EXECUTIVE SUMMARY

Assessment, in the framework of the ELMED project, of the maximum electricity production capacity from non-programmable renewable energy sources (RES) connectable to the Tunisian grid in accordance with security and quality requirements

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1 OBJECTIVES OF THE STUDY

The objectives of this study are:

a) To determine the network reinforcements required to guarantee the static and dynamic security conditions following the commissioning of the ELMED Production Units and the realization of the new 1000 MW Tunisia-Italy High Voltage Direct Current (HVDC) transmission link;

b) To determine the maximum power produced by non-programmable renewable sources (RES[1]) acceptable by the Tunisian production–transmission system in its configuration defined in objective a). The analysis shall take into account only the network reinforcements identified in the first phase of the study.

1.1 Tasks of the study

To attain the objectives described above, the study is executed in three tasks:

- Task A: work out the study scenarios, agree on the hypotheses, describe the methods and collect the data
- Task B: static and dynamic analyses for objective a): network reinforcements required for the ELMED Production Units and the HVDC Tunisia-Italy transmission link
- Task C: static and dynamic analyses for objective b): maximum production capacity with unpredictable RES.

2 METHODOLOGY

2.1 Methodology for objective a): network reinforcements for setting up the ELMED power plant and Tunisia-Italy transmission link

The scope of this phase of the study addresses the impact on the Tunisian transmission system of the new ELMED Production Units (or “ELMED Production Cluster”). More specifically, the analyses are aimed at identifying the reinforcements needed on the Tunisian grid in terms of new lines and interconnecting transformers in order to fulfil the static and dynamic criteria established by the Tunisian system operator, STEG. These reinforcements are the additional ones with respect to those already planned by STEG for the horizon year 2016.

The study has been split in two phases:

Screening phase, where we investigated the needed reinforcements following the commissioning of the new ELMED Production Cluster. Two different alternatives for the location of this new power plant are examined:

- El Hawaria, 3x400 MW;

[1] Renewable Energy Sources

- Skhira, 2x660 MW.

We did not consider all the possible combinations of generation technology for the realization of the ELMED Production Cluster. Indeed, there are several technical solutions, even with the same fuel, being aware that the supply of fossil fuels in the different sites must take into account a variety of factor, including supply infrastructures, market conditions (fuel and technologies), logistic. These factors are not treated in this study, which is limited to identifying the necessary network reinforcements in the examined reference cases.

In the screening phase, static analyses only are carried out.

Two generation levels of the thermal ELMED power plant are examined:

a) 400 MW to supply the internal demand in Tunisia. The reinforcements necessary for the evacuation of this power generation are dictated by the expected load growth in Tunisia;

b) 1200 MW to supply the internal demand in Tunisia and to export the surplus to Sicily. The additional reinforcements with respect to the previous case are closely linked to the commissioning of the HVDC interconnection towards Sicily and the connection of the ELMED Production Cluster to the high voltage Tunisian electric system. These additional reinforcements shall warrant a power exchange with Sicily up to 1000 MW, which is the target rating of the submarine interconnection.

The reinforcement possibilities for the different alternatives for the locations of the thermal ELMED power plant have been supplied by STEG through the company “ELMED Etudes” and integrated with further alternatives proposed by CESI in agreement with “ELMED Etudes” and STEG.
At the end of this screening phase the more binding solution for the operation of the power system has been chosen for the subsequent detailed analyses (dynamic analysis) as reported below.

Dynamic analysis phase, where we examined the performances of the Tunisian power system in dynamic conditions. This set of analyses helped to highlight the minimum conditions to comply with the dynamic constraints of the Tunisian system interconnected with the rest of Maghreb and in presence of the HVDC interconnection to Sicily.

All the analyses have been carried out considering the horizon year 2016. Two operating conditions have been examined:

a) yearly peak load: 3960 MW;
b) yearly minimum load: 1400 MW.

In addition to the HVDC link with Sicily, the Tunisian system is linked with Algeria through five tie-lines, (including the 400 kV line Chefia-Jendouba), while the lines with Libya have always been considered out of service; this is the less favourable situation in term of system stability.

