POLITECNICO DI TORINO

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Modelling, Simulation and Analysis of the Tunisian Power System

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It is not easy to start again…

But if you are lucky enough to be in good company, it will be marvellous!

It was so for me! I started again to study in a completely new country with new language and culture.

The way, even if not simple, was full of wonderful people who I met, new friends who inspired me and taught me a lot. Here, in Politecnico and outside.

Although it is not possible to mention all the names, I would like to thank them all.

I would like to thank my husband, *Mojtaba*, for his supports during these years.

My parents *Parvaneh* and *Mohammadrahim* who followed me from home and sent me love and *Annick*, a great person and a unique friend.

I am grateful to you all

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Acronyms and Abbreviations

ACOPF	Alternative current Optimal Power Flow
ANME	National Agency of Energy Conservation
CIA	Central Intelligence Agency
DANIDA	Danish International Development Agency
DCOPF	Direct Current Optimal Power Flow
EOH	Equivalent Operating Hours
GCI	Global Competitiveness Index
GIZ	German Development Cooperation
IAEA	International Atomic Energy Agency
IMF	International Monetary Fund
MEDREC	the Mediterranean Renewable Energy Center
MENA	Middle East and Nord Africa
mill/th	millime tunisien/thermie, one Tunisian Dinar is 1000 millime and thermie is a unit of energy equal to 3968.3 BTU
OPF	Optimal Power Flow
PIDA	The Program for Infrastructure Development in Africa
p.u.	Per unit
QGIS	Quantum Geographic Information System
RCREEE	The Regional Center for Renewable Energy and Energy Efficiency
RES	Renewable Energy Sources
STEG	Tunisian Company of Electricity and Gas
WEC	World Energy Council
WEF	World Economic Forum

Definitions

Arab Union of Electricity	Founded in 1987, a group of Arab electrical companies with the purpose of improve power manufacturing in the Arab World
COMELEC	Comité Maghrébin de l'Electricité Is the electricity part of Arab Maghreb Union (AMU), union of five African countries Algeria, Libya, Mauritania, Morocco and Tunisia with the goal of increasing economic and political relationship between members.
Global Competitiveness index (GCI)	Is an index which shows the sustainability of the economic prosperity one country offers to its citizens. It is ranked between 1 and 138. Much smaller is the rank, more economic perspective has the people of the country
Curtailment	Reduction in the output of a generator from what it could otherwise produce given available resources, typically on an involuntary basis
Dispatching	Management of electricity flow
Electricity consumption per capita	The amount of electricity one person consumes in one year. It is a factor of development and welfare in a country
Energy Sustainability	Provide the present energy need without compromising the ability of future generations
Energy trilemma index	Monitors the sustainability of the energy sector in a country. It is based on three pillars: Energy Security, Energy Equity and Environmental Sustainability
GDP per capita PPP	Gross Domestic Product (at Purchasing Power Parity) the purchasing power parity (PPP) value of all final goods and services produced within a country divided by mid-year population.
Global Sun Belt	In Renewable energy terms are all countries within 35° of the Equator

Gradient Method	The method is used in multivariable problems. The min. point is obtained by consecutive perpendicular paths that are made through maximum gradient
Interior Point Method	Is applicable to inequality constrained minimization problems
Macro-scale Modelling	Modelling the energy system of a vast region such as a country or some countries in a region
Paris agreement	Signed in July 2018, is an agreement which deals with greenhouse gas emission mitigation, adaptation and finance
per unit (p.u.)	In power systems, is a way to express the characteristics of an equipment referring to its nameplate data.
Sequential method	Are extensions of Newton methods for constrained problems

Chapter 1

Introduction

1. Introduction

United Nation's Paris Agreement, was the proof of an international common will to reduce the climate change and mitigate its effects.

As one of the policies to reach the perspectives of Paris agreement, the parties are asked to implement long-term greenhouse gas emission reduction strategies and develop climate resilience pathways[1].

At the other hand, energy sector and more specifically electricity, beyond its deep economic aspects has also a high environmental impact. It is one of the most important fields in which is possible to interact effectively towards reduction of CO2 emission and reach the Energy Sustainability[i] factors by implementing RES and diversifying generation.

However, increase penetration of RES and high electrification level, other than security in supply and transmission facilities, requires construction of certain infrastructures. To reach such security, it is essential and unavoidable to have a complete outlook of the power system.

Studying power systems apart from providing a panorama of the present situation and detecting probable problems in supply side, enables planners and decision makers to predict the evolution of system in time and its possible answers by applying different scenarios.

Furthermore, in a competitive market, analyzing power systems, enables Dispatching Management and Demand-Response programing base on minimum cost of generation [2].

Intermittent nature of the renewables, requires flexible conventional generators which are able to follow the production and demand profile fluctuations and backup the system when necessary. Of course there are several issues to take into consideration (e.g. technical limits of ramping of generators and thermal tensions exerted by it on the power plants' facilities and its effects on their life cycle.)

There are several methods to study a power system. Obviously, the model changes due to technical property of the system, data availability and purpose of the study. The models vary also based on temporal (short or long term), sectoral (economy, energy, finance) and spatial (global, national or regional) features of the target system.

Another important issue is the fact that models provided for developed countries because of several differences of two category (such as socio-economic conditions), may not be suitable to be applied to the developing countries and vice versa [3].

The present work, follows a top-down approach in the electricity optimization model filed. Such methods -used in Macroscale modeling- don't consider the technical details of the demand side (such as type of appliances and their energy efficiency level, building envelope or individual dwelling properties) but look at demand just as a whole.

The performed steps in the present work could be categories as follow:

- Data mining
- Data validation
- Implementation of data on QGIS
- Preparation of the incidence matrices of system
- MATPOWER and Direct Current Optimal Power Flow (DCOPF) simulation

Chapter 2

Overview of Tunisia

2. Tunisia at a Glance

Tunisia is a small country with about 164,000 km^2 surface and almost 12 million population. It is Africa's 34th biggest country located in the most northern part of continent. In the west side, Tunisia has the border with Algeria and at the southeast part borders Libya. The North and East side of the country is the Mediterranean see.

The country has 24 governorates (i.e. Provinces) and the city Tunis is the capital of Tunisia which is in the governorate with the same name.

Figure 1: Tunisia in the world and Africa [4][5]

Due to the geographic position, economy of the country is quiet diversified and includes Agriculture, Aquiculture, Minerals, Oil and Natural Gas (in small quantity) and Tourism.

Population density of the Tunisia is extremely high in the Mediterranean shore, relatively low in the central and northwest zone and very low in the Sothern regions.

2.1 Geography and Climate

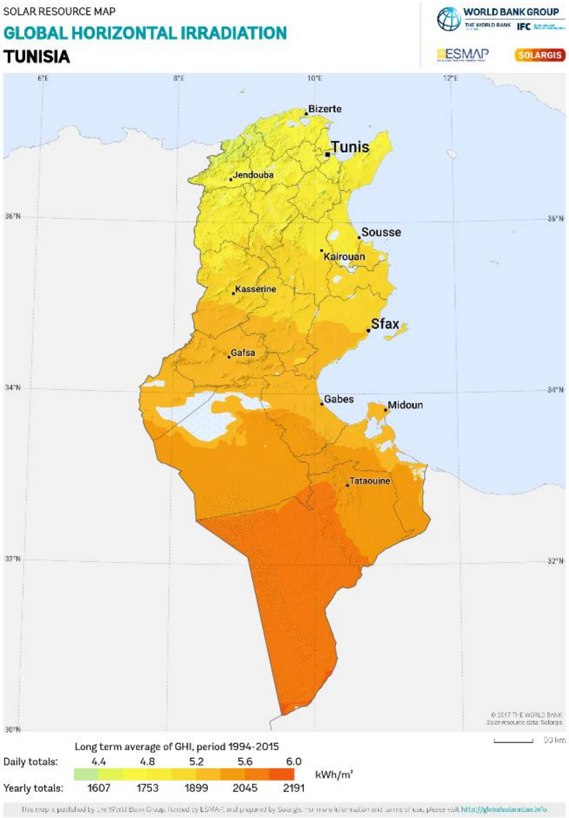


Figure 2: Global Horizontal irradiation, Tunisia [7]

Although comparing to other counties in Africa, Tunisia is not a big country, is has very different climate conditions. At the coastal zone of the Tunisia prevails Mediterranean climate while the South part has dry desert climate of Sahara. In fact, Tunisia is on the global Sun Belt[6] with more than 300 sunny days in year and the average annual solar irradiance of 1850 KWh/m^2 in north and 2600 kWh/m^2 in the south which highly favorites the potential of integration of photovoltaics[7]. Figure 2 shows the global horizontal irradiation across the country[8].

The wind velocity in Tunisia reaches 9 m/s in the Atlas mountainous region near Algeria and 6-7 m/s in other parts of the country and thus offers the possibility of wind energy implementation [7].

Moreover, the high Agriculture potential in the country, enables the biomass utilization in energy sector.

2.2 Economical Overview

In 2017, the GDP of Tunisia was 40.3 Billion US$[9] and classifies Tunisia as 14th country in Africa. The share of Industry and energy in GDP is respectively 19 and 5 percent. Because of the increasing energy demand which reduces the energy production surplus, the contribution of the energy sector in the GDP has a decreasing trend since eighties[10].

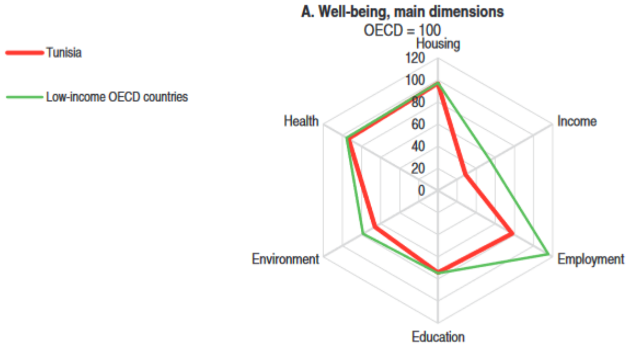


Figure 3: Tunisia and OECD countries competitiveness index comparison [11]

To have a better understanding of general challenges in the Tunisian economy, a suitable index, to refer to, is the *Global Competitiveness Index*, an index published yearly by World Economic Forum which based on its 12 pillars: Institutions, Infrastructure, Macroeconomic environment, Health and primary education, Higher education and training, Goods market efficiency, Labor market efficiency, Financial market development, Technological readiness, Market size, Business sophistication, Innovation offers a multidimensional measure of the overall situation of countries. Based on this report, in 2017 Tunisia has the *Global Competitiveness Index (GCI)* 95. Figure 3 shows the situation of Tunisia with respect to the OECD countries.

In table 1 Tunisia's global position and compared to MENA countries in 2016-17 and 2017-18 period is visible.

Table 1: GCI comparison between MENA countries, [Own Elaboration- WEC GCI data][11]

	IL	AE	QA	SA	BH	KW	OM	JO	IR	MA	DZ	TN	EG	LB
Global 2017-18	16	17	25	30	44	52	62	65	69	71	86	**95**	100	105
MENA 2017-18	1	2	3	4	5	6	7	8	9	10	11	**12**	13	14
Global 2016-17	24	16	18	29	48	38	66	63	76	70	87	**95**	115	101
MENA 2016-17	3	1	2	4	6	5	8	7	10	9	11	**12**	14	13

IL: Israel, AE:United Arab Emirates, QA:Qatar, SA: Saudi Arabia, BH: Bahrain, KW: Kuwait, OM:Oman, JO: Jordan, IR: Iran, MA: Morocco, DZ: Algeria **TN:Tunisia**; EG: Egypt, LB: Lebanon

After the Tunisian revolution in 2010 and in absence of political stability, a lot of national and international projects in the Tunisia where suspended or slowed down. Also the political situation of Libya had some negative influence on the country and causes declinations in the GDP growth rate. However, the trend starts to become positive after 2015 [12].

The urbanization in the country is relatively high: more than 65% of Tunisian population live in urban zones with complete electricity access and just 1% of population which lives in the rural area has no access to electricity.

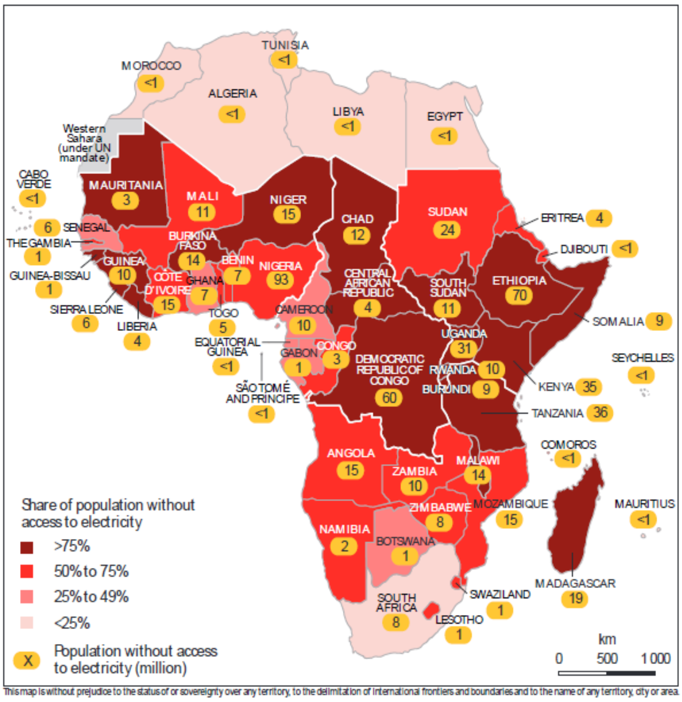


Figure 4: Electrification level in Africa in 2012[Africa Energy Outlook, IEA]

2.3 Overview of the Power Sector Management

Power generation, transition and distribution as well as Natural Gas distribution in Tunisia is under the responsibility of state-owned Société Tunisienne du Electricité et Gas (STEG) founded in 1962. In 2016, STEG covered almost 90% of electricity production of Tunisia [13].

