POLITECNICO DI TORINO

Collegio di Ingegneria Energetica e Nucleare

Corso di Laurea Magistrale in

Ingegneria Energetica e Nucleare

Tesi di Laurea Magistrale

Implementation of renewable technologies (Biomass, PV, Wind) in the Tunisian HV power system, power generation dispatch and flexibility analysis.

Relatore

Prof. Pierluigi Leone

Correlatore

Dott. Enrico Vaccariello

Candidato

Simone Pacchiotti

Marzo 2020

INDEX

CHAPTER 1) Keywords and nomenclature. Pg [5]

CHAPTER 2) Scope of the thesis. Pg [6]

CHAPTER 3) Introduction. Pg [8]

CHAPTER 4) Literature review. Pg [26]

CHAPTER 5) Tunisian solar and wind potential. Pg [32]
5.1) Tunisian Solar potential. Pg [32]
5.2) Tunisian wind potential. Pg [36]

CHAPTER 6) Tunisian biomass potential Pg [40]
6.1) Quantification of wasted biomasses available on the national territory. Pg [42]
6.2) Waste and residues of agricultural activity. Pg [43]
6.3) Waste and by-products of the processing industry of vegetable production. Pg [52]
6.4) Biogas potential. Pg [52]
6.4.1) Biogas Potential from livestock animals. Pg [52]
6.4.2) Biogas potential from OFMSW. Pg [56]
6.5) Biomass potential from industrial of animal products. Pg [59]
6.6) Biomass potential from forest residues. Pg [59]
6.7) Results Pg [61]

CHAPTER 7) Description of the model. Pg [62]
7.1) OPF Formulation. Pg [62]
7.2) Cost of generation. Pg [70]
7.3) Conclusion. Pg [76]

CHAPTER 8) Simulations performed. Pg [78]

CHAPTER 9) Validation of the model. Pg [88]

CHAPTER 10) Results and conclusion. Pg [90]

CHAPTER 11) Table appendix. Pg [98]

CHAPTER 12) Plot appendix. Pg [120]
12.1) S0M1 plot results. Pg [121]
12.1) S1M1 plot results. Pg [124]
12.1) S2M1 plot results. Pg [127]
12.1) S4M1 plot results. Pg [130]
12.1) S5M4 plot results. Pg [133]

CHAPTER 13) Reference and Tunisian HV power plants projects. Pg [111]
13.1) Tunisian HV power plants projects. Pg [137]
13.2) Reference. Pg [139]

CHAPTER 1: KEYWORDS AND NOMENCLATURE

KEYWORDS:

1) OPF.
2) UC.
3) DCOPF.
4) ECONOMIC DISPATCH.
5) MATPOWER, MOST.
6) HIGH VOLTAGE POWER TRANSMISSION.
7) TUNISIAN SOLAR PLAN.
8) TUNISIAN RENEWABLE PENETRATION.
9) RENEWABLE PENETRATION HV POWER TRANSMISSION.
10) FLEXIBILITY ANALYSIS.
11) THERMAL POWER PLANT RAMP CONSTRAINTS.
12) THERMAL POWER PLANT FLEXIBILITY.
13) GRID EXPANSION.
14) TRANSMISSION NETWORK EXPANSION PLANNING.
15) PV-ELECTRICAL PROFILE DETERMINATION FROM METEOROLOGICAL DATABASE.
16) WIND-ELECTRICAL PROFILE DETERMINATION FROM METEOROLOGICAL DATABASE.
17) BIOMASS POTENTIAL EVALUATION, GIS.
18) TUNISIAN BIOMASS POTENTIAL.

NOMENCLATURE:

1) CCGT: COMBINED CYCLE GAS TURBINE
2) ST: STEAM TURBINE
3) GT: GAS TURBINE
4) CSP: CONCENTRATING SOLAR PLANT
5) SOFC: SOLIDE OXIDE FUEL CELL
6) PEMFC: PROTON EXCANGE MEMBRANE FUEL CEL
7) PV: PHOTOVOLTAIC
8) HV: HIGH VOLTAGE
9) OPF: OPTIMAL POWER FLOW
10) UC: UNIT COMMTMENT
11) DCOPF: DIRECT CURENT OPTIMAL POWER FLOW
12) TSP: TUNISIAN SOLAR PLAN
13) OFMSW: ORGANIC FRACTION MUNICIPALITIES SOLID WASTE.

CHAPTER 2: SCOPE OF THE THESIS.

The scope of this thesis is to analyse renewable penetration in the Tunisian high voltage power system, in particular to analyse generators (CCGT, GT, ST) power dispatch behaviour caused by renewable penetration in 2035.
The base year, the reference one, the one used for comparison, is 2016.
Many input data are taken from the previous work: **R[1].**
Electric power distribution is the final stage in the delivering of electric power, it carries electricity from the transmission system to individual consumers. Distribution substations connect to the transmission system and lower the transmission voltage to medium voltage ranging between 2 kV and 35 kV with the use of transformers. [WIKIPEDIA].

National electrical demand, in this case Tunisia, must be covered by a mix of power plants: High Voltage power systems are characterized by generators (fossil or renewable) which inject active and reactive power, bus stations, branch lines and transformers.
At any time, demand must be supplied by a mix of generators with an associated cost of generation. The objective function is to satisfy the demand at lowest price. To simulate this, OPF software will be used (MATPOWER). OPF solutions are strongly dependent by many constraints, like maximum branch power flow constraint for each line (the maximum power that can flow for each line multiplied by the number of line for each branch, where a branch is a transmission line that connect, for instance, 2 different substations).
This thesis focuses on the changes in electrical demand supply caused by renewable penetration, but even caused by electrical demand growth on thermal power plants dispatch, and flexibility analysis.

This analysis could be extended for near countries, Algeria Libya etc, with the purpose to simulate interconnection to estimate electricity imported and exported and power flow (positive or negative) towards these countries changes caused by renewable penetration.
STEG and TERNA planned interconnection with HVDC submarine cables. Interconnection with Italy (the 600 MW submarine interconnection in direct current that will connect Italy and Tunisia) will be not considered because of lack of maximum branch power flow for each branch and even because the analysis must be extended to Italy.
So for these reasons that interconnections with near countries will be not considerate in the simulations.
STEG, the company that govern electricity market in Tunisia, doesn’t publish they data about electrical HV network, so maximum power flow for each electrical line cannot be determined and so, branch power flow constraints cannot be added in the simulation, this is a big limitation in this model.

Renewable penetration in the HV power transmission is strongly dependent on geographical areas, for instance some area cannot be reached by truck, so renewable potential in that area is limited, or the distance from existing electrical network is too high and the associated investment cost to connect the RE-plant is not sustainable.
Renewable plants can be on-grid or off-grid. On-grid means that renewable plants will be connected to the HV (High voltage) power transmission.
HV grid network is characterized, by generators, bus stations, transformer, and branch lines. High

capacity generator, higher than 5 MW, are connected to the HV grid. House are connected to the LV grid, while small industries are connected to the MV grid. In this work, MV and LV lines will be excluded from the analysis.
Renewable plants with capacity higher than 5 MW will be connected to the HV network, while others, like biogas digester or PV-root not, however, these RE-plants, excluded from HV network, interact with HV grid with a local demand reduction (lower demand must be meet because of low voltage renewable penetration such as PV-root).

In the first part of this thesis will be determined future Tunisian power plants location, fossil or renewable, that will be built by 2035.
For the chosen HV renewable plants, power profile will be calculated by using meteorological database, in particular electricity production from PV-panels and wind farms.
Next Tunisian biomass potential will be determined and biomass power plant site location.
Finally, Economic power dispatch and Flexibility analysis will be conduct by using MATPOWER.

The scope is to determine electricity production [%] from fossil and renewable power plants in 2035 and flexibility analysis, or, in other words, the ability of thermal power plants to satisfy demand and accommodate renewable power plants integration.

CHAPTER 3: INTRODUCTION.

Tunisia is a small country with about 164000 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. [**R14**].
40% of the total country land is occupied by **Sahara desert.**

Fig 1 [LAHISTORYCONMAPAS], Fig 2 [NATIONSONLINEPROJECT], Tunisian administrative boundary

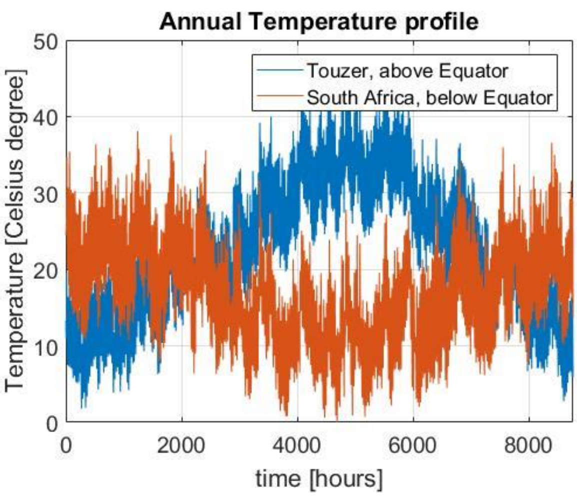


Fig 3: Temperature profile for Touzer (Tunisia).
Profile derived from METEONORM database. During summer months, the temperature reaches very high value, higher than 40 degC.

The climate is Mediterranean on the coasts, with mild and humid winters and hot and dry summers, while it is of the semi-desert or desert type in the interior, with very high summer temperatures (up to 45-47 ° C) and low rainfall. The summer heat is however limited by sea breezes (only on the coasts), while when the wind blows from the desert.

Tunisia ranks 93rd in the world with a nominal GDP of 40.26 billion US dollars (GDP per capita of 3490 $) ; in the 90s the economy grew by 5% in the media so much so that the country now has a diversified economic system ranging from agriculture, to the industrial sector (mining, manufacturing, and chemicals) to tourism which represents 7% of the GDP; as regards agriculture, the breeding is mainly sheep and goat.
The industrial sector is mainly composed of the clothing and footwear industry, the production of parts for cars and electrical machines.
Tunisia produces and exports cereals (corn, wheat, oats), olives and olive oil, fruit (in particular oranges and dates); it also has a considerable fishing fleet.
For industry, much is produced for export, thanks to the low cost of labour: the main industrial sectors are those of food processing, textiles, and since 2010 the extraction and transformation of petroleum products has increased significantly [Wikipedia].

Tunisia's consumption in 2015 was 98,000 barrels/day. Natural gas consumption is in the order of 6.5 km3, of which more than half is imported via the Trans-Mediterranean Pipeline. 70% of the gas is used for electricity production.

Electricity consumption of individual sectors in 2013[17]		
	GWh	**%**
Industry (Medium and High Voltage)	4 909	34
Transport & communication (Medium and High Voltage)	311	2
Tourism (Medium and High Voltage)	567	4
Service (Medium and High Voltage)	891	6
Agricultural pump sets (Medium and High Voltage)	556	4
Pumping stations (water, sanitation service) (Medium and High Voltage)	563	4
Low voltage	6 521	45
'*Total*'[1]	**14 380**	**100**

[ENERGYPEDIA], **Fig 4,** Electricity consumption, in Tunisia, in 2013, for different economic sectors

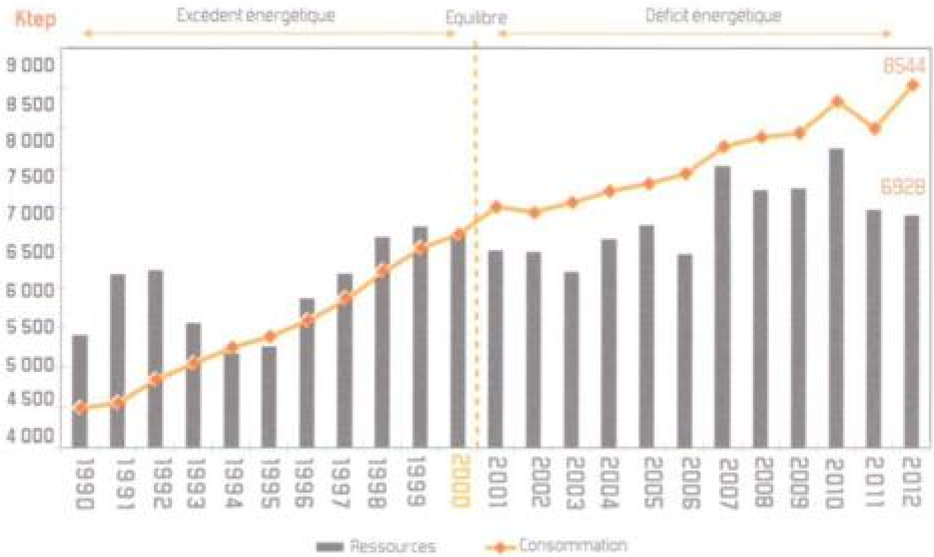
Regarding grid-connected renewables, the total installed capacity of renewable energy was an estimated of 312 MW in early 2016 (245 MW of wind energy, 62 MW of hydropower and 25 MW of PV).
There are two large wind parks in Tunisia, both operated by state utility STEG, one in the region of Bizerte in Metline and Kechabta with a capacity of 190 MW operational since 2012; and one in the region of Sidi Daoud, with a capacity of 55 MW, built in 3 phases between 2000 and 2009.

As shown in figure 6, the Tunisian energy situation has drastically changed in the last two decades. Hence the unbalanced consumption illustrated in Figure 6. Tunisia, a net energy exporter until 2000, has become a net importer.
In 2014, 49% of natural gas consumption (2,300 ktoe) was covered by domestic production. The

remaining 51% (2,400 ktoe) was imported from Algeria.
Becoming a net importer implies a rise in energy prices since the mid-2000s. [ENERGYPEDIA]

Category	2000	2005	2010	2015 P
Production of coking coal	-	-	-	-
Production of charcoal	121	152	148	149
Production of crude oil, NLG and additives	3,445	3,201	3,453	2,722
Production of natural gas	2,095	2,323	2,980	2,276
Production of electricity from biofuels and waste	0	0	0	0
Production of electricity from fossil fuels	861	1,102	1,368	1,490
Production of nuclear electricity	-	-	-	-
Production of hydro electricity	6	12	4	5
Production of geothermal electricity	-	-	-	-
Production of electricity from solar, wind, Etc.	2	4	12	40
Total production of electricity	868	1,118	1,421	1,535
Refinery output of oil products	1,635	1,569	255	1,725
Final Consumption of coking coal	66	0	0	0
Final consumption of oil	3,625	3,816	3,849	3,375
Final consumption of natural gas	641	844	1,228	1,128
Final consumption of electricity	779	966	1,165	1,523
Consumption of oil in industry	1,000	948	1,054	746
Consumption of natural gas in industry	476	593	880	1,019
Consumption of electricity in industry	397	407	440	414
Consumption of coking coal in industry	0	0	0	0
Consumption of oil in transport	1,561	1,667	1,921	1,726
Consumption of electricity in transport	9	3	26	10
Net imports of coking coal	0	0	0	0
Net imports of crude oil, NGL, Etc.	-1,623	-1,621	-3,457	-3,497
Net imports of oil product	2,568	3,080	3,806	2,959
Net imports of natural gas	1,736	1,861	2,231	2,666
Net imports of electricity	0	-3	2	-3

[AFREC],**Fig 5,** Tunisia: Total energy statistics.



[ENERGYPEDIA],**Fig 6**, from 2000, Tunisia it's became a net imported of primary energy (gas in particular).

Electricity prices can be subdivided by voltage magnitude:
For LV: On the general low voltage, tariffs depend on the sector of the consumer (residential or non-residential) and the consumption per month in kWh. Tariffs are most heavily subsidized for households whose monthly consumption is below 50, 100 and 200 kWh. These households pay 0.075 TND [0.034 EUR], 0.108 TND [0.049 EUR] and 0.140 TND [0.064 EUR] for each kWh consumed. Households whose consumption surpasses 200 kWh per month have to pay 0.151 TND (0.069 €)/kWh for the first 200 kWh, 0.184 TND (0.084 €)/kWh for the following 100 kWh, 0.280 TND (0.13 €)/kWh for the following 200 kWh, and 0.350 TND (0.16 €) for each kWh above 500 kWh/month.
For MV: Prices range from 0.088 TND/kWh (0.040 €) to 0.238 TND/kWh (0.109 €). The subsidies no

longer apply to cement producers which have paid electricity to its real cost since 2014 (cheapest slot: 0.129 TND (0.059 €)/kWh, most expensive slot 0.311 TND (0.142€)/kWh).
For HV: There are four tariff slots and prices range between 0.111 TND (0.051€)/kWh and 0.233 TND (0.106€)/kWh). [ENERGYPEDIA]

The **Tunisian Solar Plan**, a renewable energy development plan elaborated by the ANME but not officially adopted by parliament or government, foresees a 30% share of renewables in the electricity mix by 2035. This corresponds to an additional totally capacity of 3 GW and an overall investment of 4.75 billion euro.

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.

Nightlight time GIS raster map taken from **[R15]**, elaboration performed using QGIS software.

Fig 7
Nightlight time GIS raster map taken from **[R15]**, performed using QGIS software.
This is used to understand electrification of the country, to understand people that have not access to electricity or, to approximate MV network.

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 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).

Thermal Capacity 2016 [MW]	Hydro Capacity 2016 [MW]	Wind Capacity 2016 [MW]
5174	62	240

Tab 1: Tunisia installed capacity for different technologies, 2016.

In 2016, Solar energy is more used in the hot water production and power generation exists just in residential level and in a negligible quantity.

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.

[R1]: The High voltage power grid of Tunisia is more than 6000 Km long 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.
Moreover, the grid is connected to Libya through two 225 kV lines in the Southeast part and to Algeria in East anQd Northeast part through two 50 kV lines and one 150 kV line.

In [Table-appendix: Table 1] it's reported all Tunisian HV bus station, taken from **R[1]**.
In [Table-appendix: Table 2] it's reported all Tunisian generators connected to the Tunisian HV, taken from **R[1]**.
In [Table-appendix: Table 7] it's reported all Tunisian HV branch network (network that links each bus), taken from **R[1]**.
The 2nd column is the HV electrical length [km], while the 3rd and the 4th are from bus to bus respectively. The other columns will be explained later.

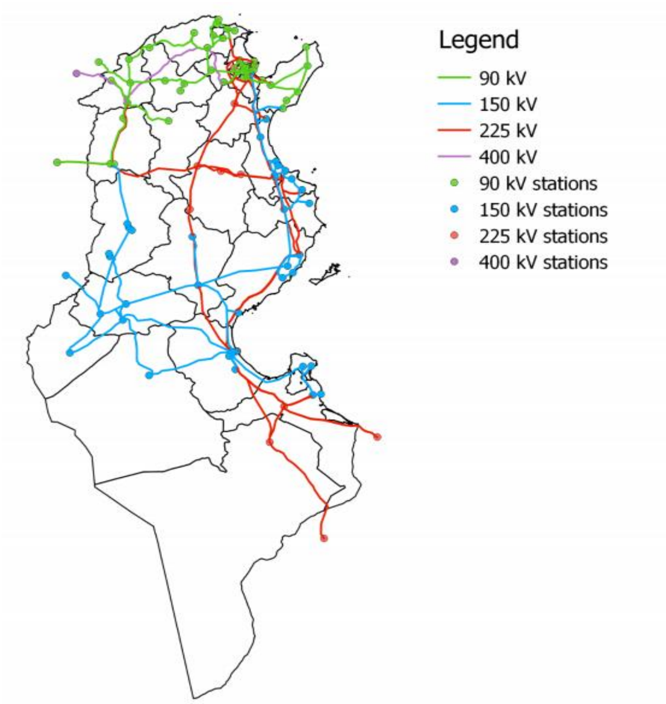
In figure 8,9 it's possible to see localization of Tunisian power plants on-grid and HV network, for 2016 **[R1]**.

So at this point, it's possible to build the Tunisian HV network.

After this, an electrical demand profile is needed for simulations: To model the Tunisian electricity demand in a precise way, the annual hourly demand profile is needed. As such information is not delivered neither by the STEG nor by any other reliable reference, the solution proposed by the author in **R[1]** was to generate the profile, starting from the total electrical demand overall 2016 year is known from STEG.
Hourly electrical profile for European countries can be download from ENTSO-e.
The idea of R[1] is to find a European countries that are similar from an energetic point of view respect to Tunisia:
R[1]: 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 for different countries 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.

R[1]: Comparing the share of different sectors in the structure of GDP of each country and Energy Trilemma Index indicators of all European countries with Tunisia's, the most significant countries to select seemed to be one between Albania, Bulgaria, Moldova and Serbia.
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.



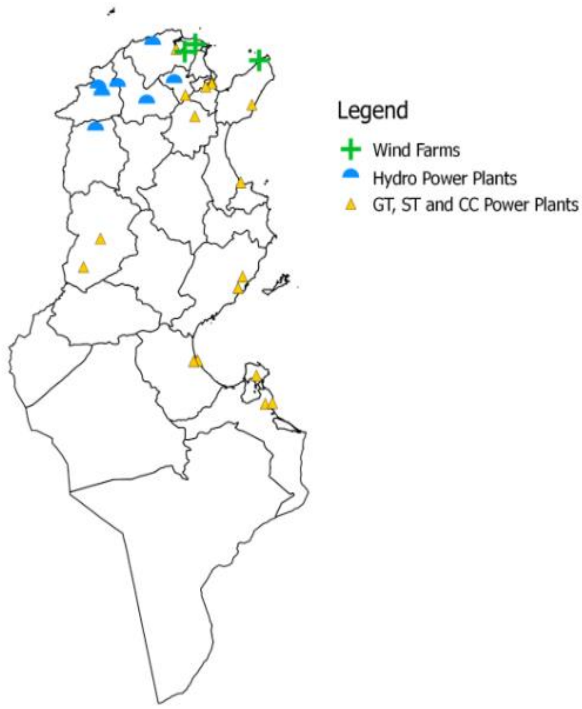


Fig 8 R[1]: Tunisian HV network **Fig 9 R[1]:** Tunisian HV power plants localization

R[1]: 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, 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 and National Institute of Statistics. The criteria for division of the population was modelled based on the data of the National Institute of Statistics and the census of the 2014.
So, at this point, an electrical hourly profile for each Tunisian High voltage bus is determined, at year 2016.

The next step is to estimate 2035 electrical demand hourly profile: A priori, GIS raster data about Tunisian population density in 2035 and internet information about future industry geo-location over all national administrative boundary are necessaries. But this is not possible, so other parameters are needed.

EDGR= Electrical demand growth rate in 2016, in Tunisia, from statistical data.
Ratio= (1e-2* (100+ EDGR)) ^(2035-2016)

EDGR	Ratio
1%	1.20
2%	1.45
3%	**1.75**
4%	2.10
5%	2.62

Tab 2: Total 2035 national demand divided by the total 2016 for different values of Electrical Demand Growth Rate

The actual electrical demand rate growth is 5%, so the idea is to multiply, for each time, for each load-bus, the 2016 demand for a coefficient that consider electrical demand growth rate.

If EDGR= 5%, this means too high value. However, since the time horizon is relative big, and since it is supposed that this rate will decreased over the next years, it's was selected to assume EDGR=3%, It's more reasonable to say that in 19 years, the nation electrical demand increased is equal to the 75% of the actual electrical demand, almost the double.
Moreover, if EDGR= 5% this means that demand cannot be satisfied, because of big growth, so new fossil plants must be included in the analysis that are not included in the real projects, otherwise demand cannot be satisfied and simulations cannot be done because it is impossible to reach the convergence.
In Fig 10 it's plotted the estimated hourly electrical profile, Tunisia 2035.

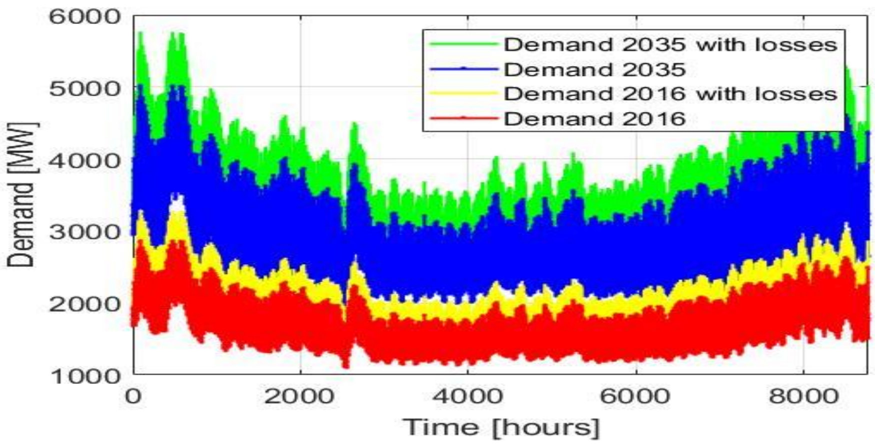


Fig 10: Tunisian estimated electrical profile.

Tunisia is following a national energy plan with the purpose to cut greenhouse gas emissions and reduce fossil fuel needs and, as consequence, to reach electricity independence, in fact, Tunisia import fuels, in particular natural gas, for electricity production (such as natural gas used in CCGT plants), this means high cost of generation because of higher fuel cost.
Renewable energy holds strong potential in Tunisia. Wind and solar photovoltaic (PV) provide the opportunity to improve Tunisia's energy security, to meet growing energy demand, and to create a future power-export industry for Tunisia **[30]**.

The Tunisian Solar Plan (TSP) has an official target for total RE share of 30% of the power mix by 2035 (ANME, 2012).

In this work, TSP will be implemented, in particular TSP-plants that will be connected to the actual Tunisian HV-network by 2035. The starting idea was to implement PV, WIND, CSP projects included in the TSP, however CSPs plants cannot be implemented for lack of information about specific data, as described later.
Before analyse TSP effects in the Tunisian HV-network, the first step is to find the new fossil or renewable plants that will be built by 2035 by doing internet research, in particular information like type of plant (PV), capacity (1700 MW), boundary (REMADA). In references chapter, there is a section available for only web link regarding these projects.

In [Appendix-Table: Table 3] it's reported the main renewable or fossil plants that will be realized by 2035.

Projects like PV-roots, electricity from biogas by anaerobic digester will be not considered because they involve medium voltage power system. However, these plants interact with high voltage power transmission because they reduce locally the demand at a certain substation, but this is not considered.

The second step is to find geographical information that give us the possibilities to locate the new plants in terms of GIS data, in terms of geographical coordinates inside the Tunisian area. Finally, to put these news plants in the Tunisian high voltage power transmission, using the obtained geographical informations, we connect these new generators with the nearest high voltage bus station.
In [Appendix-Table: Table 4] it's reported the <u>estimated nearest bus</u> at which the new power plants will be connected to the Tunisian HV network.
So, in other words:

1) Estimate position of new renewable generators.
2) Nearest Bus at which bus-plants will be connected.

To select the bus, the following method is used:

1) Renewable generators geo-localization using the link reported in [Appendix-Table: Table 3].
2) Selection of high voltage bus by minimizing the distance

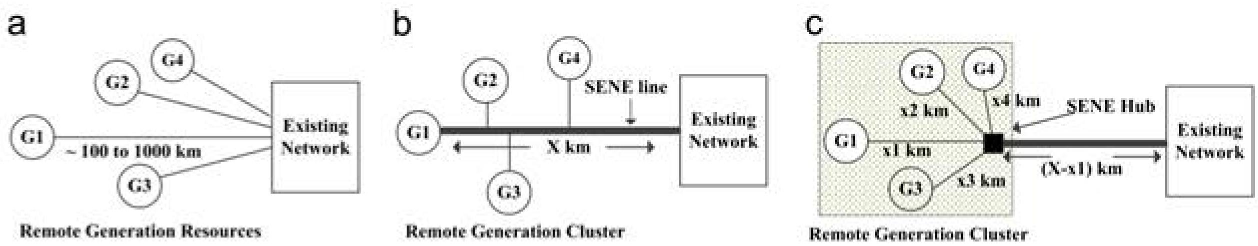


Fig 11: R[16]: Transmission topologies for remote generation connection. This figure shows different generators connection to HV network. If figure A and C are compared, then what you can see is that different connections means different network and so this will affect the results. Scheme A will be used, in this way generators will be connected to the actual HV network to the nearest bus station.

Since the <u>exact position of new RE pant is unknow (estimated position)</u>, to connect to the high voltage line, the scheme A (see Figure 11) will be used.

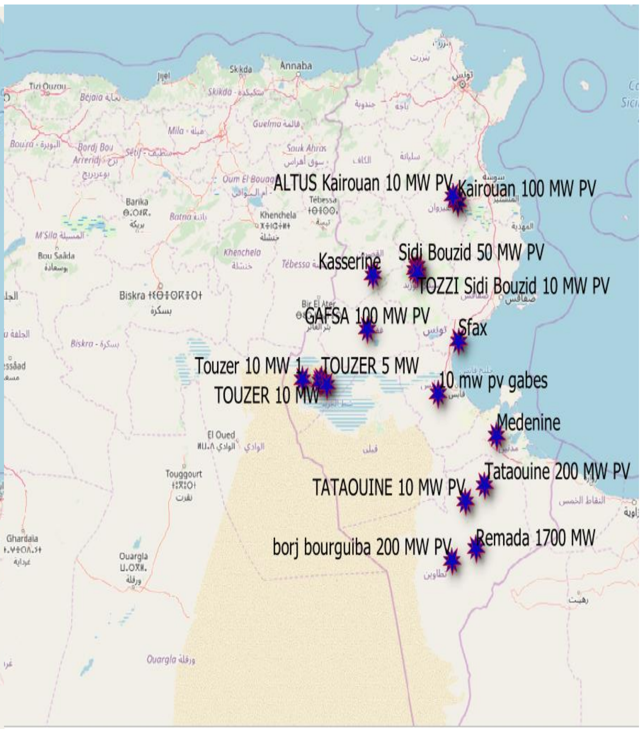


Fig 12, New wind generators localization. **Fig 13** New PV generators localization.

In figure 12, 13 are plotted the estimated location of new renewable power plants, included in the Tunisian Solar Plan, or plants that will be built by 2035.

At any time, demand must be supplied by a mix of generators with an associated cost of generation.
Natural gas is burnt in Steam turbine cycle plant, ST, and the heat of combustion is used to vaporize pressurized water to be used in an expansion device (turbine) to produce useful work (electricity).
The associated cost of generation depends on natural gas price, cost of investment of all plants and cost of operation and maintenance.
The mechanical power produced by steam turbine is used to put in rotation an electrical engine and to produce alternat current at 50 Hz, and low voltage (240 V), so a transformer is needed to increase the voltage. At the end of the story, what comes from is that thermal power plants inject active and reactive power, the amount of active power is controlled by gestor, so is the active power that must be produced by generators to satisfy the demand and safety at lowest price (economic dispatch).

No renewable penetration means that all electrical demand must be covered by thermal power plants and, since demand must be supplied at any time and at lowest price, then demand will be covered like figure 14

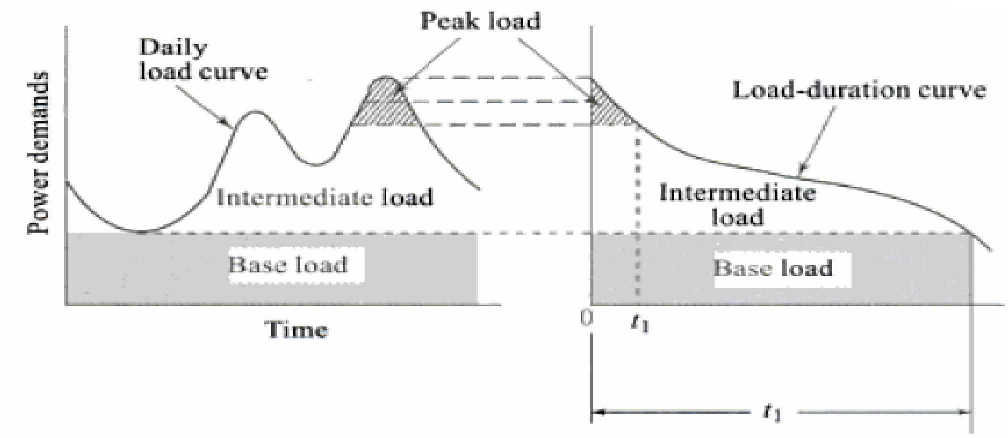


Fig 14
https://commons.wikimedia.org/wiki/File:Load_Distribution_curve_for_power_plant_(base_load,_peak_load_%26_intermediate_load).png: frr This figure plots the general way to dispatch power without renewable integration. The most economic generator will work at full and constant power overall period because of lowest price, the opposite for the most expensive generators.

1) BASE LOAD: Covered by the most economic generators, dispatch at nominal power and constant over the time.
2) INTERMEDIATE LOAD: Covered by generator characterized by higher cost of generation, the power dispatched is controlled to follow the demand.
3) PEAK LOAD: Covered by the expensive generators to meet the peak of electrical demand. When this phase it's present, base load generators and intermediate load generators works in a similar way.

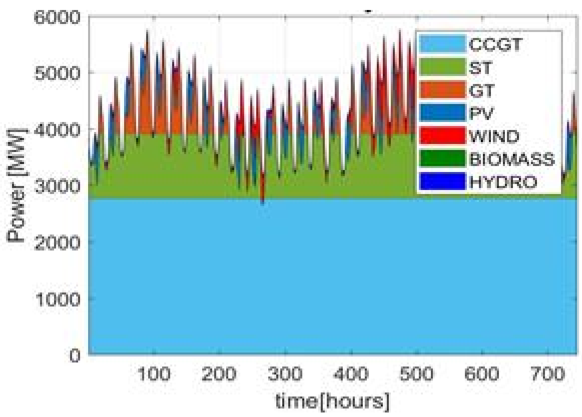
If import/export of electrical energy towards abroad countries is not considered, then demand must be satisfied by national portfolio (the total capacity installed for different types of technology and size). This capacity must meet the demand, the variability of demand and the growth of the electrical demand.
In addition to meeting the predictable daily, weekly, and seasonal variation in demand, utilities must keep additional plants available to meet unforeseen increases in demand, losses of conventional plants and transmission lines, and other contingencies.

If national energy policy is applied to promote renewable integration, then REPs will be the most economic, so they could be injected the maximum available power in the Tunisian HV network. With high renewable penetration, what could happen is that base-load generators work in the field of intermediate load or peak load, in the sense that dispatch power is not constant over the time. So high renewable penetration complete changes the dispatch and network behaviour that must be analysed.

If a thermal power plant, excluded SOFC or PEMFC, works at power lower than the nominal one, then the specific cost [$/MWh] increases because the efficiency drops (the distance from nominal condition increases). Moreover, if lower capacity factor caused by HV renewable penetration means higher lifetime because of better state at the end of the estimated lifetime caused by lower production and lower ageing that reduce performance and so maintenance cost is sustainable, then the specific cost increases because a major inflation over the time. However, if this is not true, then lower capacity factor does not mean higher lifetime because of better state, so higher specific cost of generation because the investment cost must be paid in a smaller time period.

If to meet the electrical demand expensive generators are used, then economic generators will work at nominal power, so there is no problem for these generators. But with high renewable penetration could happens that, what before were base load generators, now work as intermediate loads (see figure 15, 16) , so the power of this economic generators will increase or decrease, the amount of this increment/decrement for base load generator it depends by renewable penetration.
Higher renewable penetration means that thermal power plants units must vary quickly and much the power. If power required is lower than the minimum power factor, then the thermal power plant unit must be disconnected until it can dispatch power higher than the minimum one, so what comes from is that the number of start-up and shut down drastically increase because of renewable penetration and minimum power factor, in particular if minimum up and minimum down time are not taken in consideration. This is true even for the most economic generator.
To meet the demand, renewable curtailment can happen only because of minimum load generation (when it's more economic to reduce renewable plant output so the last generator can work at power higher than the minimum power generation rather than use one more expensive generator).

Variable renewable generators (primarily wind, solar photovoltaics, and concentrating solar power when deployed without storage) are unlike conventional generators. They cannot be dispatched (except by curtailing output) and their output varies depending on local weather conditions, which are not completely predictable. Variable generators reduce the fuel (and associated emissions), but with consequence on thermal power plant behaviour (increased of number of start-up, ramp rates etc..).
The large increase in renewables has major impacts on the power system. For example, as generation centers are shifted away from demand centers, there is an increased need for high voltage power transmission.
Moreover, the availability of electricity on windy and/or sunny days causes the electricity prices to drop **[R8]**.



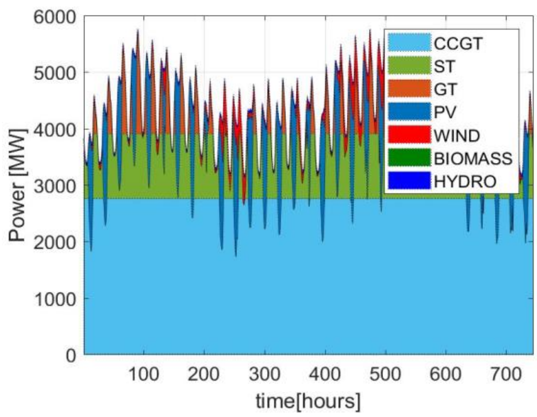


Fig 15, 16: These figures, taken from our simulation, shows that higher is the renewable penetration and higher will be the flexibility needs required by fossil thermal power plants. Number of start-up, ramp rates magnitude increase a lot. With low renewable penetration, economic generators will work as base load for overall period, while with high renewable penetration the dispatched power is not full and costant for all period.

From load-following and cycling units and in order to be of benefit, conventional generators used to meet the normal demand must be able to reduce output and accommodate wind and solar generation. **[R2]**.
There are four significant impacts of renewable plant integration in the high voltage power transmission that change how the system must be operated and affect costs. First is the increased need for frequency regulation, because wind plants can increase the short-term variability of the net load. Second is the increase in the ramping rate, or the speed at which load-following units must increase and decrease output. The third impact is the uncertainty in the wind resource and resulting net load. The final impact is the increase in overall ramping range the difference between the daily minimum and maximum demand – and the associated reduction in minimum load which can force baseload generators to reduce output, and in some cases force the units to cycle off during periods of high VG output. Together, the increased variability and uncertainty of the net load requires a greater amount of flexibility and operating reserves in the system, with more ramping capability to meet both the predicted and unpredicted changes in net load. **[R2]**.

System flexibility can be described as the general characteristic of the ability of the aggregated set of generators to respond to the variation and uncertainty in net load. At extremely high penetration of VG, a key element of system flexibility is the ability of baseload generators, as well as generators providing operating reserves, to reduce output to very low levels while maintaining system reliability. **[R2]**.
High RE penetration and higher load demand means higher peaks. These peaks must be covered by thermal generators. A higher number of thermal generators, at same capacity, means higher investment cost and lower efficiency, but at the same time higher flexibility and higher reliability. CSP plants with thermal storage, biomass plants and small GT units give higher flexibility and higher reliability. Meanwhile, CSP plants and GT can provide both reserve and load following. Storage, like batteries, CAES, SNG etc reduce load following reserve needs, but with higher losses and with a big investment cost and low volumetric energy density. For storage device geographical constraints must be considered. Storage device must be limited because of:

1) High investment cost.
2) Losses.
3) High storage capacity and low renewable production caused by not favourable meteorological conditions, means bad investment.

An increase in load cycling has a detrimental effect on a conventional power plant’s life, results in poor financial performance, and leads to increased emissions from the power plant.
With high renewable penetration, the flexibility cost becomes important. High renewable penetration means even higher number of start-up and shut down, in particular for expensive generators that are used to cover peak and ramp. Faulty designs, poor manufacturing practice, installation and operation flaws are among the numerous causes of asset ageing process, which give rise to different stressors that influence the Component and Systems (C & S) of a renewable energy generating plant. Environmental factors such as humidity, temperature, radiation, vibration and operation factors such as internal heat from mechanical or electrical loads, friction and torque, play a major role in the deterioration of components and ageing **[R10]**. In this analysis, no degradation for renewable and thermal plant is considered.

Some considerations about Renewable curtailment are needed in this work: Congestion occurs when the least-cost dispatch of generators would require power flow over a transmission line to exceed line capacity. This leads to higher local marginal electricity prices in the electricity demand center, since more electricity must be supplied by local generators rather than less expensive, distant generators. Expanding line capacity only temporarily eases congestion, since it does not address the congestion externality. The expanded line capacity may induce other developers to invest in the area, eventually leading back to congestion.
Without transmission congestion, the price of electricity is the same across all nodes of the grid. When congestion occurs, the price of meeting an additional MW of demand at one end of the line is higher than at the other **[R7]** .
Since branch power flow constraints cannot be added in the simulation because of lack of information given by STEG, this aspect cannot be considered.

Curtailment occurs when RPPs, either in response to market price signals or commands from grid operators, reduce output below their achievable output given available resources. Causes of curtailment include renewable power oversupply, transmission constraints, power balancing issues, high wind ramps (large increase in wind power supply over a short time interval), and minimum generation constraints **[R7]**.

To conduct a flexibility analysis, in particular because of high wind intermittent nature, minute-to-minute wind power generation profile is needed. However, since was not possible to download 10 minutes wind profiles from our meteorological database (METEONORM), a minute-to-minute flexibility analysis was not conducted.
Higher renewable penetration means higher probabilities of curtailment. Moreover, if plant site is far from demand centre, the probabilities of curtailment of this generator increases. **[R7]**.
Unlikely, there is no way to determine, for all branches, all information about electric lines such as:

1) Number of lines in brach-i
2) Maximum power flow per each HV electrical line.

For this reason, in this analysis curtailment caused by branch power flow constraint cannot be analysed in a complete view.

Reliable electric power system operation requires a mix of power plants that can respond to the constantly varying demand for electricity as well as provide operating reserves for contingencies **[R2]**.

Higher renewable penetration means higher uncertainty, so higher reserve is needed.
Reserves is often referred to as operating reserves and includes meeting frequency regulation (the ability to respond to small, random fluctuations around normal load), load-forecasting errors (the ability to respond to a greater or less than predicted change in demand), and contingencies (the ability to respond to a major contingency such as an unscheduled power plant or transmission line outage) . Both frequency regulation and contingency reserves are among a larger class of services often referred to as ancillary services, which require units that can rapidly change output. **[R2]**
While reactive power controls voltage, active power controls the frequency of the grid. Reserve is needed to control frequency, but even in case of generators break down, or cloud that reduce electric production from solar PV, for instance, in other words, reserve gives safety to the grid.

Reserves are designed to maintain reliability despite inherent variability and uncertainty in demand and supply, including variable renewable generation.
There are several types of reserve:

The spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power, while non-spinning reserve is the reserve given by generator that are not synchronized with the grid, and that can quickly starts.

UCTE	No specific recommendation. The recommended maximum is $\sqrt{10L_{max\ zone}+150^2}-150$
Belgium	UCTE rules. Currently at least 460 MW by generators.
France	UCTE rules. Currently at least 500 MW.
The Netherlands	UCTE rules. Currently at least 300 MW.
Spain	Between $3\sqrt{L_{max}}$ and $6\sqrt{L_{max}}$
California	$50\%\times\max(5\%\times P_{hydro}+7\%\times P_{other\ generation};P_{largest\ contingency})+P_{non-firm\ import}$
PJM	1.1% of the peak + probabilistic calculation on typical days and hours

Fig 17 [R4]: Calculation of the amount of spinning reserve for different countries

To calculate reserve needs, the following values have been chosen as reference (fig 18):

Product	Load Reqt	Wind Reqt	PV Reqt	Timescale
Spinning	3% of load	-	-	10 min
Regulation	1% of load	0.5% of wind generation	0.3% of PV capacity* during daytime hours	5 min
Flexibility	-	10% of wind generation	4% of PV capacity* during daytime hours	60 min

R[5] Fig 18, Calculation of the amount of spinning reserve for different countries: Spinning reserve is calculated as 3% of the total load in a time period of 10 minutes, respectively for regulation and flexibility reserve.

Now, one consideration about hydro power production: For run-of-river plants, no water storage capacities are assumed. For each hour, the power output of run-of-river plants is determined from the level of water discharge, which is obtained from a hydrological database capacity **[R8]**. This database is not available for Tunisia, so constant hydro dispatch output power will be assumed. This causes negligible effects in terms of thermal power plants dispatch and flexibility needs because of low hydro penetration (the total hydro capacity can be neglected if compared with total fossil capacity or with the total renewable penetration in 2035 scenarios, so if constant hydro power dispatch is assumed, the relative error is low). For the same reason, nominal power was selected, without investigate on type of hydro plants.

TSP includes many CSP plants that will be connected to the Tunisian HV network.
CSP plants both with and without thermal energy storage are unique renewable resources that

provide clean electric power and a range of operational capabilities to support continued reliability of electric power systems.
Utilizing stored thermal energy storage to operate a conventional synchronous generator, CSP plants with thermal energy storage can support power and provide ancillary services including voltage support, frequency response, regulation and spinning reserves, and ramping serves – services that would otherwise be provided, at least in part, by conventional fossil-fuel generation **[R27].**

While for PV plant and wind farm is relative easy to determine the electric profile, for CSP this is not true.
Power generation from CSP is a function of:

1) Amount of direct solar radiation.
2) Solar concentration ratio.
3) Technology (Solar tower, Parabolic through, CSP integrated in CC, CSP integrated with biomass etc…).
4) If with or without thermal storage.
5) Size of thermal storage.
6) Thermal storage material (PCM, Molten salt).
7) Minimum storage material temperature that can be reached during the night.
8) Optical properties of receiver etc…

(Fig 19, 20, 21) are taken from EnerMena CSP book:
CSP-plants without thermal storage like figure 19, the electrical profile can be easily determined: In fact in these plants, gas inlet temperature is fixed, what changes is the fuel flow rate: the primary fuel reduction quantity it depends by solar radiation; Cost of generation curve changes over the time as a function of direct radiation (if optical losses are assumed constant).

CSP plants with thermal storage can give load following reserve. The size of thermal storage will determine the electrical profile, if the thermal storage it is used to cover the peak or used to work as base load for all time.

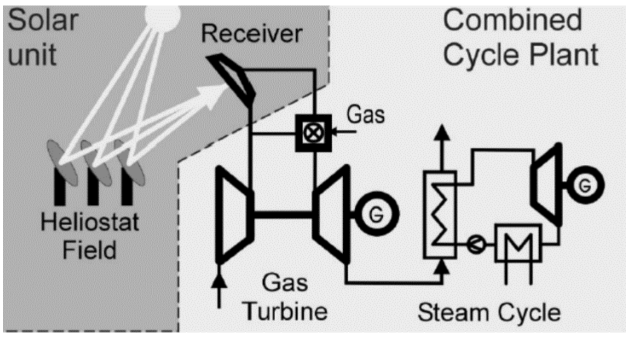


Fig 19: No thermal storage, the inlet gas turbine temperature is fixed.

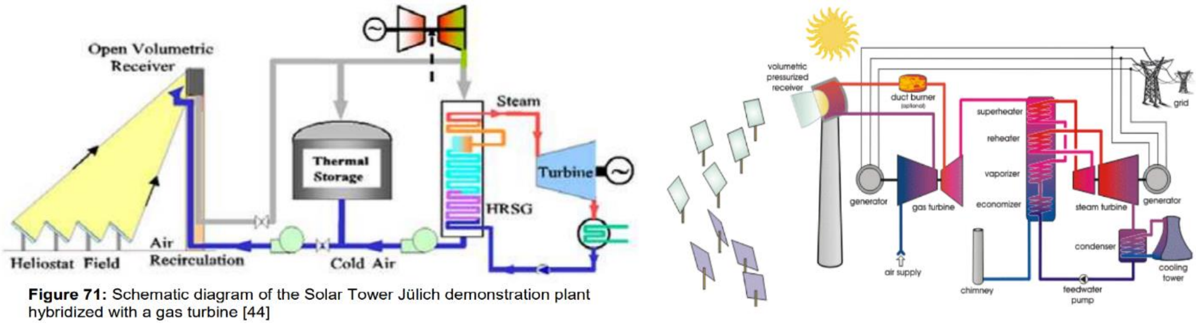


Fig 20, 21: CSPs with thermal storage (Material, size of thermal storage is unknown).

