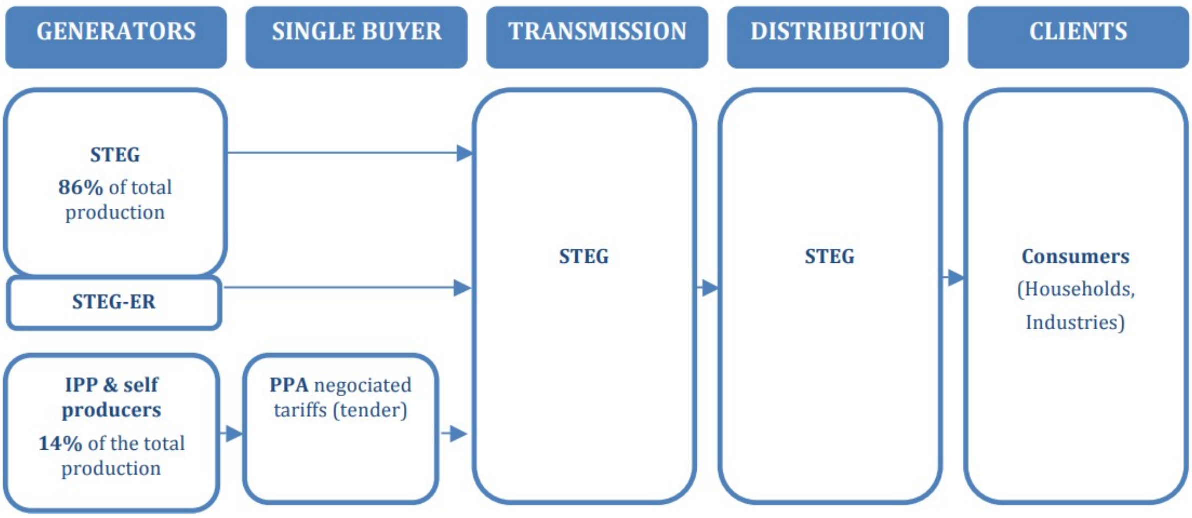


Figure 5: Renewable energy market structure in Tunisia[24]

The different schemes presented above represent 14% of the total renewable energy production in Tunisia, the remaining 86% represent the renewable energy projects fully owned by STEG, from electricity generation to distribution to the customer.

Wind energy projects in Tunisia:

To date, there are three wind farms in Tunisia representing a total of 245 MW. these wind farms are the one of **Sidi Daoud** implemented in 2000 with a capacity of 54 MW, the one of **Kachbta** implemented in 2012 with a capacity of 94 MW, and the one of **Metline** implemented in 2012 also with a capacity of 95 MW[24]

In addition to the operational wind farms previously mentioned, three other wind projects are under study for realization, it is a project of 200 MW in Nabeul under concession regime, a project of 100 MW in Kebili under concession regime also, and a project of 80 MW in Kebili also which will be realized by the STEG [25].

3.3.3. Potential of offshore wind energy in Tunisia:

The Tunisian coastline overlooking the Mediterranean Sea is about 1300 km long, allowing the installation of wind farms both offshore and onshore with an average wind speed variation of 4 to 8 m/s. The annual variation of wind in Tunisia shows that the wind speed remains almost constant with a slight decrease in summer, this stability provides a good base load to balance a part of the demand. Tunisia's good wind potential is largely due to its long coastline on the Mediterranean and the air circulation created by it, the wind productivity in Tunisia is estimated at 725 w/m²[19]

In the literature, measurements of wind potential in Tunisia exist only for onshore wind. Offshore wind is still in an early stage in Africa in general and the studies presented so far are derived from the results of the assessment of onshore wind potential and then extrapolated to the offshore wind potential.

Olaofe and Al have studied the inter-annual, annual, and seasonal wind speed and power density maps at 10 and 160 m heights derived from different grid cells across the coastal regions compared with the African wind studied findings reported for monitoring stations close to the coastline. A high wind power potential was reported for the countries near the African coastline including Tunisia and the offshore region of North East Africa has been identified as a high potential region [11]

Figure 6: Bathymetry of the Mediterranean Sea [9]

4. CONCLUSION

Tunisia is clearly a leading African country in renewable energy and its political commitment to the adoption of renewable energy proves that it is a country that will experience a clear progression and share of renewable energy in the energy mix in the next few years. It has been demonstrated that Tunisia has the necessary natural resources for the implementation of renewable energies, more specifically wind energy, where the potential is considered very interesting and the first onshore experiences are proving satisfactory. The regulatory framework remains basic in its conception since renewable energies and wind energy have not yet been generalized in Africa unlike in Europe, but it does demonstrate a political will to adopt renewable energies and to integrate them into the Tunisian energy mix in the near future with promising commitments and projects.

CHAPTER THREE:

METHODOLOGY

1. INTRODUCTION

In this chapter, the methodological framework applied in this thesis is presented as well as the different tools. The procedure involves three main steps.