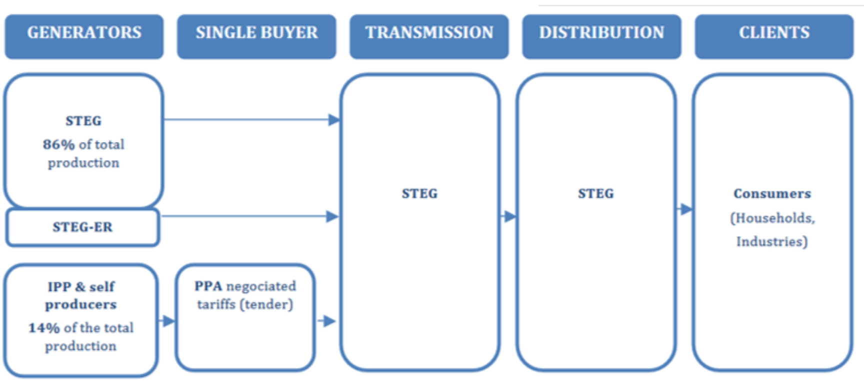


Figure 5: the structure of power sector of Tunisia [13]

In 1996 the monopoly of STEG on electricity market has been terminated by the presence of Independent Power Producers (IPP) and the liberalization of electricity market starts. Nevertheless, the private suppliers are obliged to sell their electricity with the fixed price of STEG. The share of STEG of the production on January 2017 was 79% of the market [14].

In 2010, a subsidiary part STEG ER which is responsible for renewable energies has been founded.

Tunisia is part of the *Comité Maghrébin de l'Electricité* (COMELEC), PIDA and the *Arab Union of Electricity* which establish energy market politics between the member countries.

2.4 Energy and Electricity Balance

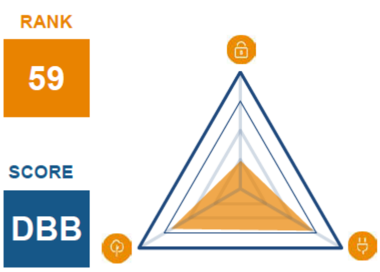
To study the energy sector of the country, the possible reference could be the energy trilemma index.

Energy trilemma index, published each year by World Energy council (WEC), is a three dimensional index: Energy Equity, Energy Security and Environmental Sustainability. This indicator gives an estimation about how good is the situation and performance of energy sector in 125 countries (out of 159) around the world:

Energy Equity index investigates how accessible and affordable is the energy for the population of a country

Environmental sustainability index looks at how much the supply and demand side apply energy efficient methods and respect environmental issues

Energy Security index determines the reliability of energy infrastructure to meet the present and future energy demand



	2015	2016	2017	Trend	Score
Overall rank and balance score	**54**	**54**	**59**	▶	**DBB**
Energy performance					
Energy security	101	101	100	▶	D
Energy equity	45	49	47	▶	B
Environmental sustainability	35	43	41	▶	B
Contextual performance	80	80	78	▶	

Figure 6: Energy Trilemma Index Ranking and Balance Score, Tunisia, [11]

Tunisia, with a DBB score, it is in the 59th global position. Figure 6 shows that the ranking of the country has worsened in the recent years. The same situation has happened also for the GDP of Tunisia. Some probable reasons of such a trend is mentioned in section 2.2.

It is worth to say that among all countries in the ranking, just 8 countries have a triple "A" score.[11]

Although the electricity balance in Tunisia is positive, with almost 4% yearly growth rate of the demand, it is necessary to construct new power infrastructures in both generation and transmission sector to avoid power shortages. Obviously, diversifying electricity generation toward RES-oriented strategies, requires also adequate power system.

In recent years, because of economic development and climate change, the consumers' habit and consequently the demand profile of the country has changed. Some specific characteristics of the Tunisian power system are[15]:

- Remarkable change in the demand profile in Ramadhan
- Lack of generation from RES compared with countries' potentials

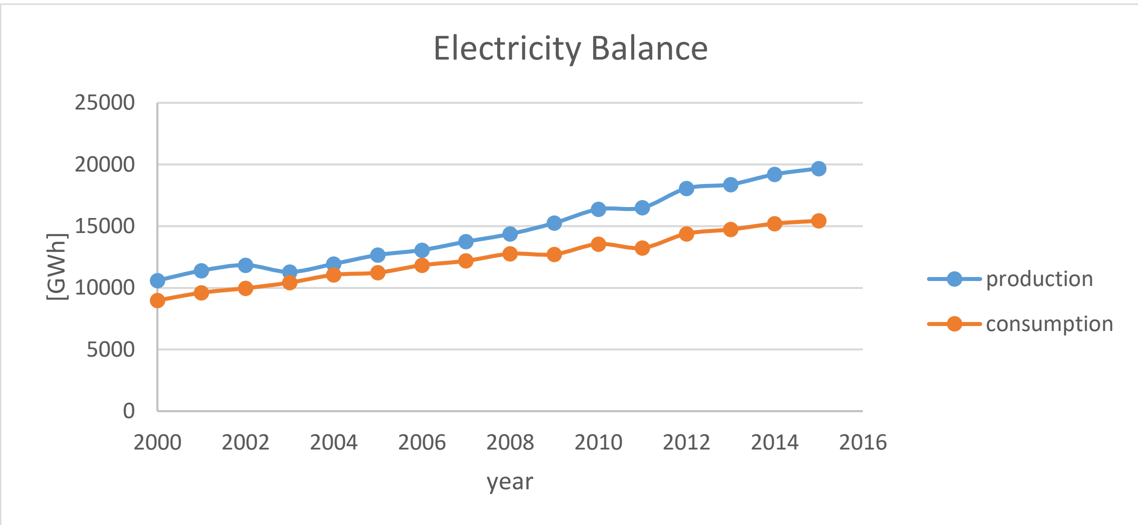


Figure 7: production and demand situation by year- [Own Elaboration- [13] and [16] data]

Chapter 3

Electricity Infrastructure in Tunisia

3 Electricity Infrastructure

The Tunisian high voltage electricity infrastructure is not uniformly distributed over the country. The grid is quiet capillary at the Northeast cost and more distributed at the center. The southwest part of the country has a very poor electricity coverage.
The Rades power plant, located in the Tunis governorate with more than 1'170 MW and 7 production units, currently has the highest generation capacity with 3 working phases and one 450 MW under construction phase (Rades C).

The total installed power of Tunisia in 2016 was 5476 MW from which 5005 MW owned by STEG and other 471 MW by independent producers (IPP).

Table 2: STEG installed capacity in 2016, [Own Elaboration- [13] Data]

Thermal [MW]	Hydro [MW]	Wind [MW]
5174	62	240

To analyze the Tunisian power system through the use of *MATPOWER,* the first step was to have complete technical information of all generators, stations and substations and transmission lines.

But unlike Europe's transparent policy toward information, the amount of published and reliable statistics about characteristics of power facilities in both generation and consumption sides in Tunisia is very low and it was a big and serious issue to establish the database of the electricity park of the country.

The present information about Tunisian power plants inventory has been gathered through several cross checks of several statistics and reports published by different authorities such as STEG[16][17][13], Manual of Power Stations in Africa (AUA)[18], ENTSO-E[19], JICA[20], Africa Information Highway[21], Global Energy Observatory[22] Res4med[23] and the available data on geo-Referenced Openstreetmap[24].

After mining all data, to check the conformity with the actual situation, some recent reports of the STEG [16] were taken into account.

3.1 Power Plants and Production

In 2016, almost 98% of the power generation in the Tunisia was through Natural Gas fired power plants (including the private generators which all use Natural Gas).

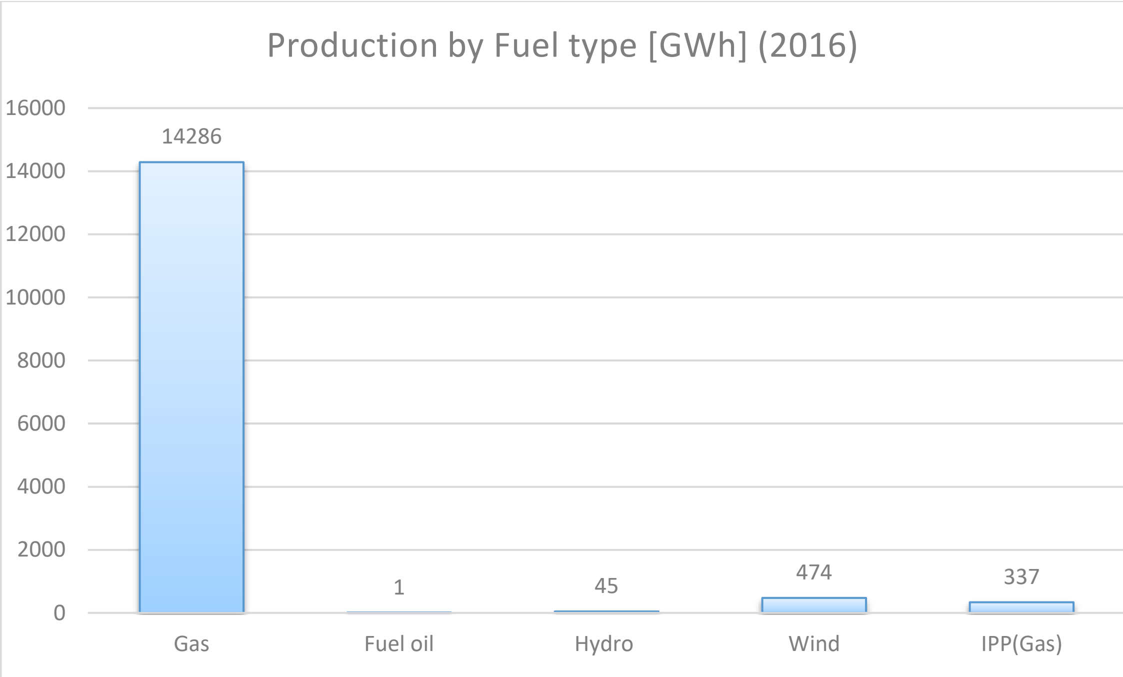


Figure 8: Electricity Generation Capacity by Source in 2016, [Own Elaboration-STEG Data]

In the same year, the share of renewables and more precisely wind, was just 2.6% and Hydro-electricity has just 0.26% of the total production of the country.

The national electricity generation park of the Tunisia is mostly composed of Gas Turbines, followed by Steam Turbines and Combined Cycle.

In figure 9 the annual evolution of the production park from 2011 until 2016 is reported.

As mentioned before and visible in the picture, renewables have a minor role in overall national electricity generation. In 2017 the share of wind energy was 2.6% which was produced by three wind farms located in the north east coastal region.

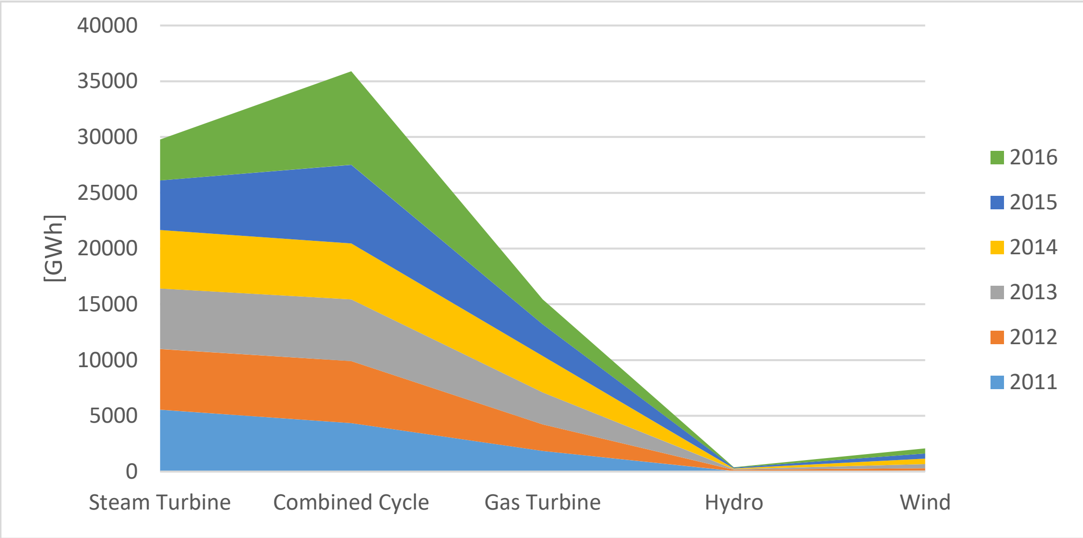


Figure 9: Evolution of production by Source 2011-2016- [Own Elaboration- STEG data]

Solar energy is more used in the hot water production and power generation exists just in residential level and in a negligible quantity, so there is no data about it in official reports. In section 6 there some present projects are mentioned.

To construct hydro power plants' inventory and extract their technical information, other than resources cited before, also the United Nations Industrial Development Organization (UNIDO) report [25] was refed. For the wind generator inventory instead, the main reference resource was "the wind power" website[26].

Figure 10: Location of Hydro plants, Northern part of Tunisia [Own Elaboration]

Hydro-electric production in country is limited to 6 small run-of-river and dam generators located in the North and Northwest mountainous region and one 33 MW dam power plant in North central part Sidi Salem.

Figure 11 represents the final elaboration about the actual power plants in the Tunisian electricity system by type and position, exported form QGIS software.