Figures 20, 21 show that it's very difficult determine, or even to estimate, the power injection profile, since this profile depends by many factors like volume storage size, material etc.
So, for this reason (lack of data) that electric profile generation from CSP plants cannot be estimated.

One of the most important tasks of this thesis was Grid Expansion, however, because of lack of data, this cannot be done, as described later. However, TNEP definition will be useful in the result section.
In literature, there are several methods about grid expansion, completely different from a conceptual point of view, the most important are:

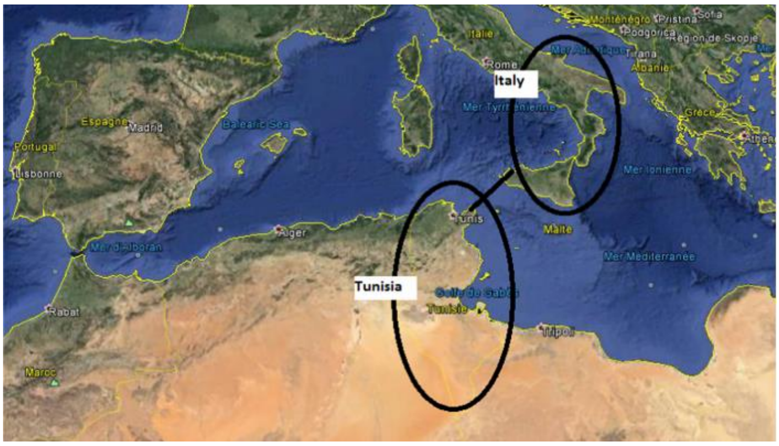
1) **MV planning distribution expansion:** not considered because only high voltage power transmission is considered.
2) **GEP (Generation Expansion Planning)**
3) **TNEP (Transmission network expansion planning)**

Transmission network expansion planning (TNEP) is a basic part of power system planning that determines where, when and how many new transmission lines should be added to the network. Transmission network expansion planning (TNEP) is an important component of power system planning. It determines the characteristic and performance of the future electric power network and influences the operation of power system directly. Its task is to minimize the network construction and operational cost, while meeting imposed technical, economic and reliability constraints.
TNEP should be satisfied required adequacy of the lines for delivering safe and reliable electric power to load centers during the planning horizon. Calculation of investment cost for network expansion is difficult because it is dependent on the various reliability criteria. Thus, the long-term TNEP is a hard, large-scale and highly non-linear combinatorial optimization problem that generally, can be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be added to the network up to the planning horizon. If in the static expansion the planning horizon is categorized in several stages, then we will have dynamic planning. **[R24]**

However, this cannot be done for the following reasons:

1) Lack of information that give us the possibilities to build branch power flow constraints for each branch line, so TNEP cannot be applied.
2) Losses must be considered, but this can be done only with ACOPF analysis, that is not executed in this thesis.

4) Grid expansion with Interconnection.



[R26] Fig 22, Tunisia-Italy interconnection, STEG-TERNA.

The project consists in a new interconnection between Tunisia and Sicily to be realized through an HVDC submarine cable, Maximum depth lower than 1000 meters below sea level.

There are different cable power options:

High power alternative: 1000 MW in bipolar configuration with connections consistent with the nominal grid power in Tunisia and in Sicily.
Low power alternative: 500/600 MW in monopolar configuration with 220 kV connections both in Tunisia and in Sicily.

The realization of the project is supported by the Italian and Tunisian Governments to increase the interconnection capacity of the Euro-Mediterranean system.
The project hereby described will allow to improve, significantly, the interconnection of the EU system with the North Africa countries in order to guarantee the possibility, in the short-mid term, to cover the African countries demand by the generation surplus of EU countries, especially in unbalanced load conditions; and in the long term, to import the large scale RES generation under development. The project will allow also to increase the operational flexibility of both systems.

Interconnection for Italy is useful because of the Improved efficiency and safety of supplies (diversification of sources and of supply areas) for southern Italy and within the entire electricity system Strengthened role of European electricity hub towards North Africa and South Eastern Europe (prospect of a “Mediterranean ring”), while for Tunisia optimize the Tunisian electricity system Possibility of becoming an electricity platform for the Maghreb region Conditions for further foreign investments in the electricity sector.

Instead, figure-23 shows TuNur ProjecT: 4.5 GW produced by solar tower CSP with Molten salt thermal storage.

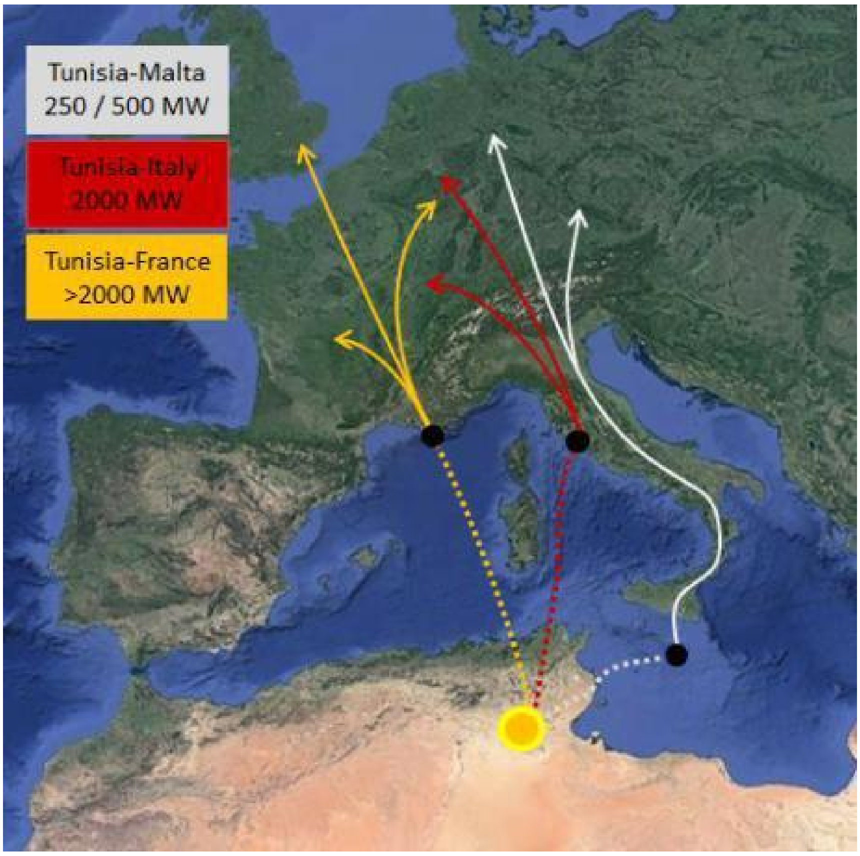


Fig 23, 4.5 GWel CSP with Molten Salt thermal storage, TuNur.

The reason why these interconnections are not analysed are:

1) The branch power flow from Tunisia to Italy depends on Branch power flow constraints, the aim of this interconnection is to increase reliability of Tunisia and reduce renewable curtailment. Since from STEG is not possible to download data such as number of lines and diameter, no branch flow constraint can be added, so no bus demand can estimate at Italy interconnection Bus.

North Africa is following a renewable penetration program, both for Tunisia, Morocco etc.
So, for this reason, no interconnection with Algeria or Nigeria will be considered, because to do this, the analysis must be extended to the near countries.(Even in this case branch power flow constraints are needed for each branch line).

CHAPTER 4: LITERATURE REVIEW.

In this section, a literature review is done: in the first part are presented different methodologies to determine biomass, solar and wind potential, while in the second part are described the problems and the analysis that must be conduct about renewable penetration in the HV power system.

In literature there are present several methods to determine solar and wind potential by using GIS (geographical information system) and Voronoi polygons.
In **[31]**, wind energy potential was estimated using the wind speed data collected by two meteorological stations installed in the Centre of Research and Technologies of Energy (CRTEn) in the Borj-Cedria area. The data collected at 30, 20 and 10 m height during 2008 and 2009, have permitted to estimate the seasonal mean wind speed, wind speed distribution and wind power density. The results have been used to estimate the net energy output of seven 1.5 MW wind turbines with taken account the air density correction and the power losses in wind farm. Weibull distribution has been commonly used in literature to express the wind speed frequency distribution and to estimate the wind power density. Then, they convert the evaluate the mean speed at wind turbine tub height by using velocity calculated at a certain height. They don't use wind turbine power curve, as done in this work, but they evaluated the power as product between air density, rotor area, speed elevate to the third degree, multiply by 0.5, where Cp(V) is the performance coefficient of the wind turbine at the wind speed V.

In **[32]**, the authors used a GIS methodology to find best wind area. They considered different geographical constraints like water zones, protected zones, forest zones, elevation zones (higher productivity, but higher cost in construction and problem for trucks to reach the site), urban zones and slope constraints (lower than 10-20 %).
To evaluate wind farms power profiles they used wind turbine power curves. In this analysis they considered the minimum distance between each turbine (in n-hectares, higher single wind turbine capacity means higher hub heights because investment cost is sustainable, but higher distance between each turbine: for the parallel distance to the prevailing speed direction is 10 times the rotor diameter, while for the cross direction the distance is 5 times the diameter, so lower number of turbines can be installed in a fixed area because diameter of the rotor increases with capacity of a single wind turbine, but however the productivity increase because of higher total installed wind park capacity that can be installed in that fixed area (lower number of installed turbines, but higher total installed capacity) and higher hub heights (the wind speed grows with height).

In **[33]**, is described a method for the optimal location and sizing of biomass fuelled gas turbine power plants. The first step is to assess the plant size that maximizes the profitability of the project. The second step is to determine the optimal location of the gas turbines in the electric system to minimize the power loss of the system.

In **[22]**, the most important study used for biomass potential quantification, is described the quantification method of agricultural and agro-industrial waste and by-products.
The estimate of the biomass-waste available on the national territory was carried out for macro-sectors: agricultural vegetable, forestry and animal production, various agro-industrial production (milk, meat, vegetables and fruit, olives, grapes), and production of wooden products with

regional detail. Attention has been focused on those production sectors that regularly generate significant quantities of high quality waste and by-products (with organic substance and practically free from of unwanted compounds), which do not always take on the characteristics of "waste" for various reasons and which consequently they often escape official forms of "monitoring and accounting". The ultimate goal is the localization in the first approximation and the identification of those biomasses waste that already represent or can potentially represent a renewable source for the production of energy, highlighting its peculiarities and critical issues. The evaluation of the real possibility of recovery of the various waste biomasses must take place on the basis of subsequent investigations relating to their effective "density" in territories of defined extension.

In **[34]**, geographic information systems technology is used to identify potential locations in a Midwestern region for collection and storage of corn stover for use as biomass feedstock. Spatial location models are developed to identify potential collection sites along an existing railroad. Site suitability analysis is developed based on two main models: agronomic productivity potential and environmental costs.

In **[35]**, the authors consider n-possible site location for biomass plant, n different plant size, and next it find the best configuration by minimization of losses in OPF.

In **[36]**, the authors present an analysis of the spatial supply and demand relationships for biomass energy potential for England, using Geographical Information System (GIS) mapping techniques.

In **[37]**, the authors first calculate the area extension by using GIS, then they used statistical information about soil quality, then they found the optimal RRR (Residual Removal Rate), they considered crop field rotation, harvesting technique and meteorological condition to determine optimal amount of crop residue. They assumed that useful surface was equal to 70% of the available surface.

[38], analyse the optimal amounts of residues that can be harvested in a sustainable way. Agricultural residues play an important role in limiting soil erosion from wind and water and in maintaining soil organic carbon. Because of this, multiple factors must be considered when assessing sustainable residue harvest limits. Validated and accepted modelling tools for assessing these impacts include the Revised Universal Soil Loss Equation Version 2 (RUSLE2), the Wind Erosion Prediction System (WEPS), and the Soil Conditioning Index.

In **[39]**, it’s used RUSLE2 model to find the optimal RRR by calculating the soil conditioning index (SCI).
This reference studies the optimal crop residue scenario as a function of SCI.
The sustainable availability of crop residues was estimated based on Soil Erosion (SE), Soil conditioning index (SCI) and economically harvestable residue yield (crop residue that can be harvested from an economic point of view).
As input, they considered crop yield, crop rotation, county, slope, slope length, crop management. A combination of these input gives different scenarios. They considered even the road network. RUSLE2 method was used to determine SE and SCI.

SCI= Soil organic matter factor
SCI= 0.4*F1 + 0.2*F2 + 0.3*F3

F1= Soil organic matter factor
F2= Soil erosion factor
F3= Field operation factor

If (SCI>0)   means accumulation of soil organic matter.
if (SCI==0) means maintenance of soil organic matter.
if (SCI<0)   bad situation, must be avoid.

SCI==0 means to find the optimal amount of residues that can be harvested without compromise the soil quality. This method does not consider sub-field level variation of crop yield. However, it considers climate change and soil topographical variation.
If SCI is determined, the optimal value of harvesting amount can be determined. To do this RUSLE2 software can be used. However, in this analysis, this method will be not applied, but constant and qualitative values will be assumed (will be used quantitative factor taken from statistical data).
So at this point, optimal RRR was determined, and finally, minimization of cost of transport was applied.

In **[40]**, the authors considered biomass resource island, biomass storage center and power plant island, this because different cost of transport because of different means of transport (tractor and truck), then a tortuosity is assumed, so in this way any curve road can be approximated with a straight line. They considered biomass power plant investment cost, the operating costs of a biomass power plant include the cost of human resources for daily operation, management, financial expenses, taxes and others.
The generation costs of a biomass power plant include the processing costs of biomass feedstock, the costs of equipment depreciation and equipment maintenance.
They considered even the pollutant discharge costs of a biomass power plant.
The objective function of this work was to minimize cost of transport and CO_2 emissions.

In **[41]**, the authors considered as input biomass production, population, city and village distribution, state and federal road transportation, rail road transportation network and boundary, then they found n-optimal site location and finally they found the best site location by minimization of cost of transport.

In **[42]**, the authors first evaluate biomass availability and geographical dispersion. In this study, the authors preferred to use biomass plants to optimize electrical grid behaviour (voltage analysis, reliability analysis etc, when biomass plants are used to optimize locally HV grid, for instance to minimize blackouts caused by voltage drop in a certain zone), so they used as input the ideal capacity that me be connected to the electrical grid and then they found the area needed to do it. GIS analysis is used even to minimize cost of transport, to find area not optimal due to high transport cost.

In **[43]**, to find the optimal site location and capacity, the authors proposed to use Voronoi cells. At each cells/mesh it’s associated soil parameters and biomass availability, then optimal site and location is determined considering many constraints (geographical, social, soil quality etc) and by minimization of cost of transport.

In **[44]** focuses on the problem for designing a logistics system for bio-methane gas (BMG) production. In practice, farm residues such as crop residue, wood residue, and livestock manure are used in reactors as reactants to generate BMG, they collected different types of biomass that can be accepted in a digester for biogas production, then they collected to different possible hub storage and the n collect different hub storage to different possible site location of biogas reactor. They found the optimal number and location of storage hub and optimal site location and number of biogas reactors (anaerobic digester) by minimization of cost of transport.

In **[45]**, describes a GIS-based Environmental Decision Support System (EDSS) to define planning and management strategies for the optimal logistics for energy production from woody biomass, such as forest biomass, agricultural scraps and industrial and urban untreated wood residues. GIS is firstly used to select area where harvesting is possible. Then they evaluate for each pixel the availability of forest residues. They selected 3 different technologies and finally they found the optimal solution by minimization of total cost:

1) forest biomass felling and processing cost(CFP);
2) forest biomass primary transportation cost(CFT);
3) transportation cost from landing points to the plant (CT);
4) non-forest biomass (i.e., agricultural or industrial residues) purchasing cost (CP);
5) plant cost related to the k-th plant installation and management CI,k,;
6) Benefits deriving from the products sale for the k-th plant Bk.

The objective function to be minimized is then C =CFP + CFT + CT + CP + CIk- Bk

In **[46]**, SRTM analysis it’s used to estimate biomass availability, where SRTM is the Shuttle radar topography mission.

In **[47]**, **[48]**, there is a complete description of power systems theory by using MATPOWER.

In **[49]**, there is a complete review of the AC Optimal Power Flow (ACOPF) problem and proposed areas where the ACOPF could be improved. They described the different types of OPF.

In **[50]**, there is described a method to build electrical grid by using QGIS, moreover, the authors study the effects caused by wind penetration into congestion for Switzerland HV network.

In **[8]**, one of the most important study for this thesis, High spatial and temporal resolution optimal power flow simulations of the 2013 and 2020 interconnected grid in Central Western and Eastern Europe regions are undertaken to assess the impact of an increased penetration of renewables on thermal power plants. The citied work models each individual transmission line and power plant within the two regions. Furthermore, for conventional plants, electricity costs are determined with respect to fuel type, nameplate capacity, operating condition and geographic location; cycling costs are modelled as function of the recent operational history to avoid excessive curtailment of renewable power in systems with high penetration of renewables, conventional power plants will have to provide more ramping capabilities and have a larger range of operation. In this thesis, this cannot be done, in particular because one cannot access to the recent operational history of thermal power plants, moreover STEG or OSM doesn’t give complete information about electrical lines (number of line for each branch and diameter).

In **[51]**, they focused on the basic problems of choosing when, where, and in what quantity new renewables plants should be added to power system. These problems arise in transitioning to a power system without fuel with significant capacity for spilling and storage, and in expanding power systems without fuel to accommodate load evolution. They analysed renewable penetration behaviour if electrical demand is satisfied without use fossil fuel.

In **[52]**, the authors presented an Academic Model of the NYISO transmission system that mimics key features of the New York network on a smaller scale without the use of confidential information. A day-ahead and real-time Market Model is developed using MATPOWER. Real time dispatch and commitment engines operate on 5 and 15 minute time scales, respectively. Start-up notification and the ability to curtail renewable resources are modelled. Simulations show the effects of doubling steam unit ramp rates on two days in both low and high renewable penetration scenarios. The day-ahead and real-time optimization problems have the same structure. They seek to minimize generator operating and start-up costs subject to a set of constraints. Renewable generators are modelled as having no operating cost with energy bids at $0/MWh and thermal units have quadratic cost functions. The optimal solution will minimize the operating cost needed to match thermal and renewable generation in each interval with the net load while ensuring generators respect their operating restrictions.

In **[53]**, the authors found the maximum PV capacity that can be integrated into the existing Zambia grid while considering the ramp rate constraints of the existing generators. An optimal power flow using MATPOWER was performed using a transmission system model of the grid. The key concerns of large scale solar PV integration include balancing the net load, system inertia, frequency and voltage ride-through capabilities. Consequently, the capability of a specific power system to integrate solar PV depends on the flexibility of its generation and the extent of demand side response.
Blackouts can be common in an event of drastic drop or rise in the solar PV output. This means that grid stability is compromised due to the risk of severe grid over- or under-frequency if conventional generation is unable to decrease or increase its power output quickly. Active power control methods for renewable power plants (RPP) include maximum power limitations, operating range limitation, delta control and ramp rate limitation as highlighted in the grid code for RPP in South Africa. Ramp rate limitation is an effective way of minimizing sudden changes in the output from RPPs by limitation of their power gradient through a set point.

In **[54]**, it's proposed a flexible ramping capacity (FRC) model, which considers the practical ramping capability of generation resources as well as the uncertainty in net load. The FRC model also incorporates the demand curve of the ramping capacity, which represents the hourly economic value of the ramping capacity. The model is formulated mathematically using ramp constraints, which are incorporated into unit commitment (UC) and economic dispatch (ED) processes. The study shows that the FRC method can improve reliability and reduce expected operating costs. The simulation results also show that, by using the FRC model, system reliability can be satisfied at high wind power generation levels while achieving economic efficiency.
The authors conducted daily simulation and determined the flexible ramping. They considered short time interval to study flexibility of thermal power plant with high wind penetration, in terms of ramping capacity. The proposed method was designed to maintain system reliability above a threshold each hour, and also secure flexibility regarding the requirements of hourly varying ramping capacity.
They drawn price curve as a function of flexible ramping capacity demand curve.

In **[55]**, It's presented an optimization model that considers the flexibility offered in demand bids from the DSOs (Distribution system operator) and optimally utilizes this flexibility by minimizing the total cost of generation; it's proposed that the DSOs embedded within a transmission network provide inelastic demand bids along with a flexibility interval; this means that the demand bids are elastic to a certain level. Such flexibility can be achieved by a DSO's own DR programs. If such information is available to a TSO then the decision problem is to optimally utilize the generation from RES while utilizing the flexibilities of the demands.

In **[56]**, it's described how spinning reserve change with high wind penetration, Spinning reserve allocation is a critical problem for active power dispatch with large-scale wind power penetration. A risk-based reserve allocation method that accounts multiple control sub-area coordination is given in this study. And a multi-objective optimization model is constructed to schedule the spinning generation reserve for online active power dispatch.

In **[57]**, the optimal spinning reserve is studied by considering the balance between the economy and reliability of a power system. However, the uncertainties from the errors of load and wind power output forecasting have been considered. In this paper, the optimal spinning reserve capacity of a power grid considering the wind speed correlation is investigated.

In **[58]**, they had optimize unit commitment with grid expansion, to do this, they considered 2 model: one model being the ENTIGRIS optimization model which optimizes the unit-commitment of renewables, short and long-term storage technologies and the imports and exports between regions as well as the expansion of all available technologies (including grid expansion). The resulting nodal transmission balance and the new grid infrastructure are then transferred into a load flow and grid expansion model.

In **[59]**, the authors analysed how renewable plants penetration into the HV network changes the grid, in terms of congestion and total emission.

In **[60]**, it's proposed a model for the generation and transmission network expansion planning problem that includes decisions related to substations' locations and sizes.
In this study, first are discussed the benefit of incorporating substation decisions to the transmission network design problem. Then they proposed a model that finds a minimum cost network, the optimal locations and sizes of substations and generation plants.
For long-term planning, in practice, generation resources are planned first, and based on the solution, transmission network is planned.

In **[61]**, The potentials of solar resources and the suitable factors for the deployment of concentrated solar power CSP in Tunisia were presented. This study was done in the framework of the enerMENA project which aims to prepare the ground towards a sustainable realization of CSP power plants in the North Africa and Middle-East countries. Moreover, the electrical interconnection between Tunisia and Italy and the opportunity of the exploitation of renewable energy sources such as CSP plants in North Africa by European countries, were discussed.

CHAPTER 5: TUNISIAN SOLAR AND WIND POTENTIAL.

5.1) Tunisian solar potential

Tunisia, has a favourable renewable potential, in particular solar potential since 40% of the total area is covered by Sahara desert and for this reason Tunisia is an optimal place for installation of solar technologies.
Actually there are not PV parks or CSP plants, many plants are in construction phase.
Because of its limited geographical extension, solar potential varies a little within Tunisian boundary, so if coordinates used to calculate solar potential are wrong, the associated error is little.

While CSPs (concentrating solar plants) use only direct radiation, PVs use both direct, diffuse and reflected radiation (if surface inclination is not zero).
The first thing to do to determine power profile production from PV plants is to analyse meteorological parameters. In fact, the PV-performance depends by:

1) Normal solar radiation [W/m2]
2) Direct horizontal radiation [W/m2]
3) Direct radiation into an inclined surface [W/m2]
4) Diffuse radiation
5) Total radiation into an inclined surface (it considers reflected radiation)
6) Air temperature [degC].

Air temperature is important because PV cells have worse performance at higher temperature (higher temperature causes voltage drops), so during summer, even if it is characterized by higher direct radiation, the productivity can decrease because of high temperature.

Fig 24, 25, 26 shows some strange features about solar radiation in Africa. The particularity is given by equator position.

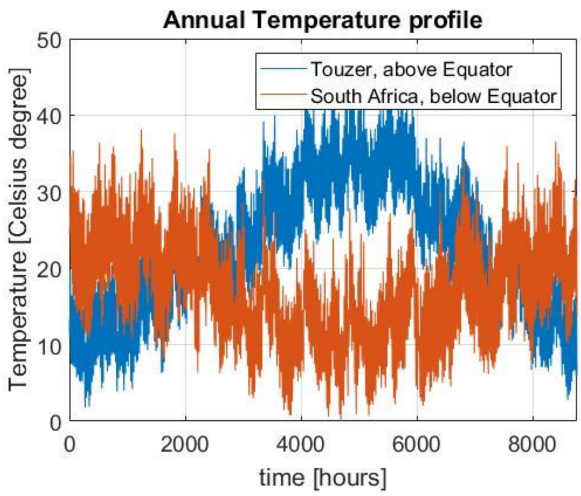


Fig 24 Air temperature profile for Tunisia (above equator) and South Africa (below), data are taken from METEONORM

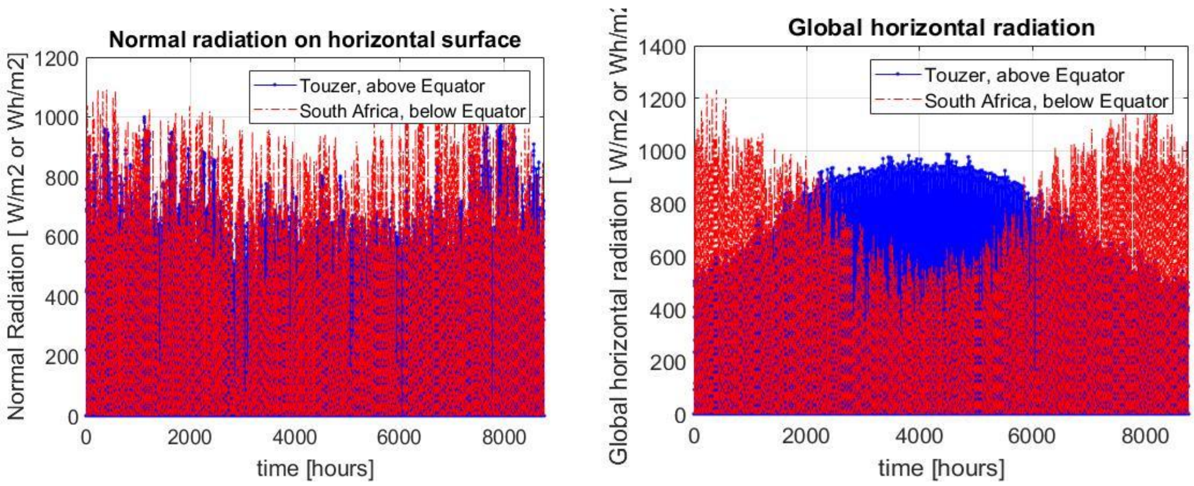


Fig 25, 26: As it's possible to see in Fig 26, mean air temperature and global horizontal radiation into an horizonal surface have the same profile because a more favourable incidence. (Heat is adsorbed by ground and transfer to air by convective heat flux).

Touzer (above Equator) and South Africa (below Equator) present the same direct normal radiation profile, but different average air temperature and direct normal radiation because of Equator position. For Touzer, during central months, the amount of heat adsorbed by ground increases because of favourable inclination and the adsorbed heat it's used to heating the surroundings air by convective heat flux, in winter months the inclination is worse and so lower absorption of heat. For these reasons that direct radiation and air temperature have the same trend.

The adopted method to determine solar profile is now described:

1) From internet link reported in [TABLE-APPENDIX, Table 3] it's determined an approximate location of the plants (since Tunisia is relative small, in terms of extension, then the error associated is low, if plant coordinates are wrong), see figure 27.
2) On QGIS, we paint an area that includes estimated generator
3) We select n-points inside this area
4) We calculate PV-production using [Wh/KWp]

To do this (point 4), optimum Azimuth and Slope angle of the PV panel are firstly calculated using Excel by maximization of energy production in the overall year. The optimal Slope and Azimuth are around 32 and 0 respectively.
The parameter shows in figure 28 and 29, expressed in [Wh_el/kWp] it's derived by using METEONORM.
At this point , we stop to focus on why PV production (inclined surface) is higher in winter (January) than in Summer, but first, to be sure that this is not a METEONORM debug, we compare the trend with data derived from [https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html].
To compare and verify PV profile given by METEONORM, we select Touzer as location. As it's possible to see from the figure 31, the trends are similar, they differs in values because different assumption about solar PV performance has been made.

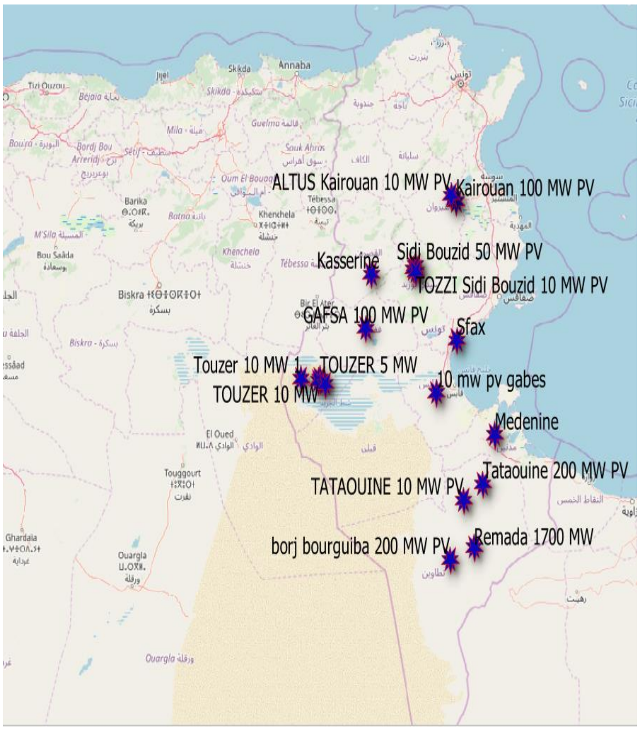
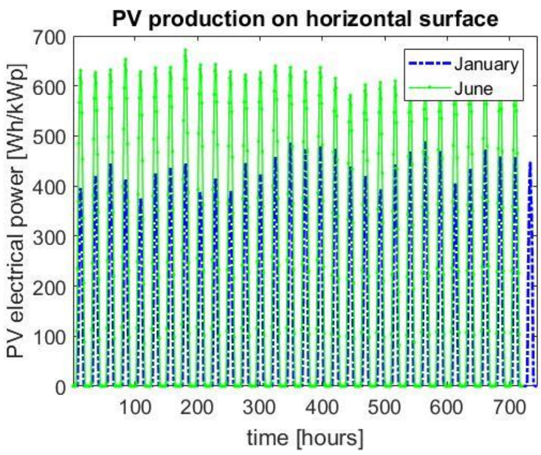


Fig 27, PV plants estimated location



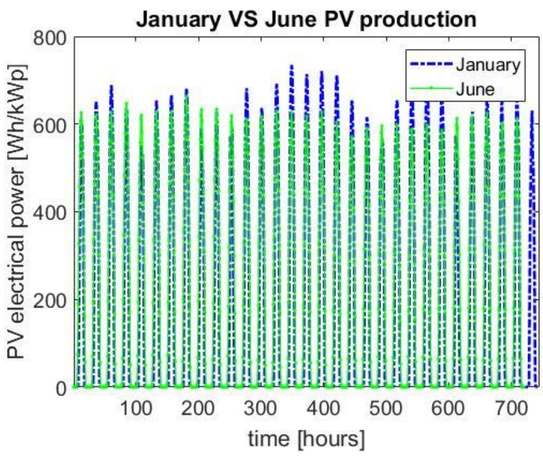


Fig 28, 29: Fig 28 shows Tunisia PV production [Wh/kWp] if surface is not inclined **,** while Fig 29 if is inclined: as it's possible to see, if optimal PV-panels inclination is determined, then, in terms of power [MW] and not in energy [GWh], at January higher power than June.

Solar PV electrical profile by PV-GRID has been used since the last option to determine a PV-power profile from PV already includes the option to optimize Slope and Azimuth angle, but in particular it offers a better performance.

The reasons of this behaviour of PV-profile are:

A) High daily air Temperature reached during summer seasons: High temperature causes a voltage drop that cannot be neglected.
B) Little rain and therefore little cloudiness over the entire period of time, including the winter months.

C) Equator is quite near to Tunisia.
D) To determine electric profile by PV plant, a fixed photovoltaic panel has been selected, a higher panel inclination means higher electricity production during winter months.
E) Presence of desert land means high solar production for all year.

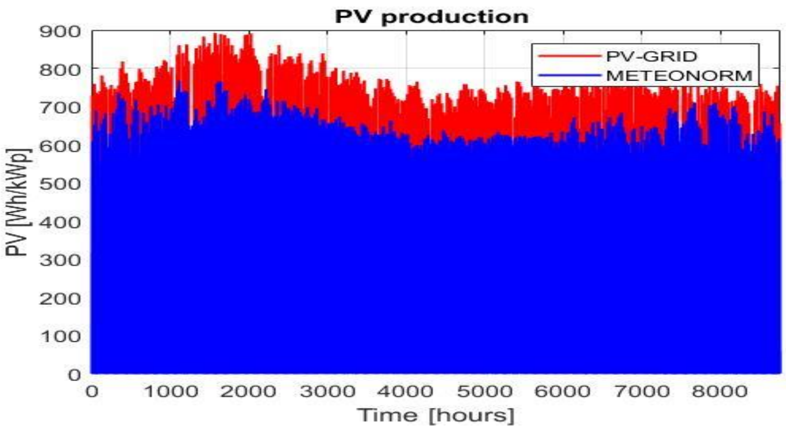


Fig 30, PV production by using 2 different software. [Wh/kWp]

5) We multiply PV production factor [Wh/kWp] by nominal capacity, but the results in MW.
6) We calculate the average power

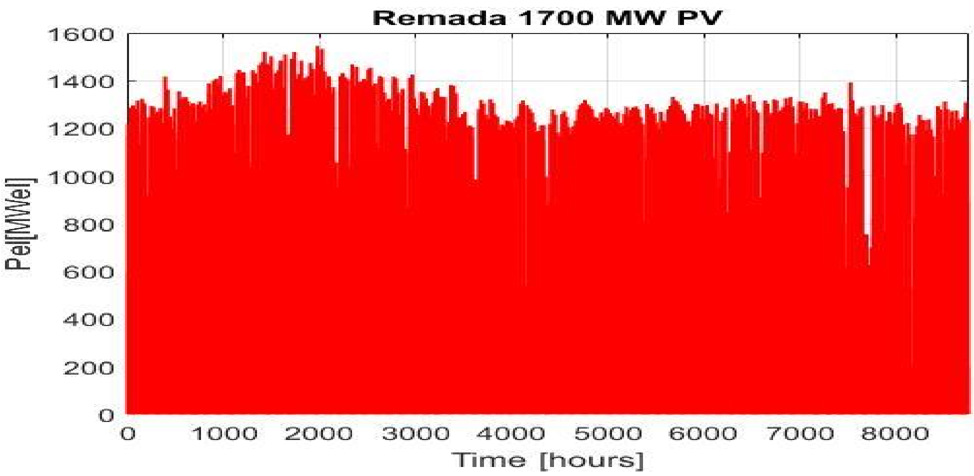


Fig 31: Estimated solar PV power profile, Remada, 1700 MW PV.

In figure 31 it's reported the electric profile of active power that could be generated by REMADA 1700 MW PV-park, estimated by using PV-GRID:
[https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html]

5.2) Tunisian wind potential

Now, in the following section will be discussed how wind power profile for different sites is determined.
There are several methods used to determine wind profile in a specific geographic site.
The classic method is to use Weibull distribution, however, this is not done in this work and the reason can easily seen in Figure 32.

In literature there are available several GIS-methods to determine the optimal wind site location, however, since an estimated wind farm location is known (from internet links), a modified approach will be used:

1) Localization of a guess location, near to the location reported in the Tunisian energy projects 2035, [TABLE-APPENDIX,Table 3].
2) Exclusion of forbidden area such as land-use area, natural area, manmade area etc..(Global land cover), exclusion of place with elevation higher than 2000m (difficulty in the wind turbine transport to the site) using GIS elevation map etc. However, since there are only 2 meteorological stations, this does not make sense (high error). A qualitative approach using GOOGLE SATELITE and OSM is sufficient to select potential site to accept wind farm.
3) Localization of the best point to locate wind farm using Wind capacity factor Raster data, Wind power density Raster data and Wind average speed Raster data (These are taken from [Energydat.info, https://energydata.info/]: in other words, the Tunisian boundary is divided in pixel and for each pixel are associated 2 values: capacity factor and power density. Wind projects position are unknown, only the regional position is known, for instance Nabeul, so to find a reasonable position will be used a qualitative maximization of capacity factor and power density GIS data.
4) Localization of one possible point.

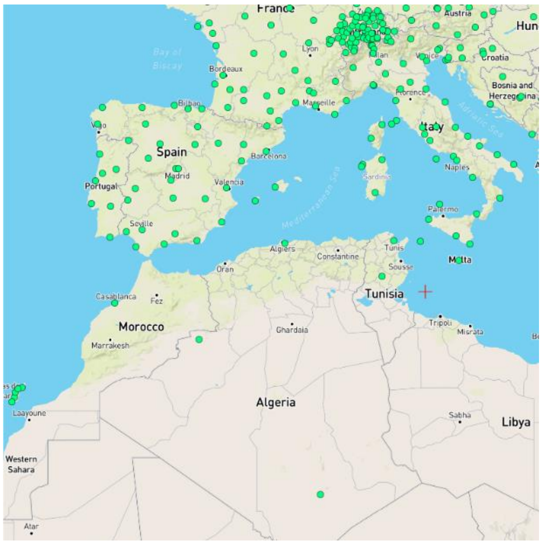


Fig 32 Wind speed data are taken from METEONORM software database. This figure shows the number of meteorological stations available in the Tunisian boundary. Since these stations are limited in number (only 2 stations in Tunisia), the results will be a big error associated to these data, in particular in wind evaluation. So for this reason, no Weibull distribution will be determined. Mean hourly wind speed values are used, calculated for different sites at different height.

It’s important to remark the fact that there are places where the power density is low and capacity factor is high(low energy produced, lower fluctuations) and viceversa. This affects dramatically the behaviour of the HV grid, however this analysis is not focused on to find the best site location of wind turbines.

The next step is to select a qualitative area, again, this is sufficient since there are only 2 METEONORM meteorological stations in Tunisia. The goal is to find a qualitative and an optimal area where wind farm will be installed with high probability, since the wind farm sites have been found through internet research.
After selected the area, will be added n-points inside this area.
In this case, for Nabeul, in this section a radius of around 15km has been used.

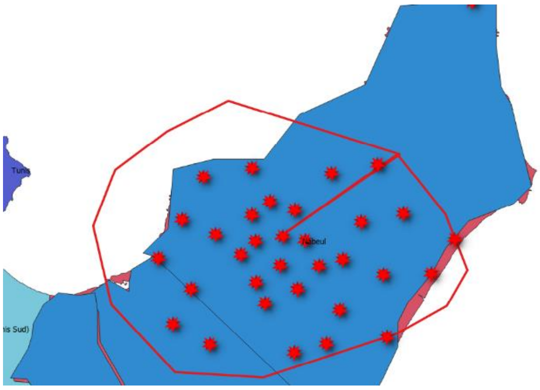


Fig 33: Point selection to determine hourly sped value

After that the points have been selected, It’s necessary to select a wind turbine model and the relative hub height. The scope is to use specific wind turbine power curve to estimate, using MATLAB best fit, the power curve equation as a function of speed.
Wind turbine model, and so the capacity, will determine the hub tower height.
Moreover, the sea-level it’s necessary to estimate the wind speed profile at a certain height.

Sea-levels has been calculated using [gpsvisualizer.com/elevation] for n-points. So the height to add as input for METEONORM is the total hub height plus sea level for each point.

At this point it’s possible to estimate the hourly average wind speed. Knowing these profiles and wind turbine power curve, built on EXCEL and/or MATLAB, it’s possible to determine the electric profile.

The main disadvantages about wind energy is its uncertainty and difficulty in the forecasting, this is translated into an error. Moreover, because of poor availability of meteorological stations, this error is even bigger.
To consider average hourly values it’s more convenient because drastically reduce the forecasting error, and this is better from a dispatch point of view. However, the production from wind turbine is not linear with velocity, as shown in the figures 35, 37. This means lower ramp flexibility required from fossil thermal power plants.

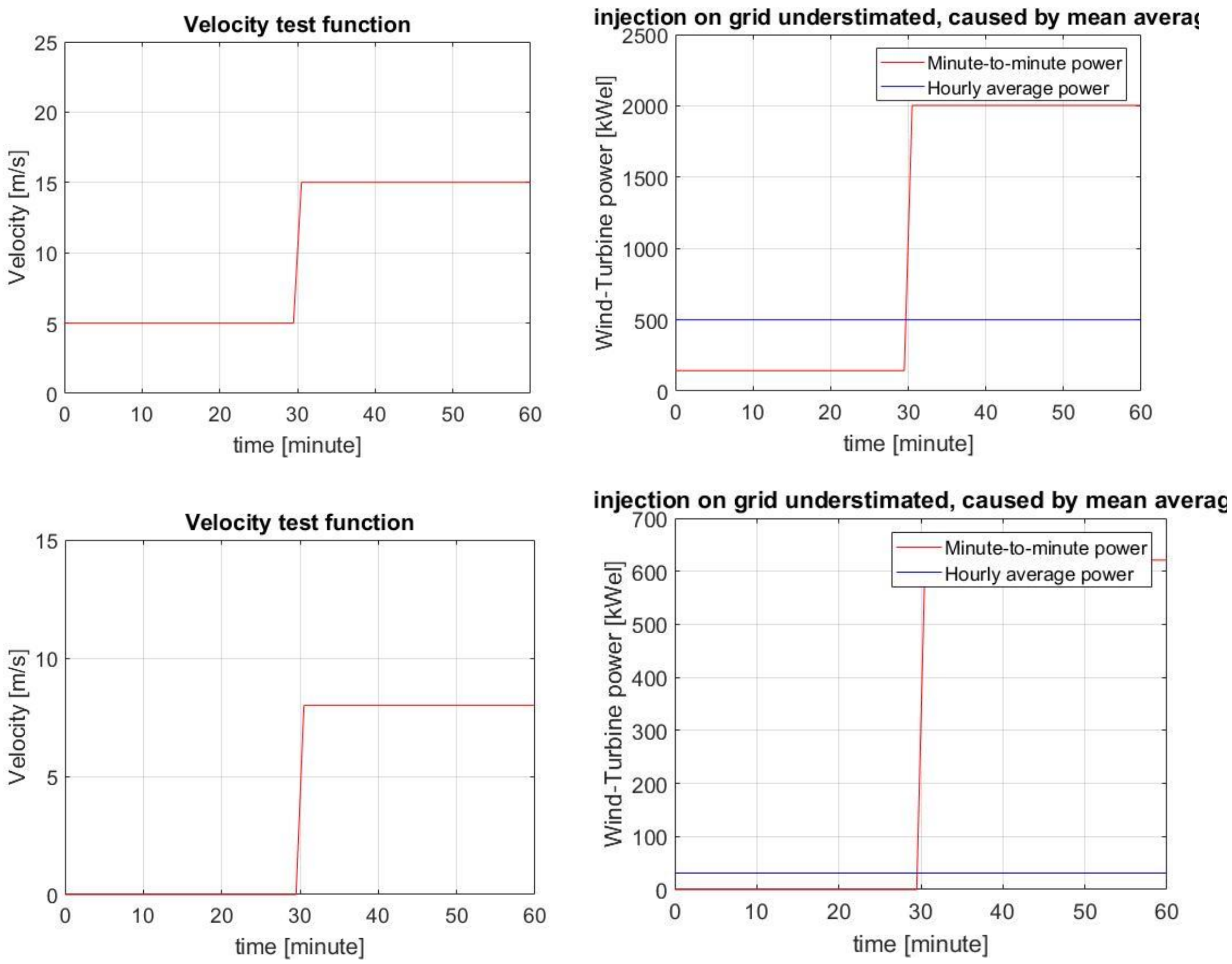


Fig 34 ,35, 36, 37 Fig 35 and 37 show in red the power profile if minute to minute speed values are used, while in blue if hourly average speed is considered. Due to non linearity of wind power curve for wind turbines, at lower wind speed what happens is that if hourly average speed is considered, then the wind power is underestimated.

Figure 34, 36 represents the minute-to-minute wind speed profile and the average hourly speed, calculated as the average of the minute-to-minute speed profile. As it's possible to see from figure 35 and 37, the electrical energy produced by wind turbine if minute to minute profile is considered is higher than the electricity produced if mean speed is considered, because the non-linearity of wind turbine power curve as a function of speed.
To consider average hourly values reduce the total forecasting error, however underestimates the productivity, this is translated as reduction of capacity factor and power density (As happened in this analysis, as it's possible to see in fig 35, 37).

The wind capacity factor and hourly power are underestimates because of hourly average values. Hourly average values of wind speed can give zero-power values, but this could not be true (as shown in the figures).

In this analysis will be implemented future wind projects, except for one site for which the model of turbine is known (Siemens-Gamesa 4.5 MW), for the other sites the model of turbine is unknown.
Capacity of single turbine depends even by road constraints (wind blade are transported by truck, higher the diameter and more difficult will be the transport), in this analysis will be chosen 2 MW wind turbines capacity.(Note: higher wind turbine capacity means higher height and so higher

productivity, this means that productivity could be overestimated. This is better since capacity factor and productivity are also underestimated because of hourly average values are considered, as shown in fig 35, 37.

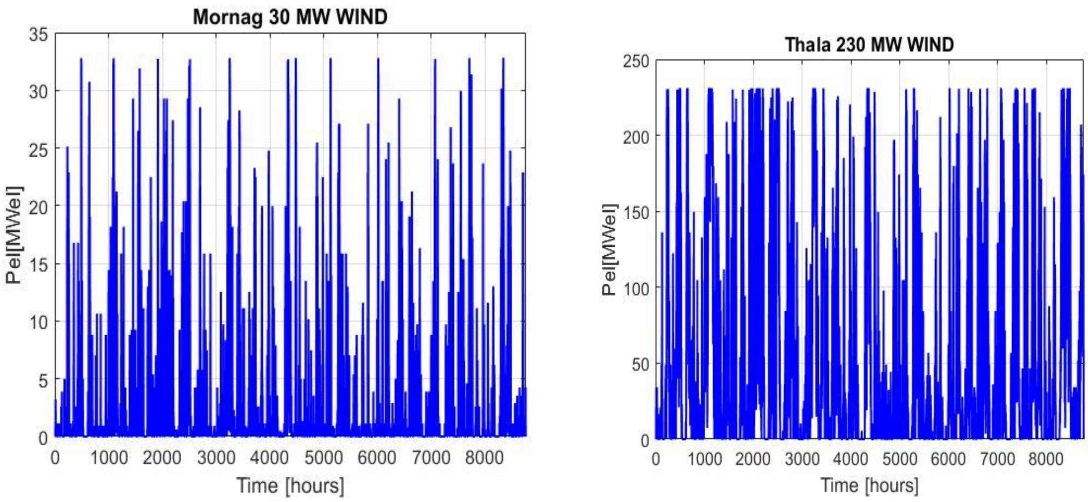


Fig 38, 39: Example of hourly wind power profile for Mornag and Thala.

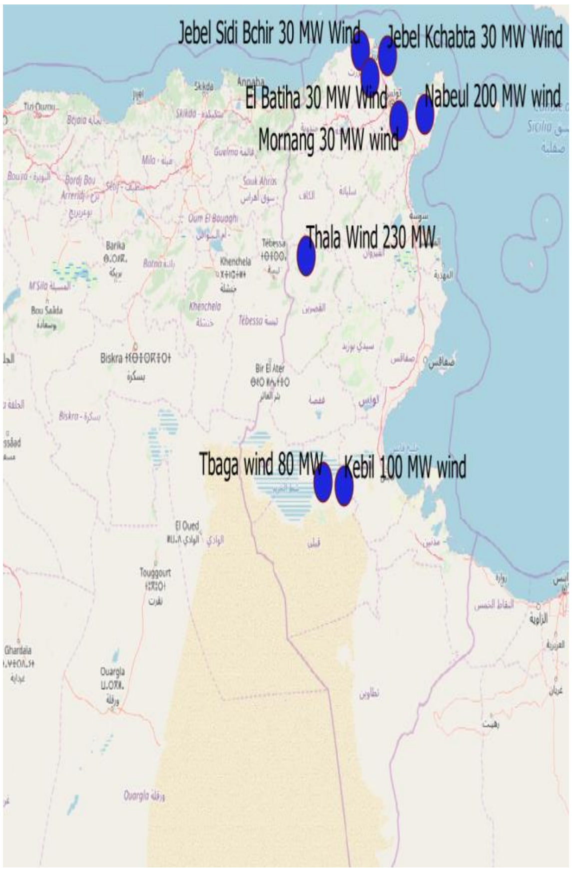


Fig 40: Wind farms projects location

CHAPTER 6: TUNISIAN BIOMASS POTENTIAL.