First, the literature review allows the analysis of the wind potential across the country and the selection of the site for investigation as well as the section of the local parameter about the national Tunisian renewable energy market. Subsequently, the numerical investigation was used of the selected offshore wind site in Tunisia to determine the energy yield needed for the LCEO model. and finally, the analysis of cost of electricity using the LCOE model developed and refined according to National market parameters.

2. METHODOLOGY

The methodology followed in this research work is to derive information about offshore wind farms, CAPEX, OPEX and environmental risk assessment from the literature review, determine the wind potential assessment and technical characteristics using the WindPRO software, and integrate all inputs into a model to calculate the LCOE.

This study was conducted using three main tools: literature review, the use of specialized professional softwareWindPro , and the development and adaptation of calculation models for the cost of energy LCOE model.

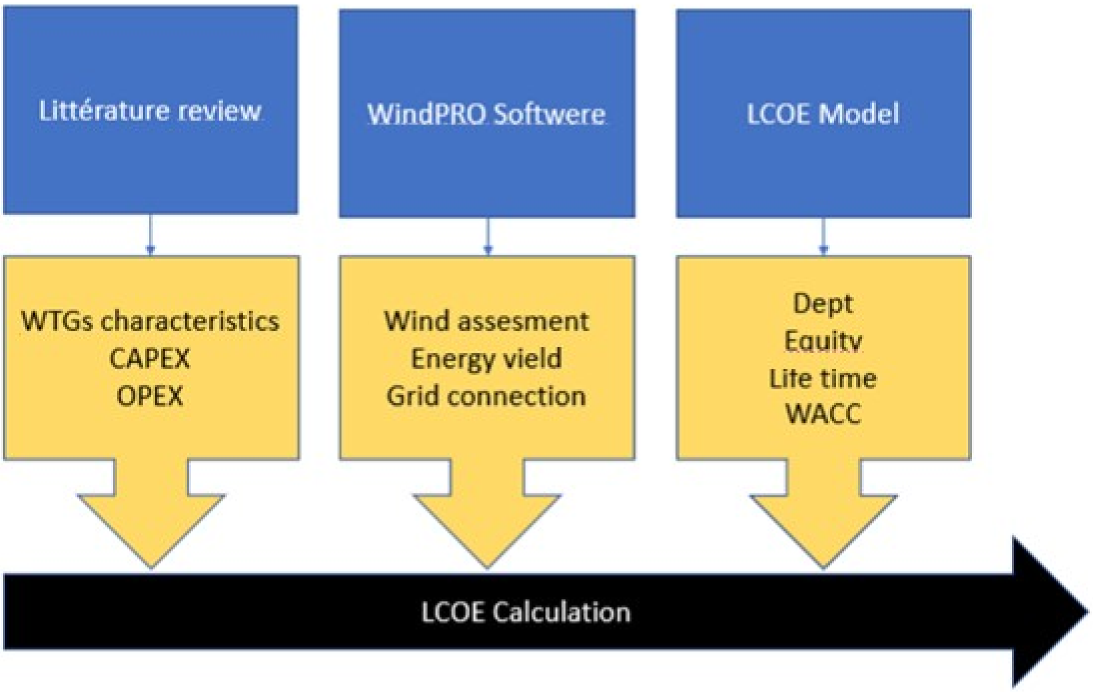


Figure 7: Methodological diagram

3. TOOLS USED FOR THIS STUDY

3.1. WindPRO software

The best way to have real and accurate estimates is to do on-site wind resource measurement, but since the aim of this study is to determine the feasibility of an offshore wind farm on a large scale and the prospection of favorable sites will be extended over a large area, data will be used from wind atlas, wind maps and the software windpro.

WindPRO is a commercial software allowing the design and the planning of wind farms projects. Successfully used by both large corporations and small entrepreneurs, windPRO is recognized and accepted by banks and authorities worldwide. WindPRO covers everything from wind data analysis, calculation of energy yields, quantification of uncertainties, assessment of site suitability, to calculation and visualization of environmental impact. windPRO can also be used for detailed post-construction analysis of production data. All available in separate modules as needed [26].

WindPRO is modular-based and covers all aspects in relation to development and planning of wind farm projects. This covers aspects, such as: Wind data analysis, Wind resource mapping, Micro-siting, Site suitability analysis, Energy production estimation, Layout optimization, Environmental impact calculations, Visualizations, Electrical and economical calculations. It also offer features for detailed production analyses of operating wind farms based on recorded data [26].

Wind atlases and wind maps have been produced for a very wide range of scales, from the world level down to the local government region, and represent the best estimate of the wind resource across a large area. They do not substitute for anemometry measurements rather they serve to focus investigations and indicate where on-site measurements would be merited [1].