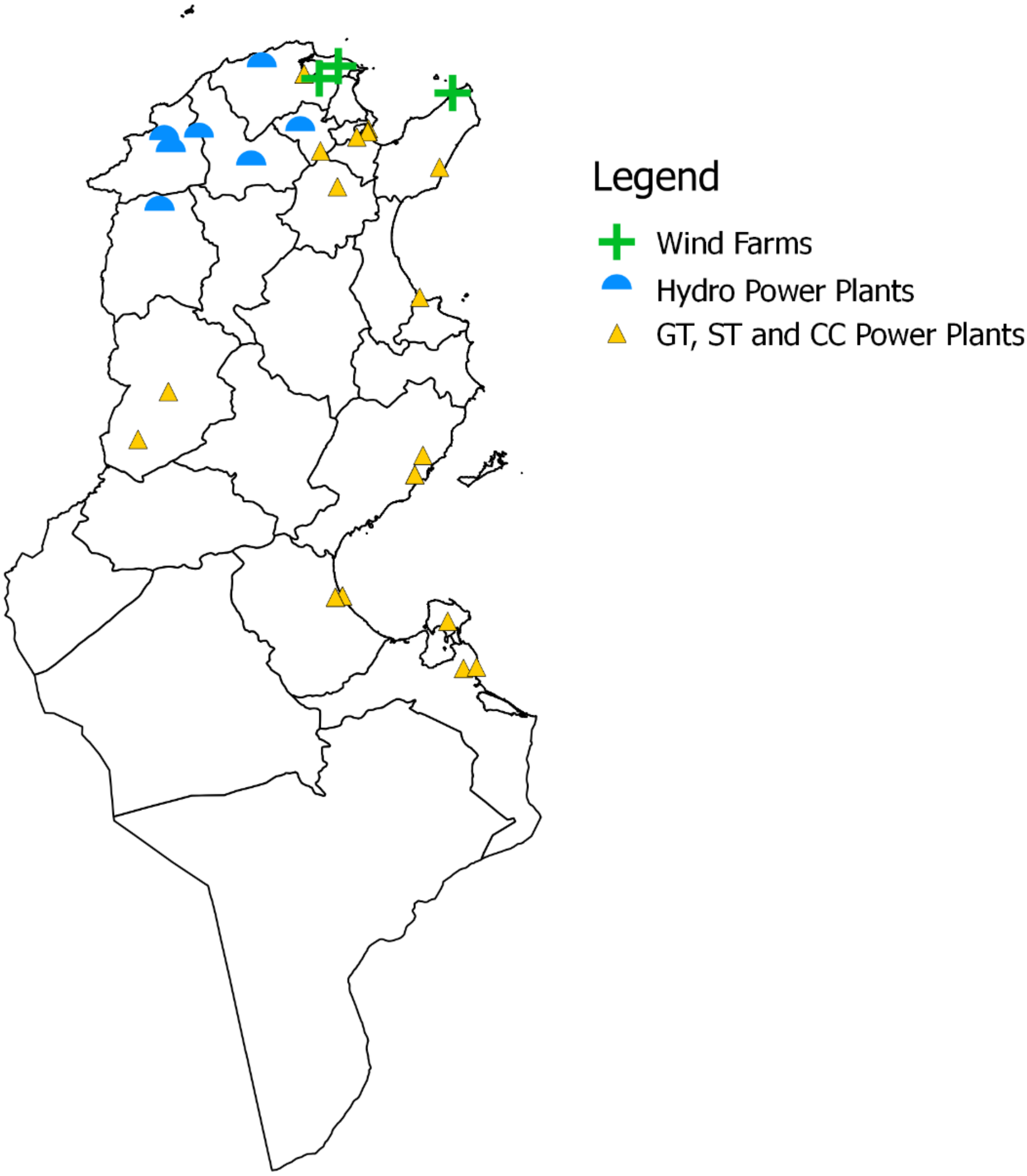


Figure 11: Tunisian Electricity Generation Inventory [Own Elaboration]

3.2 High Voltage Transmission Grid

The High voltage power grid of Tunisia is more than 6000 Km long [27] and involves principally 90 kV, 150 kV and 225 kV lines. The overall grid coverage, follows population distribution pattern.

While the 90kV grid covers just the northern territory, the 225 kV line, which is the back bone of the high voltage grid, is relatively distributed over the country. Conversely, the 150 kV lines are more concentrated in the central zones. Both 150 and 225 kV lines serve more inhabited seashore of the Mediterranean Sea.

The transmission system includes also a 200 km long 400 kV line which passes through the north part of Tunisia and connects the grid through Jendouba-Chifa stations to Algeria in Northwest.

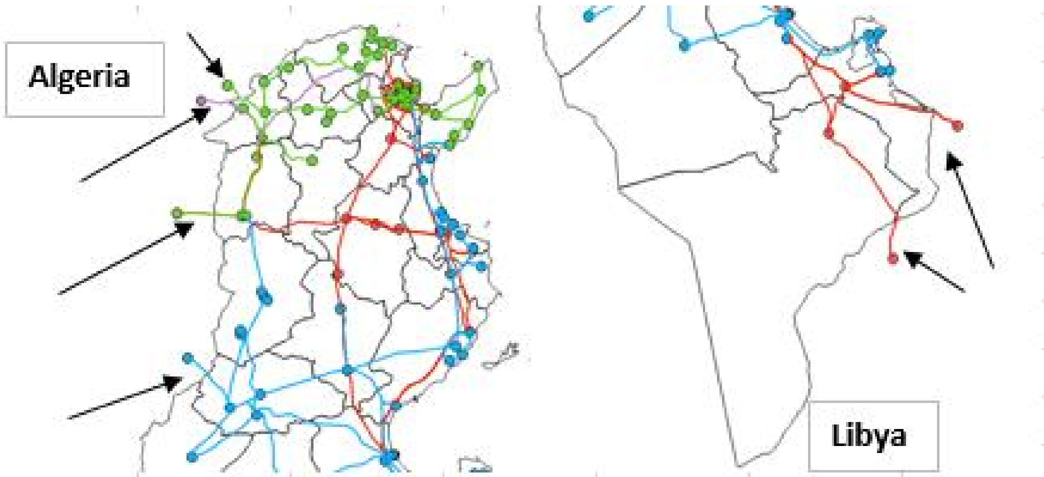


Figure 12: International Connections of the power grid [Own Elaboration]

Moreover, the grid is connected to Libya through two 225 kV lines in the Southeast part and to Algeria in East and Northeast part through two 50 kV lines and one 150 kV line.

The starting point of the present work was to construct the whole model on the QGIS software. To do this, the principal reference was the disperse information on Openstreetmap which has been completed taking advantage of the published maps on the yearly reports of the STEG. The final situation of the grid coincides with [4].

The complete model of transmission lines and respective stations is reported in figure below.

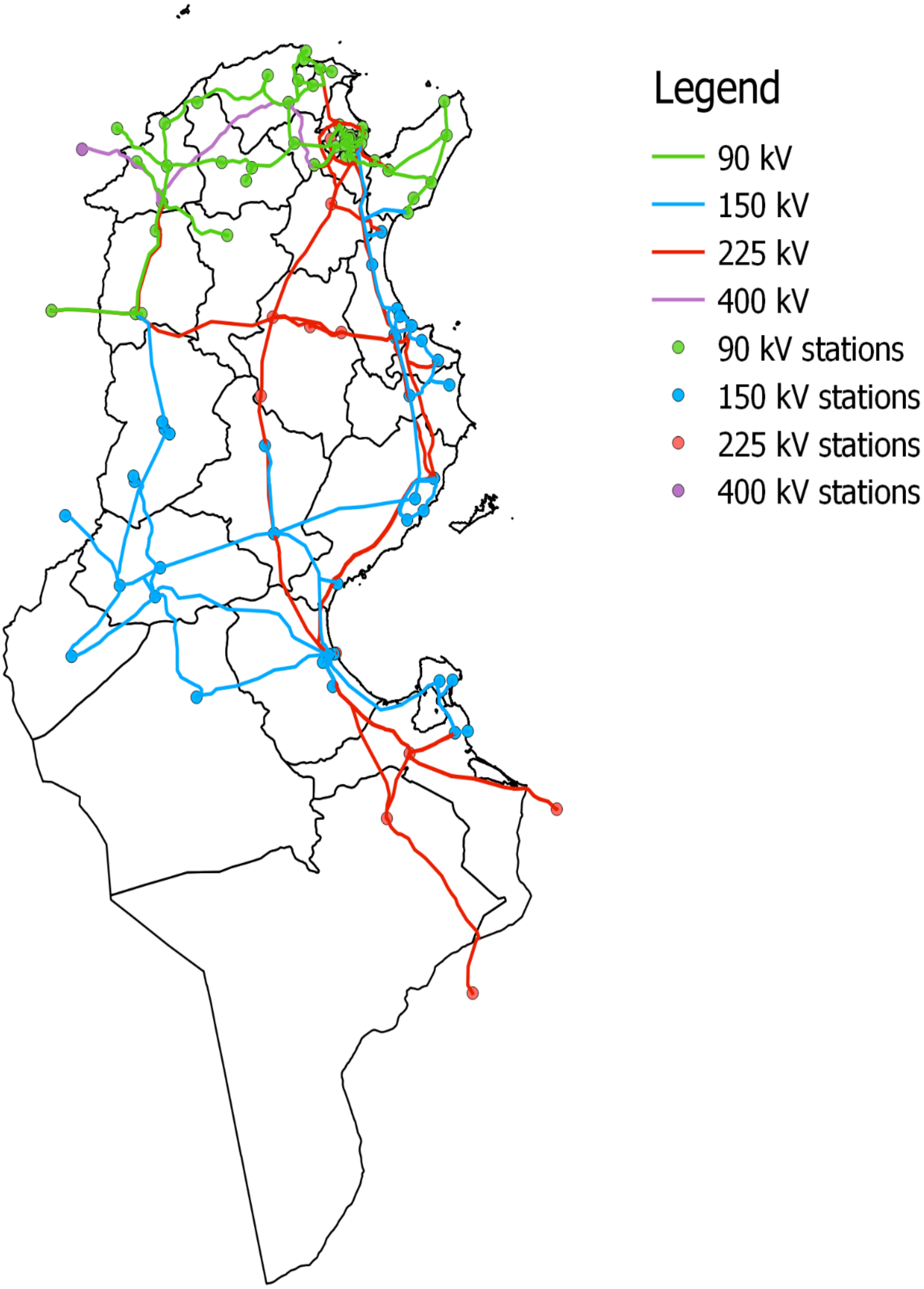


Figure 13: High Voltage Power Lines and Relative Stations, Tunisia [Own Elaboration]

Table 3: length of High Voltage Transmission Lines [Own Elaboration]

Voltage kV]	90	150	225	400
Length [km]	1217	2139	2791	242

3.3 High Voltage Stations

The localization of the power stations follows the same pattern of the grid and likewise is not adequately distributed over the whole governorates.

As an example, Tunis governorate, with 9.5 % of the population, has the highest percentage of stations (12.07%) and the statistics for four more extended governorates Sidi Bouzid, Gafsa, Tozeur, Kebili and Tataouine in the south and central zones with 10.7% of the population is 7.8% of the total stations though the latter governorates cover more than one third of the Tunisia's surface.

Also in the case of stations the data was obtained from Openstreetmap and cross-checked with [4]. The missed stations where inserted into QGIS finding their exact geographical coordinates from google map and converting them to the QGIS coordinate system.

Table 4: Number of stations by Voltage [Own Elaboration]

Voltage	90 [kV]	150 [kV]	225 [kV]	400 [kV]
Number	46	39	29	3

Chapter 4

Optimization and OPF

4 Optimization and OPF

4.1 Some Brief Theory

The scope of any optimization problem is to find what the best solution of a problem is. In case of multivariable problems, this best solution comes from minimizing or maximizing a function called "objective function" $f(x_1, x_2,\cdots, x_{n)}$ with n variables $(n > 0)$ which could be constrained $g_i(x_1, x_2,\cdots, x_n) <=> b_i$ or unconstrained.

Although the optimization problem is strictly tied to the mathematical concepts, its application domain is highly wide and could involve problems in business, industry, computer science, economics or in an energy system: optimization of an economical, environmental, technical, etc., objective function.

Sometimes, the problem concerns optimization of multiple competing variables. In such cases, the optimum point is a kind of compromise between all factors which need to be optimized (e.g. cost and efficiency)

Normally the optimization process starts with some *operational researches* to find possible solutions of the problem and their advantages which finally will lead to *decision making*.

In qualitative cases it is also necessary to make quantification of the decisions or so to say make the "*Mathematical Model*". Obviously in each step there is a loss in the realism of the problem even in low quantities.

The importance of computation methods is that it is the final mathematical result which will tell us the validity of our assumptions and computations.

Other important concept in optimization is the concept of global or local optimum solution. It is possible that some optimization method converges to the local optimum solution. Therefore it is of the crucial importance to find out in which circumstance a local optimum solution is the global one as well.

The most important characteristic to guarantee the coincidence of local and global minimum point is the convexity and concavity concepts, let us study the concept in detail:

A region R is convex if for every two points x_1 and x_2 belonging to it, the point

$$(1-\theta)x_1 + \theta x_2 \qquad (0 < \theta < 1)$$

is always inside the region.

If function f is convex, it is never underestimated by linear interpolation, in other words $\forall \boldsymbol{x}$

$$\boldsymbol{x} = (1-\theta)\boldsymbol{x_1} + \theta \boldsymbol{x_2} \qquad (0 < \theta < 1):\ f(\boldsymbol{x}) \leq (1-\theta)f(\boldsymbol{x_1}) + \theta f(\boldsymbol{x_2})$$

A linear function is both convex and concave.

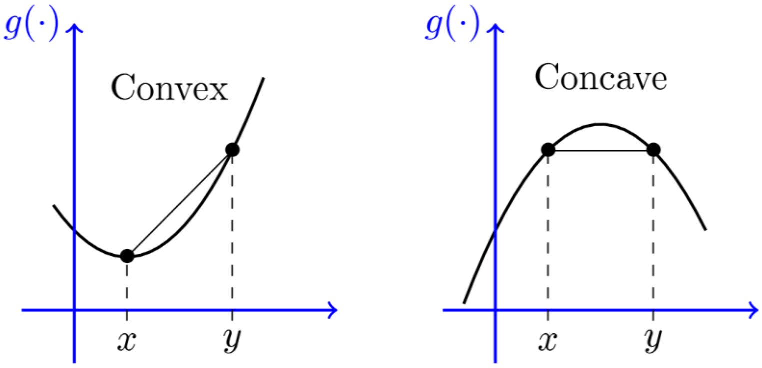


Figure 14: Convex and Concave functions [29]

A twice-differentiable function$f(x_1, x_2, \cdots, x_{n)}$ is convex if its *Hessian* matrix is *positive definite.*

Hessian matrix A of n variable function f is defined as:

$$A = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix}$$

Furthermore, if for every non-zero vector $\boldsymbol{s}$

$$\boldsymbol{s^T.A.s \geq 0}$$

then the matrix A is positive definite[30].