Biomass is the biodegradable part of products, waste and residues from agriculture (including vegetable and animal substances) and from forestry and related industries, as well as the biodegradable part of industrial and urban waste **[R18]**.

Biomass is a highly disperse and geographically dependent renewable energy source. Biomass can be used for production of a number of fuels and chemicals or electricity and heat production, if even heat is produced, then the site must be located near the user, to minimize heat losses. The transportation cost of feedstock constitutes a significant part of the total cost of production. Consequently, establishment of biomass-based facilities in suitable locations by minimizing transportation cost is one of the key issues for bioenergy economy and its sustainability. In addition, location and size of a biomass-based facility for fuels and chemical is dependent on different issues, e.g., steady supply of feedstocks, environmental regulations, stakeholders interests, etc. Siting bioenergy plants in optimal locations at optimum capacities is a challenging task. Due to high geographical dependence of biomass feedstocks, implementation of spatial information technologies such as remote sensing and geographical information system (GIS) in addressing this issue appears to be an appropriate methodology.

The options for conversion of biomass into electricity are combustion, gasification, integrated gasification combined cycle (IGCC) and pyrolysis, or even biomass plants could be integrated with wind farms etc **[R19]**. Since this thesis is not about to find the best biomass technologies, a constant electrical efficiency was assumed, without considered other details. Moreover, biomass are small plants, they could reduce flexibility needs for thermal power plants in HV- power distribution systems, however, in this analysis, biomass plants work at constant power.

Note that biomass have a dual behaviour:

1) Same biomass could be used in different technologies (anaerobic digester and/or gasification etc).
2) Same technology can use different types of biomass.

The consequence is that there is an internal conflict between 1 and 2. Optimal solution must be found, but this requires a complex analysis that is not part of this thesis (a priori, one should consider minimum cost of transport, geographical constraints, social constraints, EROI constraints, proximate analysis of biomass, harvesting equipment and consumption etc). So, this aspect has not been considered in this work. EROI is the ratio between the total energy that could be produced from 1 tonnes of dry biomass divided by the total primary energy consumed during all process, including harvesting energetic cost, cost of transport [GJ], auxiliary expenditure etc..

To Determine biomass potential, there are several methods presents in literature, already discussed in the literature review chapter.
In**[R19]**, is described the problem of defining the optimal size for plants to convert the biomass into electric energy. In this work, a method has been developed to determine the optimal electric power to install in a given agricultural area based on the biomass available in the area itself.
The study is based on finding the correlation between the plant power Pe (MW) and the quantity of dry biomass locally available. This last parameter depends on the net density of this biomass dry

(t/km2 yr d.m. dry mass) and the surface of production S (km2), accepted to be a circle with the center constituted by the power plant location and a radius R (km).

A number of resource-focused assessments have been made regarding the potential bioenergy supply including crop residues on an aggregated level, i.e. for large regions and countries or at a global level. In order to meet this objective, spatially high-resolution inventory assessments of agricultural crop residues is needed. Uncertainties about the share and composition of agricultural crop residues which can be made available reliably, steadily and in a sustainable way currently limits the validity and use of potential studies for decision-making processes in politics and industry.

Comparisons of regional residue potentials across borders and of different countries have therefore only limited validity because of differing underlying methods and assumptions, e.g. different terms and definitions of potentials such as theoretical, technical and sustainable potential.
For spatially high-resolution biomass potential analyses as well as for location and transport distance analyses, GIS-based approaches are commonly used.
In order to estimate the total amount of crop residues, i.e. the theoretical potential, average crop areas and crop yields together with average residue-to-product-ratios (RPRs) are widely used as a starting point **[R20].**

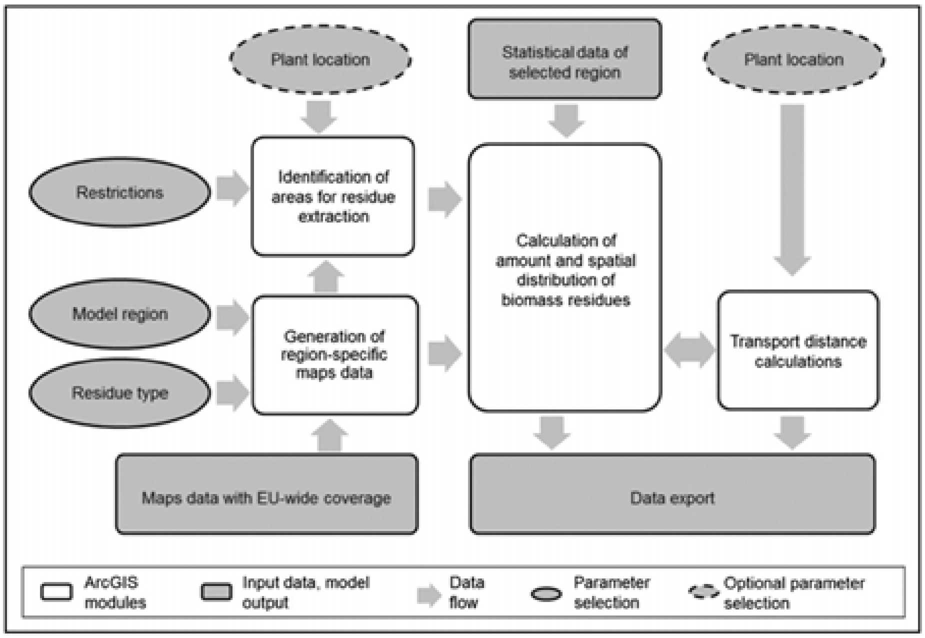


Figure taken from **[R20], Fig 41,** Classical methodology that must be applied in biomass site plant optimization

The major difference respect this model (**R[20]**) are:

1) No minimization of cost of transport.
2) No application of ecological constraints that consider soil erosion for instance.
3) It refers at energy [GJ], while this thesis to specific power

Specific Power [MW/hectares] = Energy in fuel * electrical efficiency / (Harvesting Area *Capacity factor*8760)

In **[R18]**, biomass has to be collected from a circular area and the transportation distance of feedstock is assumed to be a circle area, so, in this study, for crop residues, a radius of 30 km has been assumed to collect biomass. Some authors consider a higher radius, however, since Tunisia is characterized by harvesting machine, truck etc at higher consumption, then a lower radius has been considered.

This study, however, did not incorporate the spatial variation of biomass availability and local transport network. Moreover, this thesis is not about minimization of cost of transport, so, even, a constant radius has been assumed.

In this work, the best area was determined by maximize the producible energy in a radius of 30 km, and, again, biomass has to be collected from a circular area.
Finally, optimum capacity of plants were determined.
6 biomass plant was found, located in North Tunisia.

To conduct a more accurate analysis, data must be taken in loco, in other words, since the total associated error of LHV, geographical error (that is the biggest contribute), etc is relative high, does not make sense to use complex algorithm when, the input present large uncertainty.

Harvesting amount from crop residues depends on type of biomass: herbaceous or arboreal.
If herbaceous, the crop residues are strongly dependent on harvesting methods and machines, but in particular, it's strongly dependent on soil index: the complete removal of crop residues causes increased soil erosion and decreased Soil Organic Matter (SOM) accumulated in the soil, hence the loss of soil and its quality. Therefore, the Residue Removal Rate (RRR) should be optimized for bioenergy applications while preserving the long-term productivity of croplands. **[R21]**

Now, after that GIS methodology to determine biomass potential has been described, the principal reference about methodology to determine biomass potential from statistical data will be presented. This is **R[22]**.

6.1) QUANTIFICATION OF WASTED BIOMASSES AVAILABLE ON THE NATIONAL TERRITORY

The estimation of the biomass-waste available on the national territory is carried out for productive macro-companies, consisting of:

1) Agriculture (vegetable and animal productions);
2) Agro-industry: milk processing, slaughtering sector, fruit and vegetable processing, olive processing and grape processing;
3) Wood industry.

Agricultural and agro-industrial activities produce significant quantities of high quality organic waste and by-products, since they are made up of parts of the same raw material that are removed during collection (agricultural products) or along the industrial transformation line. By limiting the discussion to those of an organic nature, in addition to this flow, the agri-food industry generates a series of other "production waste", which are effectively managed as "waste", such as sewage sludge and products faulty packaged food and / or expired or otherwise non-compliant.

6.2) Waste and residues of agricultural activity

Agricultural activity produces waste biomass that can be used for energy purposes, consisting of all the parts of the plant that do not represent the main products, intended for human or animal food use. In practice these are stems and leaves, cobs, stalks, branches, twigs and wood.

The estimate of the quantity of each agricultural by-product was carried out taking as reference the data provided by FAOSTAT and resorting in substance to three essential parameters;
So the adopted methodology to determine biomass potential from crop residues is the following:
The following parameters, such as wasted recycle factor, sub-product /product ratio (tonnes/tonnes) are taken from **R[22]** , in particular, because of lack of data or measure taken on loco:

> **[ASSUMPTION1]:** Same crop residue ratio (sub-product/product ratio) for North Tunisia and Sicily.
> **[ASSUMPTION 2]:** Same internal waste recycle factor.

In reality, these factors are different because of

1) Different climate conditions
2) Different harvesting equipment and technique (the relevant)
3) Different soil condition, water precipitation, wind speed etc.

1) **Total production for each herbaceous and arboreal crop**: evaluated from FAOSTAT, so the harvest area (hectares) and the harvested amount (tonnes) of products (apple, peach, tobacco, potato etc) are known.

2) **Relationship between main and product by-product:** These are the coefficients that can vary in the different agricultural realities according to various factors among which the most important are mentioned: the climatic trend, the adopted variety, the cultivation technique. For the purposes of the estimate, a single coefficient was adopted per cultivated species. For tree crops only the main by-product (annual pruning) was considered.
So, Using **R[22]** it's possible to classify and quantify the types of sub-products (residues) that can be harvested for each crop. So sub-product/product ratio must be determined.

By using **R[22]**'s agricultural data, for Sicily, it's possible to determine the amount of product and sub-product harvested, so it's possible to estimate the sub-product/product ratio for Sicily.
Assuming that sub-product/product for Tunisia and Sicily are equal, this means that one can estimate the amount of crop residue that can be produced in Tunisia, for each crop.
Again, Knowing the amount (tonnes) and harvested area (hectares) for each crop (peach), and knowing the sub-product (pruning branches), using the ratio sub-product/product It's possible to determine the amount of crop residue that can be harvested (tonnes of crop residue/year) and the density (tonnes of crop/hectare).

3) **Fraction or percentage of the waste or by-product already recycled or reused.** For the main herbaceous crops (cereals) different coefficients have been adopted according to the territorial context of reference (region). For those crops for which it is known that the fraction recovered is almost zero, a constant net availability of 100% has been assumed.

The specificities of the sector present some negative aspects:

1) the production and, therefore, the possibility of starting recovery are strongly seasonal and concentrated on very limited time spans (20-40 days).
2) waste deriving from herbaceous crops (including vegetables) are characterized by very different humidity levels. It goes from 10-12% of straws to values equal to or greater than 80% of horticultural production waste; it is an extremely pulverized production in the territory. Any form of recovery must therefore face the costs of mechanization for collection (especially for tree waste) and transport costs; - any assessment of technical-economic feasibility for their recovery must therefore be carried out at a local level, as a careful preliminary analysis of their "density" in the reference territory, whose radius must be as limited as possible to contain, the costs mentioned above.
At this point, [assumption 2].

Reuse coefficients adopted for the different plant species, example

Table 3: Reuse coefficient, fraction of crop residue that is internally reused

Soft Wheat	Hard Wheat	Barley	Oats	Rice	Corn	Soy
20	20	20	20	10	50	5

Sun-flower	Dried legumes	Sugar beet	Potatoes	Tobacco	Potato
5	10	15	5	5	5

Herbaceous crops

Table 4: Subproduct/Product ratio for Herbaceous crops

Product	**Soft Wheat**	**Hard Wheat**	**Barley**	**Oats**	**Rice**	**Corn grain**	**Soy**	**Sun flower**	**Legumes**	**Sugar beet**	**Potetoes**
Product	**Kernel (Cariossidi)**		**Kernel (Cariossidi)**	**Kernel (Cariossidi)**	**Kernel (Cariossidi)**	**Kernel (Cariossidi)**	**Sees(semi)**	**Sees(semi)**	**Sees(semi)**	**Root (radice)**	**Tuber (Tubero)**
Main subproduct	**Straw (Paglia)**	**Straw (Paglia)**	**Straw (Paglia)**	**Straw (Paglia)**	**Straw (Paglia)**	**Rapiers (Stocchi)**	**stems and leaves (Steli e foglie)**	**stems and leaves (Steli e foglie)**	**stems and leaves (Steli e foglie)**	**stems and leaves (Steli e foglie)**	**stems and leaves (Steli e foglie)**
Sub-product/ Product ratio	0.8	0.8	1	0.8	0.8	1.30	1	2	1.5	0.4	0.4
Umidity	15	15	15	15	25	55	52	40	15	80	60
Recycle waste %	20	20	20	20	15	50	5	5	10	15	5

ARBOREAL CROPS

Table 5: Subproduct/Product ratio for Arboreal crops

Product	Graphes	Olive	Citrus	Peach	Apricot	Plum	Apple	Peer	Cherries	Kiwi	Almond
Main sub product	Sarmenti	Frasca	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)	Prunin branch	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)	Prunin branch (Rami potatutra)
Subproduct/product ratio	0.95	0.9	0.95	0.95	0.95	0.97	0.95	0.95	0.94	0.83	0.95
Umidity %	50	50	40	40	40	40	40	40	40	40	40
Recycle waste %	5	10	5	5	5	5	5	5	5	5	5

The next step is to download statistical data about Tunisian agricultural production, to do this, FAOSTAT database was used. These data will be not reported here, but download can be done at FAOSTAT official site.

The next step is to select the main crop residues, and to estimate the ultimate analysis of the single product derived from the respective crop residues.

TABLE 6: Low Heating Value estimation

Sub product	C	H	O	HHV [MJ/Kg]	Umidity	LHV [MJ/Kg]
Generic biomass (assumption)	42	6	42	16.14	50	6.1850759
Rice straw	38.52	6.13	39.28	15.57807	25	10.05817007
Wheat straw	42.11	6.53	40.51	17.1605	50	6.636900105
Corn straw	42.69	6.16	42.69	16.49257	55	5.464650632

Note: To conduct an accurate method, more accurate values are needed, in particular, local measurements are needed and better GIS data. Since the geographical error in crop residue location will be so high, more accurate data are not needed in the quantification of LHV.

At this point:

1) Assuming an electrical efficiency: 25% (it depends on particular biomass technology)
2) Biomass plants, since they are renewable plants, must work with higher factor utilization (higher utilization factor means lower capacity and so lower investment cost).
3) Obtain the total capacity that could be installed for each crop residues.
4) Assuming that production is constant inside the area, so power density can be calculated.

TABLE 7: Tunisia crop residue production estimation, knowing Tunisian harvested area and harvested amount for each crop (peach, apple) and knowing sub-product/product ratio, it's possible to determine the crop residue production (dry-tonnes of crop residue, dry-tonnes of crop residue /hectare).
Assuming Low Heating Value for each crop residue, and knowing the specific productivity, it's possible to determine the total primary energy that can be produced [MJ/year/hectare]. Assuming an electrical efficiency and assuming capacity factor, it's possible to determine the specific power [W_el/hectare] that can be produced ideally from each crop residue.

Product	Sub product	Fu	Work hours	CAPACITY [MW]	Specific power [W/ha]	Productivity [tonn/ha]
Graphes	Sarmenti (branch)	0.92	8059.2	16.42005586	765.0401089	7.081954992
Olive	Frasca (branch)	0.92	8059.2	91.14341821	54.08138855	0.532134616
Citrus	Pruning branches (Rami potatura)	0.92	8059.2	23.28967051	1726.823646	10.48513383
Peach	Pruning branches	0.92	8059.2	20.96569365	1591.082466	9.660924338
Apricots	Pruning branches	0.92	8059.2	5.023123409	781.6874276	4.746342982
Plum	Pruning branches	0.92	8059.2	2.7098949	894.6500166	5.320237702
Apple	Pruning branches	0.92	8059.2	20.22984724	881.7822004	5.354110365
Peer	Pruning branches	0.92	8059.2	2.640515988	775.0267061	4.705899618
Cherries	Pruning branches	0.92	8059.2	0.903444501	867.0292714	5.320537428
Almond	Pruning branches	0.92	8059.2	11.03440224	60.63491378	0.368170303
Wheat	Straw (Paglia)	0.92	8059.2	245.1798924	418.4507049	1.877379792
Barley	Straw	0.92	8059.2	111.0584207	249.7457098	1.070418228
Oats	Straw	0.92	8059.2	0.328508942	78.66593436	0.337164751
Mais corn (cereale)	Stocchi	0.92	8059.2	0.365624638	21.18948931	1
Sunflower	Leaves	0.92	8059.2	1.121390998	137.1228904	0.872340426
Grain legumes	Leaves	0.92	8059.2	7.971287978	264.2737121	0.859894573
Sugar beet	Leaves	0.92	8059.2	0.457691067	55.96613688	8.859011983

Potato	Leaves(Steli e foglie)	0.92	8059.2	25.07946703	980.0495126	16.4126612
Orange	Pruning branches	0.92	8059.2	20.753899	1882.781366	11.43209653
Lemon	Pruning branches	0.92	8059.2	9.482668842	2437.704072	14.80154242
Grapefruit	Pruning branches	0.92	8059.2	17.44110794	3636.59465	22.08110926
Tangerine	Pruning branches	0.92	8059.2	9.779938932	1378.62122	8.370876797

The total power that comes from is too high: The total specific power for each crop residues is too high because some factors are not been yet considered. These factors will be considered later.

5) Download QGIS https://www.qgis.org/it/site/

QGIS is the free software that will be used to distribute crop residues over the Tunisian boundary

6) Download Geotiff 175 crops allocation : [http://www.earthstat.org/]

Harvested Area and Yield for 175 Crops, year 2000, it's a land use data sets created by combining national, state, and county level census statistics with a recently updated global data set of croplands on a five-arc-minute by five-arc-minute (~10 km by 10 km) latitude/longitude grid. The resulting land use data sets depict circa the year 2000 the area (harvested) and yield of 175 distinct crops of the world.
Earthstat gives the possibility to download GIS data about crop product production, so it's possible to estimate, for each pixel, the harvested area for each crop (peach, apple etc).

7) Geo-localization of selected crops in Tunisia (Fig 42 shows peach-harvested area in Tunisia, graduate colour map for each pixel).
8) For each pixel, with field calculator ("Calcolatore di campo"), if local crop residue harvested area [hectares], for each crop, for each pixel, is multiplied by crop residue specific power [W_el/hectare], then the result will be the total electrical capacity, for each pixel, for each crop, for each crop residues that could be installed.

What one obtains is a map, for each crop, of total capacity that could be installed using all amount of crop residue, for each pixel.

Now it's possible to find optimal locations. But, before this, an assumption is needed: Crop residue will be located in one point. This because biomass plants can work with different types of biomass, this however depends on the specific biomass technology.

Fig 42: Peach harvested area for each pixel, graduate colour map, the darkest colour represents the highest value of peach harvested area so by using sub-product/product ratio it's possible to determine crop residue production for each crop, for each pixel. Each colour represents different pixel value (in the South, same colour that represents the zero, because no peach production in the Sahara area).

9) Selection of crop residues that can be accepted in a biomass technology, for example pruning branches from apricots and from peaches, etc….
10) After selecting type of residue for each crop (see table 7), sum of all crop residue that are inside the same pixel, this is equivalent to sum the ideal capacity that could be installed if all crop residue it's used, for each pixel (see point 8).
    So at this point, each pixel represents the total capacity that could be installed if all crop residues, from all type of considered crops, it's used to produce electricity.(Pixel area shown in figure)
11) Select n-potential site location for biomass plants with a point.
12) Draw a circle with radius of 30 km with centers the selected point.
13) Sum of the total crop residues selected. (some authors collect only one type of crop residues, while other collect different types of crop residues). In other words, sum of the total capacity all pixels inside the circle area with radius of 30 km.
    So the sum of all pixels inside the circle represent the total capacity that could be installed in that circle area with radius of 30 km.
14) Remove low biomass potential point (or pixel of 10km*10km), to see, in a qualitative way, the best area, to facilitate to found best biomass plant location (Fig 43)

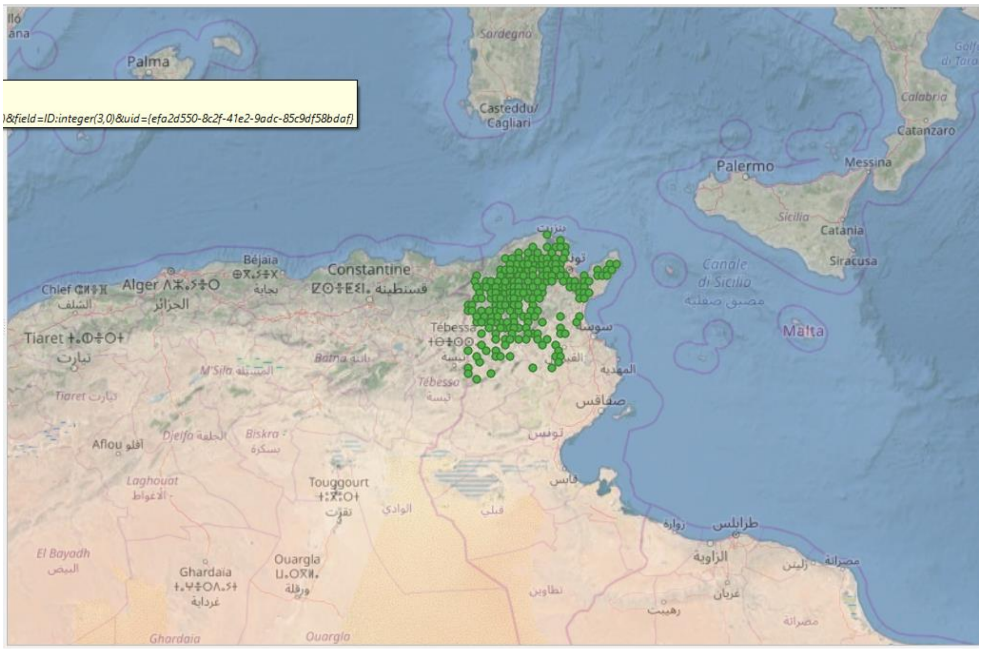


Fig 43: Are shown the points with the highest capacity [MW], these points are not biomass plants potential site locations, but they are the pixel area transformed in points that represent the total capacity that could be installed in that pixel if all crop residue it's used for electricity production.

15) Selection of circles (radius of 30 km) with the highest value of capacity.
16) Circle area must not intersect.
17) Find best areas where install biomass capacity.

Fig 44: Crop residues Biomass plants location.

Problem: If for each crop, Is determine the total harvested area given by FAOSTAT and the total area given by [http://www.earthstat.org/], what comes from is that values are different. If, a conversion factor is used, with the purpose to geo-locate the FAOSTAT values using Earthstat, worse results are obtained. So, for this reason, Earthstat values have been used to find biomass plants site location (is the unique option).

What it comes from are 6 area where it's convenient to install biomass plants. At this point, a plant to convert biomass chemical energy in electricity is needed. Moreover, the global efficiency is strongly dependent on type of crop residues (auxiliary expenditure) and technology. For instance, different types of gasifiers means different CGE (cold gas efficiency), in other words, since this thesis is not about modelling of biomass thermal power plant, a global efficiency of 25 % was assumed. The selected efficiency, take as reference, is 25 %. This could be high or low, it depends on specific biomass technology. If the technology is a traditional Rankine cycle with combustion of crop residues, the efficiency drop to around 17%, while for biomass gasification process with SOFC this efficiency could reach 30%, it depends on overall process, auxiliary ect..

If an electric efficiency of 25% is considered, I obtain the following values, shown in Table 8.

Table 8 includes 2 factors

1) Road Factor (60%)
2) Residual Unavailable factor (40%)

The residual unavailable factor is a qualitative Index that means that not all biomass residues can be harvested.

Road factor it's a factor that means that not all biomass can be harvested because of high cost of transport, or because a certain point cannot be reached by truck, This cost depends on the transport toward to the storage e and cost from storage to plant.

TABLE 8: Biomass plants capacity, crop residues

PLANT	IDEAL CAPACITY MW	ROAD FACTOR	RESIDUAL UNAVAILABLE FACTOR[complement]	TOTAL FACTOR	REAL CAPACITY ESTIMATED
CROP RESIDUE PLANT 1	**62**	**0.6**	0.6	0.36	**22.5**
CROP RESIDUE PLANT 2	**66**	**0.6**	0.6	0.36	**24**
CROP RESIDUE PLANT 3	**66**	**0.6**	0.6	0.36	**24**
CROP RESIDUE PLANT 4	**42**	**0.6**	0.6	0.36	**15**
CROP RESIDUE PLANT 5	**58**	**0.6**	0.6	0.36	**21**
CROP RESIDUE PLANT 6	**29**	**0.6**	0.6	0.36	**10.5**
TOTAL CAPACITY	**323**				**117**

It's important to remark that, since electrical efficiency is geographically independent, the location does not change if values are changed. This could not be true if an optimization process that consider cost of transport it's used.

NOTE!: From an OPF point of view, to consider an higher efficiency doesn't create big differences in the results. For this reason a high electrical efficiency was assumed. If mean electrical efficiency is 17%:

TABLE 9: Biomass plants capacity if lower efficiency is considered, crop residues

PLANT	REAL CAPACITY ESTIMATED
CROP RESIDUE PLANT 1	15.5
CROP RESIDUE PLANT 2	16.5
CROP RESIDUE PLANT 3	16.5
CROP RESIDUE PLANT 4	10
CROP RESIDUE PLANT 5	14.5
CROP RESIDUE PLANT 6	7.5
TOTAL CAPACITY	80

6.3) WASTE AND BY-PRODUCTS OF THE PROCESSING BY-PRODUCTS OF THE PROCESSING INDUSTRY OF VEGETABLE PRODUCTION.

In agricultural sector, there are industries which transform the vegetal matter in a specific product, and there are big production of residues that can be used for energetic purpose. For instance:

• tomato processing
• fruit processing (juices, jams, marmalades, etc.)
• the processing of vegetables (legumes, potatoes)
• processing of olives for oil production;
• wine production

To determine biomass potential from these production processes, more accurate GIS data are needed, but this is not the case, so this potential is not considered in this analysis, such as location, size and in particular mass flow for each industry, in such way it’s possible to determine and to locate residue production.

6.4) BIOGAS POTENTIAL

In this part will be determined the biomass potential from biogas for electricity production in an anaerobic digester. This thesis is about renewable penetration in the high voltage power transmission: to connect a biomass plant to high voltage network, a capacity higher than 5 MW is required, because of high investment cost of transformers etc.. However it’s very difficult to reach a similar capacity using biogas plants from anaerobic digester, but this must be verified.

So, the first step Is to quantify biogas potential from OFMSW or from livestock animals

6.4.1) Potential from livestock animals.

To determine potential from livestock animals the following data are necessary:

1) Selection of animals for which the production of sewage and manure can be harvested and used in an anaerobic digester.
2) Assuming a live weights for each animals.
3) Multiply, for each animal, the live weights for the total number of a certain species.

The amount of manure and sewage that can be harvested in a factory with intensive breeding, it depends on the particular housing (in Italian is called ‘Stabulazione’).

Type of the housing indicates any confinement of animals in controlled spaces constructed or artificially obtained, in which vital functions are guaranteed and monitored. [Wikipedia].
There are several types of housing, for instance fixed housing with straw, fixed housing without straw, full floor etc.

4) The quantity of effluent produced [tonnes or cubic meter/year/live weights] it's multiplied for the total number of each animal and the average live weights for each animal.
5) At this point, for each animal, the total amount of manure and sewage that can be harvested and used for biogas production is determined.
6) Dry substance can be determined by knowing the percentage of solid substance.
7) From dry substance, it's possible to determine the amount of volatile substances that can be produced by bacteria in the digester, from this quantity, as a function of animal (cattle) and type of product (manure or sewage), the amount of biogas and [CH4] can be determined.
8) Knowing [CH4], [m3 biogas/year] and assuming an electrical efficiency of 30% and capacity factor, the total capacity can be determined.
9) From total capacity, it's assumed as harvested factor 30%

TABLE 10: Total number of animals (taken from FAOSTAT).

Name	Value	Unit	Total number of heads
Asses	241646	Head	241646
Beehives	665791	No	665791
Camels	237005	Head	237005
Cattle	627614	Head	627614
Chickens	91215	1000 Head	91215000
Goats	1205526	Head	1205526
Horses	57254	Head	57254
Mules	82649	Head	82649
Pigs	5467	Head	5467
Sheep	6536762	Head	6536762
Turkeys	11483	1000 Head	11483000

1) Average life weight for animals and average amount of seawage and manure produced by each animals(it depends on particular floor of the stable).

Table 11: Production of sewage and manure

Animal	Living weight kg	Minimum production of seawage m3/tonn of living weights/year	Maximum production of seawage m3/tonn of living weights/year	Minimum production of manure m3/tonn of living weights/year	Maximum production of manure m3/tonn of living weights/year
Swine	180	22	73	3	6
Milk cattle	720	5	20	9	27
Beef cattle	560	1.4	9.1	5.6	13.6
Poultry	2	0.04	0.04	0.0126	0.0324
Goats, sheep	35	7	16	15	15

Table 12: Pt1: Determination of ideal total biogas production

Material	% minimum of dried substance	% maximum of dried substance	% minimum of volatile substance	% maximum of volatile substance	Minimum yield in biogas (m3/tonn di s.v)	Maximum yield in biogas (m3/tonn v.s)	[CH4]min	CH4 max
Milk cattle slurry	10	16	75	85	300	450	60	65
Beef cattle slurry	7	10	75	85	300	450	60	65
Swine slurry	1.5	6	65	80	450	550	60	65
Poultry slurry	19	25	70	75	300	500	60	65
Cattle manure	11	25	65	85	200	300	60	65
Swine manure	20	28	75	90	450	550	60	65
Sheep manure	22	40	70	75	240	500	60	65
Poultry manure	60	80	75	85	400	500	60	65

Table 12: Part 2: Determination of ideal total biogas production

MATERIAL	Minimum quantity tonn	Maximum quantity in tonnes	Harvesting scenario	Minimum biogas production m3	Maximum biogas production in m3
Cow slurry	492049.376	9037641.6	0.3	2324933.302	165931099.8
Swine slurry	21649.32	71836.38	0.3	28495.91745	568944.1296
Poultry slurry	7297.2	7297.2	0.3	87347.484	205233.75
Cattle manure	1968197.504	4779908.224	0.3	8443567.292	91415744.78
Swine manure	2952.18	5904.36	0.3	32733.77184	245503.2888
Manure oats, sheep	4064701.2	4064701.2	0.3	45069406.91	182911554
Poultry manure	2298.618	5910.732	0.3	124125.372	602894.664

Table 13: Total biogas capacity for each animal if harvesting scenario=30%

MATERIAL	Maximum energy from biogas MJ/year	Efficiency	En el min MWh	En el max MWh	fu	Capacity min MW	Capacity max MW
Cow slurry	3649172124	0.35	4588.603082	354780.6232	0.92	0.569362106	44.02181645
Swine slurry	12512272.03	0.35	56.24094874	1216.470891	0.92	0.006978478	0.150941891
Poultry slurry	4513519.65	0.35	172.3933044	438.8144104	0.92	0.021390871	0.05444888
Cattle manure	2010423531	0.35	16664.64104	195457.8433	0.92	2.067778568	24.25275999
Swine manure	5399131.079	0.35	64.60498727	524.9155216	0.92	0.008016303	0.06513246
Manure oats,sheep	4022607847	0.35	88951.20531	391086.874	0.92	11.0372252	48.52676122
Poultry manure	13258915.32	0.35	244.9799589	1289.061212	0.92	0.030397553	0.159949029
						13.74114908	**117.2318099**

Table 14: Total biogas capacity for each animal if harvesting scenario=30%.

MINIMUM TOTAL BIOGAS CAPACITY MW	**14**
MAXIMUM TOTAL BIOGAS CAPACITY MW	**117**

The next step is to find, using GIS data, how is distribute over the country this biogas potential, to find the position of farms. But bad GIS data are available:

TUNISIA: KEY AGRICULTURE FIGURES	
Structure (Source: Ministry of Agriculture, 2005)	
Agricultural land	10 million ha (62%)
Irrigated area	420,000 ha
Number of farms (2005)	516,000
Average farm size	10.2 ha
Farms smaller than 10 ha	75%
Role within the economy (Source: Ministry of Agriculture, 2012)	
% of GDP (2012)	12%
% of employment	16%
Distribution (source INS & BCT 2009)	
Per number of farms	
Olives	29%
Livestock	22%
Cereals	15%
Arboriculture (other non olive-related)	12%
Vegetable crops	7%
In production value	
Livestock	39.9%
Arboriculture	27.6%
Vegetable crops	16.6%
Cereals	13.3%
Others	2.6%

Fig 45: Tunisian agricultural data about farms: 516000 farms, the average farm size is 10.2 ha and the percentage of farms smaller than 10 ha is 75%.

No GIS data on Tunisia farms are available and in particular about intensive breeding, so it's not possible to distribute in a smart way the animals for each species.
Since no accurate Tunisian farm GIs data are available, it was chosen to not consider the biogas potential, even because this potential can be neglected.

6.4.2) BIOMASS POTENTIAL FROM OFMSW.

The OFMSW (Organic Fraction of Municipalities Solid Waste) is the material collected from the separate collection of organic (otherwise called wet). These are food residues or food preparations and similar fractions, such as paper for foodstuffs soiled with food residues. The OFMSW (FORSU) constitutes from 30 to 40% in weight of the urban solid waste. The material is mixed with other fractions (such as pruning cuttings) and digested thanks to the action of bacteria, there are two possibilities:

• aerobic digestion: composting takes place at about 70 ° C, in order to avoid the formation of pathogenic bacteria, and allows the production of soil improver for agricultural use

• anaerobic digestion: it is the same that occurs in landfills: bacteria that act in the absence of oxygen generate biogas which is used for electricity generation. **[Wikipedia]**.

In Tunisia there is the differentiated collection of urban waste, but not for organic fraction.
The question that in this section is try to be resolved is: if OFMSW harvesting is possible in Tunisia, is the potential sufficiently high to accommodate a biogas plants into the high voltage power system?
To answer this question will be selected the most important Tunisian cities with an acceptable value of demographical density, to do this, will be compared demographical density of Turin.

Moreover, even if not true, will be assumed that the amount of OFSSW produced per capita in Italy is equal Tunisia (500 kg of waste/year/habitant).
Only Tunisia cities with relative high population density will be chosen:

Table 15: Number of habitants for main Tunisian cities

City	Habitant	Density [hab/km2]	Density, Torino [ab/km2]
Ettadhamen-Mnihla	118487	4936.96	6750
Beja	56 677	4343,07	6750
Medjez El-Bab	21653	19333	6750
El Mourouj	81986	3813.3	6750
Bizerte	126491	3720	6750
Gafsa	84676	1882	6750
Dar Chaabane	35859	10245	6750
Al-Qayrawan	117903	173336	6750
Tunisi	1056247	4968	6750

Table 16: OFMSW harvesting scenario

Fraction of waste recovered with differentiated collection [%]	30
OFMSW fraction recovered from collection [%]	40

At this point:

1) Selection of main Tunisian cities.
2) Selection of Tunisian cities with high demographical density (similar to Turin).
3) Assumption about waste production per habitant.
4) Assuming percentage of organic waste from total wastes produced by habitant.
5) Determine total waste production for each city.
6) Assuming harvesting scenario.
7) Determine fraction of dried substance.
8) Determine fraction of volatile substance.
9) Determine biogas production from anaerobic digester
10) Determine LHV from [CH4].
11) Assuming an electrical efficiency of 30 % (clean and cold biogas can be used in internal combustion engine).
12) Assuming a capacity factor.
13) Determine total capacity.

Table 17: OFMSW data input

Material	%min dried substance	%max dried substance	%min volatile substance	%max volatile	min yield in biogas (m3/tonn di s.v)	max yield in biogas (m3/tonn di s.v)2	[CH4]min	CH4max
Forsu (OFMSW)	40	75	50	70	300	450	50	60

Table 18: OFMSW biogas potential

City	N habitants	Density [ab/km2]	Density Torino [ab/km2]	OFMSW harvested tonn wet /anno	OFMSW dried substance min tonn/ year	OFMSW dried substance mas dried substance tonn/ year	FORSU s.v min tonn/year	FORSU s.v max tonn/year
Ettadhamen-Mnihla	118487	4936.96	6750	7109.22	2843.688	5331.915	1421.844	3732.3405
Beja	56677	4343.07	6750	3400.62	1360.248	2550.465	680.124	1785.3255
Medjez El-Bab	21653	19333	6750	1299.18	519.672	974.385	259.836	682.0695
El Mourouj	81986	3813.3	6750	4919.16	1967.664	3689.37	983.832	2582.559
Bizerte	126491	3720	6750	7589.46	3035.784	5692.095	1517.892	3984.4665
Gafsa	84676	1882	6750	5080.56	2032.224	3810.42	1016.112	2667.294
Dar Chaabane	35859	10245	6750	2151.54	860.616	1613.655	430.308	1129.5585
Al-Qayrawan	117903	173336	6750	7074.18	2829.672	5305.635	1414.836	3713.9445
Tunisi	1056247	4968	6750	63374.82	25349.928	47531.115	12674.964	33271.7805

Table 19: OFMSW capacity evaluation

Città	Minimum yield biogas m3	Maximum yield in biogas m3	CH4 min	CH4 max	Electrical efficiency	En el min GWh	En el max	fu	CAPACITY [MW]	CAPACITY MAX
Ettadhamen-Mnihla	426553.2	1679553.225	50	60	0.35	0.740081199	3.496883666	0.92	**0.091830603**	**0.433899601**
Beja	204037.2	803396.475	50	60	0.35	0.354009994	1.67269722	0.92	**0.043926195**	**0.207551273**
Medjez El-Bab	77950.8	306931.275	50	60	0.35	0.135246721	0.639040756	0.92	**0.016781656**	**0.079293324**
El Mourouj	295149.6	1162151.55	50	60	0.35	0.512092442	2.41963679	0.92	**0.063541349**	**0.300232875**

Bizerte	455367.6	1793009.925	50	60	0.35	0.790074953	3.733104154	0.92	**0.098033918**	**0.463210263**
Gafsa	304833.6	1200282.3	50	60	0.35	0.528894441	2.499026234	0.92	**0.065626171**	**0.31008366**
Dar Chaabane	129092.4	508301.325	50	60	0.35	0.223978763	1.058299656	0.92	**0.027791687**	**0.131315721**
Al-Qayrawan	424450.8	1671275.025	50	60	0.35	0.736433479	3.479648189	0.92	**0.091377988**	**0.431760992**
Tunisi	3802489.2	14972301.23	50	60	0.35	6.597420362	31.17281121	0.92	**0.818619759**	**3.867978362**

Tunisi is the city that present the highest biogas potential from OFMSW (around 4 MW). This capacity but is low to be connected to HV power transmission. So, if biogas potential is neglected, no error is committed.

6.5) BIOMAS POTENTIAL FORM INDUSTRIAL OF ANIMAL PRODUCTS

The amount of milk processed or slaughter yield is known. Using **R[22]** this potential can be estimated. However, since the specific location and residues mass flows generated by each plants is unknown, this potential will be not evaluated.

6.6) BIOMASS POTENTIAL FROM FOREST RESIDUES.

Before analysing the biomass potential from forest residue, an initial estimation is made to understand what can be done in terms of total capacity: Table 20 shows the ideal capacity that could be install if 3% of the total forest land will be harvested for energetic purpose.

To estimate the capacity from forest residue, will be used the same approach used in **R[22]:**

1) Forest area estimation by using FAOSTAT.
2) Assuming harvesting scenario, so the amount of forest residue that can be harvested: 3%
3) Estimate the total wood volume of forest per hectare [150 m3/ ha]
4) From wood density, it’s possible to determine the mass of wood per hectare
5) Assuming LHV, capacity factor, humidity and efficiency it’s possible to determine the total capacity from forest harvested residues.

However, has been chosen to not consider biomass potential from wood residue from the following reasons:

1) In Tunisia, wood residue is principally used for heat applications
2) Tunisia's forests contain 9 million metric tons of carbon in living forest biomass. Biodiversity and Protected Areas: Tunisia has some 516 known species of amphibians, birds, mammals and reptiles. Of these, 0.6% are endemic, meaning they exist in no other country, and 4.3% are threatened. Tunisia is home to at least 2196 species of vascular plants. 0.2% of Tunisia is protected under IUCN categories I-V. [https://rainforests.mongabay.com/deforestation/2000/Tunisia.htm], even if land forest area is easy to find, even using OSM (OpenStreetMap) , the problem is that forest

protected area are difficult to find, in particular forest harvesting is forbidden in certain areas.

Table 20: Ideal capacity determination from forest residue

Forest area ha	1041000
Harvested fraction	0.03
Harvested Area ha	31230
Wood volume/ area [m3/ha]	150
Volume tonn/m3	0.7
LHV MJ/tonn	12
Humidity	0.2
Efficiency	0.2
Electrical energy MJ/year	6295968000
Electrical energy MWh/hear	1748880
factor utilization	0.97
Ideal Capacity	**205.8183872**

6.7) Results

Table 21 shows what the biomass plants for types of biomass that will be connected to the Tunisian high voltage power transmission.

Table 21: Biomass potential implementation

Biomass plants potential from:	Calculated?	**Implemented in the work?**	Reasons
Crop residues	Yes	**Yes**	
Biogas from livestock animals	Yes	No	Lack of farm GIS data, intensive breeding location
Biogas from OFMSW	Yes	No	Capacity lower than 5 MW
Wood residues Potential	No	No	1) Lack of GIS data 2) Lack about specific industrial process
Potential form forest residues	Yes	No	1) Principally used for thermal applications 2) Geological, natural constraints
Industry of fruit, vegetable production	No	No	1) Lack of GIS data

			2) Lack about specific industrial process
Potential from Cheese and milk industry	No	No	1) Lack of GIS data 2) Lack about specific industrial process
Potential from Energetic crops	No	No	1) Need to use RUSLE model 2) Food conflict problem

Table 22: Biomass plants integration in the HV network

NAME PLANT	Nominal capacity MW	Bus number
CROP RESIDUES PLANT 1	22.5	122
CROP RESIDUES PLANT 2	24	5
CROP RESIDUES PLANT 3	24	93
CROP RESIDUES PLANT 4	15	34
CROP RESIDUES PLANT 5	21	113
CROP RESIDUES PLANT 6	10.5	2

Fig 46: Tunisian Biomass HV power plants.

CHAPTER 7: DESCRIPTION OF THE MODEL.

7.1 OPF Formulation

In this chapter will be described how Tunisian HV network is modelled, remember that some parts are taken from the previous work: **R[1]**.

At this point a model is needed to study economic dispatch and to conduct a flexibility analysis.

For a thermal power plant, the mechanical useful work is a torque, produced by turbine, applied to the electrical engine at 3000 rpm (50Hz) and low voltage, then a transformer is needed to increase voltage to the HV (like 145 kV).
Electrical power is distributed by HV electrical line. In other HV-bus electrical power is adsorbed (PQ-bus), then a transformer is needed to put electrical power in the MV circuit.

In a power system, the fundamental elements are:

1) Generators.
2) Load bus.
3) Transmission line, modelled with π-transmission model.
4) Transformers, modelled with π-transmission model (r=0), so x=jx, so transformer normally represented by just reactor reactance.

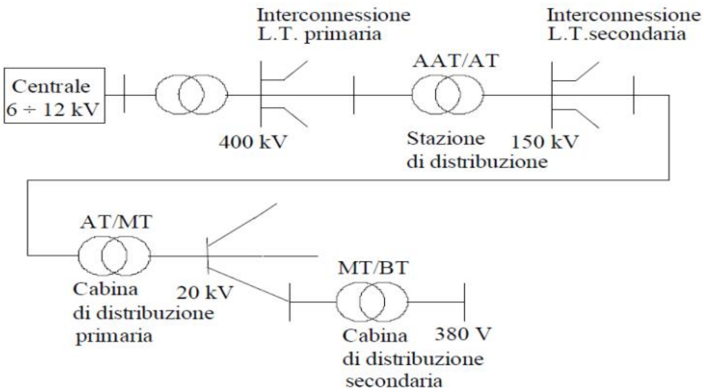


Fig 47 SISTEMI ELETTRICI DI POTENZA: Produzione, trasmissione e distribuzione dell'energia elettrica Prof. Ing. Mariacristina Roscia [29]: From thermal power plant production to users general scheme

Normally the transmission lines do not follow only radial paths, to have a greater reliability of the electrical distribution they are realized meshed networks in which the nodes are interconnected. The first necessary condition for having an electrical system interconnected is of course that the frequency of the distribution network is the same for the whole system.
A transmission line is essentially made up by a pair of parallel conductors whose ends are connected a generator and a load. From the start to the end of the line there will be one voltage variation.

Considering the line as an equivalent electrical circuit, the simplified model used is called distributed constants: the electrical parameters are in fact uniformly distributed along the whole line. The quantities R, L, C, G are called primary constants and expressed respectively: the inductance L in [H/m], resistance R in [Ω/m], capacity in C in[F/m], conductance G in [Ω^{-1}/m].

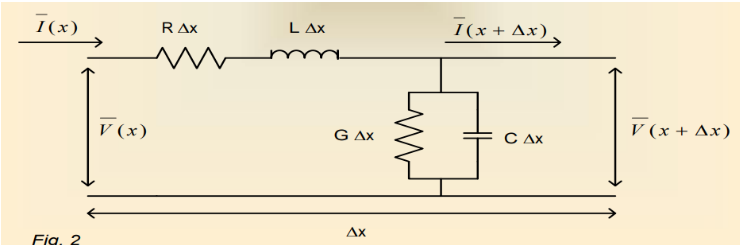


Fig 48: General HV electrical line representation: In this picture is shown the components that cause longitudinal effect (R,L) and cross effect (G,C).

These quantities are introduced to take into account the following physical phenomena:
the R resistance expresses the ohmic value of the conductor and produces a voltage drop (R*I). It is a longitudinal element and in fact it is represented in the circuit as a series element;
inductance L occurs due to effects of nature electromagnetic and also produces a voltage drop. Like R, it is longitudinal and placed in series with the circuit.
R and L give rise to what is called longitudinal impedance.

Capacity C is introduced due to electrical effects between the two conductors. It causes a loss of current and is to be considered a transversal element. It is represented as a parallel type element.
Conductance G is introduced due to imperfections insulation of conductors and causes a loss of current. It is represented as an element transverse to the line e therefore parallel like capacity.
Capacity and conductance give rise to what comes called cross admittance.

$$Zl = R + j\omega L \text{ [longitudinal impedance] . (Loss of voltage)}$$
$$Yt = G + j\omega C \text{ [cross admittance]. (Loss of current)}$$

To obtain a high transmission efficiency of electricity needs to reduce as much as possible the transmission losses that they can be of two types:

1) Losses due to the Joule effect, produced by the current flow that travels the line;
2) Losses due to the corona effect, produced by the Voltage of the line.