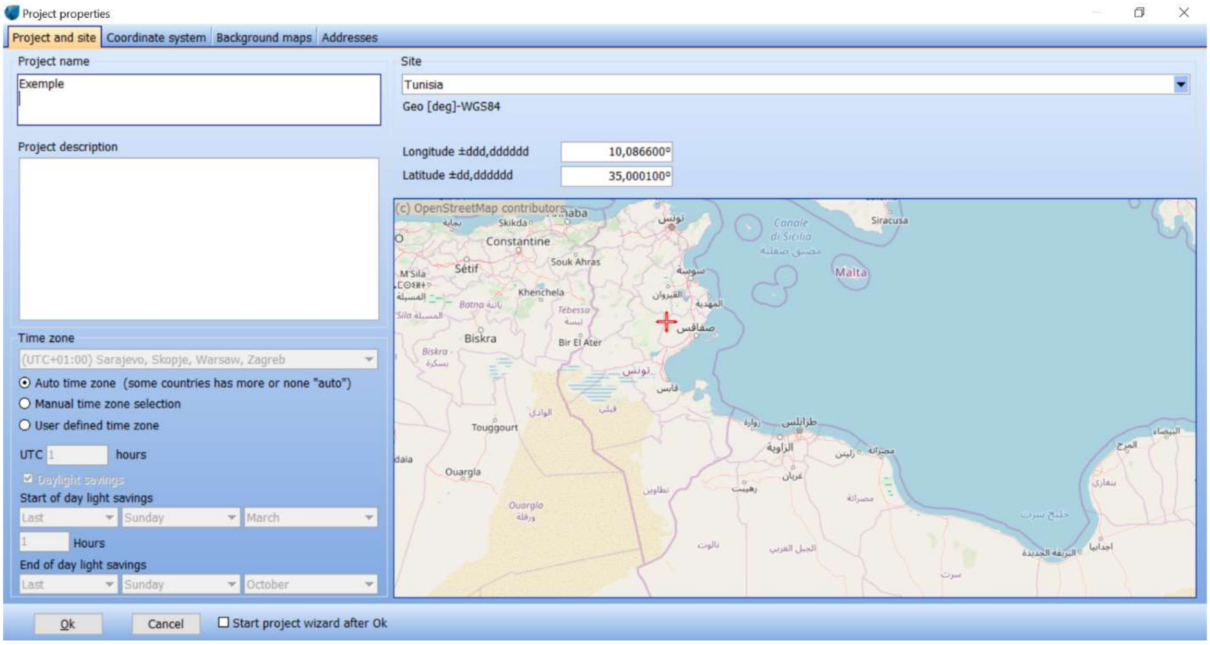


Figure 8: WindPRO software interface

3.2. The LCOE cost model

The LCOE (levelized cost of energy) SAM method was used to assess and compare the cost of producing electricity using various technologies and in various areas. It's a useful approach to compare the price of a unit of energy produced (for example in dollars per megawatt hour of electricity ($/MWh)). LCOE also ignores costs associated with balancing supply and demand. The LCEO is defined as the revenue that must be earned from all energy sources in order to obtain a return on investment equal to the discount rate over the operating life of the wind farm.

In order to estimate the value of the LCEO, it is necessary to take into account the estimated costs of the project over its lifetime, and then calculate the cost of the electricity generated by the offshore wind farm using a model. The model was developed on the basis of literature reviews, from which the equations were drawn and adapted to the context of this research, namely the Tunisian context.

To compute the LCOE, the model used in this study is the SAM (System Advisor Model) model presented previously:

$$LCOE = \frac{\sum_{i=0}^{n} \frac{CPE_i}{(1+r)^i}}{\sum_{i=0}^{n} \frac{E_i}{(1+r)^i}} \qquad Equation\ (1)$$

where CPEi is the cost to produce energy in year i and each parameter is given in the ith year. In the SAM model, the LCOE is calculated based on expected cash flows for O&M and capital expenditures. Although cash flow is important for determining the actual money spent and costs involved in a wind farm project [16].

3.2.1. CAPEX and OPEX estimation

The most important point to consider when estimating the CAPEX of an offshore wind project is the capacity of the project, this capacity dictates the number of turbines needed for the project which helps to estimate the largest part of the CAPEX as explained above. the type of turbine and the model to be chosen is directly related to the characteristics of the chosen site, the foundations which also represent a large part of the CAPEX are related to the characteristics of the site, more precisely the distance from shore, the bathymetry of the site, and the quality of the sub-sea ground.

The country manufacturing the turbines is also an essential point to study when estimating the CAPEX of a project, this includes the purchase price of the turbines but also the transport which represents important costs given the size of the turbines, but also the negotiation of the commissioning and maintenance contracts and the customs costs.

Here are the most important parameters in estimating CAPEX and OPEX:

Project and Development Cost, CP

The project and development cost constitute about 4% of the total investment cost [13].

Wind turbine Cost, CT

Wind turbine costs include the tower, shell and electrical devices of the WTGs which mainly depend on the size of the turbine. According to literature data CT is in the range of 1 162 500 USD to 1 395 000 USD/MW [13].

Support and installation costs, CS

Support and installation costs comprise of material, construction and installation costs. Material cost is factored by hub height and site conditions such as water depth and climate, meanwhile, the installation cost is a function of number of WTGs erected:

$$CS = (H/0.5)\ 0.3\ [(1700\ W^2 - 9455W + 21836)/\ 1000]$$

Where, (W) is the water depth and (H) stands for the wind turbine hub height [11].