4.2 Optimization in Power Systems

Like other types of optimization, also the electricity-based models focus on finding the feasible, optimum solution. The procedure could be classified as follow:

- They have an objective function to minimize which is often the cost of production, but environmental and financial objectives could be implemented as well
- There are a set of decision variables sometimes also time dependent such as fuel cost, demand profile
- A set of constraints which determine the feasibility of the minimization which are the technical properties of generators and transmission lines [3].

4.3 Optimization Types

As a matter of fact, since optimization is applied into many sectors, it includes a vast and variable range of properties. A possible division of Optimization problems could be as follow:

Constrained or Unconstrained optimization

If variables of optimization problem vary freely without any limit, it is said to be unconstrained optimization, otherwise, constrained. Furthermore, constrains could be classified in equality and inequality ones.

The solution of constrained problems, besides being optimal, must have some additional characteristics, or in other words be feasible. Hence, it is generally much harder to solve such problems.

Constraints could be categorized in equality constraints and inequality ones.

Deterministic or Stochastic optimization

There are several situations in which, because of the nature of the problem the complete data is not available or is not exact (e.g. Financial Planning, Electricity Capacity planning…). In such circumstance, the optimization is called Stochastic or probabilistic and optimization is performed under uncertainties. Such models require sophisticated and complicated computational and technics. At the opposite side of the stochastic optimization, in the Deterministic problems are data are known apriori.[31]

Discrete or Continuous

An optimization problem is said to be discrete if all or some variables of the problem assume just discrete integer values

Linear or Non-Linear optimization

If the optimization problem contains at least one non-linear function either in objective functions or among the constraints, the problem is of non-linear optimization [32]

4.4 Optimal Power Flow

The duty of a power system is to cover all the demand zone and supply the needed electricity in each time period. Obviously in such an expanded system, generation points and loads are not connected to same nodes and there are transmission lines in between. Looking at the distribution of generation with a just economic view (Economic Dispatch), may lead to unacceptable flows or voltages in the network. In such cases, a suitable substitution is to implement OPF.

The objective of an OPF is to minimize the cost of generation of electricity and transmission losses, guaranteeing the security of system by exerting some Equality constrains on power balance at each node (load-generation balance) and some Inequality constrains on upper and lower limits of the lines and limits on the control variables.

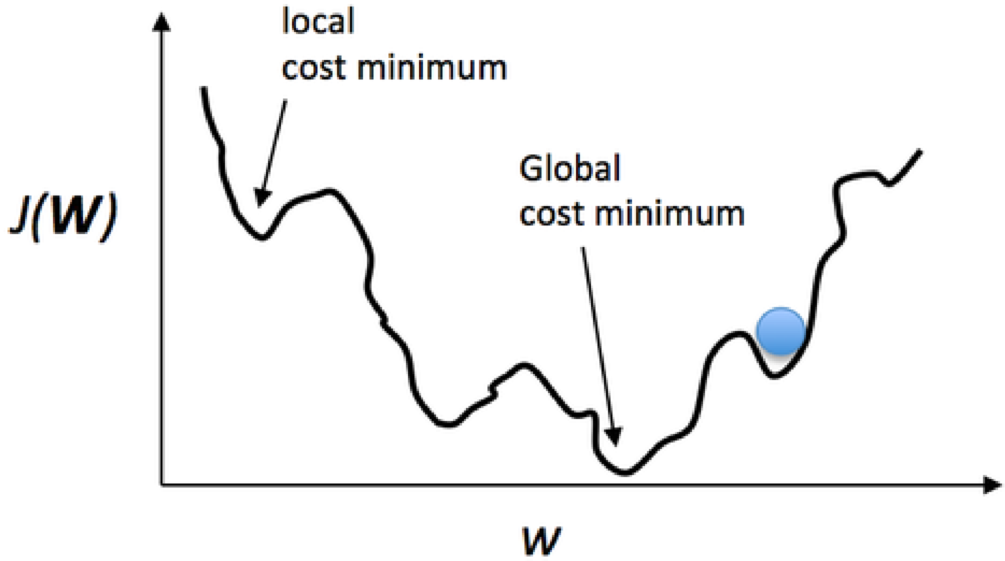


Figure 15: a non-convex function [33]

In fact, OPF is a nonlinear nonconvex optimization problem that by implementing computational algorithms and simplifications minimizes the objective function exerting constrains of Kirchhoff's and Ohm's law. [33]

4.4.1 Mathematical Formulation of OPF

In an OPF problem it is necessary to formulate:

- Decision variables
  - Active power outputs
  - Voltage of generation units
  - Transformer taps position
  - Position of phase shifters taps
  - Status of the switched capacitors and reactors
  - Control of power electronics
  - Amount of load disconnected

The vector containing all control variables is called $\boldsymbol{u}$

- State variables
  - How the system responses to the changes of the control variables
  - Voltage magnitude at each bus
  - Voltage angle at each bus

The vector containing all state variables is called $\boldsymbol{x}$

- Parameters
    - Characteristics of the system
    - Assumed constants
        - ♦ Network topology
        - ♦ Resistance, Inductance, Susceptance and voltage limits of network
        - ♦ Cost of generation of generators
        - ♦ Limits of generators

The vector containing all parameters is called $\boldsymbol{y}$

- Objective functions which should be minimized
    - It could be the classic cost function

$$min_{\boldsymbol{u}} \sum_{i=1}^{N_u} C_i(P_i)$$

- Or any other objective function such as system losses or change in controls

- Constrains $\begin{cases} Inequality \\ Equality \end{cases}$
    - Equality constrains
        - ♦ Power balance equations at each node

$$P_k^G - P_k^l = \sum_{i=1}^{N} V_k V_i [G_{ki}\cos(\theta_k - \theta_i) + B_{ki}\sin(\theta_k - \theta_i)]$$
$$Q_k^G - Q_k^l = \sum_{i=1}^{N} V_k V_i [G_{ki}\sin(\theta_k - \theta_i) - B_{ki}\cos(\theta_k - \theta_i)]$$

$$for\ k = 1 \dots N$$

Which could be written in the compact form $G(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{y}) = 0$

- Inequality constrains
    - ♦ Limits on control variables

$$\underline{\boldsymbol{u}} \leq \boldsymbol{u} \leq \overline{\boldsymbol{u}}$$

- ♦ Limits on operating flows

$$|F_{ij}| \leq \overline{F_{ij}}$$

- ♦ Limits on voltages

$$\underline{V_j} \leq V_j \leq \overline{V_j}$$

With the compact form $H(\boldsymbol{x}, \boldsymbol{u}, \boldsymbol{y}) \geq 0$

The final compact form of the mathematical formulation of OPF problem is as follow:

$$\boldsymbol{min_u f(u)}$$
$$\textbf{Subject to: } \boldsymbol{G(x, u, y) = 0}$$
$$\boldsymbol{H(x, u, y) \geq 0}$$

There are several methods to solve OPF optimization such as Interior Point Method, Gradient Method and Linear and Sequential Linearizing Methods. Each of the mentioned approaching methods has its own problematics such as the slowness of convergence or difficulties in handling inequality constrains and necessity of iterating linearization.[34]

4.4.2 OPF types

Based and the typology of approach the characteristics of the system, the optimal power flow is divided into two types:

- **ACOPF**
  Alternative current OPF is the full representation of the OPF in which a generator, called slack bus (if speaking about single slack bus), is chosen as the reference of all voltage angles and real power slack. The slack bus is a type of regulator of probable gap between the generated real power and total system load and losses.
  There are a lot of discussions on the criteria to implement for selection of the reference bus. A usual criteria is to choose the largest generator in the system as slack bus to be able to recover the system imbalances rapidly.[35]
  Furthermore, in ACOPF the model takes into account also the transmission losses and the reactive powers of generators.

- **DCOPF**
  ACOPF algorithms are highly time consuming in large scales and are very difficult to implement inside planning processes.[36]

DCOPF models instead, are simplified and approximated approach to OPF problem in which constrains are linear. Moreover, the voltage magnitudes and reactive powers are neglected and real power flows are considered to be linear functions of voltage angles.[37]

In general, Direct Current OPF is suitable to be implemented in the networks with a high amount of DC generators such as Photovoltaic cells, fuel cells, batteries and super capacitors which have DC output and DC consumptions such as Electric Vehicles and LEDs.[38]

In DCOPF the grid is considered as purely reactive, (lines' resistance is taken as negligible with respect to their reactance).

4.4.3 Mathematical Formulation of DCOPF

The mathematical model of DCOPF is like OPF but with some simplifications:

Since reactive powers are considered to be zero, the power balance equation is reduced as follow

$$P_k^I - \sum_{i=1}^{N} V_k V_i [G_{ki} \cos(\theta_k - \theta_i) + B_{ki} \sin(\theta_k - \theta_i)] = 0$$

The resistance of branches is set to be zero as well

$$P_k^I - \sum_{i=1}^{N} V_k V_i B_{ki} \sin(\theta_k - \theta_i) = 0$$

All voltage angels are assumed 1 $p.u.$

$$P_k^I - \sum_{i=1}^{N} B_{ki} \sin(\theta_k - \theta_i) = 0$$

And all angels are hypnotized to be small, in this way $\sin\theta \approx \theta$

$$P_k^I - \sum_{i=1}^{N} B_{ki} (\theta_k - \theta_i) = 0$$

Substituting susceptance with reactance

$$P_k^I = \sum_{i=1}^{N} \frac{(\theta_k - \theta_i)}{x_{ki}} = 0$$

The model is called DC because the last formula has the structure of Ohm's low:

$$P_{ki} = \frac{(\theta_k - \theta_i)}{x_{ki}} \leftrightarrow I_{ki} = \frac{(V_k - V_i)}{R_{ki}}$$

Active power as the DC current, reactance as DC resistance and voltage angles as the voltages [34].

4.5 About MATPOWER

MATPOWER[39] is an open source Matlab base software. It is a pack of predefined functions implemented in the software which perform optimizations on power systems. The version adopted for the present work is 6.0.

The structure of an OPF problem consists of 4 matrices: a matrix which contains the data about all buses (i.e. stations and generators) *mpc.bus*, another matrix with information about all generators of the system *mpc.gen*, a matrix of all lines containing technical properties and starting and ending point of them and some other information *mpc.branch* and the cost matrix which is made based on the heat curves and production costs of each type of generation *mpc.gencost*.

As mentioned before the necessary information to fill the matrices changes based on the optimization approach (AC or DC).

Chapter 5

Modeling of Power System Elements

5 Modelling of Power System Elements

The present model of the electricity system of Tunisia includes 26 generators which could have more than one production unit, 6388 Km transmission lines, 116 stations (excluding the stations which connect the grid with neighbor countries) and 23 transformers between different voltage levels in some stations. As mentioned before, the model structure relies on the data published by STEG.

In fact, the model is like a graph: Stations are the nodes and transmission lines and transformers are the edges of the graph.

5.1 Generation Modelling

The active power plants inserted in the model consist of 53 units (considering number of generation units present in each thermal plant). This amount includes thermoelectric generators, hydropower plants and wind farms.

5.1.1 Thermoelectric generation modelling

The conventional power plants in Tunisia, are mostly alimented by Natural Gas. In 2016 just 1% of national production was by oil and 96.5% by Natural Gas[13].

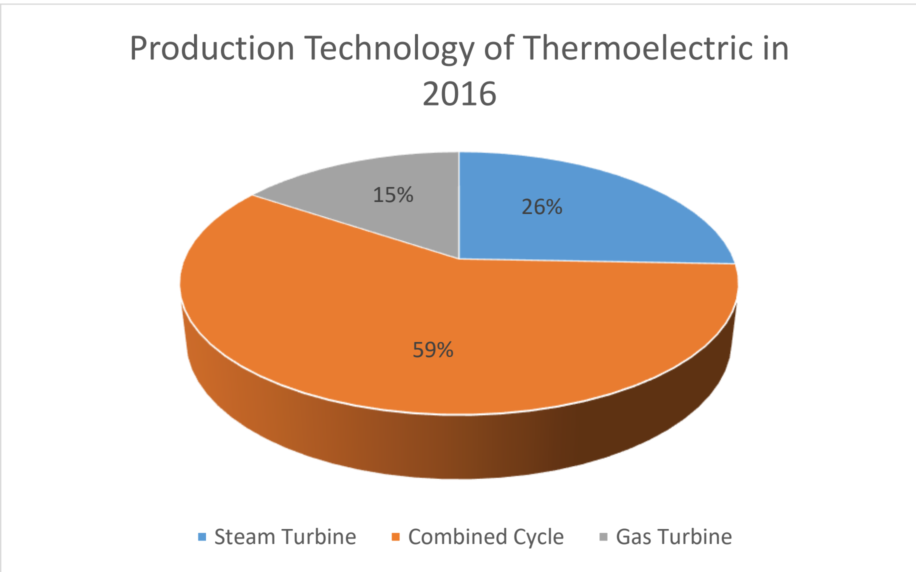


Figure 16: Conventional Electricity Production Technolgies [Own Elaboraiotn- STEG Statisticss]

After establishing national thermal generator inventory, each power plants has been splited into its generation units to increase the flexibility in generation and control if necessary. In such a way, all production units of a unique power plant are geographically presented in the same point but are individual generators for OPF.

Different levels of stations in the same point are linked together through a transformer with null resistivity.

5.1.2 Modeling of generation from Renewable Power Sources

The only Renewable generators connected to the high voltage grid of Tunisia at this moment are Onshore Wind turbines and some small Hydro plants.