For line voltages up to about 500 kV they are generally the losses due to the Joule effect are greater than those for the crown effect (effetto corona) (so if V< 500kV, then Joule effect is the relevant).

The long distance transmission made it convenient the adoption of much higher tensions how much greater was the distance itself. The development of the transformer, which only works in alternating current, allowed to raise the tension produced adapting it to the needs of the transmission. But above all, the use of the transformer it was necessary to lower the tension provided to users at much lower security values than those used for transmission and generation.
For given values of power and distance, there is a value optimal transmission voltage **R[29]**.

At this point, OPF formulation can be presented.
All generators, substation etc can be represented as bus station. There are 3 types of bus:

1) Reference Bus to serve the roles of both a voltage angle reference and a real power slack. The voltage angle at the reference bus has a known value, but the real power generation at the slack bus is taken as unknown to avoid overspecifying the problem.

2) PV Bus (generators)
3) PQ Bus (load bus station)

The main differences about them will be described in the next sentences

Let's go now to consider a generic HV power transmission network:

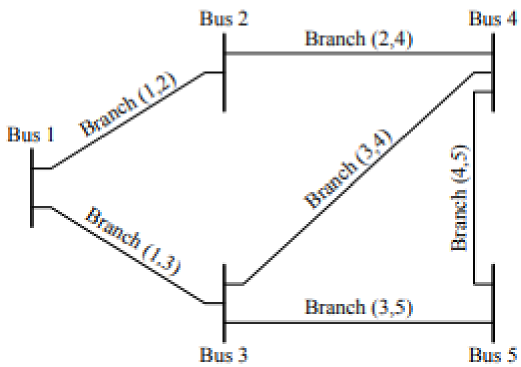
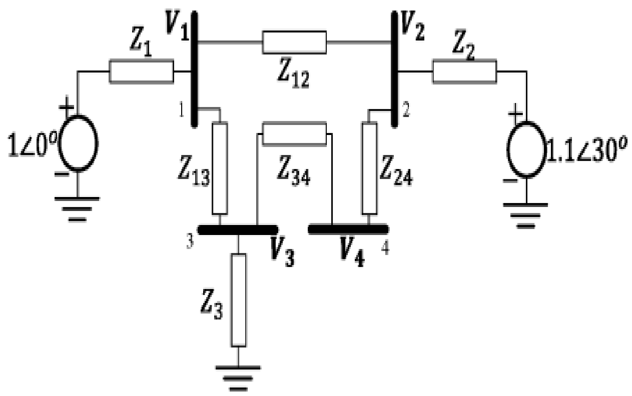


Fig 49 [A Primer on Optimal Power Flow: Theory, Formulation, and Practical Examples Stephen Frank Steffen Rebennack], example of HV network



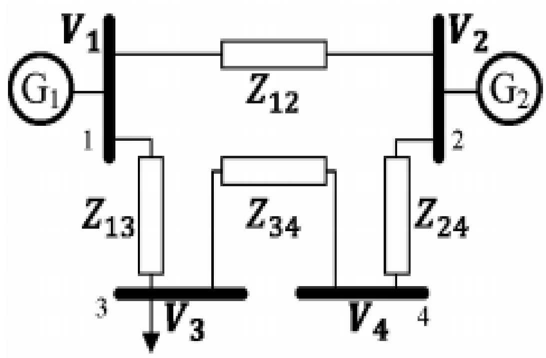


Fig 50, 51: [Simulating a Power System Presented by Prof. Tyrone Fernando], Example of HV network

$\theta_{bus,i}$= voltage angle at bus-i
$\delta_{bus,i}$= current angle at bus-i

Real and complex power injection at bus i:

$P_{bus,i}= Re(V) \cdot Re(I)= ||V|| \cdot \cos \theta_{bus,i} \cdot |I| \cdot \cos \delta_{bus,i} =|V| \cdot |I| \cdot \cos(\theta_{bus,i} - \delta_{bus,i})$

$Q_{bus,i}= Im(V) \cdot Im(I)= ||V|| \cdot \sin \theta_{bus,i} \cdot |I| \cdot \sin \delta_{bus,i} =|V| \cdot |I| \cdot \sin(\theta_{bus,i} - \delta_{bus,i})$

$\theta_{bus,i} - \delta_{bus,i}$= Power angle

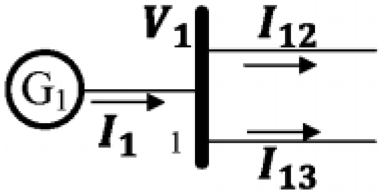


Fig 52: Kirchhoff's law to a generic bus.

If Kirchhoff's current law is now applied, according to Fig 52, then:

$$I_1 - I_{12} - I_{13} = 0;$$
$$I_1 = I_{12} + I_{13};$$
$$I_1 \cdot V_1 = I_{12} \cdot V_1 + I_{13} \cdot V_1;$$
$$P_1 = P_{12} + P_{13};$$

$$I_2 + I_{12} - I_{24} = 0;$$
$$I_2 = I_{24} - I_{12};$$
$$I_2 \cdot V_2 = I_{24} \cdot V_2 - V_2 \cdot I_{12};$$
$$P_2 = P_{24} - P_{12};$$

Similarly for Bus 3 and 4, but in bus 3 there is a bus-station that adsorb complex power.

> All transmission lines, transformers and phase shifters are modelled with a common branch model, consisting of a standard π transmission line model [MATPOWER MANUAL].

$$Z=r+Jx;$$
$$y=g+jb;$$
$$|Z|=sqrt(R^2+X^2)$$
$$|Y|=sqrt(G^2+B^2)$$

The admittance (Y) is the inverse of the impedance (Z)

$$V= Z*I;$$
$$Z=R+jX:$$
$$Z==R, \text{ if resistance}$$
$$Z==-j/(\omega*C) \text{ if condensator}$$
$$Z==j*\omega*L \text{ if induttor}$$

$$V= Z*I \leftrightarrow I=Y*V$$

$$Y=\frac{1}{Z}=\frac{1}{R+j*X}=\frac{1}{R+j*X}*\frac{R-j*X}{R-j*X}=\frac{R-j*X}{R^2+X^2}$$

$$\mathrm{Re}(Y) = G = \frac{R}{R^2+X^2} = \frac{R}{||Z||}$$

$$\mathrm{Im}(Y) = B = \frac{-X}{R^2+X^2} = \frac{-X}{||Z||}$$

If I consider Fig 53, 54, then:

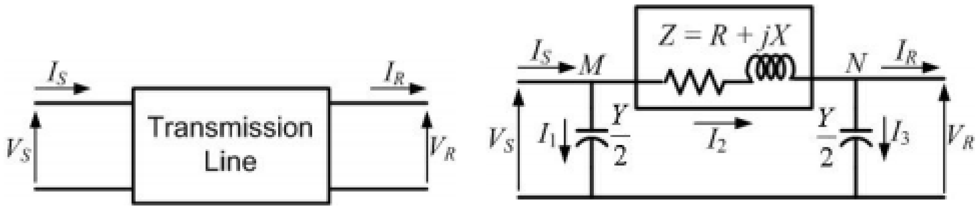


Fig 53,54: Current flows in transmission line model.

$$\begin{bmatrix} Ifrom \\ Ito \end{bmatrix} = \mathrm{Y_{branch}} * \begin{bmatrix} V\_from \\ V\_to \end{bmatrix}$$

$$\mathrm{Y_{branch}} = \begin{bmatrix} Y11 & Y12 \\ Y21 & Y21 \end{bmatrix} = \begin{bmatrix} Yfrom\_from & Yfrom\_to \\ Yto\_from & Yto\_to \end{bmatrix}$$

Tap ratio (τ) is defined as $V_{\_FROM}/V_{\_TO}$

According to fig 52:

$$I_{from} = I_1 + I_2;$$
$$I_2 = I_{to} + I_3;$$
$$I_{from} = I_1 + I_{to} + I_3 = Y_1 * V_1 + I_{to} + Y_2 * V_2 = V_1 * \frac{y}{2} + I_{to} + V_2 * \frac{y}{2} = V_{from} * \frac{y}{2} + I_{to} + Vto * \frac{y}{2} =$$

$V_{from} = \Delta V + Vto = Vto + Z * I_2 = Vto + Z * (I_3 + I_{to}) = Vto + Z * (Y_3 * V_3 + I_{to}) =$
$= V_{to} + Z * (\frac{y}{2} * V3 + I_{to}) = V_{to} + Z * (\frac{y}{2} * Vto + I_{to}) =$
$= V_{to} * (1 + Z * \frac{y}{2}) + Z * I_{to};$

$I_{from} = V_{from} * \frac{y}{2} + I_{to} + V_{to} * \frac{y}{2}$

$V_{from} = \frac{2}{y} * (Ifrom - Ito - Vto * \frac{y}{2}) = \frac{2 * Ifrom}{y} - I_{to} * \frac{2}{y} - Vto$

$$\begin{cases} Vfrom = Vto * \left(1 + Z * \frac{y}{2}\right) + Z * Ito \\ Vfrom = -Vto + \frac{2}{y} * Ifrom - \frac{2}{y} * Ito \end{cases}$$

By resolving the system, the result will be:

$I_{from} = y * (\frac{y}{4} * Z + 1) * Vfrom + (\frac{y}{2} * Z + 1) * Ito$

I_{from} and I_{to} can be expressed as a function of V_{from} and V_{to}, so the following equation can be written:

$$\begin{bmatrix} Ifrom \\ Ito \end{bmatrix} = [\begin{bmatrix} Y11 & Y12 \\ Y21 & Y22 \end{bmatrix} * \begin{bmatrix} Vfrom \\ Vto \end{bmatrix}$$

$$\begin{cases} Ifrom = Y11 * Vfrom + Y12 * Vto \\ Ito = Y21 * Vfrom + Y22 * Vto \end{cases}$$

Where Y_{11}, Y_{12}, Y_{21}, Y_{22} can be determined by exploiting I_{from} and I_{to} as a function of V_{from} and V_{to}

The previous model, does not include transformers parameters as done in the π-transmission model described in Matpower manual:

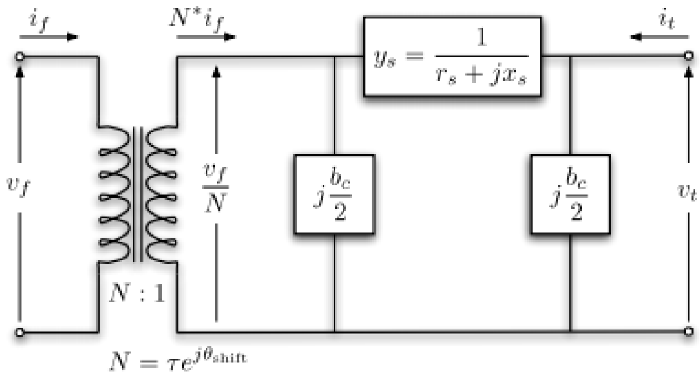


Fig 55, π-transmission model

What one obtain if same procedure is used is, but including transformers parameters is:

$$Y_{br} = \begin{bmatrix} \left(y_s + j\frac{b_c}{2}\right)\frac{1}{\tau^2} & -y_s\frac{1}{\tau e^{-j\theta_{shift}}} \\ -y_s\frac{1}{\tau e^{j\theta_{shift}}} & y_s + j\frac{b_c}{2} \end{bmatrix}$$

Where θ_{Shift} is the phase shift angle.

Now we need a tool to use π-transmission model for the overall network:

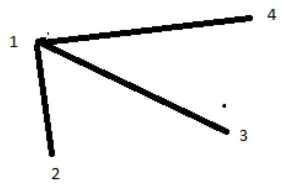
$$Y_{bus} = \begin{bmatrix} Y11 & Y12 & Y13 \ldots & Y1n \\ Y21 & Y22 & Y23 \ldots & Y2n \\ Y31 & Y32 & Y33 \ldots & Y3n \\ Yn1 & Yn2 & Yn3 & \ldots Yn4 \end{bmatrix}$$

Y_{bus}= Bus admittance matrix, sparse and symmetric.

This matrix is sparse because not all branches are linked together (it contains some zeros).

The idea is to calculate:

$I_i = \sum_{k=1}^{n} Iik$ (sum of inlet current equal to the total outlet current)
$I_i = \sum_{k=1}^{n} Yik \cdot Vk$



$Y_{12}=Y_{21}=-y_{12}$ (Transfer admittance)

$Y_{11}=Y_{10}+Y_{12}+Y_{13}+Y_{14}$(Self admittance) (from Kirchhoff's law)
Note: In 1 there is a generator.
Where $y_i = (r+jx)^{\wedge}(-1)$ for branch i;

Fig 56: Bus 1 is interconnected to Bus 2,3 and 4.

$S_{bus}(V) + S_{demand} - S_g = 0$ (complex power injection for each bus)

$$\begin{cases} Sbus(V) + Sdemand - Sg = 0 \\ Pbus(V) + Pdemand - Pg = 0 \\ Qbus(V) + Qdemand - Qg = 0 \end{cases}$$

S_{demand}, for each bus, is known.

$S_{bus,i} = (P_{g1} - P_{demand}) + j^*(Q_{gi} - Q_{demand,i})$ (net complex power injection at bus i)

S_{bus} is the complex injection power.
P_{bus} is the real injection power.
Q_{bus} is the reactive injection power.

If $(P_{gi} - P_{demand,i}) > 0$, then I have a local extra generation of real power
If $(Q_{gi} - Q_{demand,i}) > 0$, then I have a local extra generation of reactive power

If I have a local generation, then export to others bus stations is needed

$I_i = \sum_{k=1}^{n} Iik$ (sum of inlet current equal to the total outlet current)
$I_i = \sum_{k=1}^{n} Yik \cdot Vk$

$I_{bus} = Y_{bus} \cdot V$

$V_i = ||V_i|| \cdot \exp(j \cdot \theta_i) = |V_i| \cdot (\cos\theta_i + J \cdot \sin\theta_i)$ where θ_i is the voltage angle at bus i
$Y_{ik} = ||Y_{ik}|| \cdot \exp(j \cdot \theta_{ik})$ where θ_{ik} is the branch angle

$$P_i = |V_i| \cdot \sum_{k=1}^{n} Yik \cdot Vk \cdot \cos(\theta_{ik} + \delta_k - \delta_i)$$
$$Q_i = -|V_i| \sum_{k=1}^{n} Yik \cdot Vk \cdot \sin(\theta_{ik} + \delta_k - \delta_i)$$

ACOPF

Demand must be supplied at any time: P_{demand}, Q_{demand}, S_{demand} are known.
P_{gi}, Q_{gi}, $V_{bus,i}$, $\theta_{bus,i}$ are unknown (the output of the results).

$V_{bus\_min} \leq Vbus, i \leq Vbus_{\max}, i$ Voltage magnitude constraints.
$\theta_{bus\_min} \leq \theta bus, i \leq \theta bus_{\max}, i$ Voltage angle constraints.
$P_{gen\_min} \leq \mathrm{Pgen}, i \leq \mathrm{Pgen}_{\max}, i$ Real power generation constraint for generator i.
$Q_{gen\_min} \leq \mathrm{Qgen}, i \leq \mathrm{Qgen}_{\max}, i$ Reactive power generation constraint for generator i.
|Power_flow_branch_i (V, θ)| - |Max power flow branch,i| < 0 Branch power flow constraints.

V, θ, P_g, Q_g are the unknown optimization variables.
X is the optimization vector.

$$X = \begin{cases} Voltage\ magnitude\ vector\ V & [Nbus * 1] \\ Voltage\ angle\ vector\ V & [Nbus * 1] \\ Real\ power\ generation\ vector\ V & [Ngen * 1] \\ Reactive\ power\ generation\ vector\ V & [Ngen * 1] \end{cases}$$

The objective function is to minimize total cost of generation

Total_cost_generation= $\sum_{i=1}^{i=Ngenerator} Pgi * Cp(Pgi) + Qgi * Cq(Qgi)$
Cost function for generator i: $C_{p,g1}=a_n*P_{g1}\hat{}n + (a_n-1)*P_g\hat{}(n-1)+a_1*P_{g1}+a_0$;

(P_{g1}-$P_{demand,i}$) is the local real power generation at bus I minus the local demand at the same bus. (Q_{g1}-$Q_{demand,i}$) is the local reactive power generation at bus I minus the local demand at the same bus.

DCOPF

The voltages of each points (bus) in power system is a sinusoidal wave form with a frequency of 50 Hz. This means the voltage at each bus has an amplitude and a phase angle. The magnitude change of the voltages of different buses is because of transmission line resistance and having different phase angles is a result of transmission line inductance.
Nonlinear AC Optimal Power Flow (OPF) problems are approximated by linearized DCOPF problems to obtain real power solutions. In DC-OPF, we ignore the line resistances and reactive power flow in the system. Since the transmission line resistances are considered be zero, all the voltage magnitudes throughout power system are equal to the nominal voltage of the system. The voltages are only different in phase angles **[62]**

For DCOPF:

1) No losses across branches: r=0, b_c=0;
2) All bus voltage magnitude are close to 1 p.u
3) Voltage angle across branches are small enough, so $\sin(\theta from - \theta to - \theta shift) \cong \theta from - \theta to - \theta shift$

No line losses mean V_1=V_2, because no voltage losses caused by longitudinal effects. Voltage angles differences across branches are small enough.

Fig 57:

If V_1=V_2, how branch flow is possible?

From Matpower's manual can be prove that:

$$p_{branch\_flow}\,[p.u]= \frac{\theta from - \theta to - \theta shift}{\tau * xs}$$

If phase angle is zero:

$$p_{branch\_flow}\,[p.u]= \frac{\theta from - \theta to}{\tau * xs}$$

Note: If $\theta from == \theta to$ (same voltage magnitude and same voltage angle across 2 interconnected bus) then no branch power flow across HV-transmission line.

When using DC network modelling assumptions and limiting polynomial costs to second order, the standard OPF problem above can be simplified to a quadratic program, with linear constraints and a quadratic cost function. In this case, the voltage magnitudes and reactive powers are eliminated from the problem completely and real power flows are modelled as linear functions of the voltage angles. The optimization variable is:

$$X=\begin{cases} Voltage\ angle\ vector\ V & [Nbus * 1] \\ Real\ power\ generation\ vector\ V & [Ngen * 1] \end{cases}$$

Total_cost_generation= $\sum_{i=1}^{i=Ngenerator} Pgi * Cp(Pgi)$

$C_{p,g1}=a_2*P_{g1}\text{^}2 + a_1*P_g+a_0$;

$\theta\text{min} \leq \theta bus, i \leq \theta\text{max} \_i$ Voltage angle constraints
Pmin_i $\leq \text{Pgen}, i \leq \text{Pmax} \_i$ Real power generation constraint for generator i

Please, put attention to the last inequality. The last inequality means that generators must dispatch power between the minimum and the maximum value, so if you put as minimum power the minimum characteristic power factor (for example for GT minimum load factor is 35% of nominal capacity), this means that generator cannot be off because of minimum power higher than 0, so minimum power generation cannot be considered, this causes many errors in the simulations as described later.

Branch power flow constraints:
| Power_flow_branch_i (θ) | - | Max power flow branch i| < 0

7.2) COST OF GENERATION

Now some concepts about cost of generation are needed to understand the following part of this thesis. One of the biggest problems meeting during this work was cost determination.
First of all, the cost of Renewables is supposed to be zero and just the gas and oil conventional generators are considered to have production cost.
The generation cost of a power plant could be divided in Fuel cost, Operation and Maintenance (O&M) o Cycling cost.
Cost of generation are taken from the previous work, **R[1],** however will be reported the adopted methodology (**[R8]**).
To evaluate the fuel cost, heat rate curves are implemented as a function of nameplate power and load condition for each fuel type. The underlying heat rates are obtained from measurement data and literature. The price of the consumed fuel is evaluated with consideration of the time and location of the fuel sources.
The reference for Natural Gas price in 2016 was a report of STEG 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.

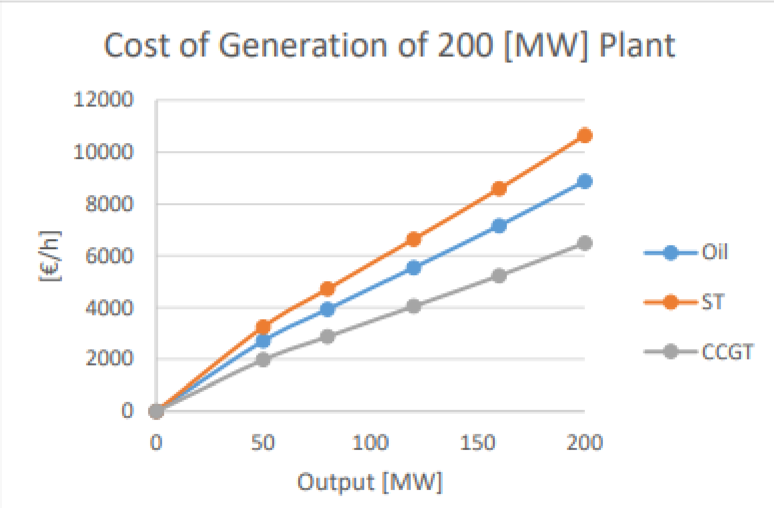


Fig 58 [R1], methodology to determine cost of generation by using heat curve.

Since the fuel cost only represents 50–80% of a thermal power plant's total O&M cost, the maintenance costs and fixed O&M costs needs to be considered as well.
The share of the fuel cost in the total cost of electricity production is evaluated as a function of primary fuel type and nameplate capacity. **[R9]**.

At this point, the author in **[R1]** did a best-fit by using Excel, so 3 degree cost polynomial is obtained.

When using DC network modelling assumptions and limiting polynomial costs to second order, the standard OPF problem above can be simplified to a quadratic program, with linear constraints and a quadratic cost function.
Now, if a generic thermal power plant it's considered, if this works at power lower than the nominal one then the specific cost must be higher because of lower efficiency, lower capacity factor, as shown in Fig 58.

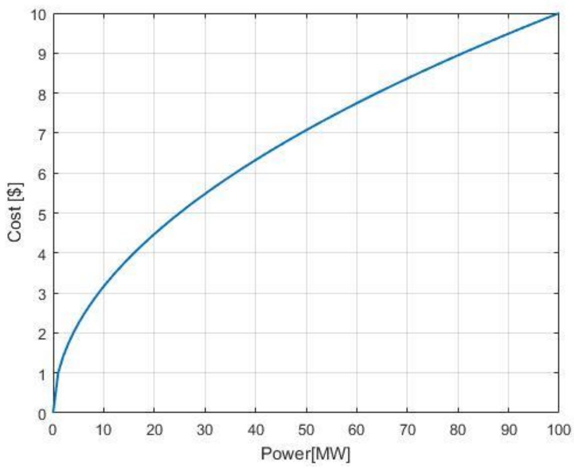


Fig 59, it is plotted the cost curve (sqrt(x) as example), as it's possible to see, if power decreases, and so the efficiency decreases (except for PEMFC, SOFC etc) because the distance from nominal condition increases, the specific cost increases.
This curve is not convex, it can be used in ACOPF, but not in DCOPF because is not convex.

If cost of generation curve for each thermal power plant is described with this equation, ACOPF can be resolved, one can resolve the problem even with a 5-degree polynomial.

Please, note the fact that, for DCOPF this cannot happen, otherwise anyone will get an error. Cost must be definite positive and convex, like a parabola (if one tries to use a 3-degree polynomial, then one will get an error), but this does not happen in the reality. However, if you approximate, for CCGT and for ST the best-fit curve with a linear curve, what you get it's a very small error, no other way for DCOPF.

The curve was obtained by using best-fit, this caused many errors in the simulations, so at the end, a lot of time has spent without understand the reasons.
If GT-cost curve best fit is tracked with a 3-degree polynomial, then cannot be applied in DCOPF, if with 1-degree, then big error from the original curve, if with 2nd-degree, low error but it's like a positive parabola.
If GT-cost curve best fit is tracked with the second-degree order, low error but what happen is that, at lower power (lower than 50MW), the cost of generation is lower than the cost of generation of OIL-ST and GAS-ST, this happen if minimum power generation constraint it's not considered. The consequence is that all results will be wrong. (If linear best-fit is done, the cost of GT will be over-estimated, but since the GT power plants are the most expensive, this is not a problem from a dispatch point of view. The problem is when the opposite happens.

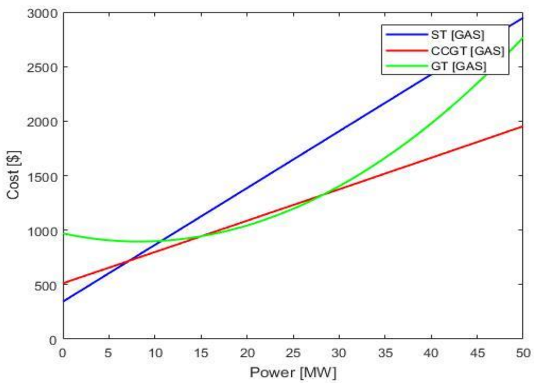


Fig 60: Cost of generation error for GT for DCOPF. This error is due to best- fit equation.

Moreover:

Table 23, what happens if cost is a positive parabola for 2 same GT-units

	Power dispatch at lower cost	Cost function 1	Cost 1
Generator 1	100 MW	= x^2 or any parabola with a>0	1e4
Generator 2	100 MW	= x^2 or any parabola with a>0	1e4
Total Load	200 MW		2e4

Table 24 what happens if cost is linear for 2 same GT-units

	Power dispatch at lower cost	Cost function 1	Cost 1
Generator 1	100 MW	= x → need of UC (removal of expensive generators)	1e2
Generator 2	100 MW	= x → need of UC, minimization of the number of online expensive generator	1e2
Total Load	200 MW		2e2

Table 25 what happens if cost is a positive non convex parabola for 2 same GT-units

	Power dispatch at lower cost	Cost function 2	Cost 2
Generator 1	200 MW	= sqrt(x) or any parabola with a<0, not for DCOPF	14
Generator 2	0 MW	= sqrt(x) or any parabola with a<0, not for DCOPF	0
Total Load	200 MW		14

However, doing linear best-fit curve, the associated equation overestimates the GT cost:

As described before, due to second order best with GT best-fit curve error, GT cost was approximated by using linear best-fit and it was overestimated. The reason why GT cost of generation has been overestimated can be understood in the tables 26…31:

Table 26 Real cost estimation of GT (it cannot be used as described before)

	PMAX	COST $/MW	DISPATCHED POWER
G1	100	10	100
G2	100	50	100
GT	100	100	50
LOAD	250		250

Table 27 GT cost is over-estimated

	PMAX	COST $/MW	DISPATCHED POWER
G1	100	10	100
G2	100	50	100
GT	100	1000	50
LOAD	250		250

Table 28 GT cost is underestimated

	PMAX	COST $/MW	DISPATCHED POWER
G1	100	10	100
G2	100	50	50
GT	100	25	100
LOAD	250		250

So, if the cost of the most expensive generators is overestimated, the economic dispatch doesn't change (in terms of dispatched power).

As described in the introduction chapter, with the increase of renewable penetration, the total number of start up, shut-down and ramp rates amount will increase because of high variability of renewable intermittent energy plants, higher penetration means higher variability. Thermal power plants cannot work at power lower than 95-97% of their minimum power generation, but however, higher is the thermal power plant unit capacity, and higher will be start-up cost, shut down cost and minimum up time. Moreover minimum up time is strongly dependent of type of technology (for instance, if start up time is equal to 6 hours and shut down time 4 hours, because limited by thermal stress etc), like ST, the associated cost is too high and so there is no sense for this technology to work for only 1 hour (if thermal stress is not considered).
Start–stop procedures, minimum load operation and load following ramps, which are commonly referred to as plant cycling, induce thermal stresses in various parts of conventional power plants. Over time, these thermal stresses can cause material fatigue and damage. Therefore, cycling of thermal power plants has detrimental effects on the financial performance and lifetime of the plant **[R9].** In this analysis this cost will be analysed.
So, with high renewable penetration, minimum power generation factor and minimum up time become 2 fundamental aspect of this study.

So, from various thermal power plant datasheet, that can be found easily by internet research, we copy the following costs, as a function of technology and capacity.

Table 29: Adopted value of start-up and shut-down cost per capacity for each technology

Technology	Start Up cost ($/MW-capacity)	Shut down cost ($/MW- capacity)
ST	125	87.5
CCGT	79	55.3
GT	103	72.1

Table 30: Adopted value of ramp-rate cost for each technology, Ramp cost are taken from **R[28]**

TECHNOLOGY	RAMP COST [$/MW]
CCGT	0.33
GT	0.7
ST	1.9

Table 31: Adopted value of start-up and shut-down cost per capacity for each technology

Technology	Minimum Load , % nominal capacity	Minimum UP time hours	Minimum DOWN time hours
ST	30	24	8
CCGT	40	24	8
GT	35	From 1 to 3	1

With increase of renewable penetration and national demand growth, the results will be higher ramp rate required by thermal power plants. Operating the power plant at its current power level during the next hour does not incur a ramping cost but ramping to different power level results in a ramping cost, where the cost of the ramping increases linearly with the magnitude of the rate.

Ramping constraints are imposed for each power unit as a function of the plant's fuel type and nameplate capacity. Even, in this analysis, ramping constraint are expressed in terms of percentage of the nominal capacity. If ramp constraints are considered, then ramp constraints are imposed as shown in the table 32.

Table 32: Adopted value of hourly ramp rates constraints for each technology

TECHNOLOGY	Positive and Negative Load Following Quantity
CCGT	30% * Nominal Capacity [MW]
ST	20% * Nominal Capacity [MW]
Small GT	50% * Nominal Capacity [MW]
Medium GT	40% * Nominal Capacity [MW]
Big GT	35% * Nominal Capacity [MW]
WIND	100% * Nominal Capacity [MW]
PV	100% * Nominal Capacity [MW]
BIOMASS	0.1% * Nominal Capacity [MW]
HYDRO	0.1% * Nominal Capacity [MW]

Typical value used for simulations, if load following cost are introduced in the optimization algorithm of minimization of total cost.

7.3) Conclusion.

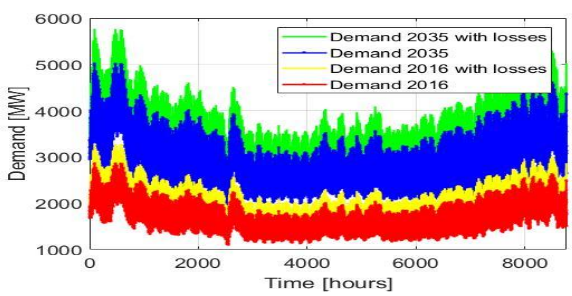
The input data, already described in the Introduction chapter, are:

1) GIS information about Tunisian thermal power plants, renewable power plants in 2016.
2) GIS information about Tunisian thermal power plants, renewable power plants in 2035.
3) GIS information about Tunisian HV bus stations.
4) GIS information about Tunisian branch network, transformers.
5) Electrical hourly demand profile for each HV bus station for 2016 and 2035.
6) Maximum active power produced from renewable plants that could be injected in the Tunisian HV power transmission.

So at this point, generation dispatch can be determined by OPF analysis.

DCOPF doesn't consider line losses, but since this total cannot be neglected, one solution to incorporate line losses in the simulation must be found.
First of all, according to R[1] and so, according to STEG, total average line losses during all 2016 was 15%. The best way to consider line losses in a DCOPF analysis is to add total line losses to the total national electrical demand, as proposed by author in the previous work R[1]. So, the electrical hourly demand at each PQ bus (Load) must be increased by 15% (it's sufficient to multiply by 1.15 the hourly load demand for each HV PQ-bus.)

In figure 60 it's plotted the total electrical national hourly demand: in red the national hourly demand estimated by **R[1]** in the previous work. The yellow curve includes losses, that must be added in demand profile since in DCOPF line losses are not considered, while the blue and green ones are conceptually identical to red and yellow curves but are referred to 2035. From 2016 to 2035 has been assumed that demand will grow by a factor equal to 1.75.
Figure 62 shows total wind generation if curtailment is null for all 2035.
Figure 63 shows total generation from PV-park if 1700 MW PV Remada it's not considered, if curtailment is null for all 2035.
Figure 64 shows total generation from PV-park if 1700 MW PV Remada it's included, if curtailment is null for all 2035.
Figure 67, 68 show the amount of demand that must be supplied by fossil thermal power plant, if curtailment is null (the curve has this equation: fossil (t)= L(t)-R(t), where L(t) is the total demand to meet as a function of time, R(t) is the total renewable production, as a function of time, if curtailment is null). In figure 65 1700 MW PV Remada it's not included, while it's included in fig 66.



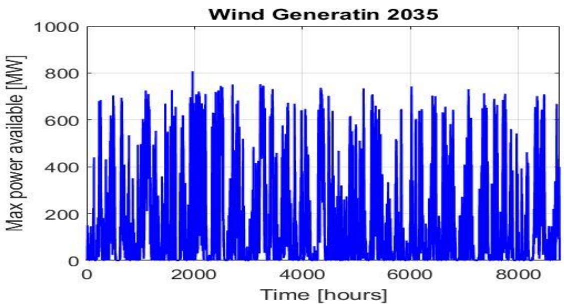
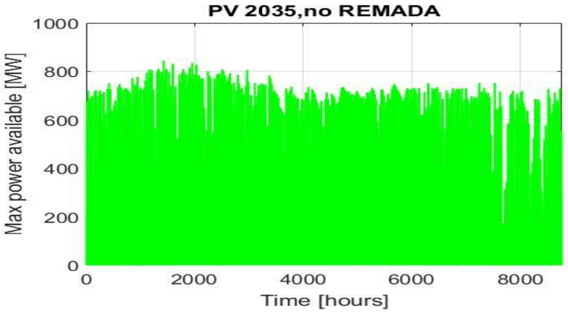


Fig 61, 62: Fig 61 shows total national electrical demand for 2016 and 2035, losses must included separately because they are not included in DCOPF. Fig 62 shows total wind generation profile in 2035



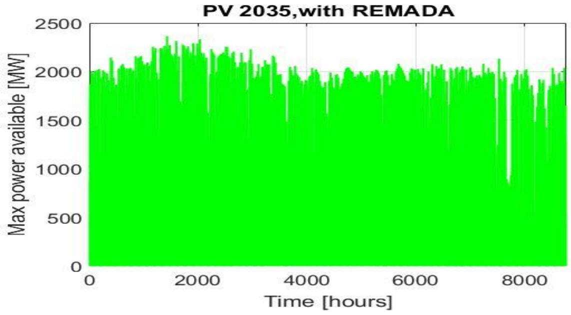
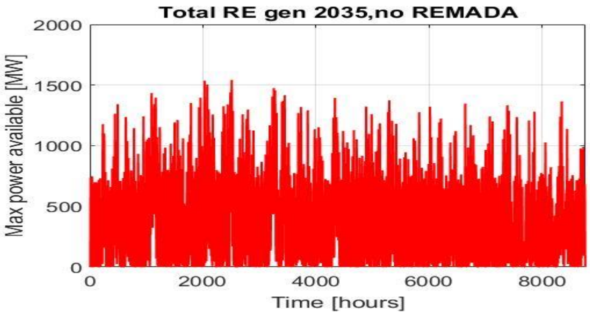


Fig 63, 64: Fig 63 shows total PV production profile if 1700 MW is not included, respectively for Fig 64:



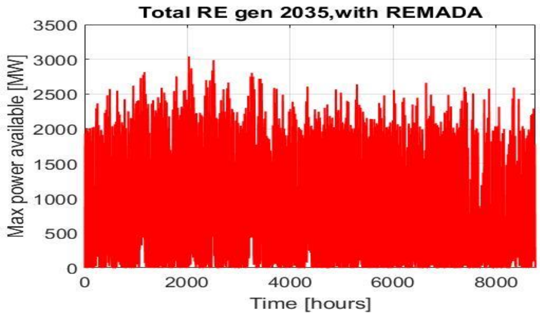
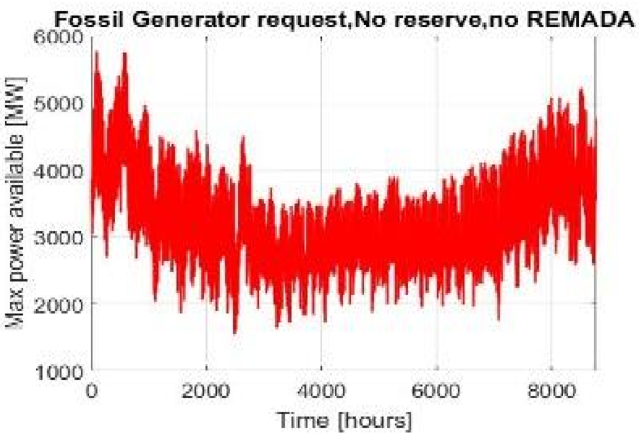


Fig 65, 66: Fig 65 shows total renewable production in 2035 if 1700 MW PV Remada is not added to HV power system, respectively for Fig 66.



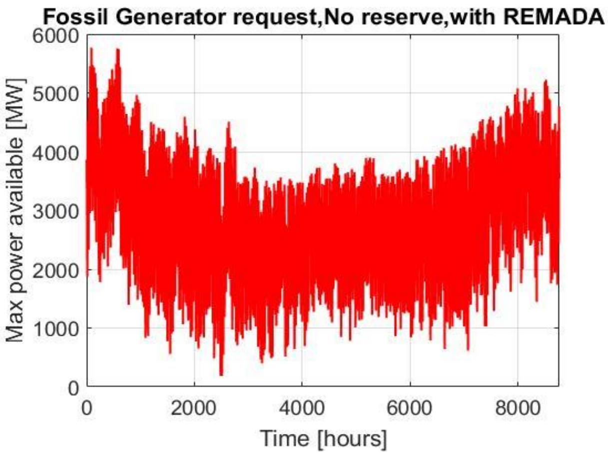


Fig 67, 68: Demand that must be covered by thermal power plants, as a function of time, in Fig 67 if 1700 MW PV Remada is not included, respectively for Fig 68.

CHAPTER 8: SIMULATION PERFORMED

To analyse renewable penetration into the Tunisian HV power transmission, OPF algorithm will be applied.

For all simulations, branch power flow constraints cannot be considered, as written before, because of lack of fundamental data such as number of lines for each branch and diameter for each line. This is the biggest limitations of this model, the biggest cause of error. No transmission constraints mean that the farthest generators could supply demand for a given PQ-bus.
So DCOPF will be use. Remember, in DCOPF, voltage magnitude constraints (fixed) and reactive power constraints are eliminated.
DCOPF is very useful to understand economic dispatch.
To conduct DCOPF, MATPOWER software will be used. However, this model presents some limitations, the most important:

1) $\mathrm{P_{gen\_min}} \leq \mathrm{Pgen}, i \leq \mathrm{Pgen_{max}}, i$ Real power generation constraint for generator i

So minimum power constraints cannot be considered, otherwise generator are forced to work between P_{min} and P_{max}, so zero (off) cannot be reach. If one tries to use algorithm like: if, from solution result, the output of a certain generator is lower than the minimum power, remove the generator and remake the simulation. If this is done, error will be, because this is a minimization algorithm.

2) Ramp constraints are not considered.
3) Line losses are not considered.
4) Minimum up time, minimum down time cannot be integrated, so, for example, CCGT can work on-off for all year.
5) The optimization algorithm considers only the total cost of generation for fossil thermal power plant includes the total cost in particular fuel and O&M, as described before while no cost for renewable plants.

With increase of renewable penetration in the Tunisian HV power transmission, number of start-up and magnitude of ramp rates increases, so this must be considered in an optimization algorithm, as it's possible to seen in figures 69, 70:

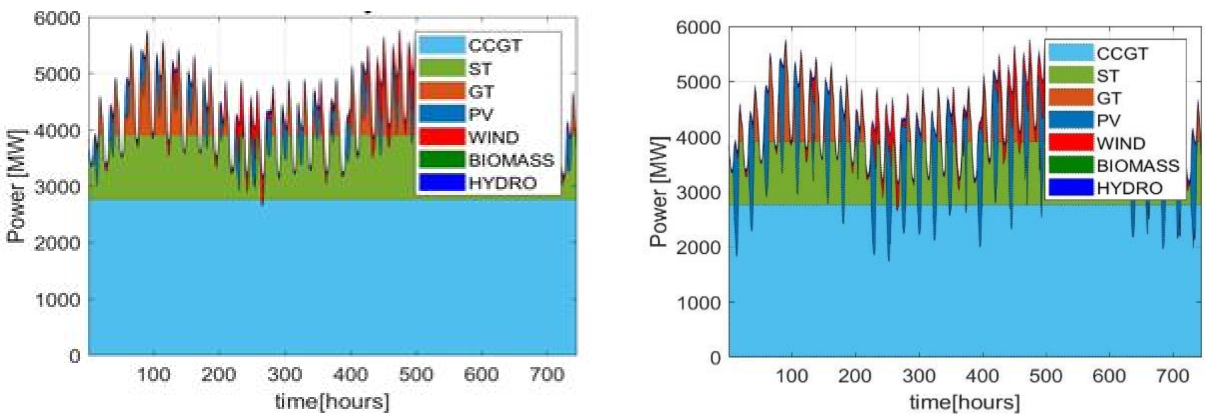


Fig 69, 70: These figures, taken from our simulation, shows that higher is the renewable penetration and higher will be the flexibility needs required by fossil thermal power plants. Number of start-up, ramp rates magnitude increase a lot.

With low renewable penetration, economic generators will work as base load for overall period, while with high renewable penetration the dispatched power is not full and costant for all period.

DCOPF algorithm doesn't remove generators, and since the dispatched power by each generator must be between 2 values, no minimum load power dispatch constraint can be considered in.
In MATPOWER, the standard OPF formulation has no mechanism for completely shutting down generators which are very expensive to operate. Instead they are simply dispatched at their minimum generation limits. **[R12]**
MATPOWER includes the capability to run an optimal power flow combined with a unit de-commitment for a single time period, which allows it to shut down these expensive units and find a least cost commitment and dispatch, so for this reason will be implemented even UCDCOPF.

Even in this case, this model presents some limitations:

1) Ramp constraints are not considered.
2) Line losses are not considered.
3) Minimum up time, minimum down time cannot be integrated, so, for example, CCGT can work on-off for all year.

The optimization algorithm considers only the cost of generation (the total cost of generation for fossil thermal power plant includes the total cost so in particular fuel and O&M, as described before while no cost for renewable plants.

In UCDCOPF, ramp constraints, that are not integrated in UCDCOPF, can be added easily, but ramp cost cannot include in the optimization algorithm.

Minimum up-time and minimum-down time cannot be considered, to understand this, time memory is now defined: (P(t) is the dispatch power of a certain generator)

1)
   If
   $P_{Generator\_i}(t)=P(t)=f(Demand(t), P(t-1), P(t-2), P(t-3)...))=f(Demand(t))$
   → no time memory
2)
   If
   $P(t)=f(Demand(t), P(t-1), P(t-2), P(t-3),....., P(t-t))$
   $=f(Demand(t), P(t-1))$
   → time memory, but for only the previous iterations
3)
   If
   $P(t)=f(Demand(t), P(t-1), P(t-2), P(t-3),....., P(t-t))$
   $=f(Demand(t), P(t-1), P(t-2), P(t-3),....., P(t-t)))$
   → time memory for overall time period, to include minimum up time for thermal power plants, this type of time memory must be considered.

Minimum up time constraints cannot be considered (one needs a powerful tool able to resolve problem where time memory of type 3 is required).
Remember that minimum up time constraint s it becomes import with high renewable

penetration, because some thermal power plants are forced to work on-off, ad this cannot happen if minimum up time is considered.

One way to include minimum up time is by using MOST (MATPOWER OPTIMAL SCHEDULING TOOL).
If minimum up time is considered in MOST simulation, the results is that the problem is not MILP (MIXED INTEGER INEAR PROGRAMMIMG), but it becomes MIQP (MIXED INTEGER QUADRATIC PROGRAMMIMG).
While MILP problem can be resolved by MATPOWER solver, this is not true for MIQP, so other solvers like GUROBI are needed.

MATPOWER OPTIMAL SCHEDULING TOOL (MOST) will be used to conduct multiperiod optimal power flow problems, with ramp constraints, minimum load power dispatch constraints, reserve constraint etc. MOST can be used to solve problems as simple as a deterministic, single period economic dispatch problem with no transmission constraints or as complex as a stochastic, security-constrained, combined unit-commitment and multiperiod optimal power flow problem with locational contingency and load-following reserves, ramping costs and constraints, deferrable demands, lossy storage resources and uncertain renewable generation. **[R13]** .
Two options are included for addressing security in the single period problem, that is the need to find a dispatch that meets some criteria for withstanding disturbances or outages. The first is a deterministic approach that simply adds fixed zonal reserve requirements using the additional variables, constraints and costs. The second is a stochastic approach, based on explicitly modelling the post-contingency state for each of a set of credible contingencies. In this approach, the base case ED or OPF problem is fully duplicated (all variables, costs and constraints) for each of the contingency states and modified to reflect the outaged equipment.
While contingencies refer to discrete low probability events, there is another kind of uncertainty introduced by errors in forecasting of demand and renewable sources of generation, such as wind and solar production. This type of uncertainty can be characterized by random system parameters with continuous probability distributions.

In this work:

1) No contingency scenario will be considered.
2) No probabilistic scenario.
3) No maintenance activity.
4) No branch power flow constraints

Since point 1 and 2 (no contingency, no probabilistic), so MOST model it becomes more easier to understand:

Figure 71 it's taken from MOST's manual, the scope it so shown in the most effective way how ramp constraints must be written in MOST algorithm.

The objective function is always minimization of total cost of generation, but includes even start-up and shutdown cost and ramp cost in the optimization algorithm.

Remember that branch power flow constraint changes drastically the power dispatch, for instance when demand must be satisfied by expensive generators because maximum flow across lines, but even line losses that are not included in DCOPF.

Add Ramping Constraints and Ramp Reserve Costs

To add back the ramping constraints and ramp reserve costs, restore the values from the original `xGenData` and re-run.

```
xgd.PositiveLoadFollowReserveQuantity(3) = 100; % restore ramp reserve
xgd.PositiveLoadFollowReservePrice(3) = 10;     % constraint and costs
xgd.NegativeLoadFollowReservePrice(3) = 10;
% equivalent to doing: xgd = xgd_full;
mdi = loadmd(mpc, nt, xgd, [], [], profiles);
mdo = most(mdi, mpopt);
```

Previously, generator 3 was ramping more than 200 MW from hour 1 to hour 3, which the newly added ramp constraint of 100 MW per hour precludes. Figure 7-7 shows that this fast ramp is reduced by shutting down generator 2 during the first two hours and starting generator 3 at a higher output level.

Fig 71, MOST manual, how add ramp constraints.

So, at this point, simulations can be presented: In this analysis will be considerate different scenarios.

S0: Tunisia 2016 (The reference simulation).
S1: Tunisian Solar Plan TSP, 2035, excluded 1700 MW PV Remada.
S2: Tunisian Solar Plan TSP, 2035.
S3: Tunisian Solar Plan TSP, with biomass plants integration, 2035.
S4: Tunisian Solar Plan TSP, with biomass plants integration, with decommissioning of older plants, 2035.
S5: Tunisian Solar Plan TSP, with biomass plants integration, with decommissioning of older plants, and reserve requirements, 2035.