Grid Connection Cost, CG

Grid connection costs are subject to the transmission system, distance from the shore-based station and also the distance from onshore point. A 20kV/ 150kV transformer costs around USD 13 175/MW and the additional costs of other devices are of USD 155 000/MW [11].

Operation and Maintenance Cost, CM

CM is tied up with the overall operational and maintenance strategy employed by the plant operator. In addition, distance from shore points and plant reliability affect the cost. It is estimated to be USD 77 500/ MW [11].

Decommissioning cost, CD

The cost of decommissioning is estimated at 5 to 7% as explained above. It is important to remember that during decommissioning, the metal is resold and made profitable [11].By summing up the estimate of all these parameters, it is possible to obtain a value relatively close to the total cost of an offshore wind farm.

CAPEX = CT (turbine costs) + CS (Support and installation costs) + CG (Grid Connection Cost) + CP (Project and Development Cost) + CD (cost of decommissioning)

LCOE model

The LCOE model used is based on equation (1) mentioned above with other parameters specific to the Tunisian context.

The following table represents some inputs of the LCOE model used:

Table 5- LCOE model inputs

Project duration	20 years
Equity:	20%
Debt:	80%
Cost of equity:	15,0%
Debt interest:	6,3%
WACC (discount factor):	8,0%
OPEX	Calculated
Additional replacement cost (CAPEX) per turbine:	Calculated
Total replacement cost (CAPEX):	Calculated

4. CONCLUSION

The energy yield of the wind farm was estimated using WindPro software and the levelized cost of electricity LCOE model was developed using local data relevant to the renewable energy framework and market expansion in Tunisia. The studied wind farm allowed an annual energy yield of 76,721 MWh and an LCOE of about $190/megawatt-hour (MWh).

CAPEX and OPEX are values that have a direct impact on the LCOE (Levelized Cost Of Energy) and the optimization of these values as well as that of the annual energy yield can reduce the cost of the energy produced and thus the value of the LCOE (Levelized Cost Of Energy).

The LCOE value could be compared with the commercial-scale offshore wind projects as the LCOE values of the offshore wind farms are reported to be between $130-110/megawatt-hour (MWh) in China [27] and $138 /megawatt-hour (MWh) in Germany [5].

CHAPTER FOUR:

RESULTS AND DISCUSSIONS

1. INTRODUCTION OF THE SITE AND ASSUMPTION

In this chapter, the results conducted on the selected site are presented. Those results are: the Energy yields calculation using the WindPro software simulations, the CAPEX and OPEX calculations, and the estimation of LCOE.

Finally, the impact of CAPEX, OPEX and Energy yield on the final LCOE values were analyzed and discussed and the impact of the current legal framework on the LCOE value is explored.

1.1. Site selection

The selection of the site is based on several parameters including sufficient space for the installation of the required number of turbines, optimal water depth (for bottom fixed infrastructures wind turbines), proximity to areas of high electricity consumption, good wind potential, good accessibility and no environmental risks. Most of these criteria can be verified by using WindPRO software which allows locating the most interesting sites in terms of wind potential, and giving other relevant information about the criteria mentioned above.

Generally, most of the Mediterranean countries as shown in Figure 9 such as Portugal has a lack of suitable water areas in term of water depth at the right distance from shore [9], except for Tunisia which has an interesting area between Sfax and Rass Djeddir with less than 50m depth and a sufficient distance from shore [9]. However, it is essential that technology is oriented towards floating structures that allow the possibility of operating in deep waters and which have a great potential for offshore wind farms in water depths between 40 m up to 200 m and more [20].