Wind power generation includes two regions and three wind farms located in the northeast Mediterranean coast:

- **Sidi Daoud site**: located in Nabeul zone, composed of 5 parts and equipped with seventy turbines of 330, 660, 800 and 1320 kW nominal power.
- **Metline site**: located in Bizerte zone. Composed of two phases each two part with 71 turbines of 1320 Kw nominal power.
- **Kchabta site**: 72 turbines close to Metline site and with the same nominal power as Sidi Daoud farm.

5.1.3 Mathematical model of wind generation

In the literature, there are several articles that study the mathematical model of the wind generators and required parameters[40]:

The maximum mechanical power of the turbine could be calculated applying

$$W_{mec,max} = \frac{1}{2}\rho A u^3 \quad [W]$$

Where

- $\rho\ [\frac{kg}{m^3}]$ is the air density calculated applying the Ideal gas law for unit atmospheric pressure (such a pressure is realistic because the altitude of the farms is some 28 meters) and the temperature profile extracted from Meteonorm.
- $A\ [m^2]$ is the swept area of blades
- $u\ [m^3]$ is the wind velocity

The real mechanical power obtained by turbine is always less than the Betz value

$$W_{real} = W_{mec,max}.C_p$$

Where C_p is called the power factor. In 1919 German physicist, Betz, realized that the real mechanical power of the turbine has a maximum value for
$C_{p,max} = 16/27 \approx 0.593.$

Power factor is not a fixed value and is function of wind velocity and tip speed ration of the rotor:

$$C_P = \frac{(1-\lambda^2)(1+\lambda)}{2}$$

where

$$\lambda = \frac{blade\ tip\ speed}{wind\ speed}$$

And

$$blade\ tip\ speed = \frac{\omega.R}{wind\ speed}$$

Where

- $\omega = \frac{2\pi.n}{60}$ [rad/s]
- $n[rpm]$ rotor velocity of each model of turbine obtained from[41].
- R is the radius of the turbine blades[m]

As an approximation for Gear box and electrical conversion efficiencies, respectively $\eta_{GB} = 0.95, \eta_{el} = 0.94$ [42] should be considered. So

$$\eta_{conv} = \eta_{BG}.\eta_{el} = 0.89$$
$$W_{el} = \eta_{conv}.W_{mec}$$

And finally the total power production could be calculated multiplying total number of wind towers of each farm to the electrical power of the single turbine.

$$W_{el,tot} = n_t.W_{el}$$

5.1.4 Wind Turbine Production Modelling by Power curve

Another way to assess the electricity production of a wind turbine, applied in the present work, is to refer directly to the so called power curve of the turbine.

A power curve provided by the manufacturer of the turbine, gives the electrical power output in each wind velocity. A sample of power curve of turbine “made-AE-61” is visible in figure 18.

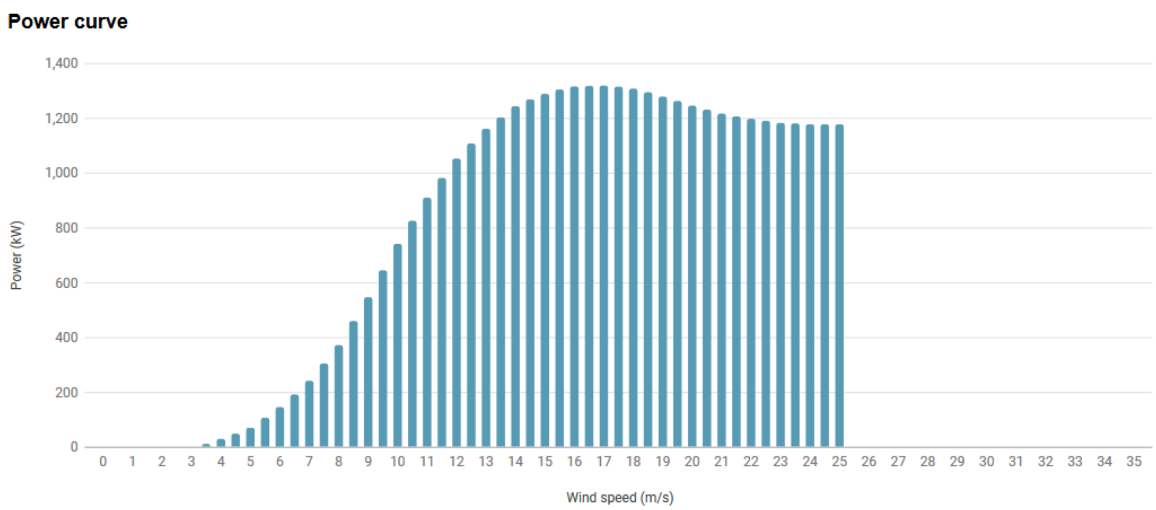


Figure 17: power curve of turbine Made-AE-61[40]

To calculate the final produced electricity, the electrical conversion efficiency η_{el} (studied in the previous section) needs to be applied on the data.

5.1.5 Wind Speed Profile

The information of wind velocity in two different coordinates "Sidi Daoud" and "Bizerte" was extracted from the software *METEONORM*[43].

Meteonorm is a licensed software which provides historical meteorological data such as velocity of wind, temperature, irradiation and some other satellite data for different coordinates on earth.

The wind velocities given by Meteonorm are measured at the height of anemometer, in Meteonorm case 10[m]. The velocities are reported into the hub's height using Hellman exponential low

$$u_2 = u_r.(\frac{z_2}{z_r})^{\alpha}$$

Where

- u_2 and u_r are respectively the wind velocity at the wanted height and at the anemometer's height
- z_2 and z_r are respectively the height of hub and the anemometer here 10[m]
- α is the wind shear coefficient and changes with the terrain property and solar irradiation, atmospheric stability, humidity and temperature of the zone [44].

Table 5: different values of wind shear based on ground type [44]

terrain type	α
lake, ocean and smooth hard ground	0.10
foot height grass on ground level	0.15
tall corps, hedges and shrubs	0.20
wooded country	0.25
small town with some trees and shrubs	0.30
city area with tall buildings	0.40

For the wind speed data extraction from Meteonorm, considering the distance of each site from sea, Sidi Daoud was defined as "lake/see" position and other two sites as "open site".

Concerning Hydro generation, as there was no available data about hourly precipitation and exact technical data of generation units, the share of each power plant was determined dividing the total yearly hydro production between plants based on the installed capacity of each.
Such an approximation does not exert too much uncertainty to the model because the share of hydro plants in total generation is just 0.25%.

5.2 Demand Modeling

To model the electricity demand of the Tunisia in a precise way, the annual hourly demand profile was needed. As such an information is not delivered neither by the STEG nor by any other reliable reference, the solution was to generate the profile.

Due to the transparency policy of the European countries toward electricity market, the aggregated demand profiles of European countries are accessible on ENTSO-e website [19], and an appropriate choice seemed to use one of them as the generator. Therefore, the next step was to decide which country is the most adequate one.

To make a more accurate comparison, some economic indicators such as GDP per capita/PPP, GDP/PPP and electricity consumption per capita published data of IMF[9] and World Bank [45] were considered.

Comparing the latter indicators of all European countries with Tunisia's, the most significant countries to select seemed to be Albania, Bulgaria, Moldova and Serbia.

At the previous step, the share of different sectors in the structure of GDP of each country and *Energy Trilemma Index* were also took into account. Based on all mentioned criteria, the most suitable case to be used to construct the Tunisian demand profile was Bulgaria because of the similar GDP sector share, similar GDP per capita/PPP and Energy Index.

Afterwards, using QGIS, the total number of stations and substations in each province was determined.

Based on CIA world Factbook [46] and [14] the total electricity demand of Tunisia in 2016 was 15.225 TWh.

Table 6: comparison of economic factors of some EU countries with Tunisia [Own Elaboration- CIA World Factbook and WEC statistics]

	Population	GDP	GDPper cap/PPP	El. Cons. per cap	En. Trilemma Index	DGP sectors			
	[Million]	[Billion $]	[$]	[kWh/pers]	[-]	% Agr.	%Ind.	%Manuf.	%Ser.
TU	**11.5**	**40.3**	**12000**	**1.326**	**DBB**	**9**	**24**	**15**	**63.5**
AL	2.8	13	12500	2.327	CCA	19	21	6	47.3
MOLD	1.3	8.1	5700	1.327	DBC	12	18	12	55.4
BUL	**7.1**	**56.8**	**20329**	**4.477**	**BBB**	**4**	**25**	**14**	**58.3**
SE.	7.0	41.4	15090	3.766	BBC	6	26	16	53.8

5.2.1 Distribution of demand in the country:

One of the most challenging task in this step, was to find a criteria to share the demand between all stations.

The adopted approach aims at assigning to each power substation a share of the national electricity consumption, based on the presence of people and industries in the surroundings. The reason relies in a general lack of reliable data, and in the preeminent role of the industrial sector in the national load: referring to the IAEA's data [47], industry sector consumes 35% of the produced electricity in Tunisia.

The industrial share of the national consumption has been distributed in the country based on collected data on the position of the main manufacturing industries. Conversely, the remaining 65% of total demand (including residential, agriculture, manufacturing, and transport and service sectors) was allocated to the substations based on the demographic distribution in the country.

Subsequently, the aggregated hourly consumption was divided between this two sectors.

To allocate properly the share of each governorate in industry sector, information about the number of registered companies in different provinces was extracted from "Tunisian industry portal" of Ministry of Industry and Trade [48] and National Institute of Statistics[49].

The criteria for division of the population was modeled based on the data of the National Institute of Statistics [49] and the census of the 2014.

The total share of each governorate from the consumption was obtained by summing the two partitions.

The total yearly demand profile in April-September period is reported in the following figure:

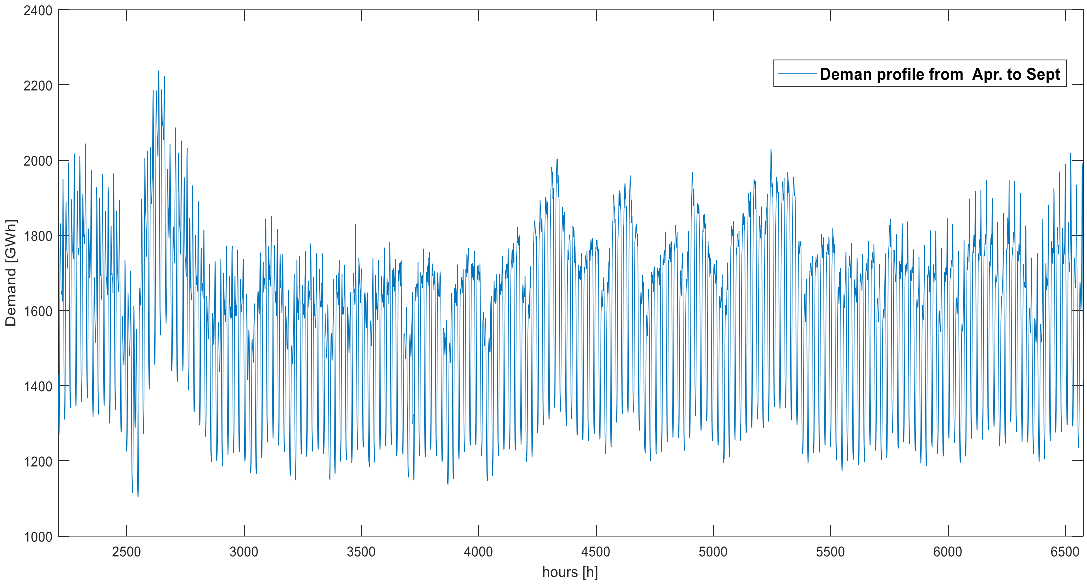


Figure 18: total Electricity Demand profile from April to September [Own Elaboration]

At the last step, the obtained value for each governorate was equally divided between present stations obtained as mentioned before, independently from the tension level. Concerning distribution behavior of demand, the three higher demand was located in stations Jenduoba, Mnhila and Jemel el Jem with values respectively 4.8e+05, 4.67e+05 and 3.28e+05 [MWh].

On the other hand, the three smallest demands are 60.1, 81.5 and 82.6 [GWh] located respectively in Tajerouine, Nebeur and Cimenterie Oum el Kelil stations.

It is important to take into account that the present distribution pattern is result of assumptions made during partition process about the structure of demand and its dependency on population and industry, described previously.

The following figure shows location of the stations with maximum and minimum demand on the map.