S0: This scenario is the reference one, the renewable penetration and demand are very low respect to 2035 scenarios.
S1: This scenario represents Tunisian Solar Plan implementation in the HV network, it does not consider CSP plants (see introduction chapter) and 1700 MW PV Remada.
S2: This scenario represents Tunisian Solar Plan implementation into HV network, it does not considers CSP plants (see introduction chapter).
1700 MW PV Remada it's very big PV plant, so it causes big impacts on the overall grid, in terms of economic dispatch (DCOPF), so for this reason that it is simulated separately.
S3: This scenario represents Tunisian Solar Plant implementation in the HV network, it does not consider CSP plants (see introduction chapter). This simulation is S2 with biomass plants integration: biomass plants that are not included in the Tunisian Solar Plant but are derived from this study (see biomass chapter), so for this reason that biomass plants are not considered in S2.
S4: 2035 will be characterized by large demand growth rate (by a factor of 1.75) and a very renewable penetration. By 2035, many plants are too old, so decommissioning of older plant is

needed.
For steam turbine cycle it's assumed a lifetime of 50 years, so plants that are putting into operation before 1985 are assumed to be too older in 2035. While for Gas turbine is assumed a value from 20 to 35 years.
Hydro plants, wind farms etc will be not decommissioned, or repowering etc. Meanwhile, ageing factor, that reduce production caused by ageing of plant, has been not considered.
By summing the data of putting into operations for each thermal power plant (renewable plant are excluded) and the estimated lifetime, then older plant that will be decommissioning by 2035 will be found.
In [APPENDIX-TABLE, TABLE 5] there are shown all generators that will be in operation by 2035.
S5: It's equal to S4, but it considers load, wind and PV uncertainty, so an additional power is required, and since total capacity removed by decommissioning of older plant is very big, this quantity is considered in this scenario to verify if this future higher estimated demand can be satisfied (very closer between demand and total maximum power that could be satisfy by all generators at time t) . S5 will be simulated separately for doing flexibility analysis.

Note: To determine hydro profile [MW], one needs to know H[m] and Q=Q(t)=[m3/s]. Since this is not possible, it was assumed that hydro power can be work at constant power or that the dispatched power can be regulated by gestor. One or other option it's around the same things because hydro capacity can be neglected.
For biomass plants, it has been always assumed that they work at constant power (biomass plants doesn't given load following quantity in this analysis).

Now, type of simulations will be described:

1) **M1**: Multiperiod DCOPF with no time memory (by using MATPOWER).
2) **M2**: Multiperiod UCDCOPF with no time memory (by using MATPOWER).
3) **M3**: Multiperiod UCDCOPF with time memory only for the previous time step, with ramp constraints, (by using MATPOWER).
4) **M4**: Multiperiod UCDCOPF with time memory for all temporal horizon (by using MOST, MATPOWER OPTIMAL SCHEDULING TOOL).

Simulation	Scenario	Time to simulate	Computational cost	Time memory
M1	S0, S1, S2, S3, S4	1 year	20 minutes	Type 1
M2	S4	1 year	24 hours	Type 1
M3	S4	1 year	24 hours	Type 2
M4	S5	1 day	0.5-1 hours	Type 3

Tab 33: Approximated computational cost.

S0M1 means Tunisia 2016 (The reference simulation), Multiperiod DCOPF with no time memory (by using MATPOWER) etc.

Tab 34: Description of type of simulations

WHAT?	M1	M2	M3	M4
Voltage magnitude constraints, reactive power are considered?	NOT	NOT	NOT	NOT
Voltage angle constraints, active power are considered?	YES	YES	YES	YES
Minimum power generation constraint is considered? (es minimum load for GT=35%	NOT	YES	YES	YES
Branch power flow constraints?	NOT (unlikely, no data are available)	NOT (unlikely, no data are available)	NOT (unlikely, no data are available)	NOT (unlikely, no data are available)
Minimum up time (for instance 24h for CCGT)	NOT	NOT	NOT	YES, but required GUROBI and MOST, and the problem it becomes MIQP
Can be simulated all year?	YES, the time is not a problem	YES, but the time is a very big problem	YES, but the time is a very big problem	No, the time expenditure is not sustainable (is not sustainable with high renewable penetration and many fossil generators)

Are ramp constraints considered?	NOT	NOT	YES	YES
Is ramp cost included in the minimization algorithm process?	NOT	NOT	NOT	YES
If shut down and start up cost included in the optimization algorithm?	NOT	NOT	NOT	YES
There is time memory?	NOT (type 1)	NOT (type 1)	YES (type 2)	YES (type 3)
Are fault scenario considered?	NOT	NOT	NOT	NOT
Deterministic or Probabilistic?	Deterministic	Deterministic	Deterministic	Deterministic
Can be calculated the variation in percentage of the number of start up/shut down for each technology:	YES, but minimum up-time generation is not considered… If minimum up time generation is considered, this means that all time horizon must be considered –> the problem it becomes MIQP (qualitative values since no minimum up	YES, but minimum up-time generation is not considered… If minimum up time generation is considered, this means that all time horizon must be considered –> the problem it becomes MIQP (qualitative values since no minimum up	YES, but minimum up-time generation is not considered… If minimum up time generation is considered, this means that all time horizon must be considered –> the problem it becomes MIQP (qualitative values since no minimum up	YES, but all year cannot be simulated.

	time is considered)	time is considered)	time is considered)	

Tab 35: Description of type of simulations

WHAT	S0	S1	S2	S3	S4	S5
Demand growth rate	NOT	YES	YES	YES	YES	YES
Tunisian Solar Plan integration?	NOT	YES	YES	YES	YES	YES
1700 MW PV REMADA integration?	NOT	NOT	YES	YES	YES	YES
Biomass integration?	NOT	NOT	NOT	YES	YES	YES
Decommissioning of older plant	NOT	NOT	NOT	NOT	YES	YES
Load uncertainty?	NOT	NOT	NOT	NOT	NOT	YES
Renewable generation uncertainty?	NOT	NOT	NOT	NOT	NOT	YES
Branch power flow constraints?	NOT	NOT	NOT	NOT	NOT	NOT

Tab 36: Description of type of simulations

QUESTION	ANSWER
Why S0M1, S1M1, S2M1, S3M1, S4M1?	To see the impacts on the HV grid if 1700 MW PV Remada is added or how branch power flow changes with different percentage of renewable penetration.
Why S4M1, S4M2, S4M3?	Because M2, M3 consider minimum power generation, an important factor with high renewable penetration
Why S4M2, S4M3?	To understand how ramp constraints changes the HV network
Why S5M4?	Used for flexibility analysis, as written in literature review, in flexibility analysis many authors consider only 2 days: day of max demand and max renewable generation (like 4th January) and minimum demand and max renewable generation (like 15th April). In flexibility analysis, we reported 12 day-simulations, that are enough.

As written in the previous table (Tab 36), does not make sense to calculate the number of start-up and shut-down for each technology if minimum up time and minimum down time are not taken in consideration, for example, if a random daily profile for a generic ST power plant with a nominal capacity of 120 MW is tracked, the number of start-up increases of 600% caused by renewable penetration, however this number is not useful because ST has to work at least 24 hours, for example, so, again, if minimum up time and minimum down time are not considered, does not make sense to calculate the number of start-up and shut-down for each technology, as one can see in the figures 72, 73. However, this will be done even if it’s not correct a priori (the values will be used as indicator).

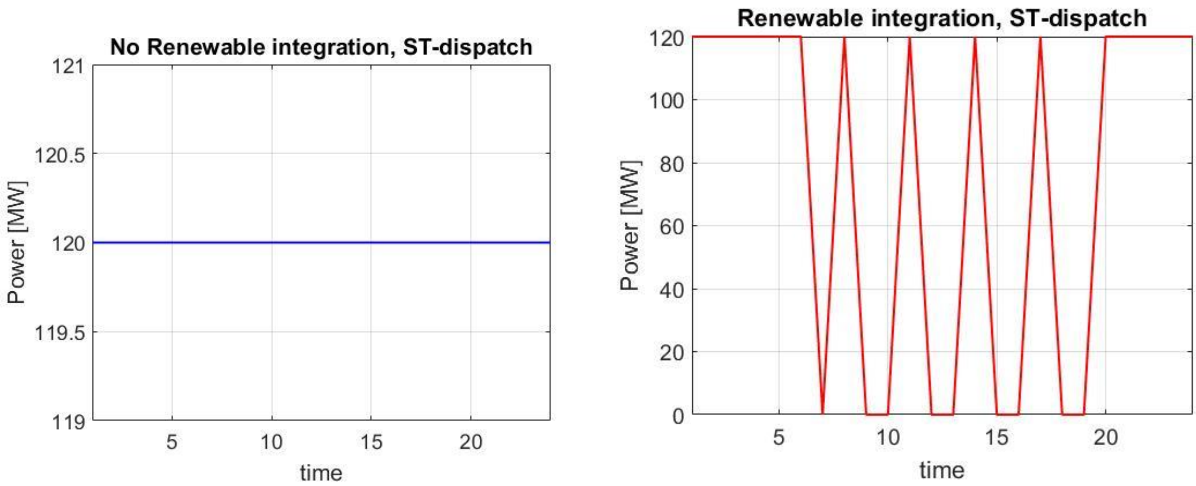


Fig 72, 73: Number of start-up for steam turbine with high renewable penetration.

It’s important to note the fact that simulation of type M3 it’s a MILP (multi integer linear programming), and can be resolved easily with only MATPOWER. However, if Unit Commitment constraints are added, such as minimum time work or minimum shut down time, as done in MOST simulations, the result is that the optimization algorithm it becomes MIQP (Mixed integer quadratic programming), which requires GUROBI. For this reason that in M3, minimum start up time and maximum shut down time will be not integrated.

CHAPTER 9: VALIDATION OF THE MODEL

As any engineering model, there is an associated error due to assumptions, wrong data input, lack of data etc. So for this reason, in this chapter it's analyse how this model is far from reality.
The comparison is made with [https://www.iea.org/data-and-statistics/data-tables?country=TUNISIA&energy=Electricity&year=2016].
Before that, I expect a big error, for the following reasons:

1) No branch power flow constraints, there are no available data given by STEG such as diameter for each line for each branch and number of lines, so any branch power flow across branches is possible and, more important, demand at any bus station can be satisfied by any generators, but this cannot happen because of branch power flow constraints.
2) No line losses considered in DCOPF: Demand at any bus station can be satisfied by any generators because line losses are not considered. Long distance means high losses and not economic condition.
3) Reactive power demand and generation are not considered in this simulation.
4) Voltage magnitude constraints is not considered (fixed at nominal values for each bus because is DCOPF).
5) Error associated to the total hourly profile demand estimation: the exact electrical profile for each bus cannot be download from STEG, but was estimated as described in the introduction chapter.
6) Error associated to the load demand profile for each PQ-bus, for the same reason in point 4.
7) Error associated to cost of generation equation, as described in model description chapter.
8) Error associated in the evaluation in the power profile produced by wind turbine, as described in the wind potential chapter.
9) Error associated to hydro plant profile: The hydro generation profile it depends by type of hydro power plant and by time (volumetric flow rate changes over the time). Since this profile cannot be determined, in particular electricity production from hydro power plants month by month, then nominal power dispatch was assumed. The associated error is low in simulation.
10) Error in Tunisia HV network modelling.
11) No interconnection with abroad countries is modelled, so the import and export electricity quantity is equal to zero.

Electricity produced by: [GWh]	https://www.iea.org/data-and-statistics/data-tables?country=TUNISIA&energy=Electricity&year=2016	Simulation, S0M1, 2016, MATPOWER + R[1]
OIL	41	**1379.6**
NATURAL GAS	18961	**15227**
HYDRO	45	**460**
SOLAR PV	109 (0)	**0**
WIND	474	**474**
TOTAL	19630	**17540.6**

Table 37: Validation of the model

Observations:

1) In figure 74 it's possible to understand why values are different: the orange curve represents the total electrical demand that must be meets for different years, from 2000 to 2016.
   The hourly electrical demand profile is determined from consumption and adding line losses (15%), so since production and consumption are different (because of export, losses, higher production to give higher safety to the grid such as load uncertainty etc), the results will be different.

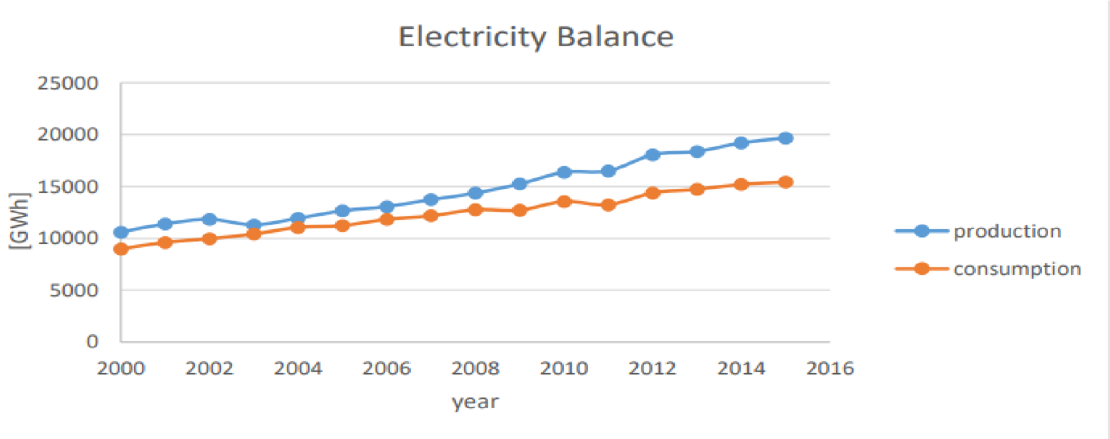


Fig 74, R[1], electricity consumption VS production

2) Electricity production from hydro plants is overestimated because constant nominal power was assumed, this could be a big error, but, as will be possible to see later, this doesn't changes nothing in 2035 simulations.
   With this assumption, the total hydro production is lower than 3% and 1.5 % in 2016 and 2025 respectively, so can be neglect in terms of OPF analysis.

CHAPTER 10: RESULTS SIMULATIONS AND CONCLUSION.

In this chapter simulations results will be discussed: plot results can be found in [Appendix-plot].
In Table-38, table-39, table-40 and table-41 are reported the total installed capacity for different scenarios.
In 2035, the total renewable capacity will be higher than 30%, but the total electricity produced by renewable plants by 2035 will be lower than 30% (25%, see table-44).
As described in wind chapter, wind productivity, in power density and capacity factor are underestimated, in particular because hourly mean values of speed are considered.
More than 1GW of thermal power plants is removed by decommissioning of older power plants by 2035.
More than 4 GW will be installed by 2035. The total electricity that will be satisfied by 2035 is 1.75 the 2016 total electricity demand.

INSTALLED CAPACITY [MW]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
CCGT	1860	2760	2760	2760	2760	2760	2760
ST	1148	1148	1148	1148	700	700	700
GT	2484	3606	3606	3606	2873	2873	2873
PV	0	955	2655	2655	2655	2655	2655
WIND	240	1024.554	1024.554	1024.554	1024.554	1024.554	1024.554
BIOMASS	0	0	0	117	117	117	117
HYDRO	62	62	62	62	62	62	62
TOTAL	**5794**	**9555.554**	**11255.55**	**11372.55**	**10191.55**	**10191.55**	**10191.55**

TABLE-38

INSTALLED CAPACITY [%]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
CCGT	32.10217	28.88372	24.52123	24.26895	27.08125	27.08125	27.08125
ST	19.8136	12.01396	10.19941	10.09448	6.868432	6.868432	6.868432
GT	42.87194	37.73721	32.03752	31.70792	28.19001	28.19001	28.19001
PV	0	9.994187	23.58835	23.34568	26.05098	26.05098	26.05098
WIND	4.142216	10.72208	9.102655	9.009008	10.05297	10.05297	10.05297
BIOMASS	0	0	0	1.028793	1.148009	1.148009	1.148009
HYDRO	1.070072	0.648837	0.550839	0.545172	0.608347	0.608347	0.608347
TOTAL	100	100	100	100	100	100	100

TABLE-39

INSTALLED CAPACITY [MW]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
FOSSIL FUEL	5492	7514	7514	7514	6333	6333	6333
RENEWABLE FUEL	302	2041.554	3741.554	3858.554	3858.554	3858.554	3858.554
TOTAL	5794	9555.554	11255.55	11372.55	10191.55	10191.55	10191.55

TABLE-40

INSTALLED CAPACITY [%]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
FOSSIL FUEL	94.78771	78.63489	66.75815	66.07135	62.13969	62.13969	62.13969
RENEWABLE FUEL	5.212289	21.36511	33.24185	33.92865	37.86031	37.86031	37.86031
TOTAL	100	100	100	100	100	100	100

TABLE-41

In [APPENDIX-PLOT, S0M1]: Plot-Results for S0M1 simulation, the reference simulation:
As is possible to see, GT works for few hours for the same reasons already discussed in the validation model chapter.

CCGTs, since very high efficiency and low fuel cost work at base load, at around 1800 MW for all year, flexibility required by CCGT is low, around zero during months characterized by higher demand, for ST this is not true, moreover, ramp constraint are not considered. As it's possible to see in the figures, renewable penetration can be neglected.
In this scenario, demand can be satisfied in any PQ bus, this is another consequence because branch power flow constraints are not included in this model.

In [APPENDIX-PLOT, S1M1]: Plot-Results for S1M1 simulation, 2035, Tunisia, with TSP excluded 1700 MW PV Remada.
In this case it's possible to see how total active power needs (Load plus losses because DCOPF doesn't consider it) reach around 6 GW, for central months between 3 and 4 GW, however, the error associated to hourly demand profile is high (lack of data). In this case, due to big load increase by 2035, the GTs capacity factor increase a lot, in particular in the winter months.
In S1M1, the total renewable penetration, in terms of capacity, is around 20%, while in terms of energy to 10%.

In [APPENDIX-PLOT, S2M1]: Plot-Results for S2M1 simulation, TSP.
If S1M2 and S1M3 are compared, flexibility needs growth due to 1700 MW PV Remada implementation can be easily seen.
As it's possible to see, renewable penetration becomes so high that, in the central months all demand can be covered by renewable plants and only CCGT if branch power flow constraints, voltage magnitude constraints line losses and minimum up time, minimum power generation factor and ramp rate constraints for thermal power plants are not considered, like April 15th:

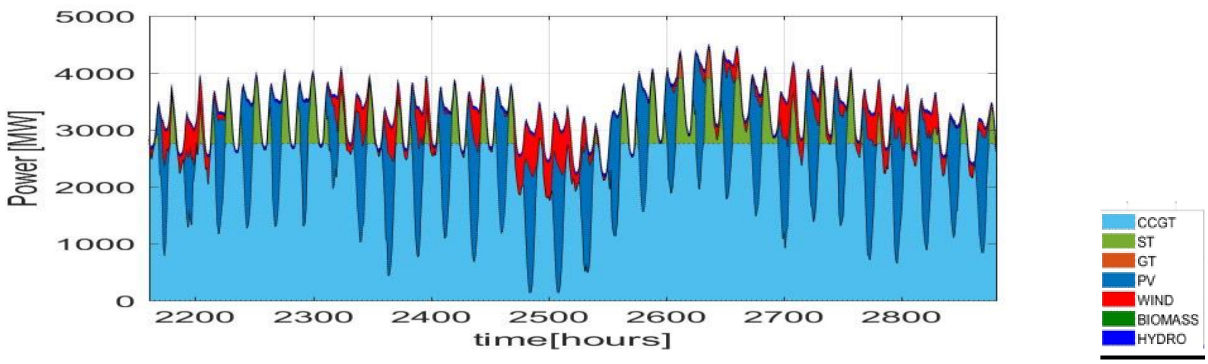


Fig 75: S2M1 Power dispatch at April

This happens because, except voltage magnitude constraints, branch power flow constraints, line losses, thermal power plants minimum up time, ramp constraints and minimum power generation factor are not considered.

Plot-Results for S3M1 simulation, TSP and biomass plants integration are not presented in Plot appendix because the biomass penetration is low (around 100 MW), so Plot-Results for S3M1 is very similar to S2M1.
Even if biomass plants penetration is low, in particular if compared with PV and WIND, they cause

positive impacts on the HV-network, biomass plants are small and they are not unpredictable, so they reduce flexibility needs caused by solar and wind penetration.

In [APPENDIX-PLOT, S4M1]: Plot-Results for S4M1 simulation.
As it's possible to see from the pictures, electricity produced by GT increases because of decommissioning of ST (more economic than GT).

[S4M1], [S4M2], [S4M3] seem identically (for this reason that result plots for S4M2 and S4M3 will are not shown), the differences can be easily seen in [Appendix-table Table 9], for instance:

Generator	Type of generator	Nominal power	Start-up number S0M1	Start-up number S1M1	Start-up number S2M1	Start-up number S3M1	Start-up number S4M1	Start-up number S4M2	Start-up number S4M3
Sousse C #1	CC	424	1	1	1	1	1	556	557
Sousse D #1	CC	424	1	1	1	1	1	187	193

TABLE-42:

The last values are wrong with high renewable penetration (too high for CCGT) because minimum up time have not been considered, so the number of start-up increase a lot.
Dispatch it's similar, but during central months, characterized by lower demand, CCGT must be put offline because of violation of minimum power generation.

Electricity produced by fuel [GWh_el]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
GAS	15226.57	23862	21544.21	20890.46	21325.38	21317.65	21317.55
OIL	1379.579	3414.873	2667.491	2296.32	1861.404	1869.209	1869.353
SOLAR (ONLY PV, NO CSP)	0	1689.905	4755.072	4755.072	4755.072	4755	4755.016
WIND	474.5922	1331.596	1331.596	1331.596	1331.596	1331.571	1331.572
BIOMASS	0	0	0	1024.92	1024.92	1024.885	1024.885
HYDRO	460.776	460.776	460.776	460.776	460.776	460.7711	460.7711
TOTAL	**17541.51**	**30759.15**	**30759.15**	**30759.15**	**30759.15**	**30759.08**	**30759.15**

TABLE-43: Electricity production, for all year, for different scenario: S0M1 it refers to 2016, while the others for 2035

Electricity produced by fuel [%]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
GAS	86.80304	77.57692	70.04165	67.91626	69.33021	69.30521	69.30475
OIL	7.86465	11.10197	8.672187	7.465487	6.051546	6.076933	6.077389
SOLAR (ONLY PV, NO CSP)	0	5.493992	15.45905	15.45905	15.45905	15.45885	15.45887
WIND	2.705537	4.329105	4.329105	4.329105	4.329105	4.329032	4.329029
BIOMASS	0	0	0	3.332082	3.332082	3.331977	3.33197
HYDRO	2.626775	1.498013	1.498013	1.498013	1.498013	1.498	1.497997
TOTAL	100	100	100	100	100	100	100

TABLE-44: Electricity production, for all year, for different scenario: S0M1 it refers to 2016, while the others for 2035

Electricity produced by fuel [GWh_el]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
FOSSIL FUEL	16606.14	27276.87	24211.71	23186.79	23186.79	23186.86	23186.9
RENEWABLE FUEL	935.3682	3482.277	6547.444	7572.364	7572.364	7572.227	7572.245
TOTAL	17541.51	30759.15	30759.15	30759.15	30759.15	30759.08	30759.15

TABLE-45: Electricity production, for all year, for different scenario: S0M1 it refers to 2016, while the others for 2035

Electricity produced by fuel [%]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
FOSSIL FUEL	94.66769	88.67889	78.71383	75.38175	75.38175	75.38214	75.38214
RENEWABLE FUEL	5.332312	11.32111	21.28617	24.61825	24.61825	24.61786	24.61786
TOTAL	100	100	100	100	100	100	100

TABLE-46: Electricity production, for all year, for different scenario: S0M1 it refers to 2016, while the others for 2035

Since renewable plants have null cost of generation, they are advantaged to inject power because of lower price. Higher renewable penetration means that demand can be meets without using expensive generators, so the capacity factor for fossil plants decreases.
In cash flow analysis, the earning increase if capacity factor increases, so a drastic reduction of capacity factor of thermal power plants like CCGT could be means a drastic reduction of earnings and so bad investment.
On the other hand, from an economic point of view, higher demand means higher production and so higher productivity for a certain generator and so higher capacity factor caused by demand growth.

CAPACITY FACTOR [%]	S0M1	S1M1	S2M1	S3M1	S4M1	S4M2	S4M3
CCGT	93.39182	96.23458	87.09512	84.83851	84.83908	84.80689	84.80871
ST	13.78807	34.83318	27.23323	23.42615	30.35558	30.48286	30.48521
GT	0.012228	1.603963	1.31532	1.009932	3.231657	3.231855	3.229724

Table 47: Capacity factor variation caused by renewable penetration and demand growth. To facilitate the reading, capacity factor it's calculated for all fossil generator for a specific technology (CCGT, GT, ST). Moreover, from this table and Table-38, it's possible to determine the total electricity produce by CCGTs, GTs, STs for different scenario.

In [APPENDIX-TABLE, TABLE 6], it's reported the variation of start-up and shut down number for different scenarios and for different type of simulations. As already explained before, this number is only a index since minimum up time constraints must be added in the optimization algorithm (time memory of type 3).

[APPENDIX-TABLE, TABLE 7]: Branch power flow variation caused by demand growth and renewable penetration.
Again, from STEG it's not possible to download data like number of lines per each branch and diameter per each line, so no branch power flow constraints can be added.
The scope of this table is to understand which lines requires TNEP or branch power repowering.
To do this, the following scenario will be take in consideration: S0M1, S1M1, S2M1, S3M1, S4M1, S4M2, S4M3.
Transmission network expansion planning (TNEP) is a basic part of power system planning that determines where, when and how many new transmission lines should be added to the network.. Its task is to minimize the network construction and operational cost, while meeting imposed technical, economic and reliability constraints. TNEP should be satisfied required adequacy of the lines for delivering safe and reliable electric power to load centers during the planning horizon. [R24].

MBPF S0M1 = maximum branch power flow measured, in MW, for a certain branch during all year, for scenario S0M1

MBPFR SiMj = ratio between maximum branch power flow measured, in MW, for a certain branch during all year for scenario SiMj, divided by maximum branch power flow measured, in MW, for the same branch during all year for scenario S0M1.

In [APPENDIX-PLOT, S5M4]: Results for S5M4 simulation, results about flexibility analysis.
Flexibility is defined as the ability to vary as quickly as possible the dispatched power by fossil plants to accommodate renewable plants.
Flexibility analysis it becomes very important when renewable penetration is relative high. Higher is the flexibility offered by thermal power plants, and higher will be the amount of renewable power that can be injected into the Tunisian HV network. Higher is the flexibility and lower will be the probability of renewable curtailment ([**R63**]).
Higher is the flexibility and higher will be the amount of solar and wind power that can be accommodate in the HV power transmission.

How can flexibility be increased?

1) Higher ramp rates offered by thermal power plants.
2) Lower minimum up time.
3) Lower start-up time.
4) Lower minimum load power generation.

Flexibility analysis It's used in this work to understand the amount of renewable power that can be accommodate in the Tunisian HV network if minimum load factor, ramp rates constraints, minimum up time constraints are considered. Flexibility analysis will be used even to determine electricity average daily cost.
Remember that, since electricity cost it's dependent by the particular technology used to satisfy the demand, this means that higher is the renewable penetration and higher will be the fluctuation in electricity price during the day, for instance at 8.00 pm demand it's covered by GT (highest cost) while at 15.00 it's covered by renewable plants (no cost) and economic generators (CCGT).

As already described, to conduct flexibility analysis, 12 days simulations are enough. One overall year could be simulated, but very high computational cost. (10 minute to minute flexibility analysis cannot be performed in this analysis).

The results of flexibility analysis will be strongly dependent by:

1) Initial Dispatched Power.
2) Initial number of hours: if positive, for instance it's online since 5 hours (minimum up time), while if negative means the generator was online since 5 hours (minimum down time).
3) Time horizon: doing 3 days simulations is different from doing daily simulation by 3 times and using, for each simulation, excluded the first one, as initial dispatched power the solution of the previous simulation.

Many authors consider only day of max demand and renewable production (January) and low demand and high renewable production (April).
So, for this reason that daily simulation are sufficient to simulate all year.

One year could be simulated, the results will be like the figures 76, 77 if simulation is done for all days.

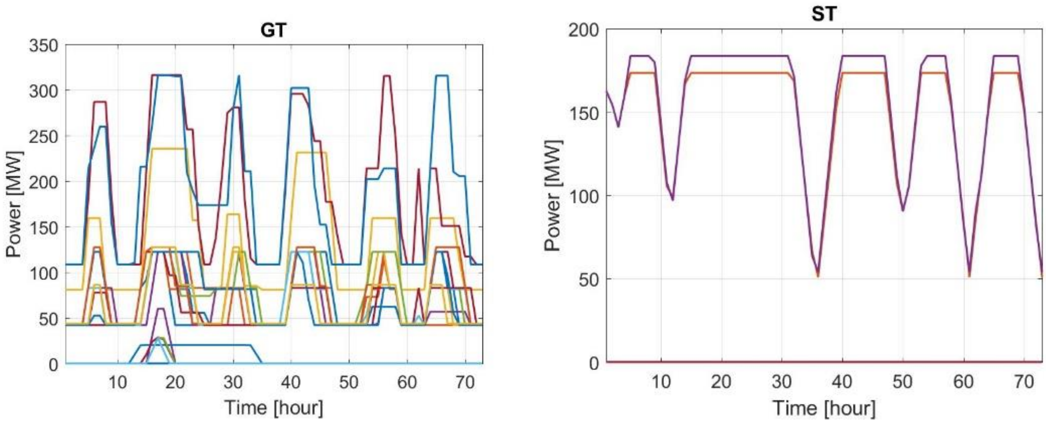


Fig 76, 77, example of multi-day power dispatch for GT and ST with high renewable penetration, Tunisia, S5M4, First week of January.

If Initial Dispatched power for each generator it's considered, then the differences are:

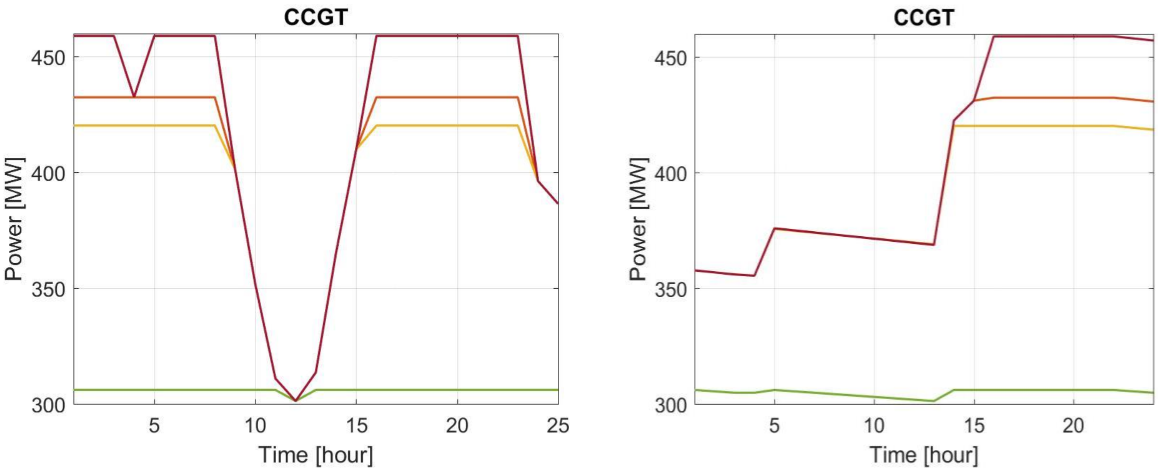


Fig 78, 79: How economic dispatch is strongly dependent by Initial Power (Economic dispatch at t=0). In fig 78, the Initial economic power dispatch for each generator is unknown, while not in figure 79. The plot results are completely different because of different initial dispatched power at t=0;

Remember that the scope of flexibility analysis, in this study, is to analyse the fossil thermal power plants behaviour with renewable penetration, in particular the ability to accommodate renewable power if ramp constraints, minimum up time and minimum load factor are fixed.

So at this point, flexibility results can be found in [APPENDIX-PLOT, S5M4].

During day of max demand (4-th January), renewable curtailment caused by minimum up time, minimum power generation and ramp constraints is very limited (almost zero), while it increases during periods of lower demand.
If [Plot-Appendix, S4M1, January] and [Plot-Appendix, S5M4, 4^{th} January] are compared, then the flexibility needs covered by CCGTs in S5M4 simulation is higher than in S4M1 caused by ST Unit Commitment constraint, in fact ST ramp constraints and minimum up time cannot be violated, but even because ST ramp cost is higher if compared with GT and CCGT ramp cost.

In April day simulation, GT dispatched power is null, however, ST flexibility required is very high, even if within ramp constraints (low demand and high renewable production).
As it's possible to see, in the central months, months characterized by lower demand and relative high renewable penetration, renewable curtailment increases.

If [Plot-Appendix, S4M1, April] and [Plot-Appendix, S5M4, 15th April] are compared:

1) For S4M1, during day (at highest solar production), demand can be satisfied by only renewable power plants, this cannot happen for S5M4 because of ramp constraints and minimum up time, this is translated in renewable curtailment, as it's possible to see in the figures. 1700 MW PV Remada power output is drastically reduced, so the ability to accommodate renewable penetration during central months is limited, because of low demand estimation.

Flexibility analysis results will be now shown:

A) % of total renewable curtailment caused by ramp, minimum power generation factor and minimum up time constraints for the central day of all months, excluded for January (4th January).

Month (one day simulated)	% Renewable curtailment
January	1
February	5.5
March	22
April	25
May	16.5
June	17
July	15
August	8
September	12
October	8
November	3
December	1.5

Tab 48: This table shows the percentage of renewable curtailment caused by ramp , minimum power factor generation and minimum up time constraints for thermal power plants.

As it's possible to see, If the distance between demand needs and renewable production decreases, then the percentage of renewable curtailment caused only by minimum power generation factor, ramp constraints and minimum up time increases.

B) Thermal power plants capacity factor for the central day of all months, excluded for January (4th January).

Month(day)	CCGT	ST	GT
January	94	86	36
February	90	81	29
March	89	64	4
April	55	45	0
May	59	42	0

June	73	44	0
July	66	73	2
August	70	59	0
September	69	66.3	4
October	63	75.56	10.5
November	80	78.96	13.8
December	74	79.63	29

Table 49:

C) In this study was assumed that renewable power plants have-not cost of generation. From a flexibility point of view, this is good because this increases the variability of thermal power plants (it's convenient a flexible dispatch because of low cost of generation), in terms of ramps, to accommodate solar and wind power. This obviously is not true and it depends by national policy.

If **S5M4** is considered (the cost includes, in the optimization algorithm start-up/shut-down cost, ramp cost, cost of generation).

MONTH	AVERAGE COST [$/MWh]
January	96.72661
February	98.27947
March	41.78026
April	24.50113
May	24.95945
June	27.74938
July	38.87798
August	29.17127
September	42.14329
October	63.9203
November	64.15173
December	96.45407

Tab 50: Average cost estimation for central day of each month

CHAPTER 11: TABLE APPENDIX.

TABLE 1, Tunisian HV bus (substation, generators) R[1]

Name	Other	Bus number	baseKV
POSTE 90 KV BORJ CEDRIA	station NABEUL	1	90
POSTE 90 KV MENZEL TEMIME	station NABEUL	2	90
POSTE 90 KV AIN KMICHA(NABEUL)	station NABEUL	3	90
POSTE 90/ 150 KV HAMMAMET	station NABEUL	4	90
POSTE 90 KV BEJA	station BEJA	5	90
POSTE 90 KV OUED ZARGA	station BEJA	6	90
STATION 90 KV AROUSSIA/HYDRO PLANT*	generator MANOUBA	7	90
POSTE 90 KV TABARKA	station JENDOUBA	8	90
POSTE 90 KV CIMENTEIRE BIZERTE	station BIZERTE	9	90
POSTE 90/225 KV LA GOULETTE*	generator TUNIS	10	90
POSTE 90/150/225 KV TAJEROUINE	station LE KEF	11	90
POSTE 90 KV TUNIS NORD	station TUNIS	12	90
POSTE 90 KV TUNIS OUEST	station TUNIS	13	90
POSTE 90 KV MGHIRA/BEN AROUS	station BEN AROUS	14	90
POSTE 90 KV HYDRO SIDI SALEM*	generator BEJA	15	90
POSTE 90/225/400 KV JENDOUBA	station JENDOUBA	16	90
POSTE 90 KV GAMMARTH	station TUNIS	17	90
POSTE 90 KV POWER PLANT MENZEL BOURGUIBA*	generator BIZERTE	18	90
STATION 90 KV GAS POWER PLANT KORBA(Nabeul)*	generator NABEUL	19	90
POSTE 90 KV WIND FARM SIDI DAOUED*	generator NABEUL	20	90
STATION 90 KV POWER PLANT TUNIS SUD(DOUBT!)*	generator TUNIS	21	90
POSTE 90 KV TUNIS CENTRE	station TUNIS	22	90
POSTE 90/225 KV NAASSEN	station BEN AROUS	23	90
POSTE 90 KV BARBARA(AIN DRAHAM)	station JENDOUBA	24	90
POSTE 90/225 KV MENZEL JEMIL	station BIZERTE	25	90
STATION 90 KV NEBEUR/Mellegue Dam*	generator LE KEF	26	90
POSTE 90 KV ETTAREF	station BIZERTE	27	90
POSTE 90 KV GAAFOUR(TEBOURSOUK)	station SILIANA	28	90
POSTE 90/225/400 KV MORNAGUIA(LA MANOUBA)*	generator MANOUBA	29	90
POSTE 90/225/400 KV MATEUR	station BIZERTE	30	90
POSTE 90 KV SIDI BARRAK(SALEM)*	generator BEJA	31	90
POSTE 90 KV WIND FARM METLINE*	generator BIZERTE	32	90
POSTE 90/225 KV EL KRAM	station TUNIS	33	90
POSTE 90/225 KV GROMBALIA	station NABEUL	34	90
POSTE 90 KV ZAHROUNI	station TUNIS	35	90
POSTE 90 KV WIND FARM KCHABTA*	generator BIZERTE	36	90
POSTE 90 KV CENTRE URBAINE NORD(CUN)	station TUNIS	37	90
POSTE 90 KV LAC OUEST	station TUNIS	38	90

POSTE 90 KV BARTHOU	station TUNIS	39	90
POSTE 90 KV KASBAH	station TUNIS	40	90
POSTE 90 KV BOUHERTMA HYDRO PLANT*	generator JENDOUBA	41	90
POSTE 90 KV CIMENTERIE OUM EL KELIL	station LE KEF	42	90
STATION 90 KV BIZERTE	station BIZERTE	43	90
POSTE 90/225 KV MNIHLA 1	station ARIANA	44	90
station 225/90 KV AL OUINET(ALGERIE)	station(ALGERIA)	45	90
POSTE 90/225 KV RADES II*	generator BEN AROUS	46	90
STATION 90 KV KALA(ALGERIE)	station (ALGERIA)	47	90
POSTE 150/225 KV MSAKEN II NORD	station SOUSSE	48	150
POSTE 150/225 KV TAJEROUINE	station EL KEF	49	150
POSTE 150 KV KASSERINE NORD/POWER PLANT*	generator KASSERINE	50	150
POSTE 150 KV METLAOUI	station GAFSA	51	150
POSTE 150 KV DE MDHILLA	station GAFSA	52	150
STATION 150/225 KV SOUSSE*	generator MONASTIR	53	150
POSTE 150 KV MONASTIR	station MONASTIR	54	150
POSTE 150 KV TOZEUR	station TOZEUR	55	150
POSTE 150 KV SIDI BOUZID	station SIDI BOUZID	56	150
STATION 150 KV JEBEL ONK (ALGERIE)	station(ALGERIA)	57	150
Poste 150 KV Akouda	station SOUSSE	58	150
POWER PLANT/POSTE ROBBANA*	generator MEDENINE	59	150
POWER PLANT THNYA*	generator SFAX	60	150
STATION 150 KV POWER PLANT FERIANA*	generator KASSERINE	61	150
POSTE 150 KV DE KEBILI	station KEBILI	62	150
POSTE 150/225 KV MEKNASSY	station SIDI BOUZID	63	150
POSTE 150 KV MIDOUN	station MEDENINE	64	150
POSTE 150 KV SFAX POWER PLANT/GREMDA*	generator SFAX	65	150
POSTE 150 KV DE LA CIMENTERIE DE GABES	station GABES	66	150
POSTE 150 KV EL JEMELJEM	station MAHDIA	67	150
POSTE 150 KV GAFSA	station GAFSA	68	150
POSTE 150 KV KASSERINE SUD	station KASSERINE	69	150
POSTE 150 KV SKHIRA	station SFAX	70	150
POSTE 170/225 KV POWER PLANT ZARZIS*	generator MEDENINE	71	150
POSTE 150 KV DE GHANNOUCH	station GABES	72	150
POSTE 150 KV GABES SUD	station GABES	73	150
POSTE 150/225 KV BOUFICHA*	generator SOUSSE	74	150
POSTE 150 KV MSAKEN	station SOUSSE	75	150
POSTE 150 KV ENNEFIDHA SUD	station SOUSSE	76	150
POSTE 150/225 KV BOUCHEMMA*	generator GABES	77	150
STATION 150 KV SOTACIB STATION	station KASSERINE	78	150
POWER PLANT IPP SEEB- EL BIBANE*	generator MEDENINE	79	150
POSTE 150 Kv TABAROURA	station SFAX	80	150
POSTE 150 KV SIDI MANSOUR	station SFAX	81	150
POSTE 150 KV- MOKNINE	station MONASTIR	82	150
POSTE 150 KV KESSOUR ESSEF	station MAHDIA	83	150

POSTE 150 KV SAHLOUL	**station SOUSSE**	84	150
POSTE 90/ 150 KV HAMMAMET	**station NABEUL**	85	150
POSTE 150 KV BOULAABA	**station KASSERINE**	86	150
POSTE 150/225 KV RADES*	**station BEN AROUS**	87	150
POSTE RADES* A	**generator BEN AROUS**	88	225
RADES I B (same zone as Carthage)*	**generator BEN AROUS**	89	225
RADES II 150/225 KV Carthage Power Company (CPC)*	**generator BEN AROUS**	90	225
POSTE 90/225 kv LA GOULETTE*	**generator TUNIS**	91	225
POSTE 90/150/225 KV MSAKEN II NORD	**station SOUSSE**	92	225
POSTE 150/225 KV TAJEROUINE	**station LE KEF**	93	225
POSTE 225 KV RWIS(LIBYA)	**station(LIBYA)**	94	225
POSTE 150/225KV SOUSSE*	**generator MONASTIR**	95	225
POSTE 225KV MEDENINE	**station MEDENINE**	96	225
POSTE 225 KV TATAOUINE	**station TATAOUINE**	97	225
POSTE 225 KV BIR MCHARGA*	**generator ZAGHOUAN**	98	225
POSTE 90/225/400 KV JENDOUBA	**station JENDOUBA**	99	225
POSTE 225 KV ABOU KAMMECH(LIBYA)	**station(LIBYA)**	100	225
POSTE 90/225 KV MNIHLA 1	**station ARIANA**	101	225
POSTE 50/225 KV NAASEN	**station BEN AROUS**	102	225
POSTE 90/225 KV MENZEL JEMIL	**station(BIZERTE)**	103	225
POSTE 225 KV GHANNOUCH*	**generator GABES**	104	225
POSTE 225 KV OUESLATIA	**station KAIROUAN**	105	225
POSTE 225 KV HAJEB LAYOUN	**station KAIROUAN**	106	225
POSTE 90/225/400 KV MORNAGUIA(LA MANOUBA)	**station MANOUBA**	107	225
POSTE 170/225 KV POWER PLANT ZARZIS*	**generator MEDNINE**	108	225
POSTE 225 KV KAIROUAN	**station KAIROUAN**	109	225
POSTE 150/225 KV BOUCHEMMA*(GABES)	**generator GABES**	110	225
POSTE 90/225 KV EL KRAM	**station TUNIS**	111	225
POSTE 150/225 KV BOUFICHA	**station SOUSSE**	112	225
POSTE 90/225 KV GROMBALIA	**station NABEUL**	113	225
POSTE 225 KV GOBAA	**station MANOUBA**	114	225
POSTE 150/250 KV SIDI MANSOUR	**station SFAX**	115	225
POSTE 150/225 KV MOKNINE	**station MONASTIR**	116	225
POSTE 150/225 KV MAKNASSY	**station SIDI BOUZID**	117	225
STATION 225 KV CEMINERIE SOTACIB	**station KAIROUAN**	118	225
station 225/90 KV EL OUINET(ALGEIRE)	**station(ALGERIA)**	119	225
POSTE 90/225/400 KV JENDOUBA	**station JENDOUBA**	120	400
POSTE 90/225/400 KV MORNAGUIA(LA MANOUBA)*	**station MANOUBA**	121	400
POSTE 90/225/400 KV MATEUR	**station BIZERTE**	122	400
POSTE 400 KV CHEFA(ALGERIE)	**station(ALGERIA)**	123	400

TABLE 2, Tunisian generators, 2016 R[1]

Name	Type	Bus	Name	Type	Bus
Rades A #1	ST	88	**Bouchemma #1**	GT	77
Rades A #2	ST	88	**Bouchemma #2**	GT	110
Rades B #1	ST	89	**Bouchemma #3**	GT	110
Rades B #2	ST	89	**Kasserine #1**	GT	50
Rades II #1	GT	90	**Kasserine #2**	GT	50
Rades II #2	GT	90	**Sfax #1**	GT	65
Rades II #3	GT	90	**Sfax #2**	GT	65
Sousse A #1	ST	95	**Korba #1**	GT	19
Sousse A #2	ST	95	**Korba #2**	GT	19
Sousse B #1	ST	95	**Menzel Bourghuiba #1**	GT	18
Sousse B #2	GT	53	**Menzel Bourghuiba #2**	GT	18
Sousse B #3	GT	53	**Zarzis #1**	GT	108
Sousse C #1	CC	53	**Robbana #1**	GT	59
Sousse D #1	CC	53	**El Bibane(IPP) #1**	GT	79
Ghannouch #1	CC	104	**Mornaguia(MANUOBA) #1**	CC	29
Ghoulette #1	GT	104	**Mornaguia(MANUOBA) #2**	CC	29
Thyina #1	GT	60	**Tunis sud #1**	GT	21
Thyina #2	GT	60	**Tunis sud #2**	GT	21
Thyina #3	GT	60	**Tunis sud #3**	GT	21
Feriana #1	GT	61	**Sidi Salem #1**	Hydro (run-of-rever)	31
Feriana #2	GT	61	**Nebeur/ Mellegue Dam #1**	Hydro(Dam)	26
Bir Mchergha #1	GT	98	**Nebeur/ Mellegue Dam #2**	Hydro(Dam)	26
Bir Mchergha #2	GT	98	**Aroussia #1**	Hydro(run-of-rever)	7
Bir Mchergha #3	GT	98	**Bouherthma #1**	Hydro(run-of-rever)	41
Bir Mchergha #4	GT	98	**Sejnane(Sidi El Barrak) #1**	Hydro(Dam)	31
			Sidi Daoued(Haouaria) #1	Wind	20
Bizerte, Kchabta #1	Wind	36	**Bizerte, Metline #1**	Wind	32

TABLE 3: Future Power Plants, Tunisia, 2035.