2.2 Methodology for objective b): determining the maximum power produced using non programmable renewable sources

The scope of this phase of the study is the assessment of the maximum connectable non-dispatchable generation to the Tunisian system.

The study has been split in three phases that can be summarised as follow:

a) *Global analysis ("single bus-bar analysis")*, whose scope is to determine the non-dispatchable RES power generation considering only the constraints of the conventional generating units (i.e. frequency regulation reserve), disregarding the constraints of the transmission system.
The analysis concerned both minimum and peak load scenarios, in order to assess a value acceptable by the grid in each loading condition.

b) *Static analysis*, which permits to determine the grid configurations with the connection schemes required for the RES power plants connection. These configurations were tested in order to verify the respect of voltage limits and the absence of overloads, both in peak and minimum load scenarios. For each loading condition, we assessed the compliance with the security constraints both in "N" (all the network components in service) and in "N-1" (presence of a fault on a network component) situations.

c) *Dynamic analysis*, where two sets of analyses have been carried out:
   - sensitivity analysis, where the effects of renewable generation fluctuations have been investigated in terms of voltage and frequency oscillations;
   - fault analysis, where the stability of the system in case of main grid contingences (i.e. three phase short circuit) has been tested to verify the behaviour of renewable power plants.

All analyses have been carried out starting from the grid configuration determined with the ELMED Production Cluster located in Skhira without any additional network reinforcements except those strictly requested for the renewable power plant connection.

3 CONCLUSIONS

3.1 Conclusions for objective a)

3.1.1 Results of the screening phase

To comply with the N-1 security criteria, two 400 kV lines are required for the connection of the thermal ELMED power plant as well as the HVDC converter station to the Tunisian power system. If El Hawaria is the adopted site, the 400 kV lines outgoing from the power plant are used only for the supply of the internal load in Tunisia, while for other sites of the thermal ELMED power plant, these lines will be used also for power export to Sicily.

For the ranking of the connection alternatives between the ELMED power plant and the Tunisian power system, the following indicators were considered:

a) length of new lines;
b) losses;
c) strength of the grid in the substation where the alternating-direct current converter is located in term of short circuit current compared with the size of converter (ESCR[2] index);
d) other environmental related indexes such as the number of new right-of-ways.

The following considerations concern the transmission system and do not consider the integrated production-transmission system as well as the general aspects deriving from the opening of cross-border trading of electricity, the integration of the power systems at regional level (Maghreb-Europe) and the market of primary energy sources.

ELMED power plant located in El Hawaria: this is the simplest alternative, and therefore the least expensive, in term of network reinforcements. This alternative doesn't require any network reinforcement for the energy export to Sicily. Network reinforcements are needed only to supply power to cover the internal load in Tunisia. To this aim, two 400 kV lines are required to connect El Hawaria to Mornaguia, each with a capacity equal to 1000 MW. Moreover, this is a favourable solution because it assures a high value of short circuit power where the HVDC converter is located

Thermal ELMED power plant located in Skhira: the location of the ELMED power plant in Skhira requires the doubling of the south-north 400 kV corridor up to Mornaguia.
For the supply of the internal load with a power production level of 400 MW, two basic solutions are feasible:

a) a turn-in/turn-out 400/225 kV substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with 2 x 400 MVA auto-transformers;

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[2] Effective Short Circuit Ratio. A high value of the ESCR ("strong" network) limits voltage oscillations due to the alternating current network or the variations of direct current power. In particular:

- ESCR > 3 means a "strong" system
- ESCR < 2 "weak" system means

ESCR values lower than 2 normally require special devices of reactive compensation, while for intermediate ESCR values, between 2 and 3, the need for flexible compensation devices must be verified with dedicated studies.

b) one 400 kV line outcoming from Skhira (the shortest one being Skhira-Macknassy 70 km) and the 400/225 kV turn-in/turn-out substation on the 225 kV double circuit line Bouchemma-Sidi Mansour equipped with one 400 MVA auto-transformer.