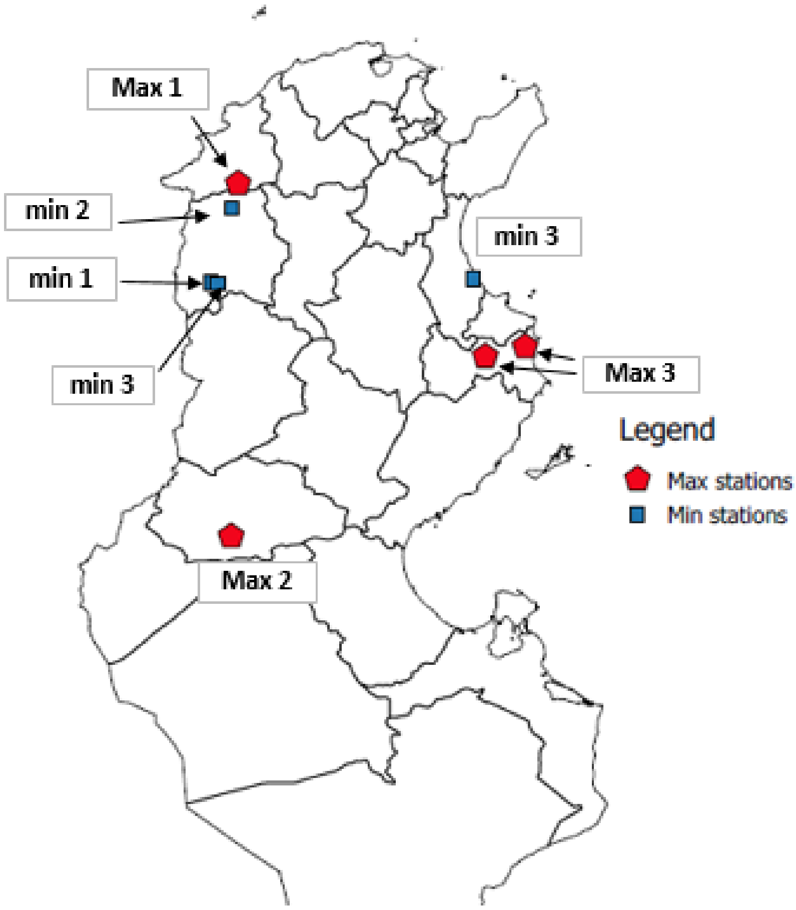


Figure 19: location of stations with Max and min demand on map [Own Elaboration]

The different values of demand in the first day of May for all 123 stations present in the model is reported in the following figure. Stations in which the demand is zero are the ones located in the neighbor countries. As said in the section 3.2 because the value

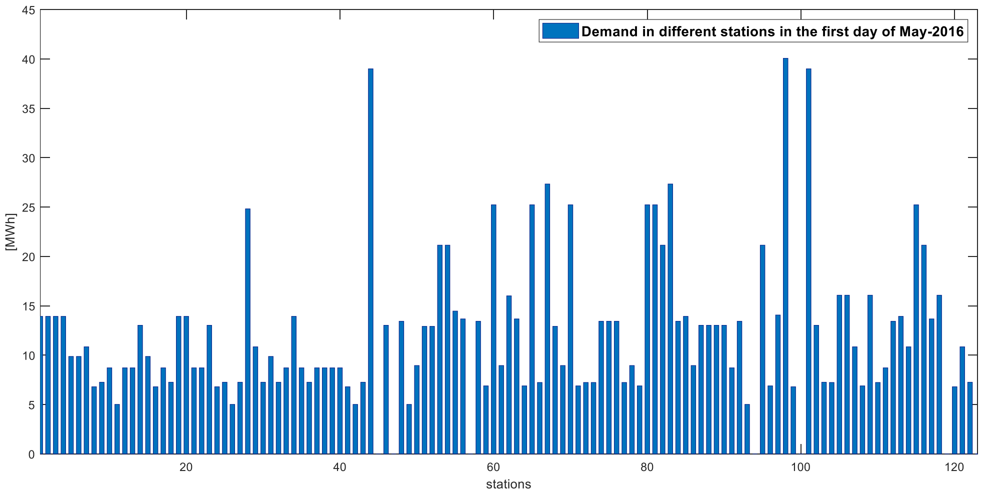


Figure 20: Demand values by station [Own Elaboration]

of exported and imported electricity are quite the same, they are not considered in the model and as a consequence the demand value in the respective locations is set to zero.

The maximum demand in this specific day is 40.1 [MWh] and is located in the station Bir M'Chergha in Zaghouan governorate in the northeast part of Tunisia.

5.3 Cost Modelling

The principle objective of OPF is to supply the demand in the minimum production cost possible.

To reach this goal, the information of production cost formulation of each generator is a key concept in the input of the MATPOWER.

In the present work, the cost of Renewables is supposed to be zero and just the gas and oil conventional generators are considered to have production cost.

As a consequence, the renewable generation have priority of dispatch if there is suitable situation (e.g. wind velocity inside range) and the remaining capacity will be covered by the generators which guarantee the minimum cost of production.

The generation cost of a power plant could be divided in following items:

- Fuel cost
- Operation and Maintenance (O&M)
- Cycling cost

As mentioned before, the share of oil fueled power plants in Tunisia is very low and because of lack of information, the fuel is considered to be fuel oil.

Furthermore; Tunisian electricity production don't have any coal fired generators.

The reference for Natural Gas price in 2016 was a report of STEG[50] and amounts 56,9935 mill/th (millime Tunisian Dinar/thermie) equal to 18.08 €/MWh. The change rate of Dinar/Euro was taken as 2017's value. The Oil price is considered to be 15.3 €/MWh.

After constructing the heat curves of the power plants based on the fuel type, the cost of production was calculated for different load factors.

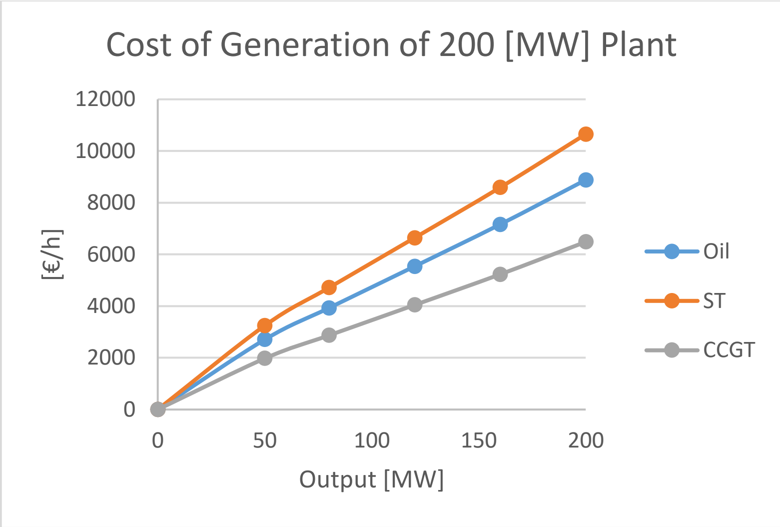


Figure 21: Cost of Generation [Own Elaboration]

Because of the higher efficiency of the combined cycle, the production cost of such plants is less than Oil power plants although the price of Oil is lower than Natural Gas.

5.4 Grid modelling

Technical and electrical properties of transmission lines are function of the material, cross section and length of the line. Based on the information extracted from QGIS in the Tunisian grid there are a not negligible amount of short length lines and as a consequence, this fact needs to be considered when calculating the resistance and reactance of such lines. The criteria to distinguish short and long lines was take from [51] i.e. a line which has the length less than 100 [km] is considered to be short.

Furthermore the information about if a power line is simple or double, was extracted from STEG map[28].

Chapter 6

Renewables in Tunisian Energy and Electricity System

6 Renewable Energy Resources

The benefits of implementing renewables in the energy system of Tunisia like every other county is multilateral: other than reduction of emission of climate altering gases could be seen as an opportunity to interact on economy and politics sectors in the country and region.

Reduction of the dependency of importing natural gas from other countries, job creation, economic stability and possibility to export electricity to Europe because of the strategic position of Tunisia are some examples of these opportunities.

By the way, the pathway for supplying electricity from low carbon generation resources has several issues to overcome. The fluctuating nature of Renewables, and in particular wind and photovoltaic, implies the necessity of energy storage and demand side management methods. A high renewable penetrated electricity system requires also flexible generators able to follow the variability and uncertainty of the renewable through ramping[52].

Since the geographic expansion of renewable-based power systems is high, also the development of transmission infrastructures is irremediable. It is important to say also that the peak of generation of renewables does not coincides necessarily with the peak of electricity demand, which consequently may cause curtailments of production [53].

6.1 RES in Tunisia

As mentioned before, the suitable geographic situation of Tunisia gives a great possibility to implement RES and take advantage of it in both national and international levels.

Tunisian interest to renewables starts in 1995 by ratifying (Decree 95/744) which foresaw tax exemption for the importation of renewable energy equipment [54] starting supporting policies for implementation of renewables.

In 2004, the National Agency of Energy Conservation (ANME) [55], a state agency, was founded. ANME's goal is to improve energy efficiency, promote and support research in the RES sector and implement alternative energy sources.

In Jan. 2004, as a collaboration between ANME and the *Italian ministry of the Environmental and Land* the Mediterranean Renewable Energy Center (MEDREC)[56] was founded. Today, some institutes from Algeria, Morocco, Egypt and Libya are also involved in the center. The center try to transfer energy technologies to the member countries, bold the importance of energy efficiency and promote the private sector to investments in RES and related infrastructures.

In 2009 another decree concerning self-consumption RES was introduces in the Tunisian energy system.

In December 2016, the Tunisian government has announced the so called "Tunisian Renewable Energy Action Plan 2030". Based on this document, both renewable and fossil electricity production will be subject of reinforcements, improving the energy intensity and increasing the renewable usage by 30% until 2030 installing additive 2250 [MW] renewable production capacity in two phases starting from 2017. The first phase contemplates installing 650 [MW] solar capacity and 350 [MW] wind.

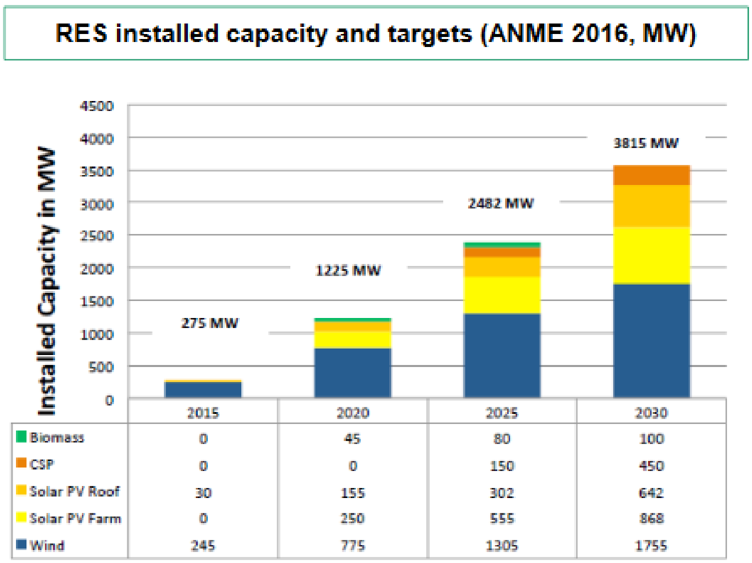


Figure 22: RES project, Tunisia. [58]

At the international level, Tunisia is a member of *The Regional Center for Renewable Energy and Energy Efficiency (RCREEE)* [57]. RCREEE is and international intergovernmental organization of 17 Arab countries. Other than the member states' contributions, the organization is financed by some European countries such as German Development Cooperation (GIZ) and Danish International Development Agency (DANIDA).

Based on [13], also STEG has several innovative projects in energy sector such as

- Smart grid program
- Experimental microgrids
-

6.2 Two RES projects

Two of actually active RES projects financed in international level in Tunisian power system are described below::

TuNur:

It is a project between Tunisia and Europe to open an energy corridor between two regions. The project is practically a Concentrated Solar Power (CSP) generator in 10,000 hectares area with an annual power output of 2.25 GW (18 towers 125 MW each).

PROSOL ELEC and PROCSOL

PROSOL ELEC was launched after the successful implementation of PROSOL, in 2010 and aims installation a total capacity of 15 [MW] by equipping the rooftops of 6000 houses and 1000 public and private buildings with photovoltaic panels.

The project requires also the reinforcement of the existing electricity infrastructures such as transmission lines.

PROSOL was a water heating program, active between 2005 and 2015 which provided loans and subsidies to install solar collectors in residential level.

Chapter 7

Results of Simulation

7 Results of the Simulation

In this section, some results of the DCOPF simulation are studied in detail.

The resolution of the present simulation for power plants is unit level, this means each cost function is applied on individual production units in each power plant. In addition, the resolution of the demand profile is hourly.

One need to take into consideration that DCOPF does considers the transmission losses of the electricity system.

Based on IEA statistics [59], the transmission and distribution losses in Tunisia were 14.49% in 2014. Therefore, in order to take into account grid losses, the total national electricity demand of 2016 (15.225 TWh, as declared by STEG), was increased by 15%, resulting into 17.51 TWh. Because of the equal amount of electricity export and import, this share is not considered in the simulation.

The figure below shows a November week 'demand' and 'supply by electricity source type' behavior. As said in previous sections, because of the lack of information about the technical features of the hydro plants and precipitation profile of the country, the share of hydro power generation is considered to be constant and wind generation profile varies as a function of wind speed in the farms.

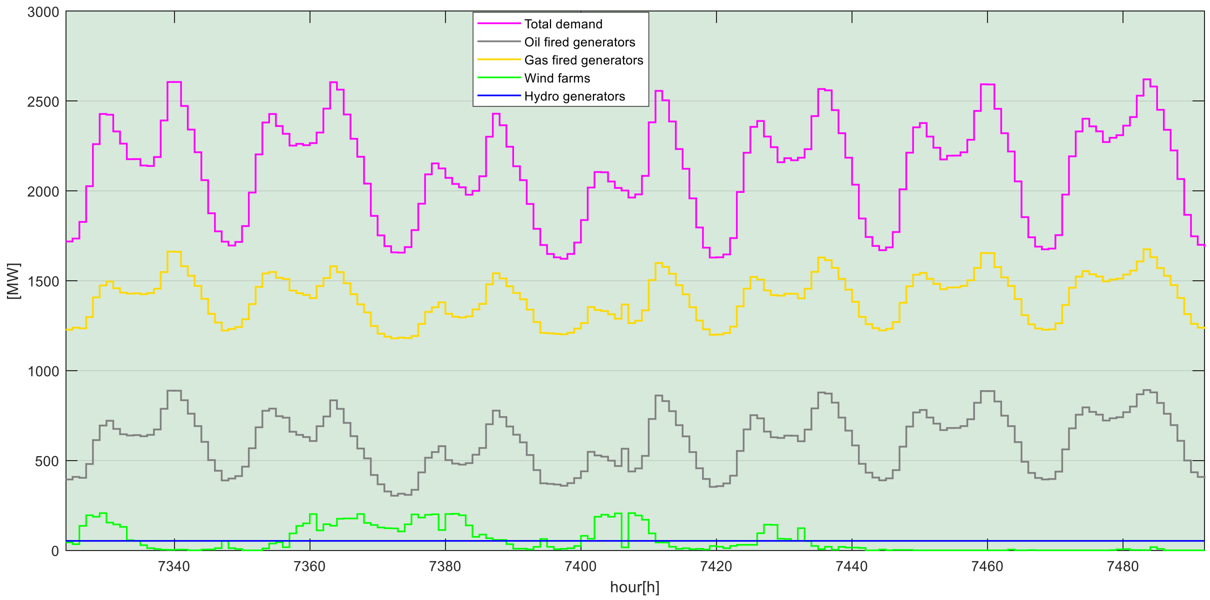


Figure 23: Generation and Demand in a generic week [Own Elaboration]

7-1 Wind and Hydro Generation

As cited previously, renewables have a very small share in the national electricity park of the Tunisia. Photovoltaic is applied in the residential and private level in small quantities and the only renewable sites are three wind farms.