PROJECT	INFORMATION
100 MW WIND in Kebili'	Jbel Tbaga
100 MW PV Gafsa	LOCATION: https://www.protenders.com/projects/gafsa-100-mw-solar-photovoltaic-plant
200 MW PV in Borj Bourguiba (Tataouine)	LOCATION: https://www.africa-energy.com/database
200 MW PV in Tataouine	LOCATION: https://www.africa-energy.com/database
50 MW PV in Medenine	Location: from TunisiaSolarPlan picture
50 MW PV in Kasserine	Location: from TunisiaSolarPlan picture
100 MW PV in Sidi Bouzid	LOCATION: https://www.protenders.com/projects/sidi-bouzid-50-mw-solar-photovoltaic-plant
30 MW PV Sfax	
Remada , 1700 MW PV	LOCATION: https://www.africa-energy.com/database
TuNur: 4.5 GW in Sahara, Rejim Maatoug in Kebili'.	2000 MW from Tunisia to Italy >2000 MW from Tunisia to France [250-500] MW from Tunisia to Malta. 250 km^2 required CSP central tower Heat stored in Molten salt storage Construnction of 250 MW followed by a second construction of 2.25 GW and finally other 2GW construction
TOZEUR 1 10 MW-PV	The goal is to achieve 50 MW at touzer
TOZEUR 2 10 MW-PV	50 MW PV will be considered in the analysis.
TOUZER 50 MW PV	LOCATION: https://www.africa-energy.com/database
Gabes, 10 MW PV	
Tataouine , 10 MW PV	
Altus Kairouan 10 MW PV	LOCATION: https://www.africa-energy.com/database
Tozzi Sidi Bouzid 10 MW PV	LOCATION: https://www.africa-energy.com/database
EPPM Sidi Bouzid 10 MW PV	LOCATION: https://www.africa-energy.com/database
Rades C 450 MW CCGT	380 MW GT, Ramp Rate=38 MW/min LOCATION :
9 GT heavy duty at TUNISIA's Bir M'Cherga plant	New 256 MWel to existing plant, actual plant made of 475 MW
625 MW in Mornaguia, South west of Tunis	Open cycle ,gas fired power plant ,2 turbine,10ha needed

250 MW, Bouchemma plant,near the city of Gabes	2 heavy duty gas turbines
Skhira CCGT ,450 MW	Location : https://www.africa-energy.com/database
100 MW PV in the province of Kaiouran	LOCALIZATION: https://www.protenders.com/en/projects/kairouan-100-mw-solar-photovoltaic-plant
30 MW wind Mornag (Ben Arous)	Siemens Gamesa SG145 wind turbines 4.5 MW Mornag, Ben Arous governate
30 MW wind Jebel Sidi Bchir Bizerte	Jebel Kchabta, Bizerte governate
30 MW wind Jebel KochBata (Bizerte)	Jebel Sidi Bchir, Bizerte governate https://www.africa-energy.com/database
30 MW wind Batiha (Bizerte)	https://www.africa-energy.com/database/7384 El Batiha, Bizerte governate
ISGC 40MW ,CSP, ElBorna	
200 MW wind Nabeul	Jbel Abderrahmane Rades C electricity output will be distributed from the nearby Rades III switchyard to the 225kV Rades II substation via a 0.4km single-circuit transmission line and to the 225kV Kram substation via a 9km double-circuit transmission line.
100 MW wind Kabil Wind	Localization (approximate): https://www.africa-energy.com/database
Tbaga 80 MW WIND	Localization (approximate): https://www.africa-energy.com/database
Thala 230 MW wind (Kasserine)	Localization (approximate): https://www.africa-energy.com/database
Tunisian Solar Plan,Project 12: Construction of a concentrated solar power plant of 25 MW, integrated to combine cycle of 150 MW	
Tunisian Solar Plan,Project 13: Construnction of a CSP plant of 75 MW capacity whose production is totally or partially intended for exportation.	
Tunisian Solar Plan,Project 14: Construction of a solar/gas combine CSP plants in El borma by SITEP	3 gas turbines of 14 MW for each, 5 MWel of CSP to integrate with CCGT(steam integration)

TABLE 4: Future power plants, Tunisia 2035.

NAME	TYPE	BUS	NAME	TYPE	BUS
M'Cherga plant TG1	GT	98	SIDI BOUZID PV	PV	56
M'Cherga plant TG2	GT	98	KAIROUAN PV	PV	109
M'Cherga plant TG3	GT	98	TATAOUINE PV	PV	97
M'Cherga plant TG4	GT	98	MEDENINE PV	PV	96
M'Cherga plant TG5	GT	98	TOUZER 10 MW PV 1	PV	55
M'Cherga plant TG6	GT	98	SFAX PV	PV	70
M'Cherga plant TG7	GT	98	Tataouine 10 MW PV	PV	97
M'Cherga plant TG8	GT	98	Gabes 10 MW PV	PV	66
M'Cherga plant TG9	GT	98	Borj Bourguiba 200 MW PV	PV	97
Mornaguia GT1	GT	29	Touzer 10 MW PV 2	PV	55
Mornaguia GT2	GT	29	Touzer 5 MW PV	PV	55
Gabes TG1	GT	110	Touzer 50 MW PV	PV	55
Gabes TG2	GT	110	Altus Kairouan 10 MW PV	PV	109
Rades C	CCGT	90	Tozzi Sidi Bouzid 10 MW PV	PV	56
Skhira	CCGT	112	EPPM Sidi Bouzid 10 MW PV	PV	56
GAFSA PV	PV	68	Jebel Sidi Bchir 30 MW WIND	WIND	27
KASSERINE PV	PV	69	Khebili 100 MW WIND	WIND	62
JEBEL KCHABTA 30 MW WIND	WIND	32	Tbaga 80 MW WIND	WIND	62
EL BATIHA 30 MW WIND	WIND	30	Thala 230 MW WIND	WIND	93
Remada 1700 MW PV	PV	97	Mornag 30 MW WIND	WIND	113
			Nabeul 200 MW WIND	WIND	113

Tab 5: Decommissioning of older plant: Active power plants by 2035.

Active Power Plants in 2035	Type	Active Power Plants in 2035	Type
RADES A1	ST	M'Cherga plant TG5	GT
RADES A2	ST	M'Cherga plant TG6	GT
RADES B1	ST	M'Cherga plant TG7	GT
RADES B2	ST	M'Cherga plant TG8	GT
Rades II #1	GT	M'Cherga plant TG9	GT
Rades II #2	GT	Mornaguia GT1	GT
Rades II #3	GT	Mornaguia GT2	GT
Sousse C #1	CC	Gabes TG1	GT
Sousse D #1	CC	Gabes TG2	GT
Ghannouch #1	CC	Rades C	CC
Ghoulette #1	GT	Skhira	CC
Thyina #1	GT	GAFSA PV	PV
Thyina #2	GT	KASSERINE PV	PV
Thyina #3	GT	SIDI BOUZID PV	PV

Feriana #1	GT	KAIROUAN PV	PV
Feriana #2	GT	TATAOUINE PV	PV
Bir Mchergha #1	GT	MEDENINE PV	PV
Bir Mchergha #2	GT	TOUZER 10 MW PV 1	PV
Bir Mchergha #3	GT	SFAX PV	PV
Bir Mchergha #4	GT	Tataouine 10 MW PV	PV
Bouchemma #3	GT	Gabes 10 MW PV	PV
El Bibane(IPP) #1	GT	Borj Bourguiba 200 MW PV	PV
Mornaguia(MANUOBA) #1	CC	Touzer 10 MW PV 2	PV
Mornaguia(MANUOBA) #2	CC	Touzer 5 MW PV	PV
Sidi Salem #1	Hydro (run-of-rever)	Touzer 50 MW PV	PV
Nebeur/ Mellegue Dam #1	Hydro(Dam)	Altus Kairouan 10 MW PV	PV
Nebeur/ Mellegue Dam #2	Hydro(Dam)	Tozzi Sidi Bouzid 10 MW PV	PV
Aroussia #1	Hydro(run-of-rever)	EPPM Sidi Bouzid 10 MW PV	PV
Bouherthma #1	Hydro(run-of-rever)	Jebel Sidi Bchir 30 MW WIND	WIND
Sejnane(Sidi El Barrak) #1	Hydro(Dam)	Khebili 100 MW WIND	WIND
Sidi Daoued(Haouaria) #1	Wind	Tbaga 80 MW WIND	WIND
Bizerte, Metline #1	Wind	Thala 230 MW WIND	WIND
Bizerte, Kchabta #1	Wind	Mornag 30 MW WIND	WIND
M’Cherga plant TG1	GT	Nabeul 200 MW WIND	WIND
M’Cherga plant TG2	GT	JEBEL KCHABTA 30 MW WIND	WIND
M’Cherga plant TG3	GT	EL BATIHA 30 MW WIND	WIND
M’Cherga plant TG4	GT	Remada 1700 MW PV	PV

Table 6: Number of start-up for each thermal power plant, for overall year, for different scenario.

Generator	Type of generator	Nominal power	Start-up number S0M1	Start-up number S1M1	Start-up number S2M1	Start-up number S3M1	Start-up number S4M1	Start-up number S4M2	Start-up number S4M3
Rades A #1	ST	170	452	433	500	485	484	475	476
Rades A #2	ST	170	452	433	500	485	484	522	523
Rades B #1	ST	180	452	433	500	485	484	474	475
Rades B #2	ST	180	452	433	500	485	484	509	510
Rades II #1	GT	120	0	1	3	11	31	137	137
Rades II #2	GT	120	0	17	11	11	115	235	235
Rades II #3	GT	231	4	183	180	152	303	88	89
Sousse A #1	ST	160	452	433	500	485	0	0	0
Sousse A #2	ST	160	452	433	500	485	0	0	0
Sousse B #1	ST	128	28	231	241	209	0	0	0
Sousse B #2	GT	118	0	120	116	131	0	0	0
Sousse B #3	GT	118	4	227	200	134	0	0	0
Sousse C #1	CC	424	1	1	1	1	1	556	557
Sousse D #1	CC	424	1	1	1	1	1	187	193
Ghannouch #1	CC	412	1	1	1	1	1	522	519

Ghoulette #1	GT	120	4	220	205	155	311	135	135
Thyina #1	GT	120	0	37	28	36	140	117	117
Thyina #2	GT	120	0	50	40	32	117	246	247
Thyina #3	GT	120	4	203	184	151	332	281	279
Feriana #1	GT	120	0	95	67	77	131	136	136
Feriana #2	GT	120	4	221	200	137	327	253	254
Bir Mchergha #1	GT	120	0	0	0	0	9	108	107
Bir Mchergha #2	GT	120	0	0	0	0	20	220	220
Bir Mchergha #3	GT	120	0	3	0	0	48	258	257
Bir Mchergha #4	GT	120	4	7	6	4	118	267	267
Bouchemma #1	GT	120	3	177	175	144	0	0	0
Bouchemma #2	GT	60	0	6	6	0	0	0	0
Bouchemma #3	GT	60	0	8	8	1	28	152	152
Kasserine #1	GT	30	4	147	105	146	0	0	0
Kasserine #2	GT	30	0	238	214	149	0	0	0
Sfax #1	GT	20	0	89	74	88	0	0	0
Sfax #2	GT	20	4	223	205	138	0	0	0
Korba #1	GT	20	4	231	193	129	0	0	0
Korba #2	GT	20	0	184	156	166	0	0	0
Menzel Bourghuiba #1	GT	20	7	199	199	161	0	0	0
Menzel Bourghuiba #2	GT	30	14	206	207	168	0	0	0
Zarzis #1	GT	20	4	180	178	145	0	0	0
Robbana #1	GT	20	14	205	209	173	0	0	0
El Bibane(IPP) #1	GT	20	14	205	209	173	300	302	303
Mornaguia(MA NUOBA) #1	CC	300	1	1	1	1	1	35	33
Mornaguia(MA NUOBA) #2	CC	300	1	1	1	1	1	5	5
Tunis sud #1	GT	30	0	171	145	140	0	0	0
Tunis sud #2	GT	30	0	164	133	103	0	0	0
Tunis sud #3	GT	27	4	202	188	141	0	0	0
M'Cherga plant TG1	GT	28	0	6	4	4	71	172	172
M'Cherga plant TG2	GT	28	0	14	12	6	104	332	333
M'Cherga plant TG3	GT	28	0	17	13	12	128	417	417
M'Cherga plant TG4	GT	28	0	31	27	15	151	414	414
M'Cherga plant TG5	GT	28	0	51	49	34	180	380	382

M'Cherga plant TG6	GT	28	0	71	69	56	210	356	358
M'Cherga plant TG7	GT	28	0	105	98	79	241	331	333
M'Cherga plant TG8	GT	28	0	131	123	108	290	320	321
M'Cherga plant TG9	GT	28	0	196	190	159	361	313	313
Mornaguia GT1	GT	310	0	230	206	149	346	65	64
Mornaguia GT2	GT	310	0	198	180	119	279	97	97
Gabes TG1	GT	125	0	35	33	20	123	86	86
Gabes TG2	GT	125	0	160	135	81	328	147	147
Rades C	CCGT	450	0	1	1	1	1	605	606
Skhira	CCGT	450	0	1	1	1	1	594	592

TABLE 7: Branch power flow matrix for different scenario.

name	**length []**	**voltage**	**Fbus**	**tbus**	**MBPF S0M1 [MW]**	**MBPFR S0 M1**	**MBPFR S1M1**	**MBPFR S2M1**	**MBPFR S3M1**	**MBPFR S4M1**	**MBPFR S4M2**	**MBPFR S4M3**
LINE 90 KV ZAHROUNIA-MNHLIA I-2	19.749 [km]	90 KV	35	44	63.57225979	1	1.469196099	1.469196099	1.449058373	1.812516354	1.783334668	1.783334668
LINE 90 KV OUED ZARGA- BEJA	26.549 [km]	90 KV	6	5	26.46906427	1	1.805836533	1.805836533	1.318219308	1.443547622	1.580926916	1.580926916
LINE 90 KV MENZEL JEMIL-METLINE	9.614[km]	90 KV	25	32	87.6368052	1	1.133663383	1.133663383	1.133663383	1.133663383	1.133663383	1.133663383
LIGNE 90 Kv MENZEL BOURGUIBA-KCHABTA	11.734 [km]	90 KV	18	36	64.77241105	1	1.117879945	1.104100539	1.072588524	1.137465536	1.146895875	1.146895875
LIGNE 90 Kv NAASAN BOURJ CEDRIA	18.753 [km]	90 KV	23	1	56.18000954	1	1.643739974	2.013754661	1.910916341	1.910916341	2.071605773	2.071605773
LINE 90 KV MENZEL TEMIM - GROMBALIA	46.922 [km]	90 KV	2	34	13.89450713	1	2.768997228	2.921262058	2.962606264	3.058809433	3.01768358	3.01768358
LINE 90 KV KORBA-GROMBALIA	32.001 [km]	90 KV	19	34	36.234375	1	1.923102277	2.081823685	2.217253539	2.21725354	2.482495087	2.482495087
LINE 90 KV MORNAGUIA-ZAHROUNI-2	22.268 [km]	90 KV	29	35	122.8268408	1	1.485206153	1.485206153	1.416441811	1.861799513	1.835050771	1.835050771

LINE 90 KV MORNAGUIA-ZAHROUNI-1	22.059 [km]	90 KV	29	35	124.02 32842	1	1.4852 06153	1.4852 06153	1.4164 41811	1.8617 99513	1.8350 50771	1.8350 50771
LINE 90 KV TABARSOUK(GAAFOUR)-JENDOUBA	55.971 [km]	90 KV	28	16	55.792 80136	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 90 Kv ETTAREF SIDI EL BARRAK	60.158 [km]	90 KV	27	31	16.918 2	1	2.2986 93026	2.2986 93026	2.2449 39307	2.3200 19268	2.3717 71714	2.3717 71714
LIGNE 90 Kv MENZEL BOURGUIBA MATEUR-1	19.304 [km]	90 KV	18	30	40.141 09843	1	1.3292 00853	1.3292 00853	1.2634 55695	0.8481 58358	0.8850 97851	0.8850 97851
LIGNE 90 Kv MATEUR ETTAREF	30.822 [km]	90 KV	30	27	33.209 73711	1	2.0026 50891	2.0026 50891	1.9518 34197	1.9586 04643	1.9712 0715	1.9712 0715
LINE 90 KV ZAHROUNIA-MNHLIA I-1	19.789 [km]	90 KV	35	44	63.439 23042	1	1.4691 96099	1.4691 96099	1.4490 58373	1.8125 16354	1.7833 34668	1.7833 34668
LINE 90 KV T.OUEST-MNHILA I	10.572 [km]	90 KV	13	44	14.055 20797	1	0.7093 22688	0.7423 59033	0.7858 1704	0.9268 71566	1.3433 34165	1.3433 34165
LINE 90 KV T.NORD-MNHLIA I-1	6.348[km]	90 KV	12	44	25.811 75063	1	2.0228 24991	2.0228 24991	2.0051 81641	1.9887 01761	2.1038 31734	2.1038 31734
LINE 90 KV KORBA-MENZEL TEMIME	31.161 [km]	90 KV	19	2	57.294 72257	1	0.9792 21014	0.9826 49899	0.9164 68225	0.8703 8842	0.9183 89966	0.9183 89966
LINE 90 KV KORBA-AIN KMICHA(NAB EUL)	15.875 [km]	90 KV	19	3	123.50 68537	1	0.8729 50812	0.9133 2437	0.8349 97446	0.8117 5225	0.8978 21464	0.8978 21464
LINE 90 KV AIN KMICHA(NAB EUL)-HAMMAMAT	10.343 [km]	90 KV	3	4	153.48 46098	1	0.9903 20105	1.0774 2396	1.0086 05091	0.9887 41952	0.9890 00307	0.9890 00307
LIGNE 90 KV BOURJ CEDRIA MENZEL TEMIM	13.011 [km]	90 KV	1	2	36.805 97016	1	1.4645 66322	1.7515 97439	1.5946 26769	1.5946 26769	1.7794 29839	1.7794 29839
LINE 90 KV AROUSSIA-OUED ZARGA	35.442 [km]	90 KV	7	6	70.762 36196	1	1.7471 42835	1.7471 42835	1.5450 7367	1.6366 35745	1.6550 01329	1.6550 01329
LINE 90 KV OUED ZARGA- SIDI SALEM	9.161[km]	90 KV	6	15	22.187 24479	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053

LINE 90 KV JENDOUBA-NEBEUR	18.409 [km]	90 KV	16	26	7.0116 97228	1	3.8825 65694	8.2052 02293	7.9971 31736	7.9971 31736	7.8396 16964	7.8396 16964
LINE 90 KV JENDOUBA-BARBARA/FE RNANA	35.394 [km]	90 KV	16	24	15.289 2258	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LINE 90 KV BEJA-BOUHERTMA	38.513 [km]	90 KV	5	41	4.9501 19991	1	3.7433 45896	8.2689 38596	6.5224 40489	6.5224 4049	6.5561 61462	6.5561 61462
LINE 90 KV MATEUR-AROUSSIA	26.068 [km]	90 KV	30	7	16.717 21799	1	2.2984 0807	2.8866 90707	2.7071 78534	2.7071 78534	2.2261 68674	2.2261 68674
LIGNE 90 Kv MENZEL BOURGUIBA MATEUR-2	19.25[km]	90 KV	18	30	21.044 10054	1	1.3292 00853	1.3292 00853	1.2634 55695	0.8481 58358	0.8850 97851	0.8850 97851
LINE 90 KV SIDI BARAK-TABARKA	29.894 [km]	90 KV	31	8	28.365 30563	1	1.2754 48702	1.2754 48702	1.2106 25691	1.2325 71604	1.2784 70939	1.2784 70939
LINE 90 KV TABARKA-BOUHERTMA	26.792 [km]	90 KV	8	41	15.906 30901	1	0.9897 95149	0.9897 95149	0.8409 71323	0.8409 71323	0.8772 23843	0.8772 23843
LINE 90 KV JENDOUBA-BOUHETRMA	25.269 [km]	90 KV	16	41	13.005 90782	1	2.5718 69305	4.7493 94677	4.2666 80397	4.2666 80398	4.2385 56177	4.2385 56177
LINE 90 KV NEBEUR-TAJEROUNIE	57.21[km]	90 KV	26	11	8.2170 91889	1	3.0534 88049	6.7420 21592	6.5644 73651	6.5644 73651	6.4946 0865	6.4946 0865
LINE 90 KV TAJEROUINE-CIMENTTRE OUM EL KELIL	4.78[k m]	90 KV	11	42	11.269 91986	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LINE 90 KV MORNAGUIA-ZAHROUNI-3	22.234 [km]	90 KV	29	35	64.606 36072	1	1.4852 06153	1.4852 06153	1.4164 41811	1.8617 99513	1.8350 50771	1.8350 50771
LINE 90 KV MORNAGUIA-ZAHROUNI-4	22.045 [km]	90 KV	29	35	65.160 25513	1	1.4852 06153	1.4852 06153	1.4164 41811	1.8617 99513	1.8350 50771	1.8350 50771
LINE 90 KV ZAHROUNI-BEN AROUSSIA	28.996 [km]	90 KV	35	7	90.475 42102	1	1.7029 11776	1.7029 11776	1.5806 99694	1.8360 12845	1.8721 545	1.8721 545
LINE 90 KV ZAHROUNI-KASBAH	6.955[km]	90 KV	35	40	67.012 28047	1	1.5301 6059	1.5301 6059	1.5165 95899	1.8070 49341	1.7642 70908	1.7642 70908
LINE 90 KV KASBAH-T.OUEST	3.211[km]	90 KV	40	13	48.031 71617	1	1.4580 3846	1.4580 3846	1.4367 97737	1.8124 28063	1.7872 99755	1.7872 99755
LINE 90 KV ZAHROUNI-T. SUD	11.523 [km]	90 KV	35	21	117.12 97962	1	0.8639 43854	0.8635 56101	0.8683 00629	1.2963 01954	1.4435 88768	1.4435 88768

LINE 90 KV T.SUD-MGHIRA(BEN AROUS)	6.256[km]	90 KV	21	14	17.30812904	1	2.024621493	2.024621493	2.028815448	2.295126235	2.255272955	2.255272955
LINE 90 KV NASSAN-MGHIRA(BEN AROUS)	5.343[km]	90 KV	23	14	12.50619703	1	1.624166271	2.002311905	1.963711075	1.890232411	1.958692363	1.958692363
LINE 90 KV NAASSAN-T.SUD-1	6.885[km]	90 KV	23	21	15.69021139	1	1.353554895	1.353554895	1.250734099	1.849850577	1.986130605	1.986130605
LINE 90 KV NAASSAN-T.SUD-2	6.796[km]	90 KV	23	21	15.89568944	1	1.353554895	1.353554895	1.250734099	1.849850577	1.986130605	1.986130605
LINE 90 KV NAASSAN-T.SUD-3	6.719[km]	90 KV	23	21	16.07785466	1	1.353554895	1.353554895	1.250734099	1.849850577	1.986130605	1.986130605
LINE 90 KV T.SUD-T.CENTRE	4.392[km]	90 KV	21	22	26.13937696	1	1.223277966	1.223277966	1.30308173	1.388637825	1.379675692	1.379675692
LINE 90 KV T.CENTRE-BARTHOU	3.541[km]	90 KV	22	39	19.59482354	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV LAC OUEST-URBAINE NORD(CUN)	1.891[km]	90 KV	38	37	19.59482354	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV CUN-T.NORD	4.615[km]	90 KV	37	12	39.18964708	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV GAMMARTH-EL KRAM-1	5.105[km]	90 KV	17	33	9.817521794	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV GAMMARTH-EL KRAM-2	5.126[km]	90 KV	17	33	9.777301747	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV EL KRAM-LA GOULETTE	3.979[km]	90 KV	33	10	11.03850714	1	0.783287476	0.688238857	0.655667518	0.92792705	1.153600415	1.153600415
LINE 90 KV T.CENTRE-LA GOULETTE	8.784[km]	90 KV	22	10	14.68425139	1	3.025049824	3.030779206	3.110238698	3.430914993	3.749722232	3.749722232
LINE 1- 90 KV LA GOULETTE-RADES II(CARTAGE)	2.017[km]	90 KV	10	46	6.106379351	1	1.296204431	1.171159424	1.182781938	1.514014383	1.764746864	1.764746864
LINE 2- 90 KV LA GOULETTE-RADES II (CARTAGE)	2.001[km]	90 KV	10	46	6.155205973	1	1.296204431	1.171159424	1.182781938	1.514014383	1.764746864	1.764746864

LINE-1 90 KV/ T. SUD-RADES II (CARTAGE)	9.794[km]	90 KV	21	46	11.97974672	1	2.557281768	2.387560796	2.489916996	3.170029142	3.56117726	3.56117726
LINE-2 90 KV-T. SUD-RADES II (CARTAGE)	9.796[km]	90 KV	21	46	11.97730087	1	2.557281768	2.387560796	2.489916996	3.170029142	3.56117726	3.56117726
LINE 90KV T NORD-T OUEST	4.75[km]	90 KV	12	13	22.06117751	1	1.468884862	1.468884862	1.448716369	1.812513891	1.783396957	1.783396957
LINE 90 KV T.NORD-MNHLIA I-2	6.342[km]	90 KV	12	44	11.44399944	1	2.022824991	2.022824991	2.005181641	1.988701761	2.103831734	2.103831734
LINE 90 KV MENZEL TEMIME-SIDI DAOUD	21.201 [km]	90 KV	2	20	31.31313689	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 90 KV KCHABTA-MENZEL JEMIL	17.735 [km]	90 KV	36	25	45.92982931	1	1.344456884	1.281375928	1.236894221	1.562951436	1.548940899	1.548940899
LINE 90 KV MENZEL JEMIL-CIMENTERIE BIZERTE	14.56[km]	90 KV	25	9	38.4709909	1	1.515562544	1.515562544	1.519812276	1.737225281	1.716709823	1.716709823
LINE 90 KV MATEUR-KCHABTA	21.976 [km]	90 KV	30	36	33.32012387	1	1.192052743	1.192052743	1.145383253	1.055312079	1.070744757	1.070744757
LINE 90 KV CIMENNTRIE BIZERTE-BIZERTE	6.112[km]	90 KV	9	43	24.15535958	1	1.373585053	1.275392786	1.255882271	1.60214471	1.569470803	1.569470803
LINE 90 KV BIZERTE-MENZEL BOURGUIBA	23.519 [km]	90 KV	43	18	10.9769967	1	1.318963523	1.899989681	2.100337909	2.100337909	2.175942767	2.175942767
LINE 150 KV-SIDI MANSOUR-THYNA	44.054 [km]	150 KV	81	60	26.05357206	1	1.302248809	1.905102393	1.918973329	1.918973329	1.997312486	1.997312486
LIGNE 150 KV METLAOUI TOZEUR	61.569 [km]	150 kv	51	55	8.168192694	1	3.394663297	4.809351634	4.739288555	4.739288555	4.811113232	4.811113232
LINE 150 KV MDHILA-TOZEUR	71.335 [km]	150 kv	52	55	24.69640386	1	1.529558029	1.788837503	1.786565201	1.726676486	1.847412556	1.847412556
LINE 150 KV MDHILA-METLOUI	32.808 [km]	150 KV	52	51	39.88877601	1	1.554086737	2.713890514	2.655770893	2.655770893	2.699119901	2.699119901

LIGNE 150 KV FERIANA SOTACIB	3.571[km]	150 KV	61	78	20.120 19223	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 150 Kv GHANNOUCH BOUCHEMM A 1	4.079[km]	150 KV	72	77	12.291 00971	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 150 Kv BOUCHEMM A CIMENTERIE DE GABES	6.627[km]	150 KV	77	66	16.260 53241	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 150 Kv SFAX SIDI MANSOUR	22.822 [km]	150 KV	65	81	53.475 01176	1	1.3576 32707	1.3576 32707	1.3900 30317	1.2668 33502	1.4220 66893	1.4220 66893
LIGNE 150 Kv SOUSSE MSAKEN NORD II	13.672 [km]	150 KV	53	48	208.54 54187	1	1.1316 9821	1.1287 1948	1.1094 43714	1.0114 63342	1.0064 99824	1.0064 99824
LIGNE 150 Kv MSAKEN NORDII-MSAKEN 3	2.304[km]	150 KV	48	75	9.9602 35154	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 150 Kv MSAKEN NORD-AKOUDA	22.739 [km]	150 KV	48	58	44.422 53914	1	1.6318 64354	1.6318 64354	1.6655 46714	2.0048 67605	2.1650 76857	2.1650 76857
LIGNE 150 Kv BOUCHEMM A KEBILI	100.61 6[km]	150 KV	77	62	61.288 18391	1	1.4982 31337	2.3480 07734	2.3279 91617	2.3220 56453	2.3208 85491	2.3208 85491
LIGNE 150 Kv MAKNASSY-THYNA	108.87 6[km]	150 KV	63	60	40.780 63536	1	3.7131 8184	6.9496 89251	6.9774 25026	6.9774 25026	7.4362 73554	7.4362 73554
LIGNE 150 Kv SFAX THYNA	23.159 [km]	150 KV	65	60	3.5352 5477	1	13.167 72102	21.604 95839	21.702 89819	24.708 92185	26.897 1747	26.897 1747
LIGNE 150 Kv MSAKEN II-ELJEM	39.734 [km]	150 KV	48	67	201.11 68709	1	1.4299 38586	1.4289 22798	1.4591 7448	1.4301 01468	1.5324 34642	1.5324 34642
LINE 150 KV M'SAKEN-MSAKEN II 1	2.256[km]	150 KV	75	48	10.172 15505	1	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053	1.7535 06053
LIGNE 150 Kv SOUSSE AKKOUDA	15.457 [km]	150 KV	53	58	145.13 27322	1	0.9364 51284	1.1668 92124	1.1640 60288	1.1640 60286	1.3467 92554	1.3467 92554
LIGNE 150 Kv ENFIDHA SUD-BOUFICHA	29.311 [km]	150 KV	76	74	96.592 89526	1	0.8184 75878	0.9499 63153	0.9286 20749	1.3618 50648	1.6562 33483	1.6562 33483
LIGNE 150 KV BOUFICHA-HAMMAMET	53.029 [km]	150 KV	74	85	110.20 50032	1	1.3634 08667	1.9278 89105	1.9100 31159	1.9100 31159	1.9587 97847	1.9587 97847

LIGNE 150 Kv BOUCHEMMA GABES SUD	21.557 [km]	150 KV	77	73	9.789607663	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
ligne 150 Kv ROBANA-ZARZIS	36.941 [km]	150 KV	59	71	19.63234067	1	2.025087984	6.045543403	6.023401555	6.023401555	6.031809312	6.031809312
ligne 150 Kv ROBANA Midoun	24.262 [km]	150 KV	59	64	2.071394366	1	5.416897453	26.60021351	26.48257942	26.48257942	26.45494613	26.45494613
LIGNE 150 Kv MEKNASSY SIDI BOUZID	56.676 [km]	150 KV	63	56	30.73545917	1	2.435838109	2.435838109	2.435838109	2.435838109	2.435838109	2.435838109
LIGNE 150 Kv BOUCHEMMA MDHILLA	142.486[km]	150 KV	77	52	58.96602058	1	1.462424058	2.577661633	2.550600515	2.542576373	2.540993272	2.540993272
Ligne 150 KV Feriana Mdhilla	83.926 [km]	150 KV	61	52	20.11874669	1	2.771765626	6.174851578	6.005124055	6.005124055	6.254398374	6.1917065
LIGNE 150 Kv MKSNASSY-SKHIRA	60.887 [km]	150 KV	63	70	6.757541392	1	4.917352347	20.90247932	20.74474975	20.74474975	21.74017	21.74017
LIGNE 150 KV METLAOUI FERIANA	72.83[km]	150 KV	51	61	9.658014818	1	4.730701653	10.37891777	10.07962134	10.07962134	10.52483414	10.38316111
LIGNE 150 Kv RADES HAMMAMET	82.233 [km]	150 KV	87	85	321.935596	1	0.906381029	0.906381029	0.899826497	0.917514755	0.917206782	0.917206782
LIGNE 150 KV MDHILLA KEBILI	86.728 [km]	150 KV	52	62	26.58960119	1	3.860073632	5.399756668	5.329112391	5.329112391	5.280722508	5.280722508
LINE 150 KV KASSERIN NORTH-SOUTH	6.218[km]	150 KV	50	69	42.68059729	1	2.398115631	4.54816352	4.40043095	4.40043095	4.624530056	4.624530056
LINE 150 KV FERIANA-KASSERIN SOUTH	44.297 [km]	150 KV	61	69	23.02612635	1	3.218943216	7.796610373	7.522777328	7.522777328	7.865866543	7.716243359
LIGNE 150 KV MDHILLA GAFSA	28.375 [km]	150 KV	52	68	27.94531917	1	2.906203392	2.460677166	2.38918051	2.375037206	2.531427232	2.531427232
LIGNE 150 Kv BOUCHEMMA SKHIRA	63.998 [km]	150 KV	77	70	55.45939527	1	1.792729953	3.265538111	3.246319291	3.246319291	3.39148597	3.39148597
LIGNE 150 Kv GHANNOUCH BOUCHEMMA 2	4.802[km]	150 KV	72	77	10.44044744	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
150 KV LINE BOUCHEMMA ROBANA	99.946 [km]	150 KV	77	59	19.53769424	1	2.028969075	7.969065081	7.934344356	7.934344356	7.92773135	7.92773135

LINE 150 KV-ZARZIS-MIDOUN	41.64[km]	150 KV	71	64	16.46757855	1	1.812456279	4.444495304	4.429698557	4.429698557	4.44061625	4.44061625
LIGNE 150 Kv SIDI MANSOUR TABAROURA	24.11[km]	150 KV	81	80	50.8361336	1	1.343742558	1.343742558	1.374725712	1.22438106	1.402613653	1.402613653
LINE 150 KV THYNA-TAPARURA	13.487 [km]	150 KV	60	80	11.02490953	1	6.592602426	8.6768242	8.715232947	9.97877925	10.83563469	10.83563469
LIGNE 150 Kv SIDI MANSOUR EL JEM	64.117 [km]	150 KV	81	67	186.9764214	1	1.360819022	1.360819022	1.394199188	1.277317581	1.431921618	1.431921618
LINE 150 KV ELJEM-KESSOUR ESSEF	34.501 [km]	150 KV	67	83	47.67565377	1	1.187516662	1.187516662	1.204890646	1.079493273	1.223963079	1.223963079
LIGNE 150 Kv MOKNINE-KESSOUR ESSEF	28.533 [km]	150 KV	82	83	108.53506	1	1.327801165	1.327801165	1.369792263	1.316824917	1.404024817	1.404024817
LINE 150 KV MONASTIR-SOUSSE	16.139 [km]	150 KV	54	53	203.4028012	1	1.507369464	1.507369464	1.524210784	1.452929848	1.498311091	1.498311091
LINE 150 KV MONASTIR-MOKNINE	17.451 [km]	150 KV	54	82	155.9689306	1	1.432793733	1.432793733	1.454476626	1.403009157	1.458222527	1.458222527
LINE 150 KV M'SAKEN-M'SAKEN II 2	2.28[km]	150 KV	75	48	10.06507973	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 150 KV SAHLOUL-M'SAKEN II	13.727 [km]	150 KV	84	48	103.5891481	1	1.064011565	1.044225883	1.029811578	0.989250785	0.957678447	1.010697626
LINE 150 KV SAHLUOL-SOUSSE	10.787 [km]	150 KV	84	53	132.498816	1	1.213086199	1.213086199	1.188669321	1.061653774	1.080650715	1.080650715
LINE 150 KV AKOUDA-ENFIDHA SUD	37.222 [km]	150 KV	58	76	114.1428743	1	0.74449817	1.183184119	1.182226227	1.182226225	1.713791124	1.713791124
LINE 150 KV GHANNOUCH-GABES SUD	24.865 [km]	150 KV	72	73	6.470924745	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LINE 150 KV ZARZIS-SEEB IPP	9.562[km]	150 KV	71	79	15.16122479	1	1.598428943	1.715178052	1.715178052	1.704839578	1.704839578	1.704839578
LIGNE 150 Kv MEKNASSY GAFSA	84.185 [km]	150 KV	63	68	55.74611191	1	1.277226932	1.297235986	1.362652931	1.613571451	1.83650947	1.83650947
LINE 150 KV KASSARINE	5.695[km]	150 KV	50	86	62.37318233	1	2.093730072	2.785322271	2.684232122	2.684232122	2.823566537	2.823566537

NORD-BOULAABA												
LINE 150 KV BOULAABA-TAJEROUNIE	75.247 [km]	150 KV	86	49	82.286 91809	1	1.9302 24284	1.9302 24284	2.0419 90764	1.8907 0634	2.1440 41159	2.1440 41159
LIGNE 1- 225 KV ZERZIS-MEDENINE	35.774 [km]	225 kv	10 8	96	40.526 49422	1	1.6962 50107	3.2014 49929	3.1969 85253	3.1942 02754	3.1942 02754	3.1942 02754
LINE 225 KV MEDININE-TATAOUINE	45.64[km]	225 kv	96	97	4.5082 35731	1	47.752 92492	253.76 93879	253.73 77092	253.73 77092	253.52 79851	253.52 79851
LINE 1-225 KV GANNOUCH-BOUCHEMM A	4.996[km]	225 kv	10 4	11 0	207.95 14855	1	1.2160 33937	1.2160 33937	1.2123 7255	1.2204 98606	1.2251 42776	1.2251 42776
LINE 2- 225 KV BOUCHEMM A GANNOUCH	4.969[km]	225 kv	10 4	11 0	209.08 14292	1	1.2160 33937	1.2160 33937	1.2123 7255	1.2204 98606	1.2251 42776	1.2251 42776
LIGNE 225 Kv NAASAN BIR MCHARGA	32.501 [km]	225 kv	10 2	98	37.560 49421	1	3.0166 59438	5.7066 85978	5.4955 00266	5.4955 00263	7.6367 24644	7.6367 24644
LIGNE 225 Kv TAJEROUIN JANDOUBA	74.154 [km]	225 kv	93	99	26.536 40583	1	5.6536 43746	10.092 11335	10.010 43104	10.010 43105	9.8999 85259	9.8999 85259
LIGNE 225 Kv SOUSSE-MSAKEN NORD II-3	14.116 [km]	225 kv	95	92	148.05 20647	1	1.4557 83853	1.4557 83853	1.3848 8001	1.0583 51782	1.0400 08664	1.0400 08664
LIGNE 225 Kv SOUSSE MSAKEN NORD II	22.836 [km]	225 kv	95	92	91.517 9079	1	1.4557 83853	1.4557 83853	1.3848 8001	1.0583 51782	1.0400 08664	1.0400 08664
LIGNE 225 Kv MOKNINE-SIDI MANSOUR	101.06 4[km]	225 kv	11 6	11 5	49.672 74511	1	1.8242 46356	6.4341 38822	6.3985 5478	6.3985 5478	7.2169 2728	7.2169 2728
LIGNE 225 Kv SOUSSE MOKNINE	47.754 [km]	225 kv	95	11 6	97.106 61573	1	1.6856 86123	2.8165 2588	2.7983 23649	2.7983 23649	3.1744 99767	3.1744 99767
LIGNE 1- 225 Kv BOUCHEMM A SIDI MANSOUR	154.47 6[km]	225 kv	11 0	11 5	37.997 98922	1	3.0199 67419	11.263 07744	11.199 3822	11.199 3822	12.536 39258	12.536 39258
LIGNE 225 Kv SIDI MANSOUR MSAKEN NORD II	98.282 [km]	225 kv	11 5	92	82.012 4866	1	1.8341 07172	5.7368 00731	5.6994 34274	5.6994 34274	6.4943 72223	6.4943 72223

LIGNE 225 Kv SOUSSE NAASAN	125.666[km]	225 kv	95	102	92.42873638	1	1.137894257	2.570439875	2.460210415	2.460210415	3.045750395	3.045750395
LIGNE 225 Kv OUESLATIA HAJEB LAYOUN	50.106 [km]	225 kv	105	106	116.8854666	1	1.994312154	3.809645732	3.752256383	3.752256383	4.165677481	4.165677481
LIGNE 225 Kv OUESLATIA TAJEROUIN	102.348[km]	225 kv	105	93	134.829108	1	1.419461061	1.710709797	1.525946884	1.429919335	1.431207996	1.431207996
LIGNE2- 225 Kv LA GOULETTE MNIHLA 2	25.807 [km]	225 kv	91	101	62.90519105	1	3.134292432	3.134292432	3.325175337	3.175355954	3.530558856	3.530558856
LIGNE1- 225 Kv LA GOULETTE MNIHLA 1	25.544 [km]	225 kv	91	101	63.55286038	1	3.134292432	3.134292432	3.325175337	3.175355954	3.530558856	3.530558856
LIGNE 1- 225 Kv BOUCHEMMA MEDENINE	93.334 [km]	225 kv	110	96	47.14164677	1	1.489115461	9.808291693	9.813972588	9.813972588	9.850210204	9.850210204
LIGNE 225 Kv KAIROUAN CIMENTERIE SOTACIB	23.787 [km]	225 kv	109	118	36.12622966	1	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053	1.753506053
LIGNE 225 Kv KAIROUAN OUESLATEIA	50.86[km]	225 kv	109	105	106.3642201	1	1.231131887	1.189457518	1.042963778	0.649768454	0.821474956	0.821474956
LIGNE 225 Kv MSAKEN NORD OUESLATEIA	90.137 [km]	225 kv	92	105	135.3953247	1	1.057408477	1.057408477	1.013949391	0.585948029	0.649601054	0.703592896
LIGNE 225 Kv MEKNASSY HAJEB LAYOUN	87.495 [km]	225 kv	117	106	81.52701468	1	2.237311274	5.928792737	5.846513497	5.846513497	6.440627048	6.440627048
LIGNE 225 Kv BOUCHEMMA MEKNASSY	89.654 [km]	225 kv	110	117	127.9729085	1	1.772967185	5.000596912	4.949846885	4.949846885	5.259734837	5.259734837
LIGNE 225 Kv BOUFICHA BIR M'CHERGA(ZAGHOUAN)	41.887 [km]	225 kv	112	98	140.3992306	1	2.396411568	2.808537345	2.620860966	2.465549502	2.660889794	2.660889794
LIGNE 225 Kv OUESLATIA BIR MCHARGA	83.694 [km]	225 kv	105	98	58.67278345	1	4.153367411	5.808183512	5.756556635	6.042170345	6.737247156	6.737247156
DIV 225 Kv MORNAGUIA-	36.769 [km]	225 kv	107	98	75.03238172	1	2.098525977	3.049256346	2.863002141	2.768200777	3.367217845	3.367217845

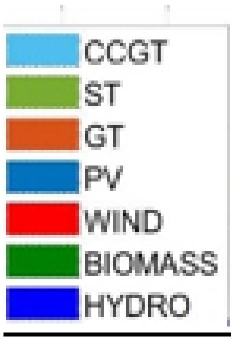
BIR MCHARGA											
LIGNE 225 Kv MNIHLA 1 MENZEL JEMIL	40.133 [km]	225 kv	101	103	105.317842	1	1.811482754	1.811482754	1.777895732	1.969854358	1.966819614	1.966819614
LIGNE 225 Kv BOUCHEMMA TATAOUINE	118.047[km]	225 kv	110	97	33.21022456	1	3.66100518	22.19463508	22.19893542	22.19893542	22.22740514	22.22740514
LINE 225 KV GROMBALIA-RADES A	27.883 [km]	225 kv	113	88	38.69009713	1	1.787091527	2.156764669	1.9431819	1.9431819	2.193900502	2.193900502
LINE 225 KV GROMBALIA RADES II(CARTAGE)	27.831 [km]	225 kv	113	90	36.38481137	1	2.47088019	2.569203539	2.218857767	2.491944927	2.46150773	2.46150773
LIGNE 2- 225 Kv BOUCHEMMA SIDI MANSOUR	155.021[km]	225 kv	110	115	37.86440148	1	3.019967419	11.26307744	11.1993822	11.1993822	12.53639258	12.53639258
LIGNE 2- 225 Kv BOUCHEMMA MEDENINE	93.357 [km]	225 kv	110	96	47.13003267	1	1.489115461	9.808291693	9.813972588	9.813972588	9.850210204	9.850210204
LIGNE 225 Kv SOUSSE MSAKEN NORD II	22.678 [km]	225 kv	95	92	92.15552275	1	1.455783853	1.455783853	1.38488001	1.058351782	1.040008664	1.040008664
LINE 225KV KAIROUAN-M'SAKEN NORDII	39.102 [km]	225 kv	109	92	174.6242435	1	1.202476767	1.202476767	1.17190358	0.765841035	0.813448633	0.813448633
LINE 225KV BOUFICHA-SOUSSE	88.471 [km]	225 kv	112	95	79.5866986	1	1.888233868	2.55935517	2.520448658	3.471850957	3.839391571	3.839391571
LINE 225 KV MORNAGUIA-MNIHLA I	44.826 [km]	225 kv	107	101	46.48130012	1	1.092467103	1.89502416	1.873921637	1.873921636	2.630033461	2.630033461
LIGNE 225 Kv NAASAN MORNAGUIA	33.877 [km]	225 kv	102	107	65.89182802	1	1.063417868	1.200911281	1.069356774	0.981875056	1.182247251	1.182247251
LINE 225 KV MNHLIA-GOBBA	10.767 [km]	225 kv	101	114	43.9612503	1	0.920600409	1.839533393	1.792730554	1.792730554	2.683891081	2.683891081
LINE 225 KV MORNAGUIA-GOBBA	27.699 [km]	225 kv	107	114	58.13350581	1	1.142987396	1.929348697	1.921969634	1.921969633	2.614201989	2.614201989
LINE 1-225 KV RADES A-LA GOULETTE	2.234[km]	225 kv	88	91	123.8014398	1	0.726289328	0.74492073	0.736934294	0.736934294	0.963740633	0.963740633

LINE2- 225 KV RADES A -LA GOULETTE	2.185[km]	225 kv	88	91	126.577765	1	0.726289328	0.74492073	0.736934294	0.736934294	0.963740633	0.963740633
LINE 1- 225 KV LA GOULETTE-RADES II(CARTAGE)	2.315[km]	225 kv	91	90	40.70060535	1	6.676396142	6.676396142	7.502519451	7.911947603	8.653067764	8.653067764
LINE 2- 225 KV LA GOULETTE-RADES II(CARTAGE)	2.294[km]	225 kv	91	90	41.07319153	1	6.676396142	6.676396142	7.502519451	7.911947603	8.653067764	8.653067764
LINE 225 KV EL KRAM-RADES A	5.838[km]	225 kv	111	88	55.70250684	1	1.892423847	1.9124601	1.915487601	1.955731092	2.03961117	2.03961117
LIGNE 225 Kv RADES A-NAASAN	13.908 [km]	225 kv	88	102	103.086127	1	2.167115839	2.573687971	2.442047522	3.447360451	3.686863839	3.686863839
LIGNE-2 225 KV ZERZIS-MEDENINE	35.495 [km]	225 kv	108	96	40.84504309	1	1.696250107	3.201449929	3.196985253	3.194202754	3.194202754	3.194202754
LIGNE 400 Kv MATEUR MORNAGUIA	49.42[km]	400 KV	122	121	148.6552376	1	1.865770126	1.865770126	1.734305746	2.005021658	2.027475919	2.027475919
LIGNE 400 Kv JANDOUBA MATEUR	117.11 [km]	400 kv	120	122	117.5171395	1	1.724545538	1.724545538	1.629283905	1.937881296	2.081169153	2.081169153
HAMMAMET 90/150 KV TRANSF. LINE	Transformator		85	4	183.4623659	1	1.070228231	1.187895795	1.125477747	1.107891409	1.108108677	1.108108677
GOULETTE 90/225 KV TRANSF. LINE	Transformator		91	10	36.40964874	1	2.314456576	2.340352426	2.369295395	2.490446076	2.650874701	2.650874701
TAJEROUINE 90/150 KV TRANSF. LINE	Transformator		49	11	23.24015483	1	2.47849604	3.46969511	3.422044022	3.422044022	3.422044018	3.422044018
TAJEROUINE 150/225 KV TRANSF. LINE	Transformator		93	49	110.4040099	1	1.830837139	1.830837139	1.918884589	1.870369677	1.959503514	1.959503514
JENDOUBA 90/225 KV TRANSF. LINE	Transformator		99	16	88.48920591	1	1.91033895	1.91033895	1.855164137	1.845622484	1.854019194	1.854019194
JENDOUBA 225/400 KV TRANSF. LINE	Transformator		120	99	102.5527921	1	1.728856946	1.728856946	1.644736747	1.993683225	2.136180409	2.136180409
NAASSEN 90/225KV TRANSF. LINE	Transformator		102	23	46.49891713	1	2.248005056	3.27913235	3.187065415	3.173279312	3.192577074	3.192577074
MENZEL JEMIL 90/225	Transformator		25	103	89.69688975	1	1.807976279	1.807976279	1.768539988	1.994781729	1.990365467	1.990365467