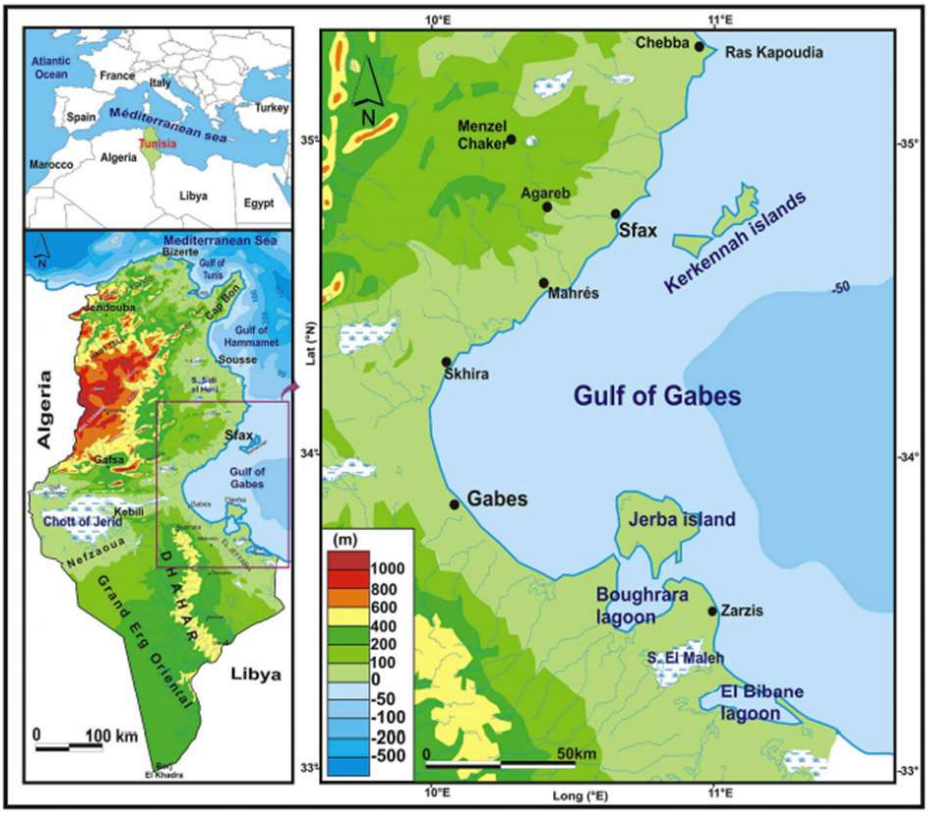


Figure 9: Selected site "Gulf of Gabes".

The selected site is the maritime area with a distance from shore of 25-30 km between the city of "Sfax " and "Ras Djedir" including « the gulf of Gabes ». The coastal cities in front of this site are Sfax, Chaffar, Gabes and Djerba.

The Gulf of Gabes, named "Petite Syrte", is located in the southeastern part of Tunisia with the town of Chebba in the north and the Tunisian-Libyan border in the south (Fig 8). It occupies a wide continental shelf area and represents approximately 33% of the Tunisian coastal waters and more than 50% of the 700 km long Tunisian coastline. It shelters various islands (Kerkennah, Kneiss and Jerba) and lagoons (Boughrara and El Bibane) and several towns, such as Gabes, Sfax, Jerzis and Jerba.

In the case of this study, the chosen site largely meets the spatial requirements of such a project (30 MWh), hence the freedom to estimate a higher capacity density value than the one mentioned in the literature.

The site has a mean power density of 467 W/m2, a mean wind speed of 7.22 m/s and a wind class II . With 2MW wind turbines, the project needed the implementation of 15 wind turbines placed about 900 m apart in the direction of the wind, and about 650 m apart in the opposite direction of the wind according to the following rule:

Distance between wind turbines in the wind direction = rotor diameter × 7

Distance between wind turbines in the opposite direction to the wind direction = rotor diameter × 5[28]

Simulation

For the wind potential assessment and the energy yield calculation, WindPRO software was used. The WindPro software is also used to analyze the environment risk assessment and the noise effect assessment.

Table 6- Wind farm characteristics

Geographical Coordinates Of The Site (longitude/latitude)	11,41 N / 34,16 E
Water Depth	0-50 m
Capacity Factor	26,3 %
Annual Energy Production	76 721,0 MWh/y
Annual Wind Speed	6.7 m/s

<table>
<tr><td>Wind Data</td><td colspan="2">The dataset used is ERA5, it is a climate reanalysis dataset developed through the Copernicus Climate Change Service (C3S) with the raw-data processed and delivered by ECMWF.

ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km.

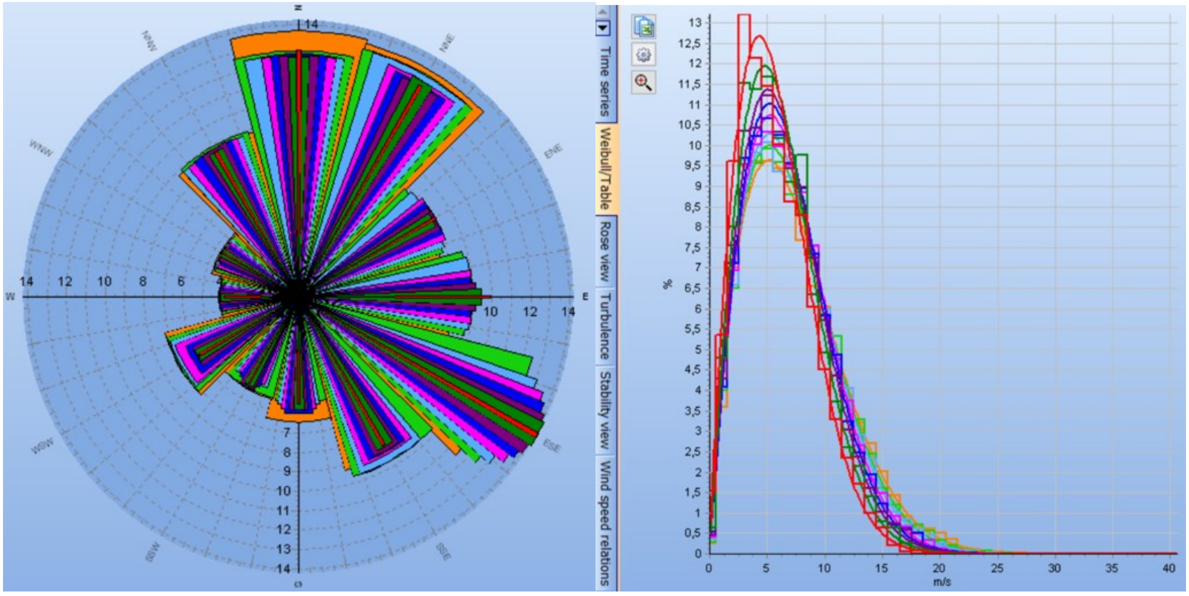
the results of the wind potential assessment obtained by online data are still relevant but cannot be considered as accurate, hence the importance of carrying out on site measurements during the project development</td></tr>
<tr><td>Distance From Grid Connection
(Kerkennah Island)</td><td colspan="2">20 km</td></tr>
<tr><td>Park Surface</td><td colspan="2">3.4 km²</td></tr>
<tr><td rowspan="3">Turbine Characteristics</td><td rowspan="3">VESTAS V80-2.0MW offshore-2 000</td><td>Power rated: 2MW</td></tr>
<tr><td>Rotor diameter: 80m</td></tr>
<tr><td>Hub height: 67m</td></tr>
</table>