While the production cost of the renewables is set to zero in the model, it is obvious that the demand, even in small quantities, will be covered by such resources at the starting phase of optimization of production cost.

A comparison between output of DCOPF model and data declared by STEG is visible in the figure 17.

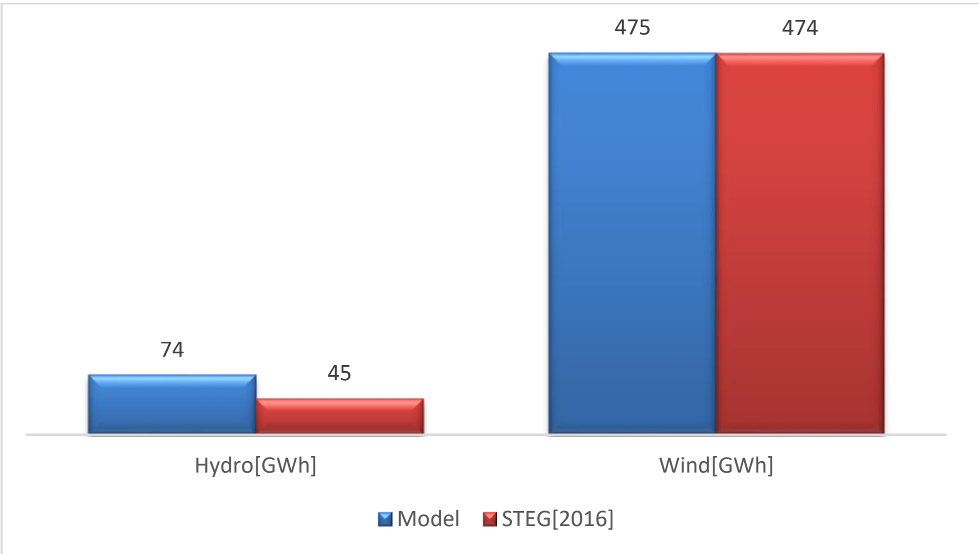


Figure 24: comparison of model and STEG data [Own Elaboration]

The hydro generation is slightly higher than the real value because of the overestimation through the constant production capacity. Conversely, the modelled wind production exhibits an accurate agreement to the produced capacity declared by STEG.

The following picture shows national demand profile in the first week of July, 2016 and the generation profile of three Tunisian wind farms.

In fact, the gap between two profiles is highly evident and improves the necessity and possibility of implementation more wind farms in the national generation profile.

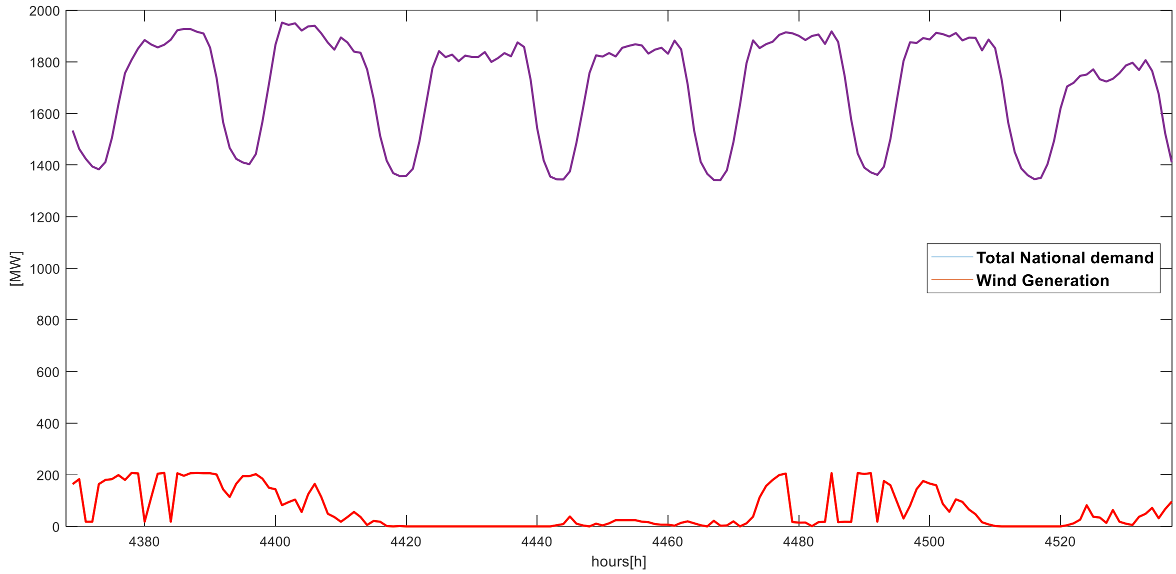


Figure 25: National Demand and Wind Generation profiles [Own Elaboration]

The total installed capacity of three wind farms Sidi Daoud, Metline and Kchabta (studied more in details in section 5.2.1) are respectively 54, 95 and 94 [MW]. Considering same week, the share of each park in the total production is shown in following graphic:

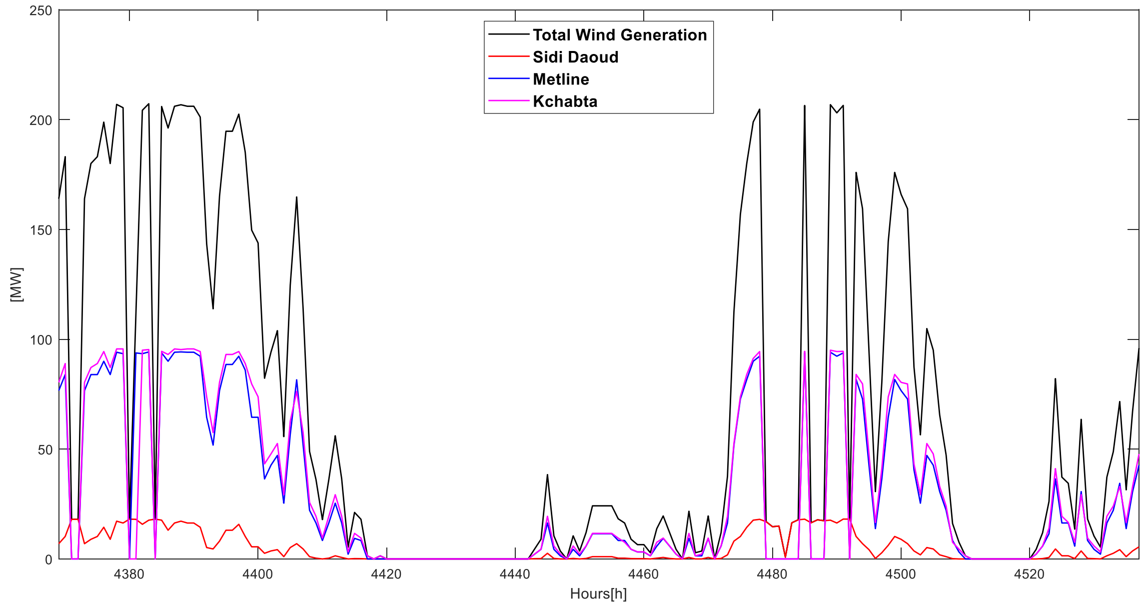


Figure 26: Wind Generation by farm [Own Elaboration]

One can see that the performance of Sidi Daoud site is not as expected (considering the fact that installed capacity of this farm is quiet half of the other two farms, produced power is expected to be quiet half of the other sites). This may be because of relatively old turbine models in the farm wake effect [60] of other present turbines. It is worth to say that the generation profile of each site is evaluated based on modeling individual turbine's power curve by fitting piecewise polynomial curves with very high R^2 values.

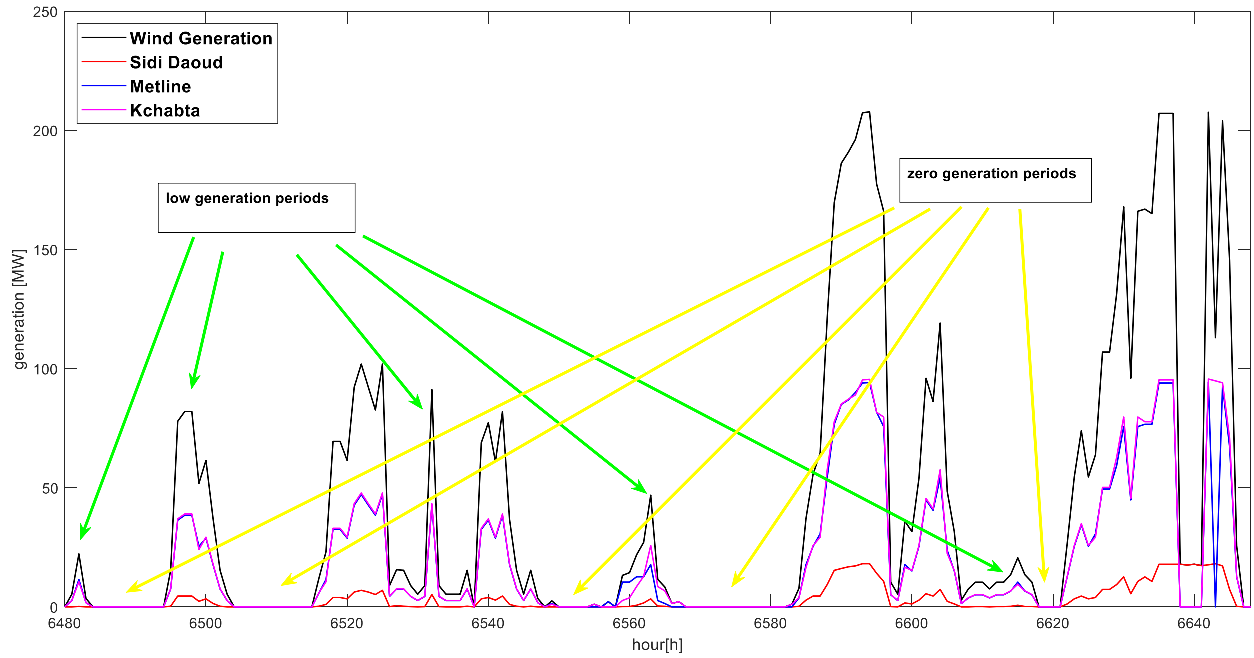


Figure 27: Periods with zero or small Wind Generation [Own Elaboration]

One important point to take into account is the qualitative behavior of production profile in different sites and the *small or null production periods* visible in both figures 18 and 19. Since all present Tunisian wind farms are located relatively close to each other (in the northeast Mediterranean coastal zone), the wind profile (although is not exactly the same) is more probable to have a general similar tendency and it leads to several overlapping of the periods in which no suitable wind profile is available.

This phenomenon is more remarkable in the case of Metline and Kchabta farms which are very close to each other (see the figure below).

Figure 28: Geographic position of wind farms [Own Elaboration on Google map]

An appropriate plan for the extension of the wind power generation capacity in future, could be locating more potential zones far from the present farms to increase the capacity of exploitation of the wind power and cover possible cases in which the production in the existing sites is low because of the meteorological situations.

7-2 Thermal Power Plants

In the Tunisian power generation system, the generators are either oil fired with 20% of total production share (STEG statistics) or gas fired. Coal is not used in the electricity system as a primary energy source.

The production profile of all thermal power plants in December 2016 is reported in the following graph. The general characteristic of both gas and oil generator's profile is that they follow the fluctuations of the demand profile.

It is because of the high ability of ramping in such technologies. In case of coal fired power plants, the plant's ramping capacity is not high and needs more time to reach a higher production capacity, so normally such generators are designed to cover a base load with minimum possible ramping and change in output.

In order to reach the minimum generation cost and cover 17.54 [TWh] electricity demand in 2016, the DCOPF model assigns a total of 4.7 [TWh] to oil fired generators and 11.9 [TWh] to gas fired generators. This quantity is about 40% of total thermal production.