KV TRANSF. LINE											
MORNAGUILA 90/225 KV TRANSF. LINE	Transformator	107	29	254.7035613	1	1.218260859	1.218260859	1.104184619	1.69608022	1.942627699	1.942627699
MORNAGUILA 225/400 KV TRANSF. LINE	Transformator	121	107	172.000861	1	1.861134566	1.861134566	1.747513806	1.980820719	1.999615973	1.999615973
MATEUR 90/400 TRANSF. LINE	Transformator	122	30	57.33862934	1	1.403664753	2.02113889	2.045071466	2.005866405	2.005866405	2.005866405
EL KRAM 90/225 KV TRANSF. LINE	Transformator	111	33	36.13802011	1	1.983673727	2.02835682	2.033023357	2.091842291	2.194503434	2.194503434
GROMBALIA 90/225 KV TRANSF. LINE	Transformator	113	34	55.70086912	1	2.611331204	2.962452294	2.791569386	2.791569386	2.836664495	2.836664495
MNHILA 1 90/225 KV TRANSF. LINE	Transformator	101	44	74.38778708	1	1.01705974	1.288149968	1.340121368	1.340121368	1.436772428	1.436772428
RADES II(CPC) 90/225 KV TRANSF. LINE	Transformator	90	46	34.65143761		2.741689511	2.732917798	2.884447429	2.997311553	3.241373551	3.241373551
MSAKEN II NORD 150/225 KV TRANSF. LINE	Transformator	92	48	152.5304227		0.745942357	1.309399108	1.383125616	1.383125616	1.725990498	1.725990498
SOUSSE 150/225 KV TRANSF. LINE	Transformator	95	53	250.2386705		0.810485334	0.810485334	0.781444611	0.781446557	0.998898805	0.998898805
MEKNASSY 150/225 KV TRANSF. LINE	Transformator	117	63	162.1641844		1.452234928	1.588386087	1.587165916	1.558469894	1.641015331	1.641015331
ZARZIS 150/220KV TRANSF. LINE	Transformator	71	108	66.21031252		1.73042885	3.558645413	3.55315839	3.549738738	3.549738738	3.549738738
BUOFICHA 150/225 KV TRANSF. LINE	Transformator	74	112	102.7583855		1.519007185	1.715794363	1.734465026	1.734465026	2.164270479	2.164270479
BOUCHEMMA 150/225 KV TRANSF. LINE	Transformator	77	110	222.8493721		1.409985698	1.95868484	1.947367666	1.926183018	1.925538139	1.925538139
RADES A 150/225 KV TRANSF. LINE	Transformator	87	89	349.967798		0.931223273	0.931223273	0.928208514	0.936344234	0.936202582	0.936202582