In this wind park we used the turbine model: VESTAS V80-2.0MW offshore 2000 80.0 - as wind turbine generator, having a capacity of 2MW, with a diameter of 80 meters and a hub height of 67 meters.

The capacity of the project is fixed to 30 MW, for that, the park had 15 wind turbines generators as described above, fitting into the distancing rule required as mentioned above.

For the wind potential assessment, the mean wind speed is estimated at 6.7 m/s, the wind rose shows that the windiest directions are three; (N) (NNE) and (ESE).

Also, the wind speed can reach 13m/s at the hub height for the chosen wind turbines generators, and the annual energy yield is estimated at 76,721 MWh, a value considered minimal in relation to the project design, since it can be improved by techniques such as wind turbine generator layout and project optimization.



Calculated Annual Energy for Wind Farm

WTG combination	Result PARK [MWh/y]	Result-10,0% [MWh/y]	GROSS (no loss) Free WTGs [MWh/y]	Wake loss [%]	Specific results¤) Capacity factor [%]	Specific results¤) Mean WTG result [MWh/y]	Specific results¤) Full load hours [Hours/year]	Mean wind speed @hub height [m/s]
Wind farm	76 721,0	69 048,9	76 758,9	0,0	26,3	4 603,3	2 302	6,7

Figure 10: WindPRO simulation results

2. IMPACT OF LEGAL FRAMEWORK FOR THE PROMOTION OF RENEWABLE ENERGY IMPLEMENTATION

The chosen site is located in the maritime region overlooking two different local development zones, these local development zones (zone 1 and zone 2) shown in figure 10 benefit from important aids and tax exemptions. The situation of this project can allow it to benefit from the advantages of the two regional development zones and thus reduce its CAPEX (Capital Expenditures) and OPEX (Operational Expenditures).

Regardless of the company's revenues, corporate tax is reduced to 10% instead of 25% in regional development zones (zones 1 and 2). In addition, a tax exemption of 5 (zone 2) to 10 years (zone 1) can be granted. The period of tax exemption for projects in regional development zones is counted from the date of expiry of the four-year exemption period [24].

Figure 11: Regional development zones receiving government aid[24]

The major laws and aids of the Tunisian government to a wind project are presented below

Table 7- Direct impacts of legal framework on the LCOE

Legal framework program	Details of the decree	Estimated impact on LCOE
Schemes for « Projects of National Interest »	investment premium within the limit of a third of the investment cost including the expenses of the intramural infrastructure works with a ceiling of 30 million Dinars (10 500 000 USD)	-24%
Incentives for the import of components in the field of renewable energy	raw materials, semi-finished products and equipment used in the field of renewable energy benefit from minimum VAT rate at 6% for "RE components" that do not have similar products manufactured locally.	Used in estimating wind turbine cost
Schemes for « Regional Development Zones »	Tax is reduced to 10% instead of 25% in regional development zones (zones 1 and 2).	Included in the model

3. IMPACT OF OPEX AND CAPEX DEVIATION

Results showed that for a 30 MW wind farm, annual energy yield could reach 76,721 MWh and the LCEO is about $ 190/megawatt-hour (MWh). Moreover, figures 6 and 7 show a sensitivity analysis of the LCOE calculated deviation from input values of Capital expenditure (CAPEX) and operating expenditure (OPEX). Table 8 presents the inputs used for the LCOE model.

The variation in CAPEX and OPEX results in a proportional variation in the value of LCOE, which does not contradict the rule stating that the higher the CAPEX and the OPEX, the higher the cost of the energy produced, which results in a high value of the LCOE.