Indeed, the above solutions do not fulfil the security constraints when the ELMED power plant generates its rated power. The additional reinforcements are illustrated in the table below.

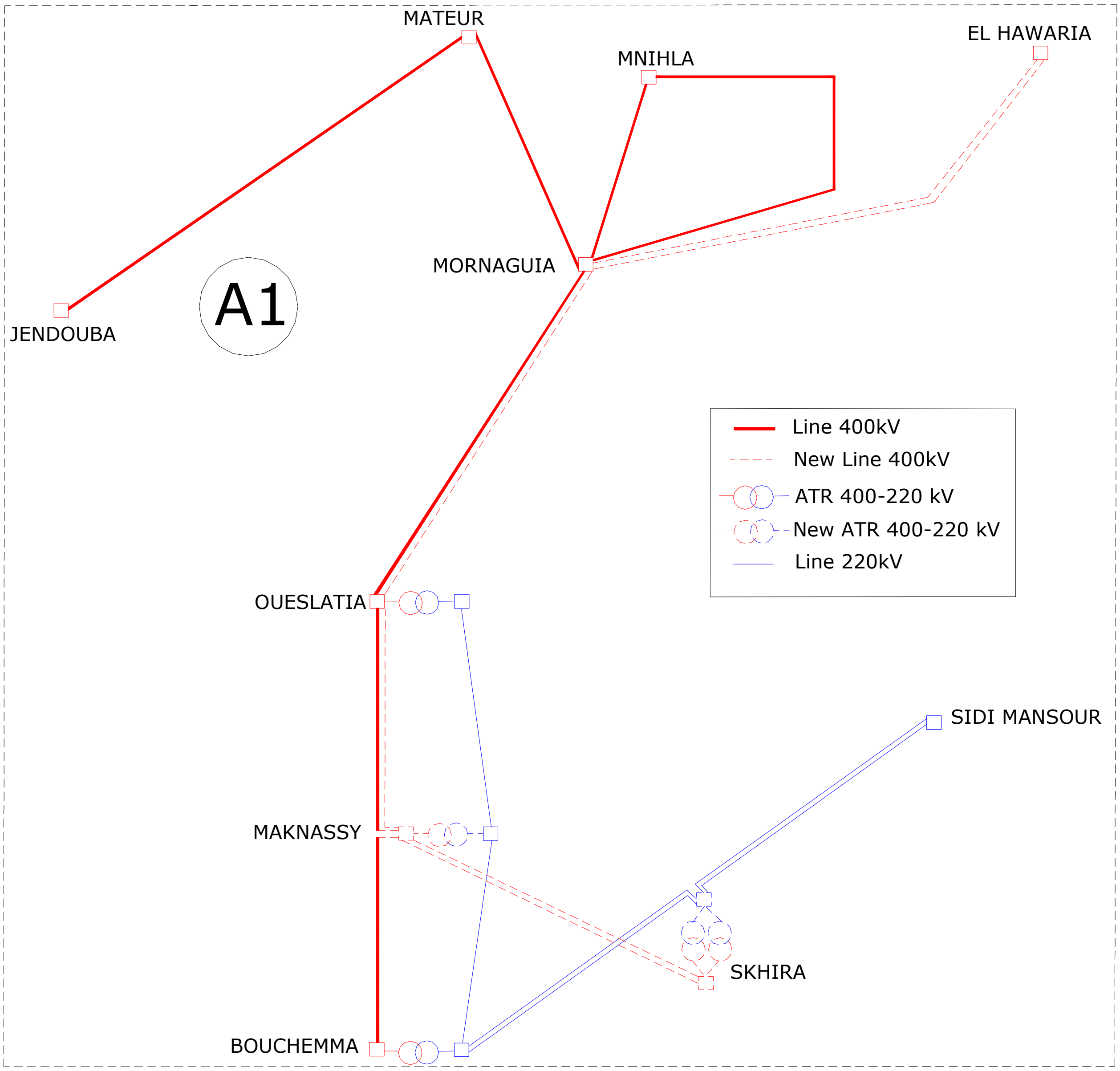
The comments for the different solutions are the following:

- Solution C is characterised by the poorer performances in terms of power losses;
- Solutions A1, A2 and B, involving a 400 kV connection with the existing 225 kV substation of Maknassy may be completed by the addition of a 400/225 kV auto-transformer (ATR) at the Maknassy substation for more flexibility in the system operation.
- Solutions A2 and B entailing the erection of very long 400 kV may be critical for the voltage control and an appropriate reactive power compensation scheme shall be investigated. Dynamic controlled shunt compensation devices are probably needed. Moreover, the energisation procedure of the long 400 kV line might reveal critical, especially in low load conditions characterised by low short circuit power. If chosen, these solutions require the execution of dedicated studies and, very likely, extra costs are to be considered for the voltage control;
- All solutions show a poor loading on the Skhira 400/225 kV auto-transformers. As a matter of fact, if we consider two 400 kV lines outgoing from Skhira power plant, one might consider the connection of one autotransformer only or, better, two autotransformers with lower rate (e.g.: 250 MVA). This latter solution warrants a better reliability and operation flexibility.

Solution	Reinforcements	New lines total length (km)	New ATR 400/225 kV	Losses in peak conditions (MW)	Notes
A1	- Turn-in/Turn-out on the 225 kV double circuit line Bouchemma-Sidi Mansour at the Skhira power plant, - 400 kV double circuit line Skhira-Maknassy - 400 kV single circuit line Maknassy-Oueslatia - 400 kV single circuit line Oueslatia-Mornaguia - Two 400 kV single circuit lines El Hawaria-Mornaguia	**2x20** **2x70** **180** **130** **300**	**3****	**113.6**	ESCR: 3.28 ÷ 3.67 p.u
A2	- Turn-in/Turn-out on the 225 kV double circuit line Bouchemma-Sidi Mansour at the Skhira power plant, - 400 kV single circuit line Skhira-Maknassy - 400 kV single circuit line Shkira-El Hawaria - One 400 kV single circuit line El Hawaria-Mornaguia	**2x20** **70** **410** **150**	**3****	**112.1**	ESCR: 2.79 ÷ 3.13 p.u
B	- Turn-in/Turn-out on the 225 kV double circuit line Bouchemma-Sidi Mansour at the Skhira power plant, - 400 kV single circuit line Skhira-Maknassy - 400 kV single circuit line Skhira-Mornaguia - Two 400 kV single circuit lines El Hawaria-Mornaguia	**2x20** **70** **350** **300**	**3****	**114.1**	ESCR: 3.28 ÷ 3.67 p.u
C	- Turn-in/Turn-out on the 225 kV double circuit line Bouchemma-Sidi Mansour at the Skhira power plant, - 400 kV double circuit line Skhira-Bouchemma - 400 kV single circuit line Bouchemma-Oueslatia - 400 kV single circuit line Oueslatia-Mornaguia - Two 400 kV single circuit lines El Hawaria-Mornaguia	**2x20** **2x70** **280** **130** **300**	**2*****	**130.7**	ESCR: 3.23 ÷ 3.63 p.u
D	- Turn-in/Turn-out on the 225 kV double circuit line Bouchemma-Sidi Mansour at the Skhira power plant, - 400 kV single circuit line Skhira to the 400 kV line Bouchemma – Oueslatia - 400 kV single circuit line Skhira-Oueslatia - 400 kV single circuit line Oueslatia-Mornaguia - Two 400 kV single circuit lines El Hawaria-Mornaguia	**2x20** **85** **245** **130** **300**	**2*****	**119.6**	ESCR: 3.27 ÷ 3.66 p.u

*** 1 ATR 400 MVA in Maknassy and 2 ATR in Skhira with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*

**** 2 ATR in Skhira for the T-in/T-out along the line Bouchemma-Sidi Mansour with appropriate size (e.g.: 250 MVA). Alternatively, one can foresee 1 ATR only in Skhira with the standard rating of 400 MVA.*



In conclusion, the location of the ELMED power plant in Skhira turns out to be the most binding alternative with respect to the other ones in terms of network reinforcements. By considering the technical performances solution "A1" is the most favourable since:

- it avoids very long transmission lines that can cause voltage problems in case of low power flows;
- it uses an already planned corridor to build most of the new reinforcements;
- it will hardly cause under-excitation problems for generators in case of restoration;
- it is one of the solution with the lowest network losses.