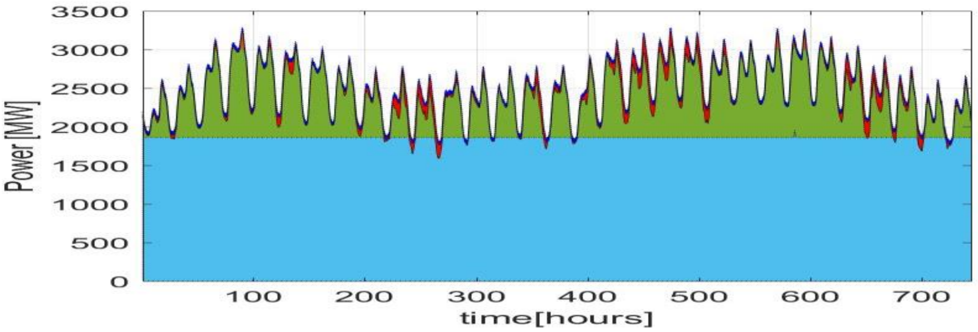
CHAPTER 12: PLOT APPENDIX

COLOUR LEGEND

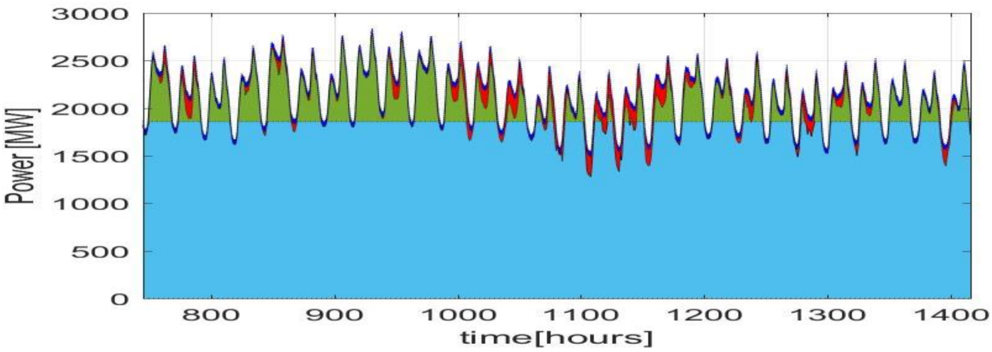


S0M1

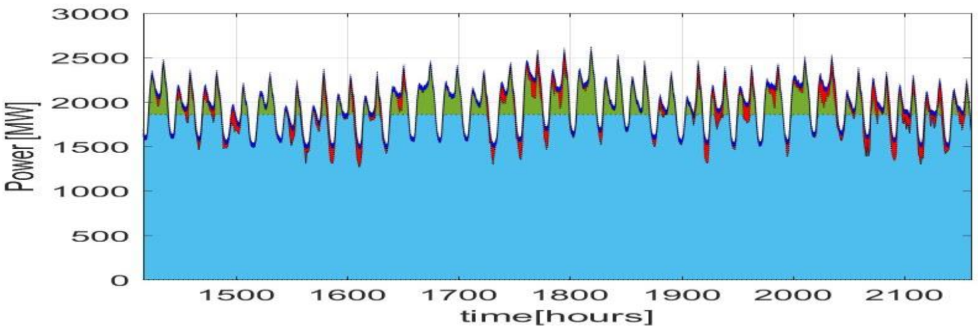
JENUARY



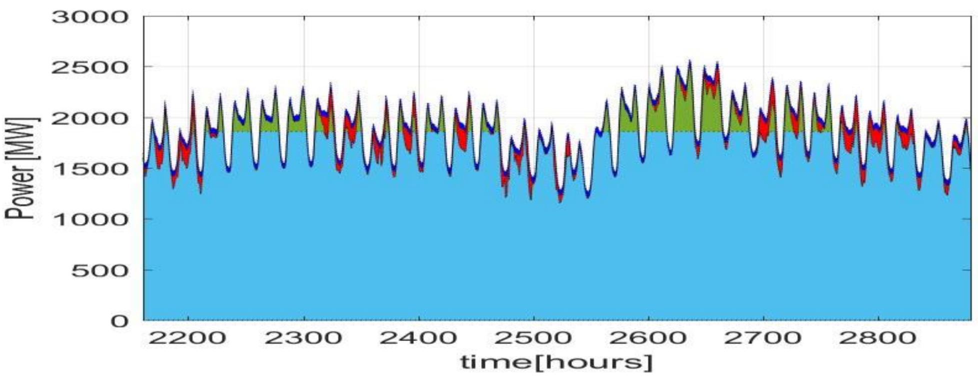
FEBRUARY



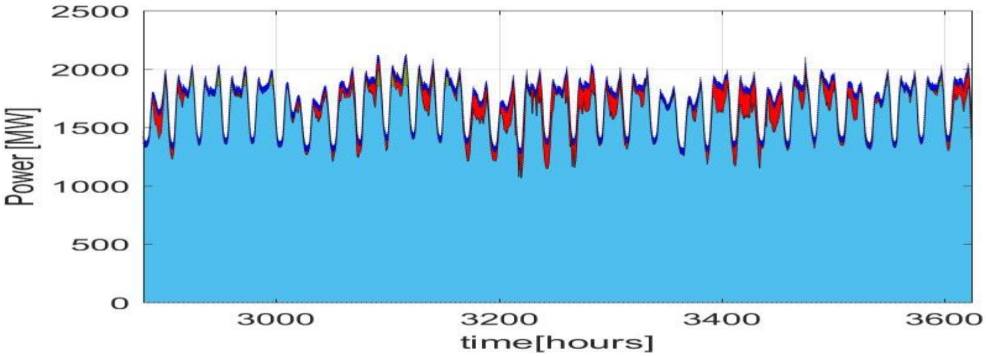
MARCH



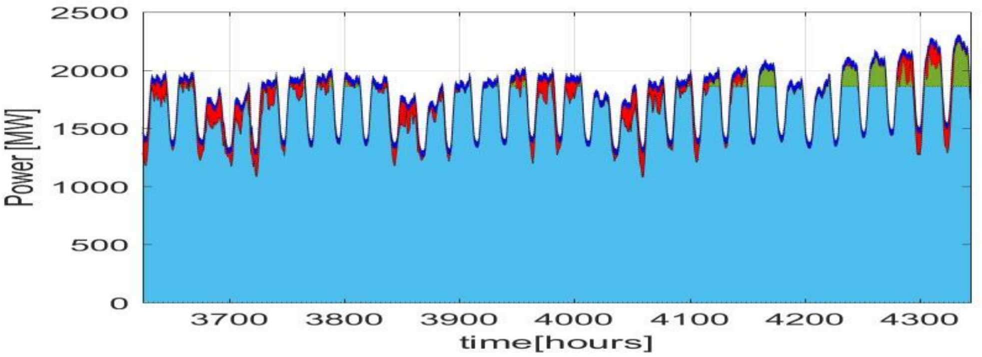
APRIL



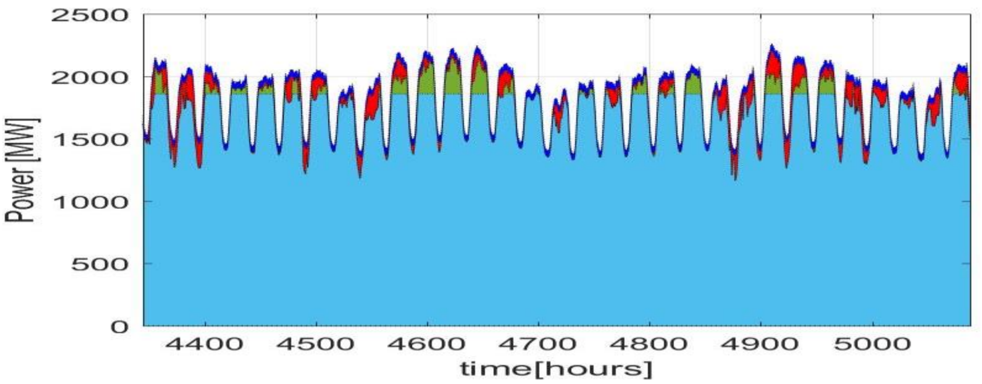
MAY



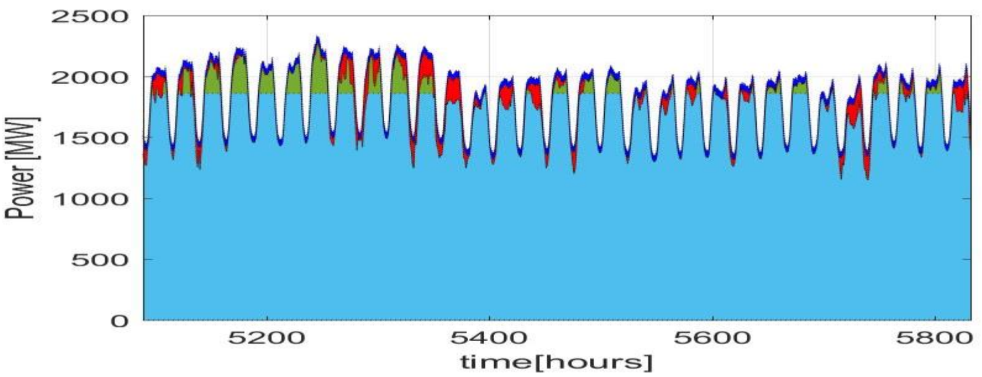
JUNE



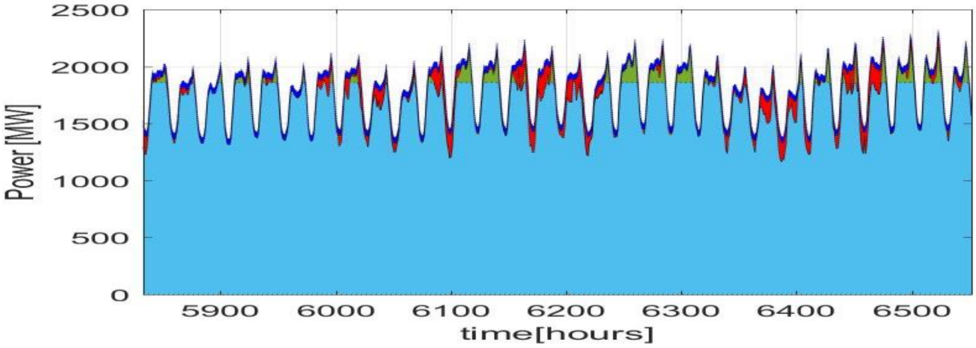
JULY



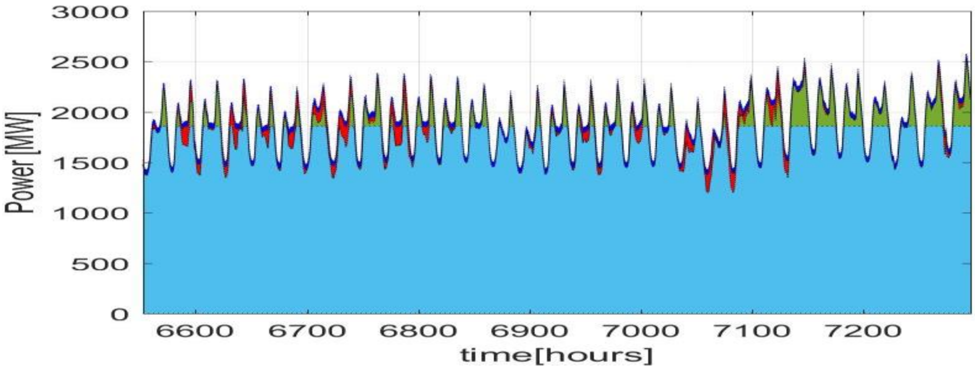
AUGUST



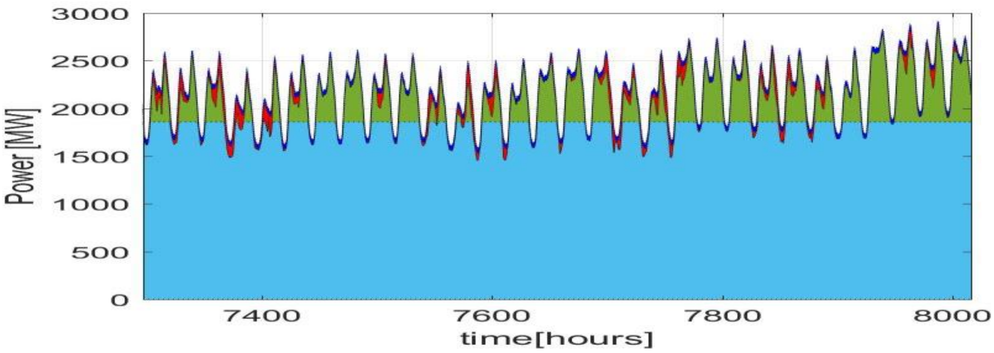
SEPTEMBER



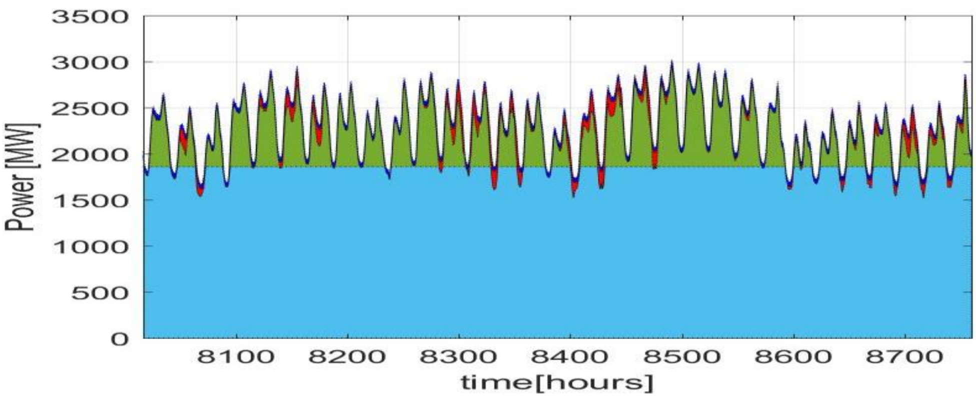
OCTOBER



NOVEMBER

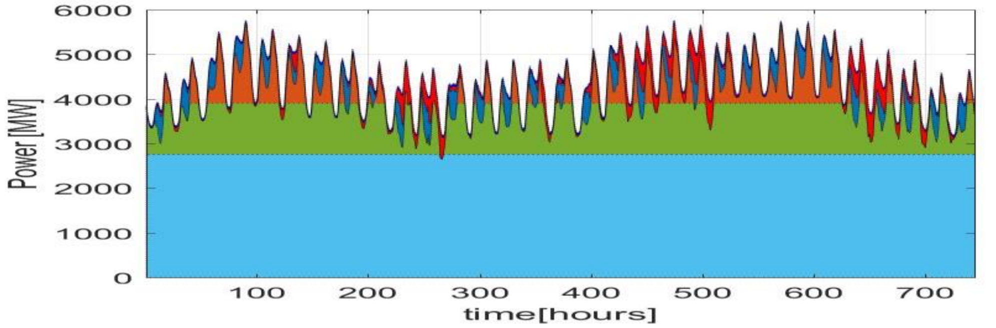


DECEMBER

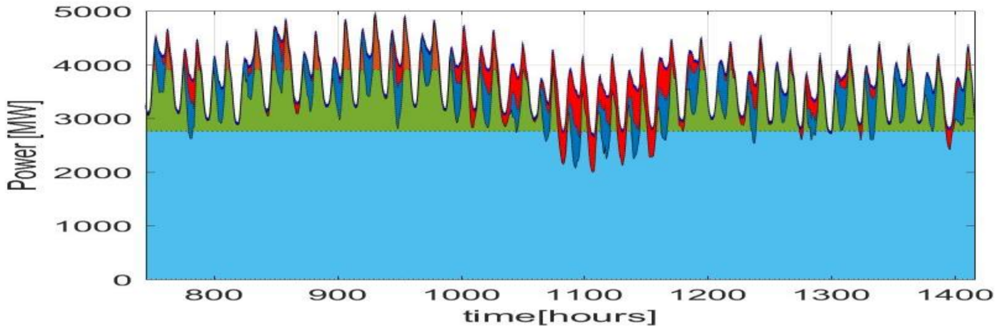


S1M1

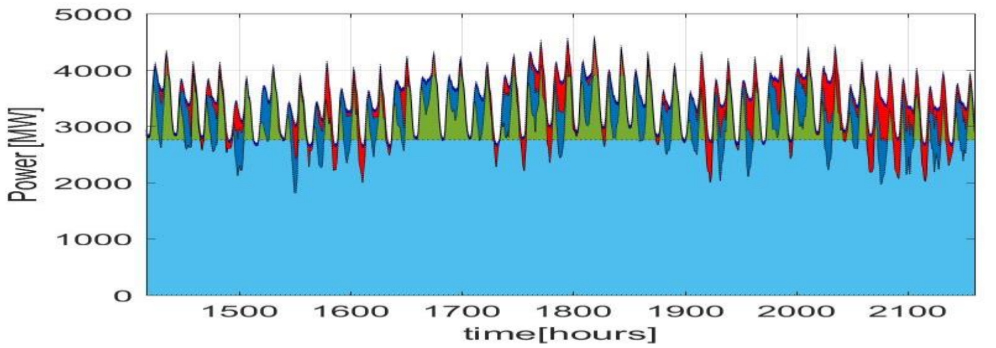
JENUARY



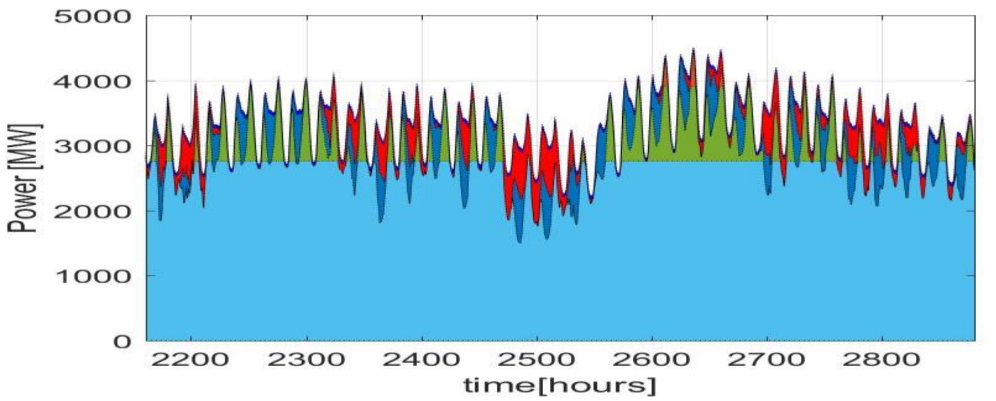
FEBRUARY



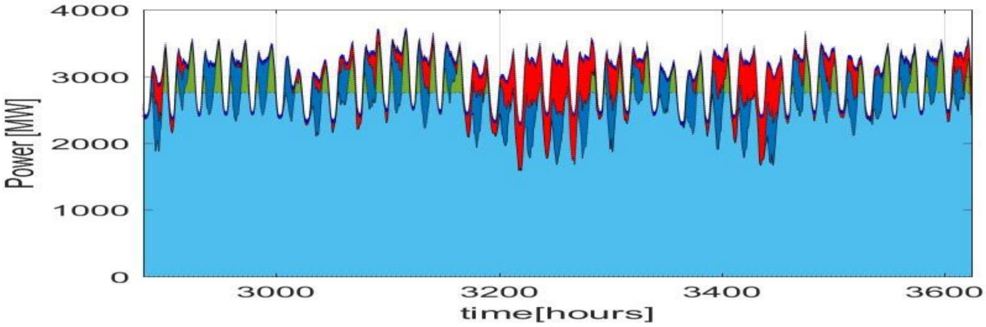
MARCH



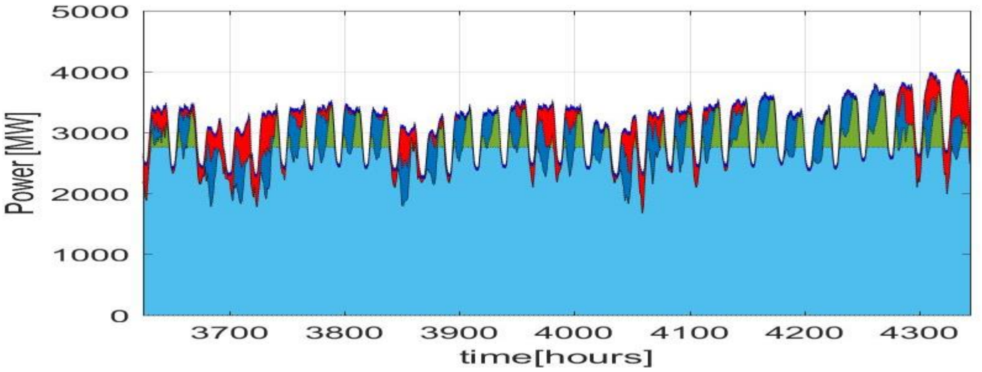
APRIL



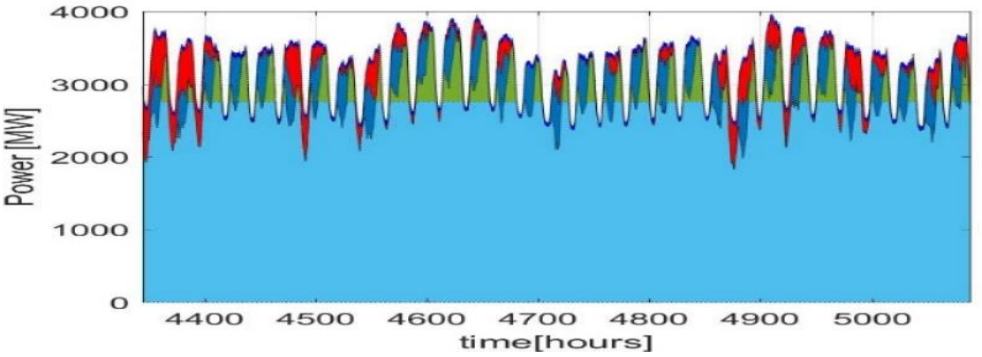
MAY



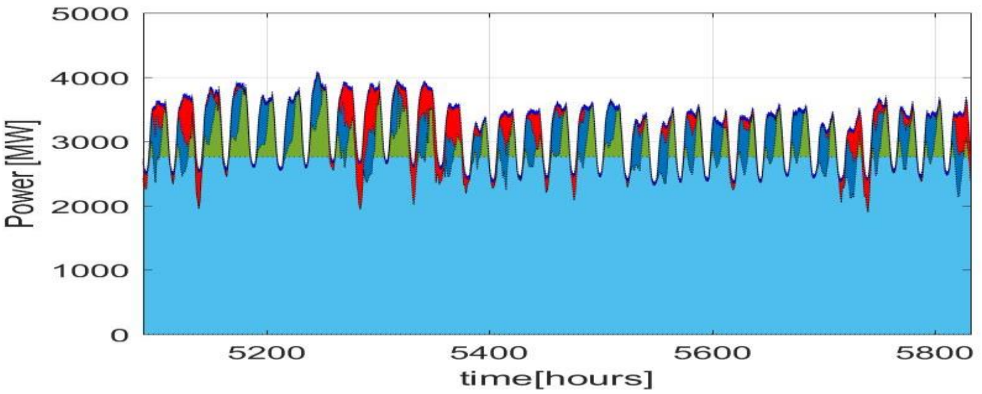
JUNE



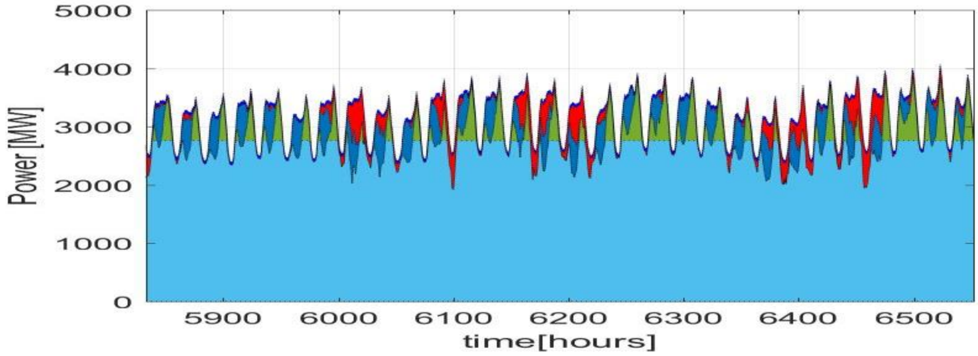
JULY



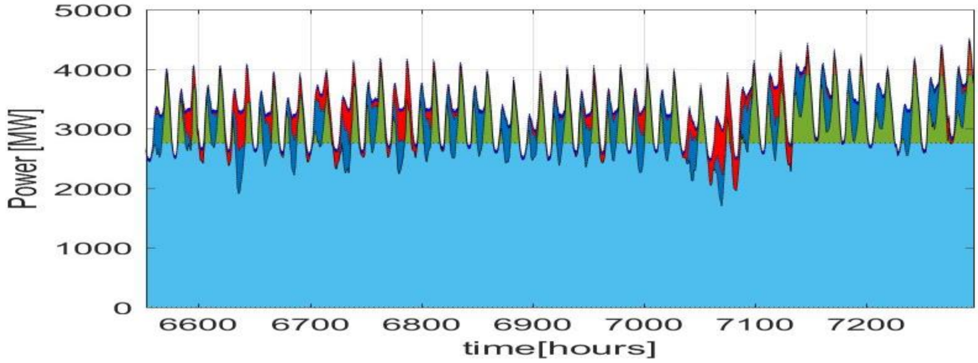
AUGUST



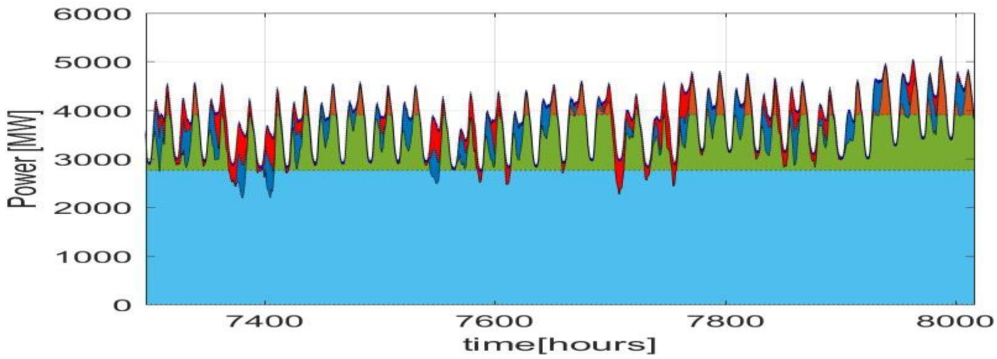
SEPTEMBER



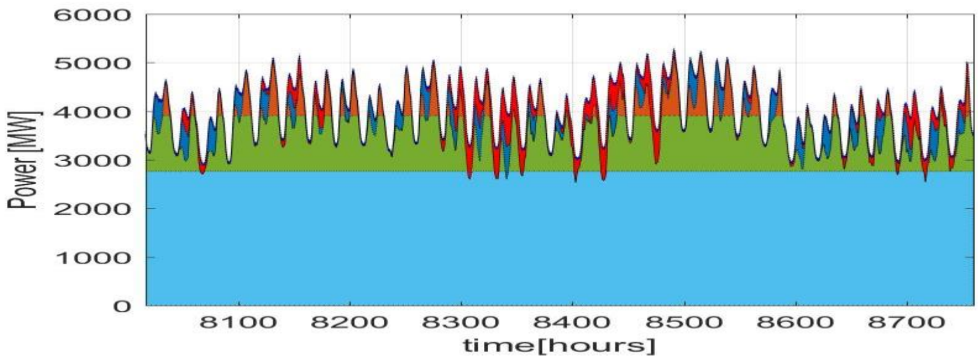
OCTOBER



NOVEMBER

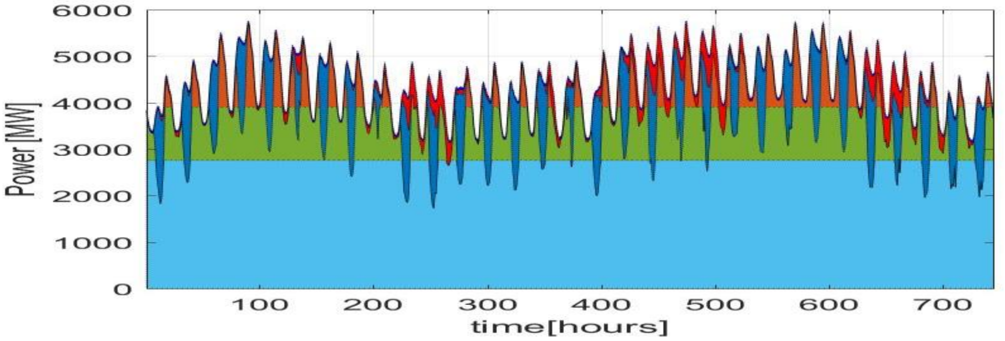


DECEMBER

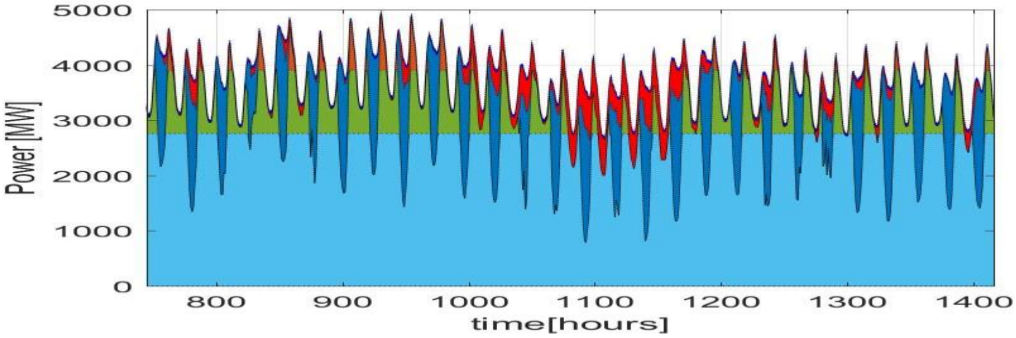


S2M1

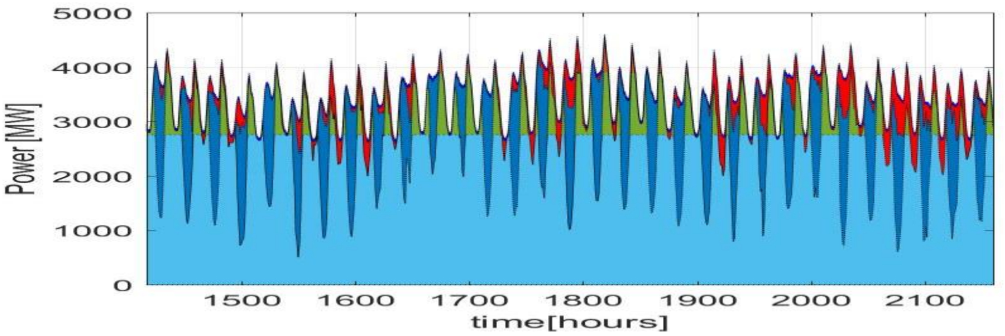
JENUARY



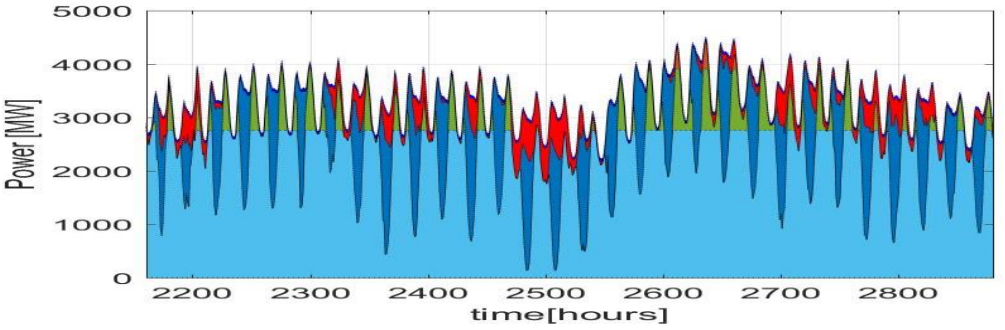
FEBRUARY



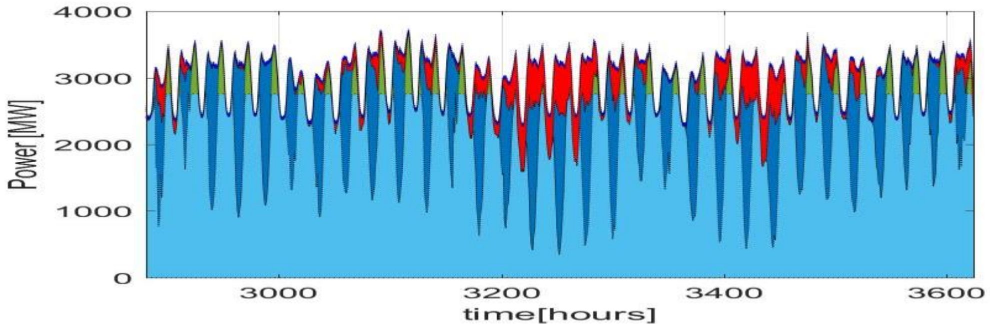
MARCH



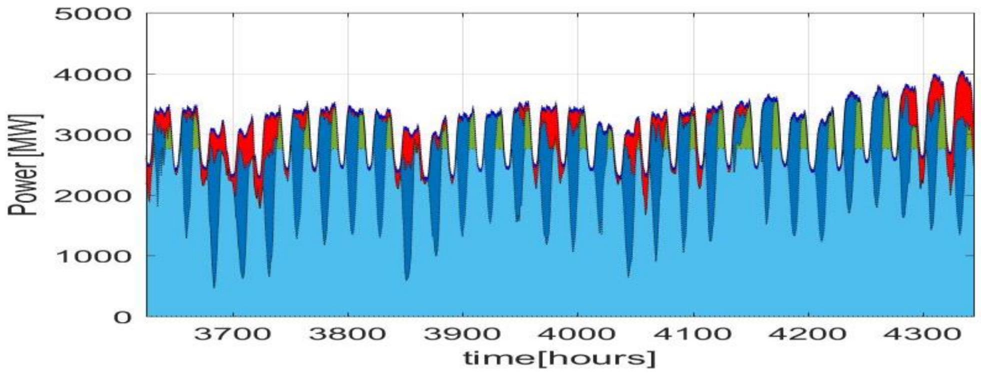
APRIL



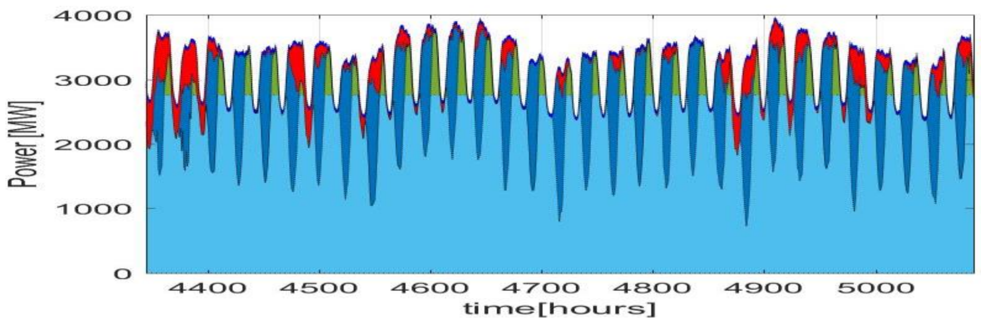
MAY



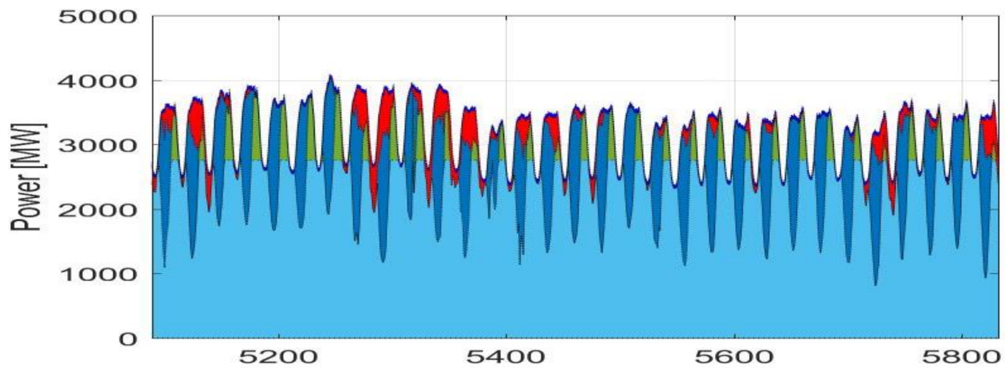
JUNE



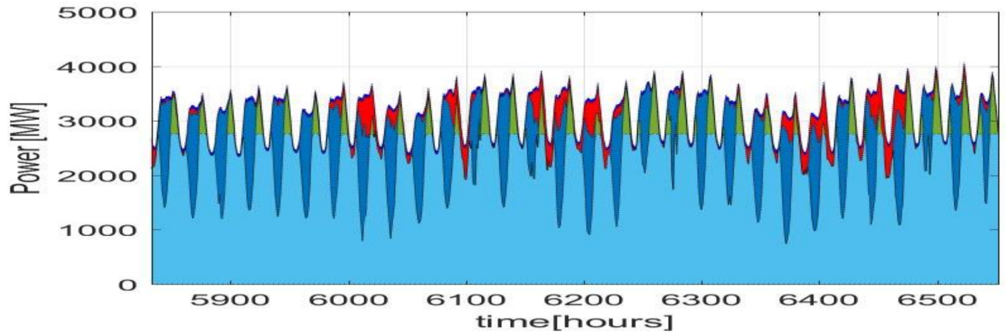
JULY



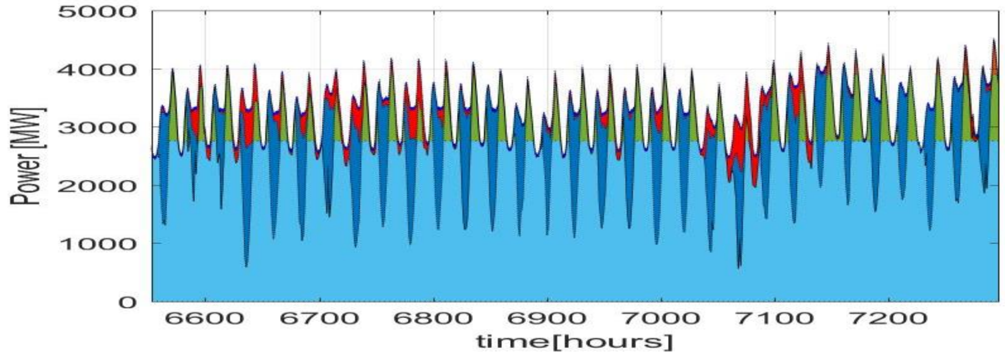
AUGUST



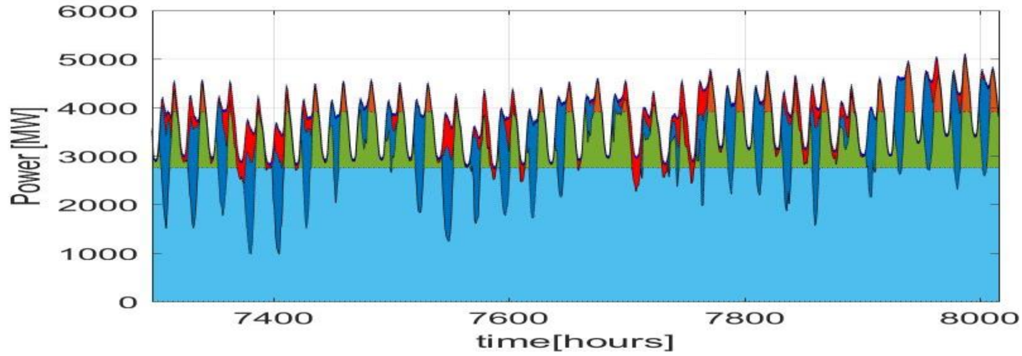
SEPTEMBER



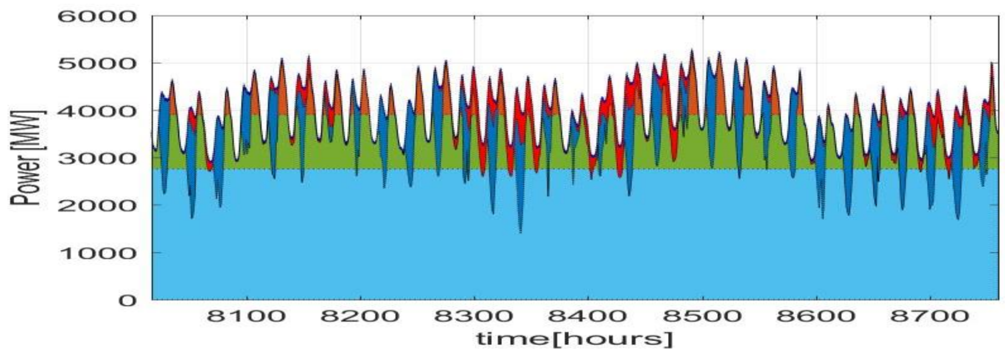
OCTOBER



NOVEMBER

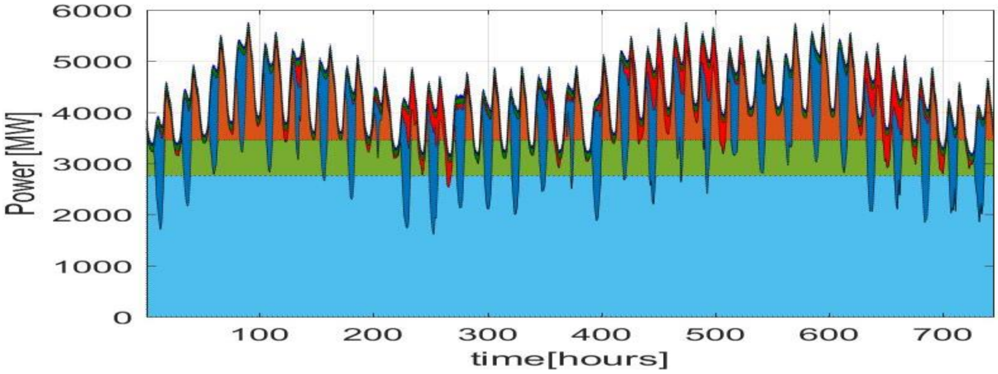


DECEMBER

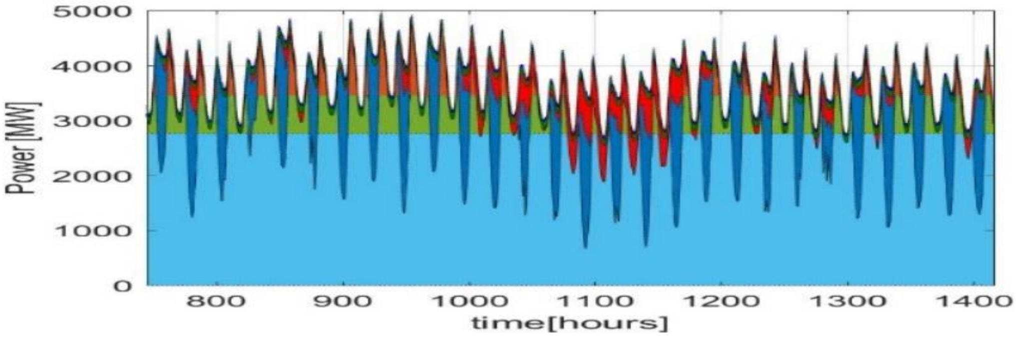


S4M1

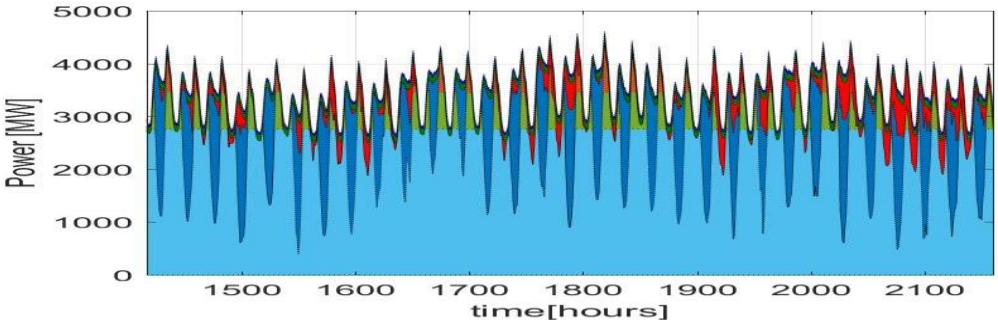
JENUARY



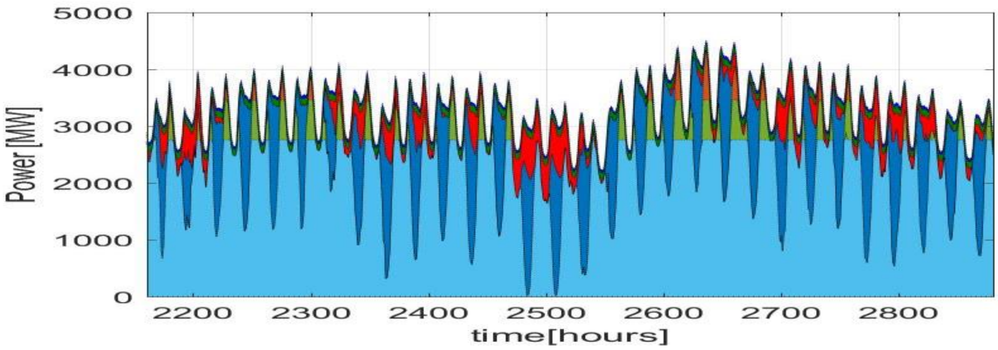
FEBRUARY



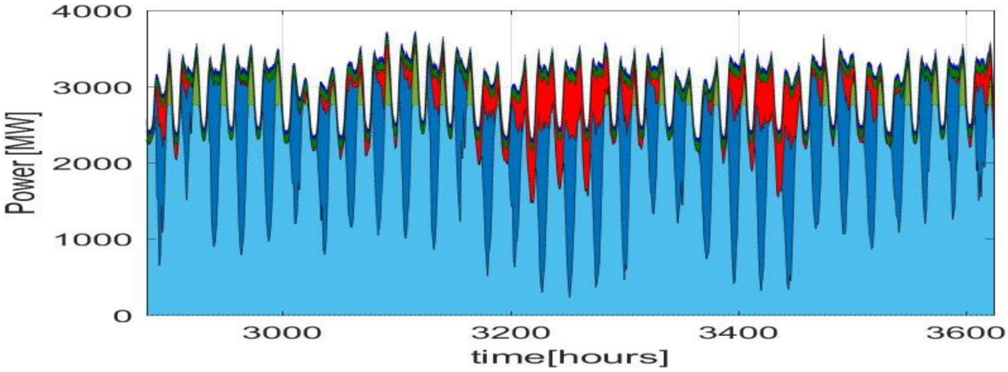
MARCH



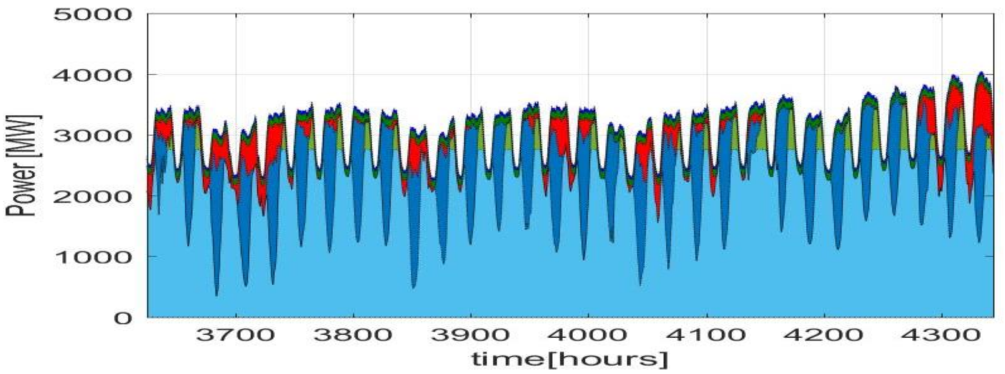
APRIL



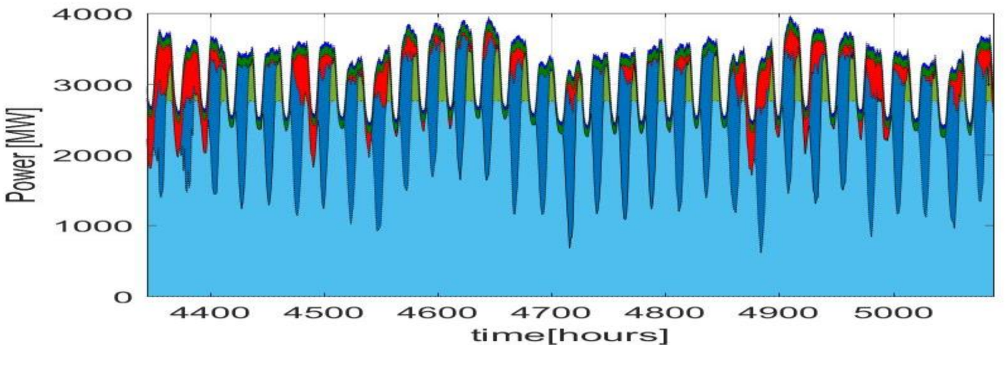
MAY



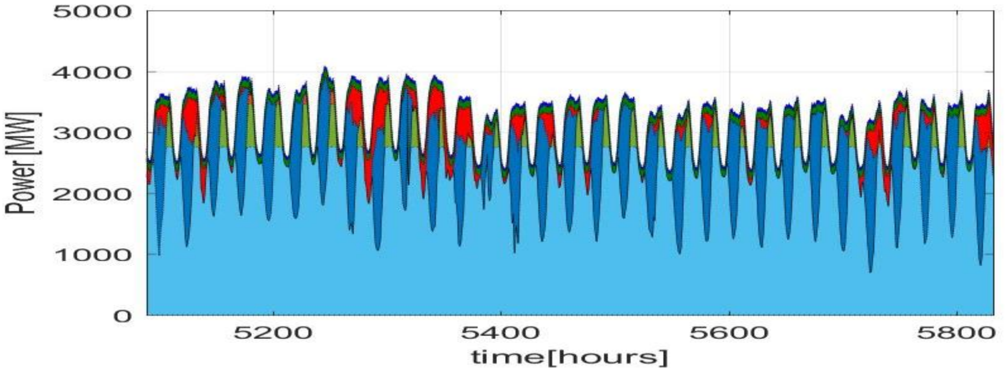
JUNE



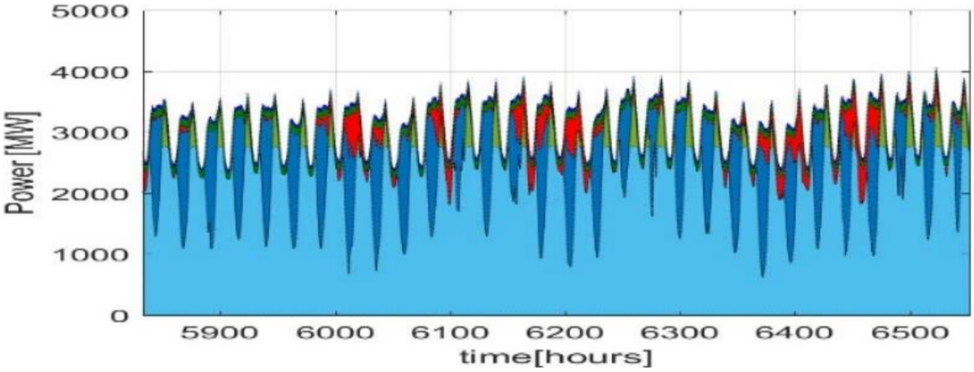
JULY



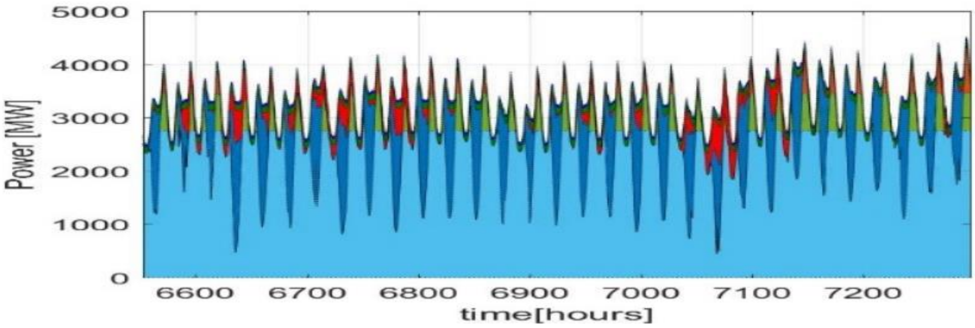
AUGUST



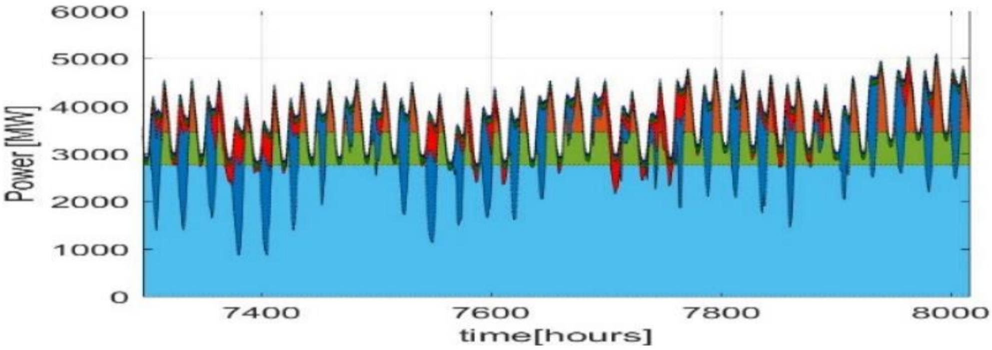
SEPTEMBER



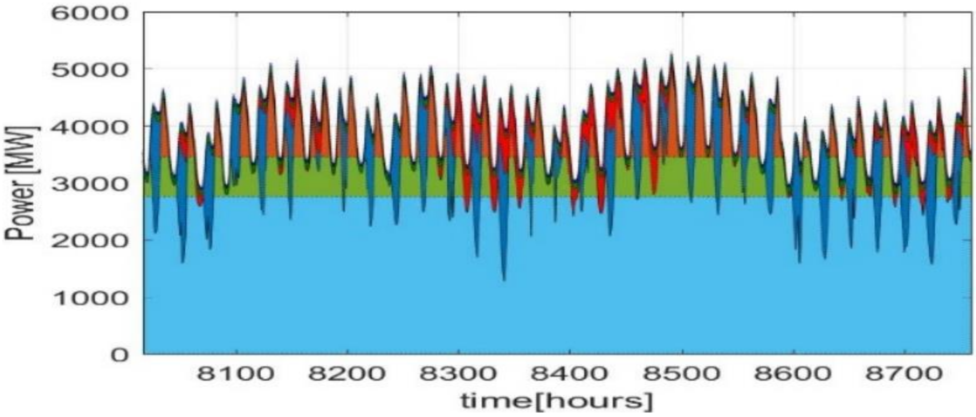
OCTOBER



NOVEMBER



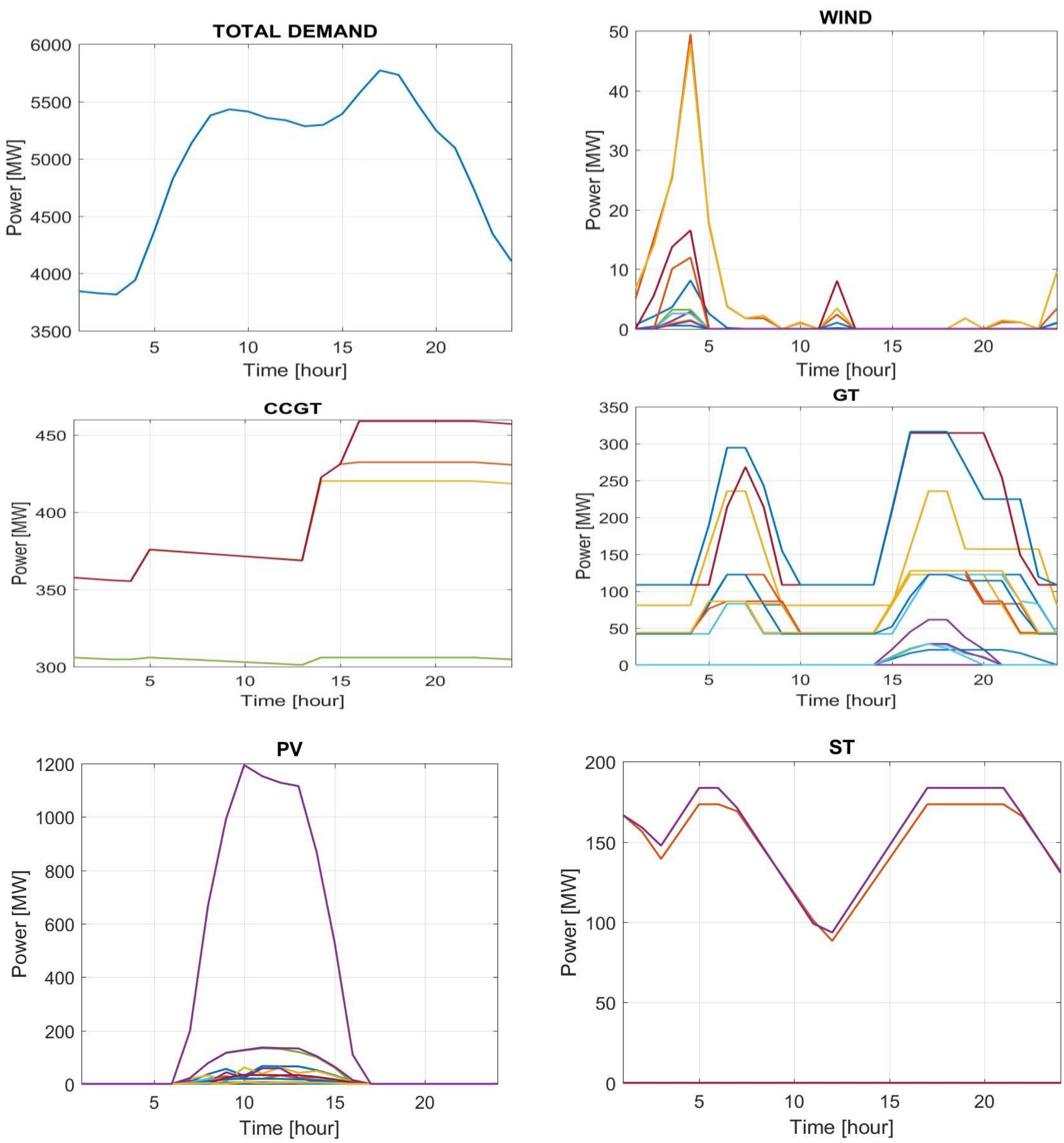
DECEMBER



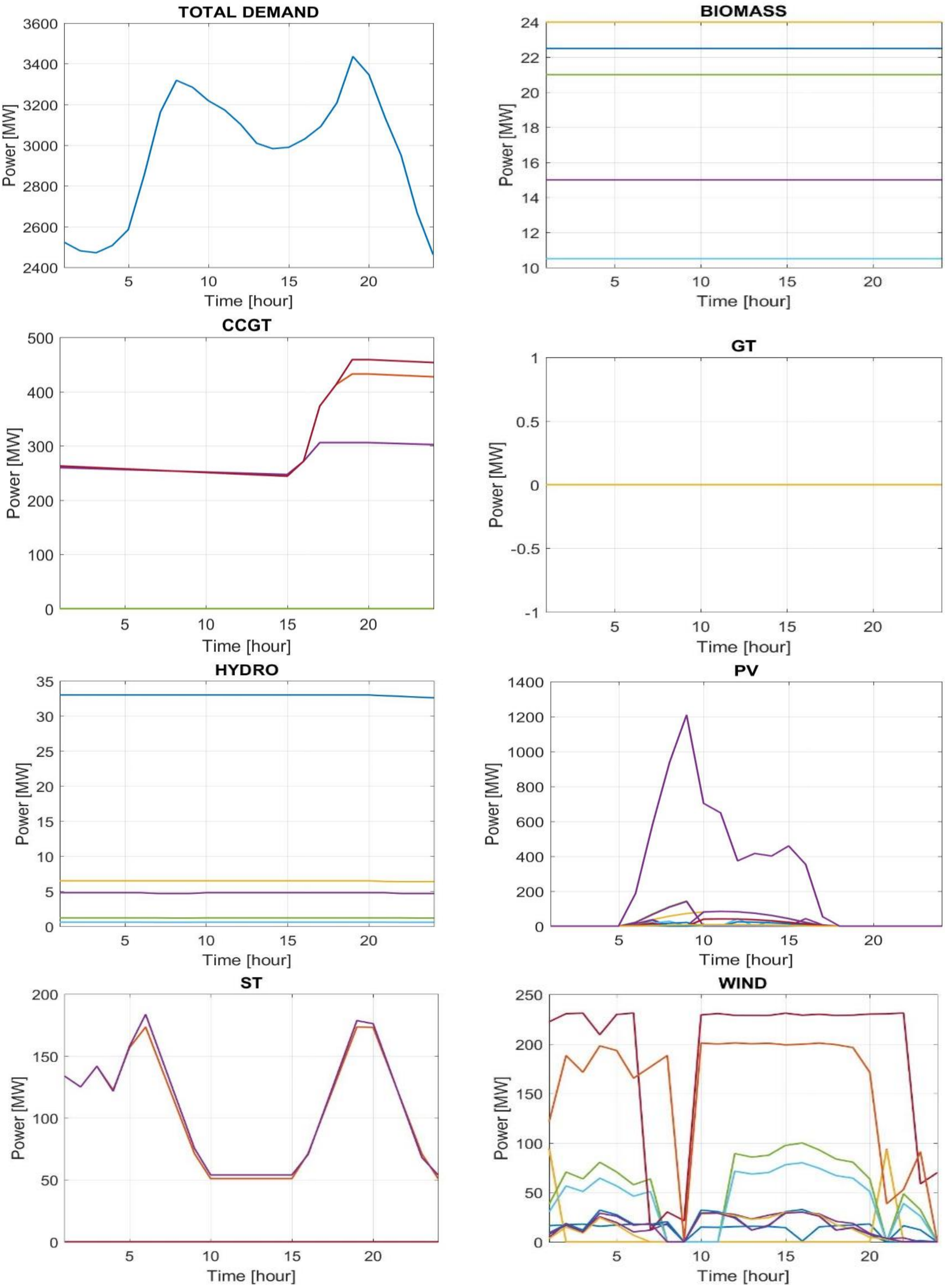
S5M4, Hour-to-hour flexibility analysis plot:

In these figures will be plotted single generator dispatch, for type of technology, so <u>each line represents the dispatched power for a certain technology as a function of time.</u>

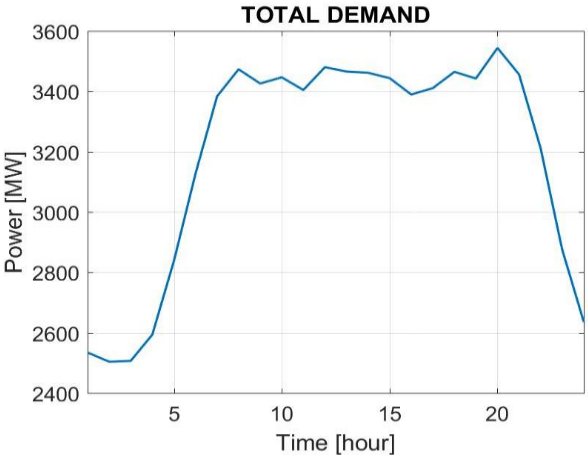
1) **DAY OF MAX DEMAND (4th January)**

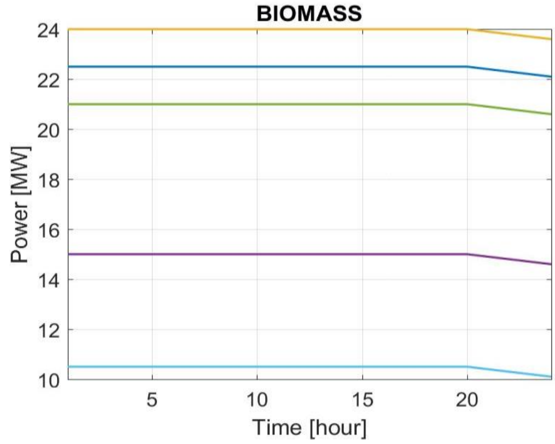


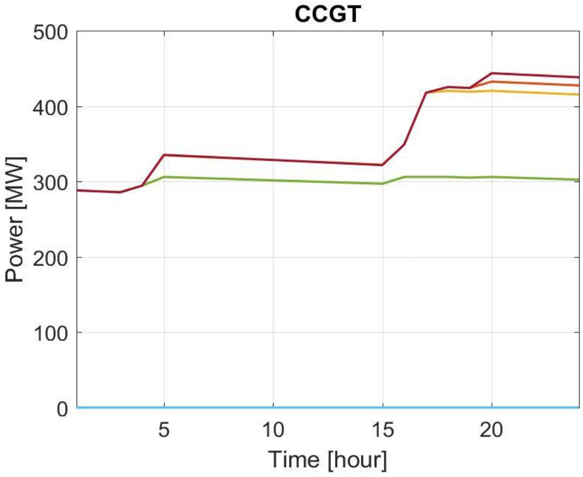
APRIL, 15^{th}

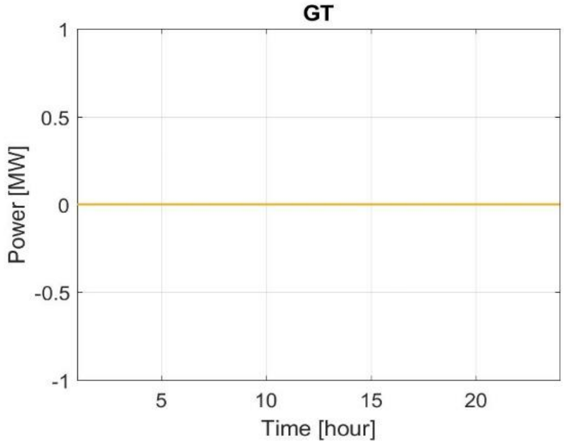

TOTAL DEMAND
BIOMASS
CCGT
GT
HYDRO
PV
ST
WIND
Power [MW]
Time [hour]

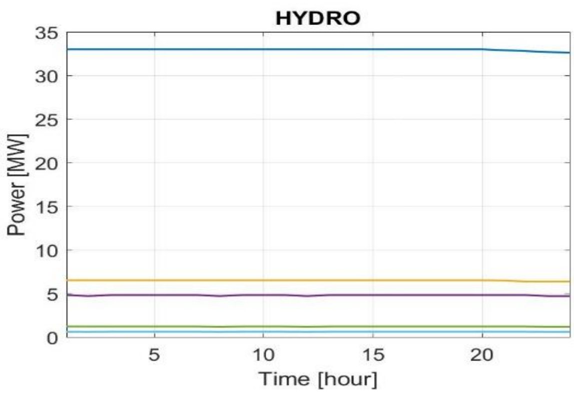
JUNE, 15th

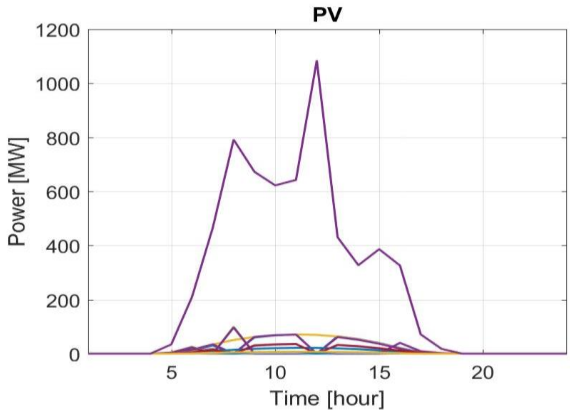

TOTAL DEMAND
Power [MW]
Time [hour]

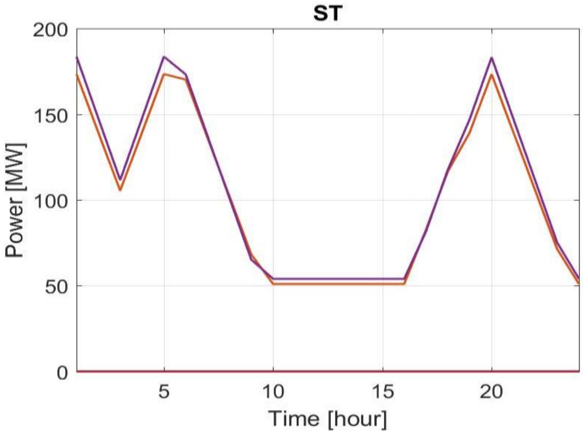

BIOMASS
Power [MW]
Time [hour]

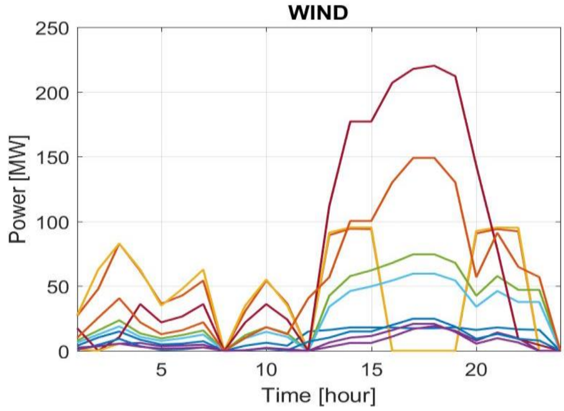

CCGT
Power [MW]
Time [hour]


GT
Power [MW]
Time [hour]

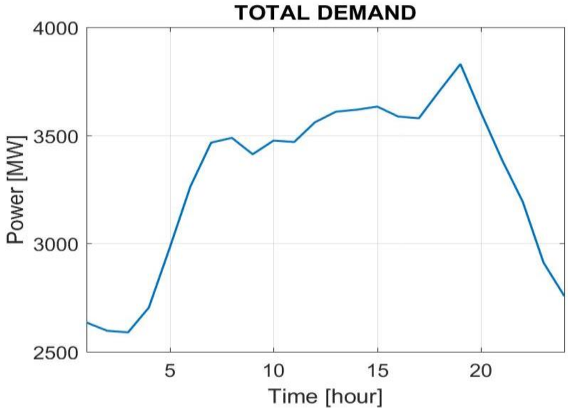

HYDRO
Power [MW]
Time [hour]

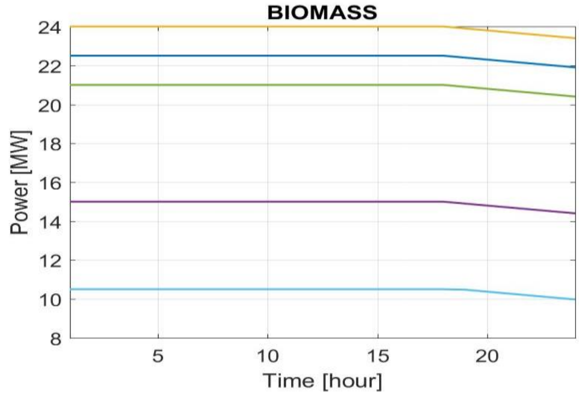

PV
Power [MW]
Time [hour]

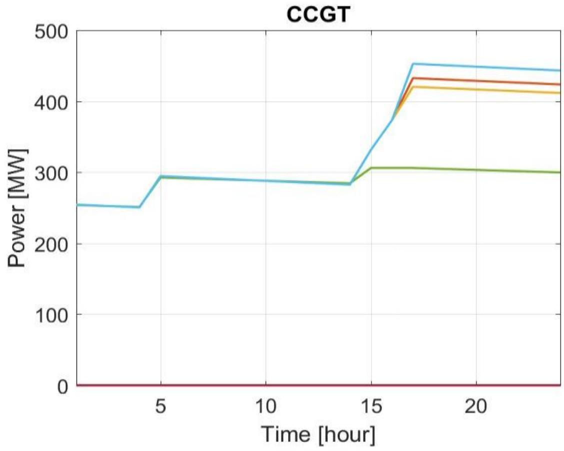

ST
Power [MW]
Time [hour]

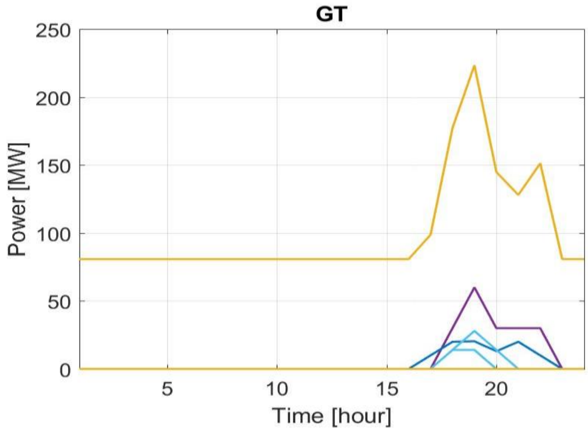

WIND
Power [MW]
Time [hour]

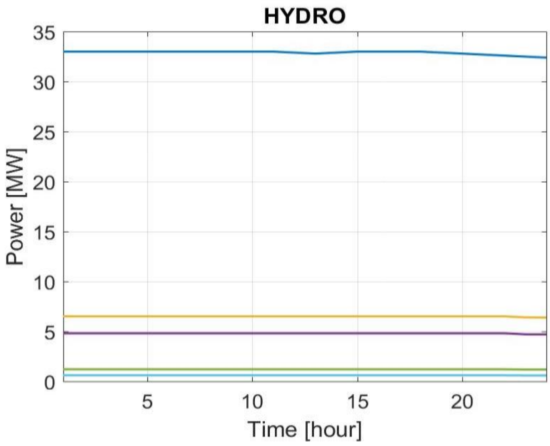
SEPTEMBER, 15th

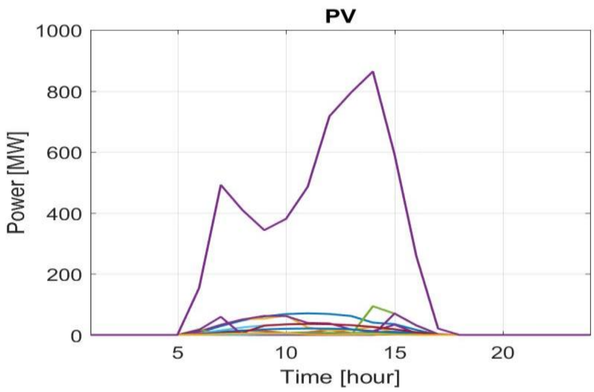


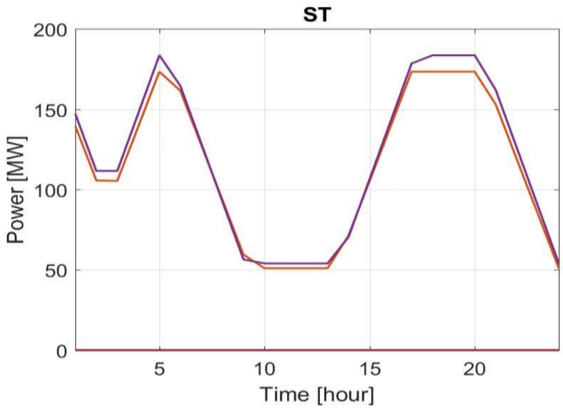


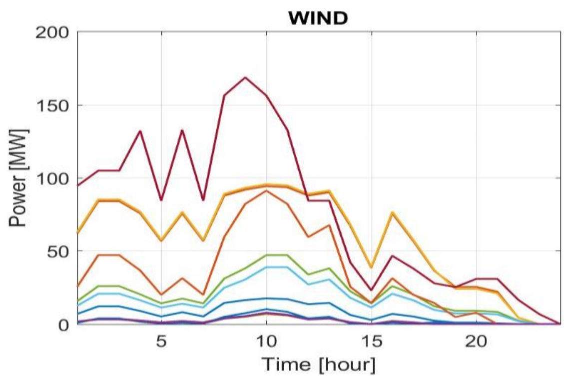












CHAPTER 13: REFERENCES

13.1) TUNISIAN FUTURE PLANTS BY 2035 REFERENCES TUNISIAN HV POWER PLANTS PROJECTS.

1) https://oxfordbusinessgroup.com/analysis/promoting-renewables-authorities-take-steps-diversify-country%E2%80%99s-energy-mix
2) https://oxfordbusinessgroup.com/interview/power-moncef-harrabi-chairman-soci%C3%A9t%C3%A9-tunisienne-de-l%E2%80%99electricit%C3%A9-et-du-gaz-steg-increasing-energy
3) http://www.ansamed.info/ansamed/en/news/nations/tunisia/2019/01/11/tunisia-awards-first-wind-power-project-contracts_2ec02e53-cfe3-4df1-8938-64f469cea259.htmlvernorate.
4) http://www.opusenergyblog.com/concentrated-solar-power-soon-come-tunisia/
5) http://www.nurenergie.com/tunur/
6) http://www.nurenergie.com/tunur/index.php/news/118/66/TuNur-files-for-authorisation-for-4-5-GW-solar-export-project
7) https://newsbase.com/topstories/tunisian-csp-project-takes-step-forward
8) https://www.saharaforestproject.com/tunisia/
9) https://www.power-technology.com/features/sahara-solar-battery-europe/
10) http://helioscsp.com/plans-for-sahara-to-export-concentrated-solar-power-to-europe-revive/
11) https://www.clarke-energy.com/2016/return-investment-maintenance-successes-nejma-huiles-tunisia/
12) https://www.ise.fraunhofer.de/en/business-areas/power-electronics-grids-and-smart-systems/energy-system-analysis/energy-system-models-at-fraunhofer-ise/entigris.html
13) https://www.afdb.org/fileadmin/uploads/afdb/Documents/Project-and-Operations/ADB-BD-IF-97-260-EN-ESPS-003682995.PDF
14) https://www.energycentral.com/news/tozeur-solar-power-plant-be-inaugurated-summer
15) https://www.pv-magazine.com/2017/12/08/tunisias-power-utility-steg-plans-another-10-mw-solar-park/
16) https://en.econostrum.info/Tunisia-seeking-to-close-renewable-energy-gap_a476.html
17) https://www.aa.com.tr/en/energy/finance/mitsubishi-to-build-power-plant-in-tunisia-for-350m-/1914
18) https://www.nsenergybusiness.com/projects/rades-c-combined-cycle-power-plant/
19) https://www.industryabout.com/country-territories-3/1556-tunisia/fossil-fuels-energy/22797-rades-ii-gas-power-plant
20) https://www.mhps.com/news/20170621.html
21) https://www.ge.com/menat/company/tunisia
22) http://www.nurenergie.com/tunur/
23) http://www.themeditelegraph.com/en/markets/2018/04/28/ansaldo-energia-signs-contracts-worth-million-tunisia-TpzntO2lguGUVDC9wnS2uL/index.html
24) https://www.pv-tech.org/news/tunisia-awards-60mw-of-solar-awards
25) https://www-pub.iaea.org/MTCD/Publications/PDF/cnpp2018/countryprofiles/Tunisia/Tunisia.htm

26) https://www.genewsroom.com/press-releases/power-ge-store-alstom-engineered-technology-tunisia-prepares-2016-summer-demand-ge
27) https://www.ge.com/power/gas/gas-turbines/9e-03
28) https://www.zawya.com/mena/en/story/Installation_works_of_first_gas_turbine_at_Tunisias_Mornaguia_power_plant_starts-SNG_130709987/
29) http://www.abengoa.com/web/en/noticias_y_publicaciones/noticias/historico/2017/12_diciembre/20171222_NP_Tunez.html
30) https://www.developmentaid.org/#!/news-stream/post/22443/tunisia-launches-500-mw-solar-tender
31) https://alerbey.com/development-of-the-electricity-transmission-network-of-the-tunisian-electricity-and-gas-company-steg-within-the-framework-of-the-xiiith-plan/?lang=en
32) http://www.world-nuclear-news.org/NP-Russia-and-Tunisia-sign-nuclear-MOU-02061503.html
33) https://www.evwind.es/tags/africa
34) https://www.evwind.es/2019/01/11/tunisia-awards-first-wind-energy-contracts/65753
35) https://www.thewindpower.net/windfarm_en_4117_sidi-daoud.php
36) https://www.abo-wind.com/en/media-center/press/2019-01-15.html
37) http://www.afrol.com/articles/31700
38) https://cdm.unfccc.int/Projects/DB/AENOR1350630320.17/view
39) https://renews.biz/51001/abo-kicks-off-tunisian-run/
40) http://www.ansa.it/english/newswire/english_service/2018/03/14/energy-algeria-to-export-electricity-to-tunisia-libya_f79b7ba4-3d34-473d-a4f1-d17a1067d973.html
41) https://datacatalog.worldbank.org/dataset/tunisia-electricity-transmission-network-2017
42) https://www.energy-reporters.com/transmission/italy-and-tunisia-agree-600mw-interconnector-deal/
43) https://www.enerdata.net/publications/daily-energy-news/tunisia-will-invest-us5bn-energy-projects-over-2018-2020-period.html
44) http://www.medrec.org/En/Electric%20Tunisian%20%20%20Italian%20Interconnection_11_53
45) http://www.reegle.info/policy-and-regulatory-overviews/TN
46) https://www.pv-magazine.com/2018/09/03/tunisia-plans-1-7-gw-solar-complex/
47) https://www.pv-magazine.com/2018/05/08/tunisia-reveals-winners-of-70-mw-solar-tender/
48) https://www.pv-magazine.com/2018/05/14/tunisia-launches-500-mw-solar-tender/
49) https://www.pv-magazine.com/2018/05/30/tunisia-tenders-another-70-mw-of-solar/
50) http://www.nurenergie.com/index.php/english/projects/tunisia
51) https://newsbase.com/topstories/tunisia-issue-renewable-energy-tenders-month
52) http://www.rcreee.org/sites/default/files/tunisia_fact_sheet_print.pdf
53) https://renewablesnow.com/news/tunisia-grants-licences-to-120-mw-of-wind-projects-639583/

54) https://renewablesnow.com/news/tunisia-picks-bidders-for-800-mw-of-solar-wind-projects-634542/
55) https://www.windpowermonthly.com/article/1523024/first-tunisia-tender-rewards-european-firms
56) https://www.res4med.org/2018/06/27/res4med-conference-in-tunis-renewables-and-infrastructure-for-the-clean-energy-transition-of-tunisia-the-italian-journey-on-renewable-energies-excellency-and-best-practices/
57) http://steg.com.tn/en/institutionnel/electricite_chiffres.html DATI STEG
58) http://steg.com.tn/en/clients_ind/nouveau.html
59) https://data.worldbank.org/country/tunisia
60) http://beta.ins.tn/en/glossaire-satistique
61) http://beta.ins.tn/en/themes/agriculture
62) http://beta.ins.tn/en/themes/industrie
63) http://beta.ins.tn/en/themes/energie
64) http://beta.ins.tn/en/themes/population
65) https://www.globaldatabase.com/tunisia-companies-database
66) https://simplemaps.com/data/tn-cities
67) http://www.nama-database.org/index.php/Tunisia
68) http://www.nama-database.org/index.php/Energy_conservation_in_the_building_sector
69) https://www.africa-energy.com/database TUNISIA PROJECT MAP
70) http://www.fao.org/countryprofiles/index/en/?iso3=TUN

13.2) REFERENCES

1) Modelling, Simulation and Analysis of the Tunisian Power System, Farzaneh Amir kavei
2) Grid flexibility and storage required to achieve very high penetration of variable renewable electricity Paul Denholm a,n , Maureen Hand.
3) Yann REBOURS Daniel KIRSCHEN, Spinning reserve
4) Determination of Load-Following Reserves in Power Systems with High Wind Penetration: An Application to the Greek Power System Emmanouil A. Bakirtzis, Dimitris I. Chatzigiannis* , Andreas V. Ntomaris, Christos K. Simoglou, Pandelis N. Biskas, and Anastasios G. Bakirtzis
5) Operating Reserves in Long-term Planning Models Wesley Cole, Kelly Eurek, Nina Vincent, Trieu Mai, Matt Mowers, and Greg Brinkman.
6) Operating Reserves and Variable Generation. Erik Ela, Michael Milligan, and Brendan Kirby
7) Location matters: The impact of renewable power on transmission congestion and emissions Claudia Hitaj
8) Effect of increased renewables generation on operation of thermal power plants Patrick Eser ⇑ , Antriksh Singh, Ndaona Chokani, Reza S. Abhari
9) Effect of increased renewables generation on operation of thermal power plants Patrick Eser ⇑ , Antriksh Singh, Ndaona Chokani, Reza S. Abhari.
10) Optimal renewable energy generation – Approaches for managing ageing assets mechanisms Chinedu I. Ossai
11) Intermittent wind generation in optimal power flow dispatching R.A. Jabr1 B.C. Pal2
12) MATPOWER MANUAL
13) MATPOWER OPTIMAL SCHEDULING TOOL (MOST) MANUAL
14) Wikipedia

15) energydat.info
16) Review of transmission schemes and case studies for renewable power integration into the remote grid Kazi Nazmul Hasan a,b , Tapan Kumar Saha a,b,n , Mehdi Eghbal a,b , Deb Chattopadhyay b
17) Potential of renewable energy development for water desalination in Tunisia F[BenJemaa\ Houcine\ M[H[Chahban
18) Optimal siting and size of bioenergy facilities using geographic information system Arifa Sultana, Amit Kumar
19) Optimal placement of biomass fuelled gas turbines for reduced losses Francisco Jurado *, Antonio Cano]
20) GIS-based assessment of sustainable crop residue potentials in European regions Martina Haase* , Christine Rosch, Daniel Ketzer
21) GIS-based biomass assessment and supply logistics system for a sustainable biorefinery: A case study with cotton stalks in the Southeastern US K. Sahoo a , G.L. Hawkins b , X.A. Yao c , K. Samples d , S. Mani a
22) Studio sull'utilizzo di biomasse combustibili e biomasse rifiuto per la produzione di energia, ISPRA – Istituto Superiore per la protezione e la ricerca ambientale
23) B. Ruggieri, Dispense del corso di " Uso ottimale delle biomasse a scopi energetici, POLITECNICO DI TORINO.
24) Discrete PSO algorithm based optimization of transmission lines loading in TNEP problem H. Shayeghi a,*, M. Mahdavi b , A. Bagheri b].
25) OnSSet Manual
26) Potential of concentrating solar power (CSP) technology in Tunisia and the possibility of interconnection with Europe Moncef Balghouthi n , Seif Eddine Trabelsi, Mahmoud Ben Amara, Abdessalem Bel Hadj Ali, Amenallah Guizani
27) The value of CSP with thermal energy storage in providing grid stability J. Forrester
28) Power Plant Cycling Costs Prepared By Nikhil Kumar Philip M. Besuner Steven A. Lefton Dwight D. Agan Douglas D. Hilleman
29) SISTEMI ELETTRICI DI POTENZA:Produzione, trasmissione e distribuzione dell'energia elettrica Prof. Ing. Mariacristina Roscia Università di Bergamo
30) Tunisia: Derisking Renewable Energy Investment 2018 Selecting Public Instruments to Promote Renewable Energy Investment for the Tunisia Solar Plan
31) Assessment of wind energy potential and optimal electricity generation in Borj-Cedria, Tunisia A.W. Dahmouni a, M. Ben Salah c, F. Askri b, C. Kerkeni a, S. Ben Nasrallah
32) Assessing the technical wind energy potential in Africa a GIS-based approach, Dimitrios Mentis, Sebastian Hermann, Mark Howells, Manuel Welsch, Shahid Hussain Siyal
33) Optimal placement of biomass fuelled gas turbines for reduced losses Francisco Jurado Antonio Cano
34) A GIS methodology to identify potential corn stover collection locations Monica A. Haddada, Paul F. Andersonb
35) Location of small-scale biomass based energy systems using probabilistic load flow and metaheuristic techniques F. J. Ruiz-Rodrfguez, M. Gomez-Gonzalez, F. Jurado, Senior Member, IEEE

36) A GIS based assessment of bioenergy potential in England within existing energy systems Amy Thomas, Alan Bond, Kevin Hiscock
37) GIS-based assessment of sustainable crop residues for optimal siting of biogas plants, Kamalakanta Sahooa, Sudhagar Mania, Lalitendu Dasb, Pete Bettingerc
38) An integrated model for assessment of sustainable agricultural residue removal limits for bioenergy systemsq D.J. Muth Jr. a, K.M. Bryden b
39) GIS-based biomass assessment and supply logistics system for a sustainable biorefinery: A case study with cotton stalks in the Southeastern US K. Sahoo a , G.L. Hawkins b , X.A. Yao c , K. Samples d , S. Mani a
40) A multi-objective sustainable location model for biomass power plants: Case of China Xin-gang Zhao, Ang Li
41) A GIS-based method for identifying the optimal location for a facility to convert forest biomass to biofuel Fengli Zhang a , Dana M. Johnson b, *, John W. Sutherland c
42) Locating a bioenergy facility using a hybrid optimization method Athanasios A. Rentizelas , Ilias P. Tatsiopoulos
43) Optimal siting and size of bioenergy facilities using geographic information system Arifa Sultana, Amit Kumar
44) Optimal number and location of storage hubs and biogas production reactors in farmlands with allocation of multiple feedstocks Bhaba R. Sarker a, Bingqing Wua, Krishna P Paudel
45) Planning woody biomass logistics for energy production: A strategic decision model F. Fromboa,b,c, R. Minciardia,b , M. Robbaa,b,c, *, F. Rossob,c , R. Sacilea,b
46) The assessment of mangrove biomass and carbon in West Africa: a spatially explicit analytical framework Wenwu Tang, Wenpeng Feng . Meijuan Jia, Jiyang Shi . Huifang Zuo . Carl C. Trettin
47) Teaching Power System Analysis Courses using MATPOWER Mudathir F. Akorede, Hashim Hizam
48) DC Optimal Power Flow: Uniqueness and Algorithms Chee Wei Tant, Desmond W. H. Cai* and Xin Lout
49) Optimal power flow and formulation, Mary B. Chain, Richiard O'Neil, Anya Castillo
50) Optimal power flow analysis of a Switzerland's transmission system for long-term capacity planning Antriksh Singh n, David Willi, Ndaona Chokani, Reza S. Abhari
51) Power systems without fuel Josh A. Taylor, Sairaj V. Dhople, Duncan S. Callaway c
52) Investigation of Generator Ramp Rates in High Renewable Penetration Systems using an Academic New York Network Model, Stephen M. Burchett, Joe Chow, and Koushik Kar, Ray Zimmerman, Mike Swider, Muhammad Marwali, and Gary Zhang
53) Integration of Solar Energy into the Zambia Power Grid Considering Ramp Rate Constraints B.Kumwenda, W.Mwaku, D.Mulongoti, H.Louie
54) A Flexible Ramping Capacity Model for Generation Scheduling with High Levels of Wind Energy Penetration Hungyu Kwon, Jong-Keun Park 1, Dam Kim 1, Jihyun Yi 1 and Hyeongon Park
55) An Integrated Multiperiod OPF Model With Demand Response and Renewable Generation Uncertainty Waqquas A. Bukhsh, Member, IEEE, Chunyu Zhang, Member, IEEE, and Pierre Pinson, Senior Member, IEEE

56) A Spinning Reserve Allocation Method for Power Generation Dispatch Accommodating Large-Scale Wind Power Integration Jianhua Chen, Wenchuan Wu *, Boming Zhang, Bin Wang and Qinglai Guo
57) Spinning Reserve Capacity Optimization of a Power System When Considering Wind Speed Correlation Jianglin Zhang, Huimin Zhuang, Li Zhang and Jinyu Gao
58) Evaluation of load flow and grid expansion in a unit commitment and expansion optimization model SciGRID International Conference on Power Grid Modelling
59) Location matters: The impact of renewable power on transmission congestion and emissions Claudia Hitaj
60) Substation Location and Transmission Network Expansion Problem in Power System Meltem Pekera , Ayse Selin Kocamana , Bahar Y. Karaa
61) Potential of concentrating solar power (CSP) technology in Tunisia and the possibility of interconnection with Europe Moncef Balghouthi n , Seif Eddine Trabelsi, Mahmoud Ben Amara, Abdessalem Bel Hadj Ali, Amenallah Guizani
62) Economic Load Dispatch and Optimal Power Flow in Power System Team Members: Zagros Shahooei Guna R. Bharati Barzin Moridian
63) Flexibility in conventional power plants innovation landscape brief, IRENA.