Table 8-LCOE model inputs

Project duration	20
Equity:	20%
Debt:	80%
Cost of equity:	15,0%
Debt interest:	6,3%
WACC (discount factor):	8,0%
OPEX	Calculated
Additional replacement cost (CAPEX) per turbine:	Calculated
Total replacement cost (CAPEX):	Calculated

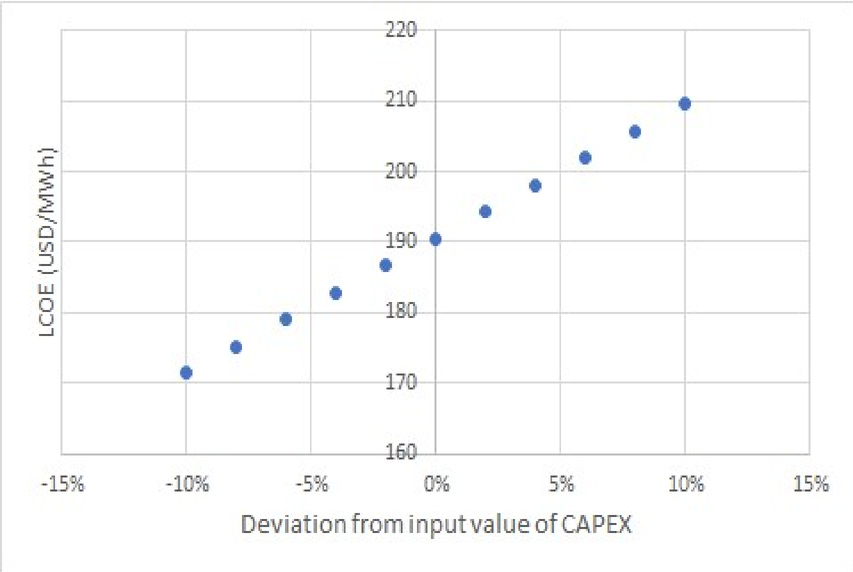


Figure 12: Deviation from input value of CAPEX

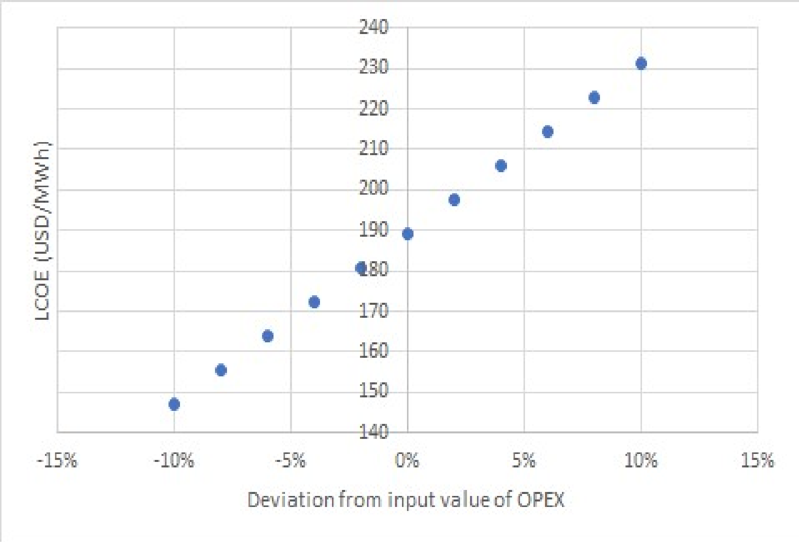


Figure 13: Deviation from input value of OPEX

4. IMPACT OF THE ENERGY YIELD DEVIATION

Any variation in the value of the energy yield results in a proportional variation in the value of the LCOE, which illustrates the importance of optimization in the design of the windfarm, and of micro-siting to adjust the most favorable location for a high energy production.

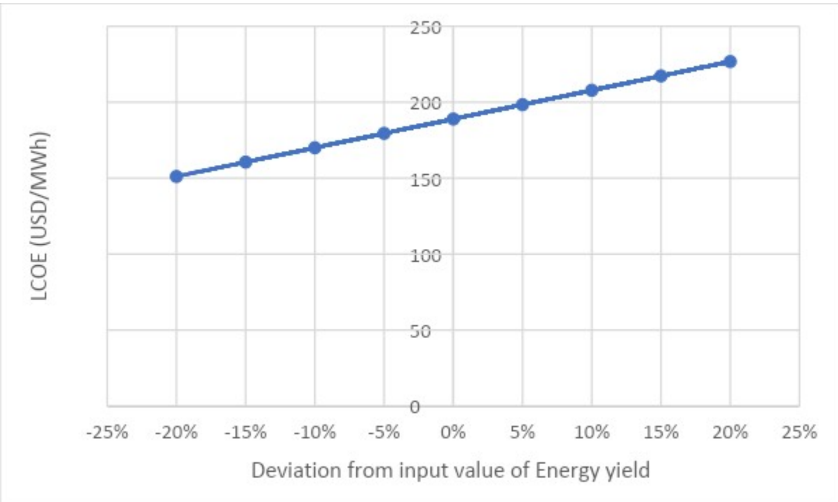


Figure 14: Deviation from input value of Energy yield

5. CONCLUSION

The results showed that the prospected site could contain an offshore wind farm with a capacity of 30 MWh in terms of water depth, wind potential assessment, environmental characteristics and distance from shore. Such a project can generate a quantity of energy of about 78 000 MWh per year, and can connect to the national grid through several possible locations of which the closest chosen is "Kerkennah Island".