On the other hand, STEG declares different amounts of production by source in 2016 [13] which is compared with the DCOPF results in the following figure:

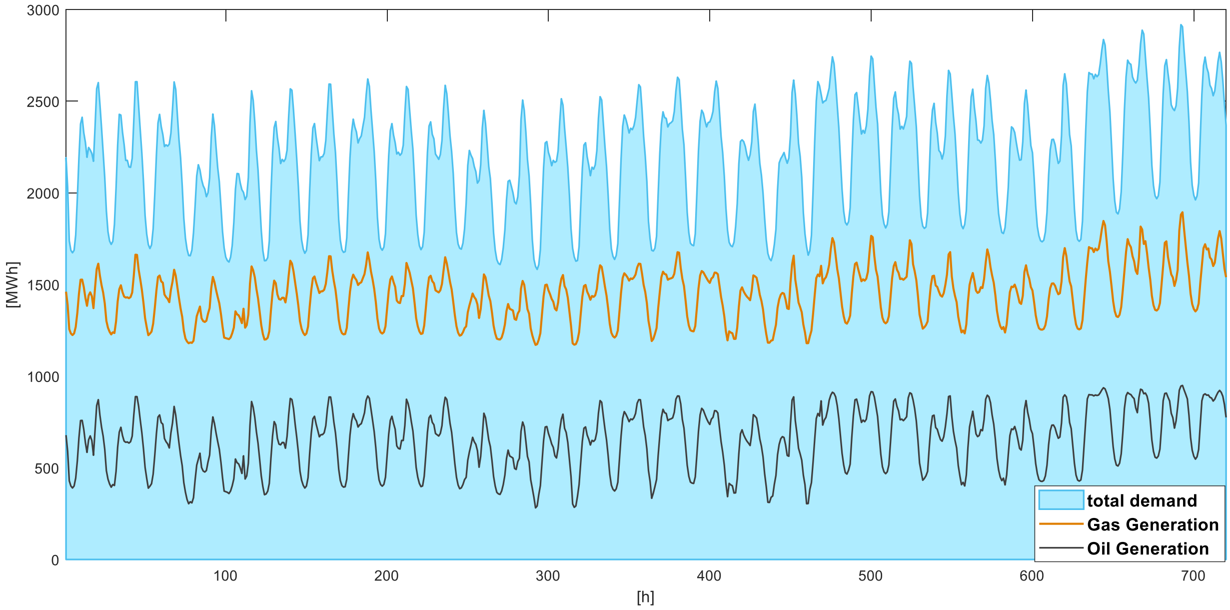


Figure 29: Demand and Thermic Generation profile in Dec. 2016 [Own Elaboration]

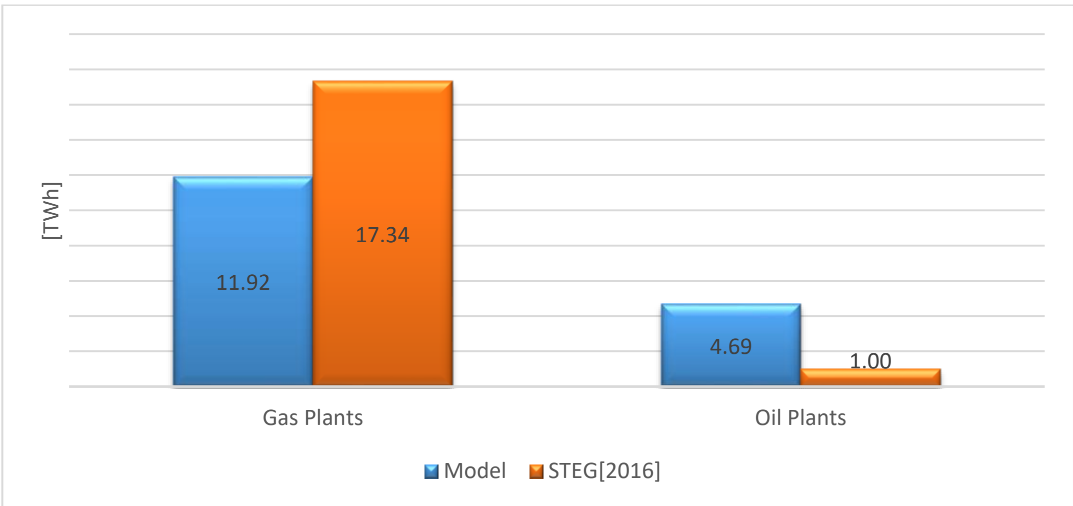


Figure 30: OPF model and STEG thermic generation comparison [Own Elaboration- Simulation and STEG data]

One reason of such difference between the economic way and actual situation could be the monopole and not competitive nature of the electricity market in the country. STEG, produces, distributes and sells to the final customer as said in previous sections. Notwithstanding the presence of IPPs, the final price of electricity is determined by STEG itself and not in a bidding market.

Other reason may be the fact that STEG has also the responsibility of the national distribution of gas and instead, oil, should be bought from other suppliers.

Another interesting statistic obtained from the DCOPF, concerns the number of shut downs of units of the system.

Total shutdown-startup and ramping cases in the DCOPF model are reported in table 6 below. As visible, the number of ramps and start up in gas fuel power plants is remarkably higher than oil fuel plants.

The ramp was defined as a shift (increase) of 30% of nominal power of the unit during 3 consecutive hours.

Table 7: Start ups and Ramps by fuel type [Own Elaboration]

	Oil fired	Gas fired
Starts	12	2412
Ramps	0	2345

Since the Tunisian power system is not renewable dependent, the generation profile is more stable and less intermittent. Therefore, the only reason to change the production capacity is the daily alteration in the demand profile.

In general, load cycling and ramping in power systems with high penetration of renewables is used to avoid curtailment of the later resources. Obviously, such interventions have high negative effects on the lifetime of the power plants' parts which are subjected to the temperature change. Such a phenomena other than financial cost exerts also the increment of the specific emissions from the conventional power plants [53].

Following graphs show the performance of two Oil and two Gas power plants with high and low capacity in the same week of the year.

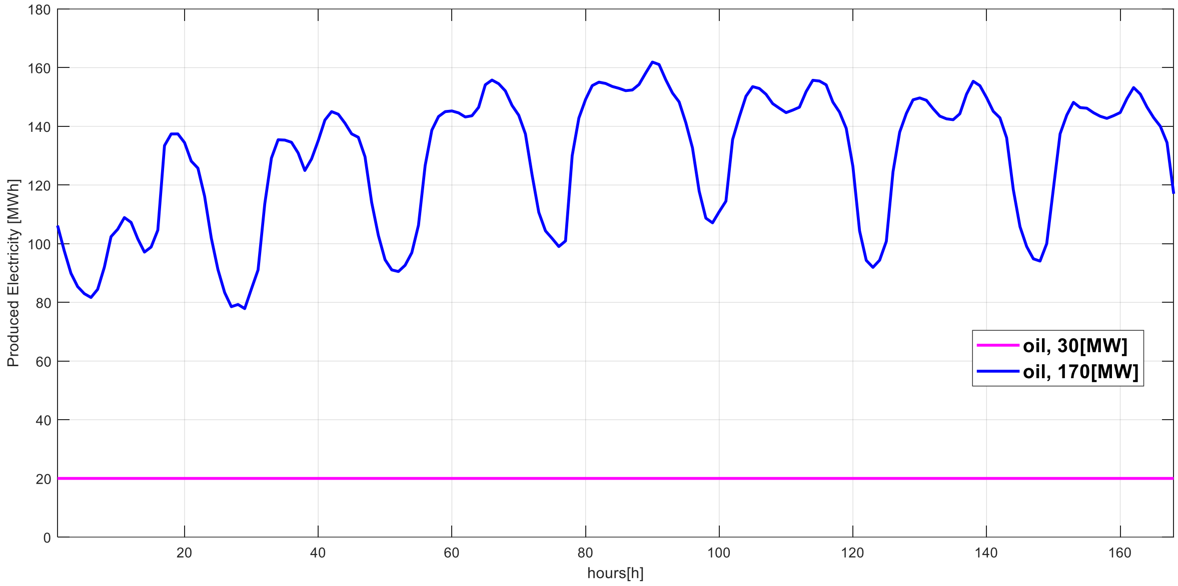


Figure 31: 30 [MW] and 170[MW] Oil power plants Comparison [Own Elaboration]

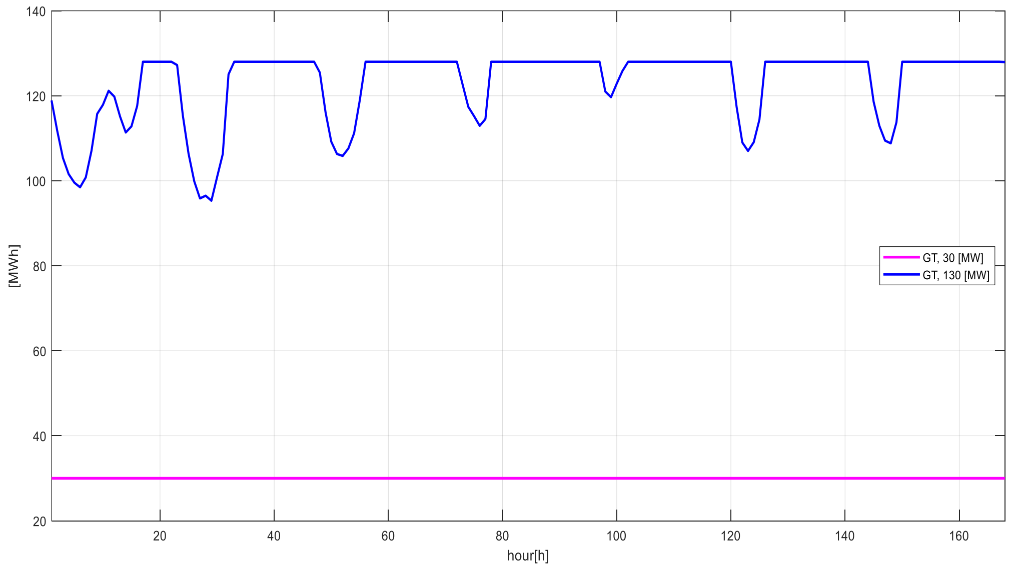


Figure 32: 130 [MW] and 30 [MW] Gas power plants comparison [Own Elaboration]

From the figures is clearly observable that small power plants are set to cover the base load, since the plants with higher capacity are the ones which follow the load fluctuations. It is important to say that in the DCOPF, no limits were set on the production power (minimum load factor) of the plants.

Another remarkable feature of the graphics above is that the gas turbine power plants are set to work with full load while the oil plants work with a production capacity lower than the nameplate power (curtailment). This could be because of the higher performance and lower production cost of gas turbines discussed in section 5.3.

Analyzing the output concerning load factors, on average the gas fired power plants in the simulation work with 65% of nominal power. This value for the oil power plants is quiet the half and is 38%.

Load factor is an indicator which shows the average load with which a power unit tends to generate electricity. In the studied case, final load factor is calculated as weighted average on number of oil and gas power plants and is 59.48%.

The above values of load factor result in 3364 Equivalent Operating Hours (EOH) for oil plants and 5676 equivalent hours for gas plants. The EOH of the national thermal park is 5210. The results are reported in table 7.

Table 8: load factor and EOH by fuel type [Own Elaboration]

	Oil fired	Gas fired
Load Factor	38.4%	64.8%
EOH	3364	5676

7.1 Transmission lines

As mentioned before, total number of present lines based on voltages are as follow:

Table 9: Number and Length of transmission lines by Voltage level [Own Elaboration]

voltage [Kv]	90	150	225	400
number	65	53	50	3
length [km]	1216	2139	2791	242

The simulation foresees a yearly average transmitted power flow equal to 13.4 [MW] for 90 kV lines, 19.6 [MW] for 150 kV lines, 27.1 [MW] for 225 kV lines and 33.2 [MW] for 400 kV lines.

Table 10: Average yearly and maximum power flow based on voltage level of lines [Own Elaboration]

voltage [Kv]	90	150	225	400
Average Power Flow [MW]	13.4	19.6	27.1	33.2
Maximum Power Flow [MW]	107.6	265.3	134.7	136.2

Since no thermal limit was set on the transmission lines, these values could be reasonable and acceptable.

In the figure below the location of the lines in which maximum power flow of each voltage level occurs is visible. The maximum value for 90, 150 and 225 [kV] lines are respectively 107.6, 265.3 and 134.7 [MW]. As there are just two lines if 400 [kV], the latter data is not represented.

In fact this zones have a relatively high population density.

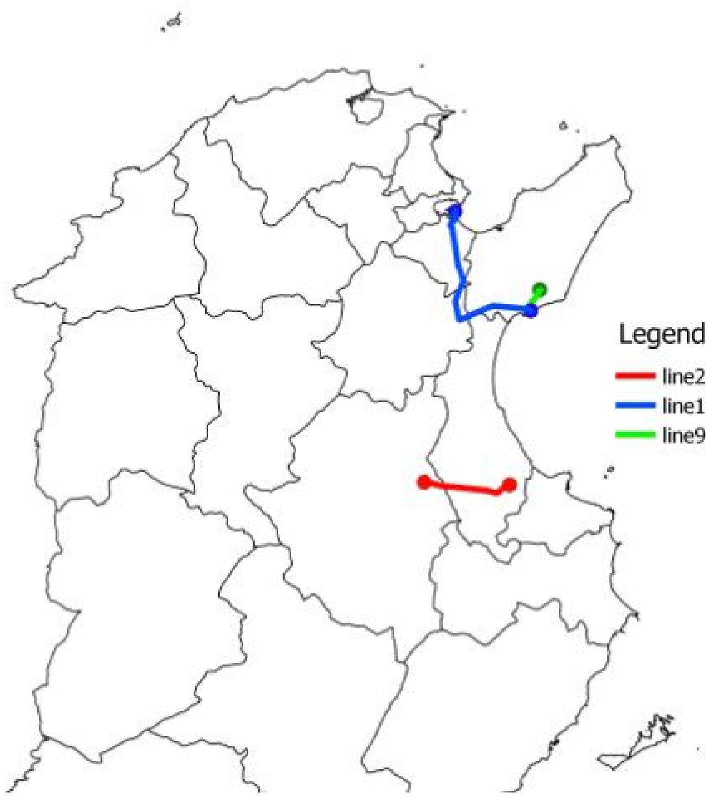


Figure 33: position of lines with maximum power flow by voltage [Own Elaboration]

CONCLUSION

8 Conclusion

The present work, starts without any data about the Electricity Park of Tunisia[1] and a big part of the study time was dedicated to establish such database. Even if the existing information has a high coincidence with the inventory of the country and could be seen as the starting point of further detailed studies on future energy policies and scenarios applicable in Tunisia, it need to be more investigated and crosschecked to increase the precision level.

Also the global situation of energy systems (like every dynamic system) which tend to transit from conventional technologies toward more renewable based methods, redoubles the need of such reviews. Other reason, is the probable retirement or upgrade of some present power plants.

Concerning OPF simulation, such studies gives the decision makers a better idea about both overall situation and detailed productivity of the system and enables them to find necessary intervention points to improve the performance of whole electricity system. While OPF requires a lot of specific information about every part of power system like fuel type and cost or the production technologies and the characteristic of transmission lines (such as material, cross section and length), more precise information lead to more reliable results.

Other important issue of such simulations is the peculiarities of demand profile in each country. Though to select the proper demand profile, a lot of factors was take into consideration, it is important to mention that every country has its own economic, geographic and cultural structure which affect the energy consumption trend.

[1] A common issue about the developing countries is the lack of accessible and reliable data and statistics

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