Thus, this solution is examined more in detail to assess the performances of the system in dynamic conditions.

3.1.2 *Results of the detailed analysis phase*

The dynamic analyses focused on examining the system stability at the occurrence of large credible perturbations, namely:

1. three-phase short circuit without fault impedance on the 400 kV line Skhira – Maknassy;
2. loss of one Skhira generator;
3. loss of one pole of HVDC system.

The occurrence of a three-phase short circuit on the 400 kV is a very critical perturbation for the transient stability of the Shkira units. Indeed, to ensure an adequate CCT[3] we recommend that both Skhira generators shall be equipped with:

- Power System Stabilizer (PSS)
- Fast Valving device for both high and medium pressure valves
- Independent supply excitation system.

By adopting the above measures, the CCT with Skhira at full generation level (1200 MW) attains 170 ms, independently from the control system installed at the HVDC converter station. The CCT is strongly affected by the generation level of the Skhira units (e.g.: CCT = 280 ms when the power plant generates 1050 MW). For short circuits occurring farther from the ELMED power plant in Skhira, the CCT are larger and warrant the stability also in case of intervention of the distance protections in second steps.

The loss of one unit in Skhira has a moderate impact on the Tunisian power system when it is interconnected with Algeria and the HVDC link is equipped with a frequency regulator; in peak load conditions, the loss of 600 MW in Skhira is recovered by reducing the power export to Sicily by about 320 MW, increasing the import from Algeria of about 200 MW, whilst the remaining amount of power is generated inside Tunisia. In case of Tunisia operated in isolated mode from the rest of Maghreb, to avoid the intervention of load shedding the HVDC converter station must be equipped with a frequency regulator having an appropriate droop.

Finally, the loss of one pole in the HVDC converter station (500 MW with a bipolar configuration), which is equivalent to the sudden disconnection of a load, doesn’t show any transient stability problems; the surplus of power is conveyed towards Algeria with a consequent increase of cross-border power flows. Only in case of Tunisia operated in isolated mode, the frequency increases in a significant way, particularly in minimum load scenario. This fact is mainly due to reduced frequency regulation margins for the other HVDC pole in service. In this case, a high value of power exported to Italy in pre-fault conditions exposes the Tunisian grid to possible over-frequency problems at the occurrence of the loss of one HVDC pole, if the tie-lines with Algeria are out of service. To avoid reaching frequency values that exceed the limits set by the System Operator, it is necessary to reduce the exportation to Sicily in case of Tunisian electric system isolated from the rest of Maghreb.

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[3]CCT: Critical Clearing Time.

3.2 Conclusions for objective b)

3.2.1 Results of the Global "single bus bar" analysis

Firstly, the peak load scenario has been investigated. The starting condition derives from Task B analyses:

- total internal load equal to 3960 MW;
- 950 MW is the export to Sicily through HVDC system (a 5% regulation bandwidth referred to the rating of the link has been considered);
- tertiary frequency regulation reserve calculated as the 8% of the total load, according to the rules of ENTSO-E[4] (the export with HVDC system is not included in this calculation because the system has its frequency regulation capability).

This scenario does not present any particular restrictive condition.

The restrictive scenario is, indeed, the minimum load one, where the difference between conventional generated power and downward reserve appears quite low, still keeping the assumption of never stopping the conventional units, i.e.: no changes in the unit commitment.

The starting condition is:

- total internal load equal to 1400 MW;
- 950 MW is the export to Sicily through the HVDC link (a 5% regulation bandwidth has been considered);
- tertiary frequency regulation reserve calculated as the 8% of the total load as in the previous case.

The maximum power of non-dispachable RES generation is about 530 MW that corresponds to an installed power of about 660 MW, considering a generating rate for RES equal to 80%.
The previous result is valid under the assumption of thermal production at the ELMED power plant equal to 400 MW in low load conditions. However, if the level of thermal generation at the ELMED power plant exceeds 400 MW, the non-dispachable RES generation shall be reduced according to the following table.