It has been shown that legal framework can have a real impact on the profitability of a renewable energy project, and that the Tunisian legal context presents a series of laws that are advantageous to the implementation of renewable energies.

The lack of Tunisian experience in offshore wind energy and in the "concession regime" for private investors does not allow to evaluate with accuracy the impact of the legal framework on the selling price of the electricity produced by an offshore wind farm, which highlights the importance of a first experience as a "pilot project" for the development of a renewable energy technology in a country, and highlights also the importance of the monitoring policy that requires policy makers to assist and popularize the laws and aid programs presented in the legal framework.

CONCLUSION AND RECOMMENDATION

The African continent is probably the most affected continent by climate change and its repercussions in addition to the problems of poverty, drought and poor access to energy. African leaders must respond with policies aimed at sustainable development and solutions that are both effective and environmentally friendly.

Africa has the capacity to switch between renewable and non-renewable energy while simultaneously increasing productivity and reducing greenhouse gas emissions. If is to conserve its environment while still achieving the Sustainable Development Goals, it must develop its institutions in addition to the three important challenges that must be addressed; Political unpredictability, Electricity grid infrastructure and supply (Improved grid usage and integration is needed as increasing numbers of rural and previously disadvantaged areas go online), Technical skills (Skills required to deploy RE and build the RE industry are in limited supply; more renewable energy skills are needed.)

Tunisia has made an irrevocable commitment to include green economic strategies in its national planning, as evidenced by the legislative and regulatory framework adopted in recent years. Tunisia is among the most prepared countries in Africa in terms of adopting renewable energies so as to have a significant percentage of these energies in its energy mix, but still, it remains far from European standards and the state of progress of leading countries in the field of renewable energies. recommendations have been made to fill the gaps in a policy that proves to be promising but still far from the expected objectives.

Wind energy has established itself as a significant player in the global energy industry. The wind business also generates a large number of new jobs and more than 1.5 percent of the world's electricity is now generated by wind. Employment related to wind energy has increased significantly in recent years, and in the coming years, offshore wind energy employment will surpass onshore employment.

Onshore wind farms currently generate the vast majority of wind energy. However, the paucity of affordable land near major population centers and the visual pollution created by enormous wind turbines are limiting their growth. On the other hand, offshore wind sources provide a better wind energy potential, less turbulence, steadier wind, higher mean wind speed, more aesthetics, and more power transmission possibilities and wind turbines produce more energy than onshore turbines due to greater and more consistent wind speeds. Furthermore, offshore wind turbine generators often have greater blade diameters and produce more rated power.

The lack of Tunisian experience with offshore wind energy and the "concession regime" for private investors makes it difficult to assess the impact of the legal framework on the selling price of electricity generated by an offshore wind farm, recognizing the role of a first experience as a "pilot project" for the development of a renewable energy technology in a country, as well as the importance of a monitoring policy that requires policymakers to assist and promote the laws and aid programs established in the legal framework.

Governments and other public actors are critical to offshore wind development, as they drive the planning process for offshore wind farms and provide support mechanisms. Defining the marine spatial planning with the permissible wind farm locations and acquiring the relevant environmental or other licenses may be part of the planning. By designing, pre-permitting, and sustaining wind farms, public actors play a key role in sending long-term signals to private actors., these private actors are, in turn, the primary stakeholders responsible for lowering offshore wind costs, and as a result, the existing offshore wind costs interact with the signals produced by public actors and the market.

Following the European model, the energy market must be liberalized to allow the harmonization and integration of several regulatory frameworks of neighboring countries with common objectives.

The implementation of offshore wind projects will increase the knowledge in this field and to acquire skills, each new wind farm implementation expands the industry's knowledge and pushes the technology, installation methods, operation and maintenance methods, and finance methods to new heights.

The prospected site is an optimal site for the installation of an offshore wind farm, since it presents a bathymetric advantage in terms of depth and underwater geography, and a strategic and technical advantage since it allows to supply electricity to a region where the demand is important and where the socio-economic impact of this project is important.

The model developed in this research has allowed to predict the price of electricity produced by this offshore wind farm, and has allowed us to conclude that the offshore wind in Tunisia can present a solution to the energy diversification, and that it can be competitive in terms of profitability and price of electricity with further political efforts in its favor.

It has been demonstrated through this study that the natural potential is important in Tunisia for the implementation of offshore wind projects, and that the results simulating the implementation of an offshore wind farm in Tunisia are satisfactory and confirm the feasibility of such a project in Tunisia.

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