Tab. E-1 – Maximum non-dispatchable RES generation and installation in function of thermal ELMED production

Production of ELMED power plant [MW]	Maximum RES power generation [MW]	Installed RES power (*) [MW]
400 *(limit condition)*	530	660
500	450	560
600	370	460
700	285	355
800	205	255

(*) generation rate equal to 80%

[4] ENTSO-E: European Network of Transmission System Operators of Electricity.

In conclusion, from the above values it is possible to point out that if the production of ELMED power plant increases of 100 MW, the non-dispatchable RES power generation must decrease of about 80 MW in linear way.
The most problematic situation for the Tunisian system is that one characterised by the highest amount of renewable generation (reference scenario). For this reason, all static and dynamic analyses have been carried out considering a RES power generation equal to 530 MW.

3.2.2 Results of the static analysis

The static analysis has the objective of defining the best solution to connect the new RES power plants to the Tunisian grid fulfilling the “N-1” security criterion both in peak and minimum load conditions.

To ensure a non-dispatchable RES power production equal to 530 MW (value obtained from the “global analysis”), the RES generation plants have been connected to the network as shown in the following table.

Name of site	Region	Connection stations	Generated RES power (MW)
Sidi Daoued	Cap Bon	Menzel Temime **90 kV: 29 km**	54
Metline	Bizerte	Menzel Jemil **90 kV: 11 km**	97
Kechabta	Bizerte	E/S on existing line **90 kV** Menzel Jemil-Menzel Bourguiba: **6 km**	93
Ben Aouf	Bizerte	Bizerte **90 kV: 12 km**	25
Jebel Abderrahmen	Cap Bon	Grombalia **225 kV: 43 km**	200
Zonkar	Bizerte	Menzel Bourguiba **225 kV: 30 km**	200

The redispatching, carried out considering the merit order of the units, is different in the two examined conditions (peak and low load conditions) since the unit commitment is different.

In particular, in minimum load conditions and with a generation level of renewable power RES equal to 530 MW, it is inevitable to change the dispatching of the ELMED power plant up to 400 MW increased by its regulation bandwidth equal to 5% of its nominal power. The downward redispatching of ELMED power plant is necessary, because all other plants in service are already to their technical minimums. We observe that the decrease of ELMED generation to a value close to its technical minimum with the aim to give priority to RES generation, can have negative effects in term of the unit efficiency.

On the other hand, it is noteworthy that this operation mode relates to very stringent operating conditions of the Tunisian system, namely: maximum non-programmable RES production in minimum loading conditions.

For both scenarios the exportation to Sicily with the HVDC interconnection is always considered equal to 950 MW.

Numerical results

Static analyses carried out considering these two scenarios show that:

- In N condition, both in peak and in minimum load scenarios, no voltage violations or overloads are present.
- In N-1 conditions the security criteria are fulfilled. However, two additional violations with respect to the base case are detected in peak load condition:
    - after the tripping of the double circuit 90 kV line Grombalia-Korba: the voltage at Sidi Daoued station decreases to 79.7 kV (-11.4 %);
    - the line Rades 2 – Kram 225 kV has a load factor equal to 121% after the tripping of the double circuit Goulette – Rades 2 225 kV.

However, these latter situations occur after a fault involving a double-circuit, so, strictly speaking, they refer to N-2 security operation modes.

3.2.3 Results of the dynamic analysis

The scope of this analysis is to test the dynamic behaviour of the system, starting from the scenarios (peak and minimum load conditions) deriving from static analysis.
Since from the very first simulations the voltage levels appear to be too high if the RES power plants are operated at a null reactive power exchange with the grid (power factor equal to 1), an absorption of reactive power equal to 20% of rated power has been fixed for each RES generator. It means that the power factor would be about 0.97 (lagging reactive generation).

Sensitivity analysis examining the unpredictability of production RES

This analysis consisted of the simulation of RES generation power fluctuations, due to unpredictability and variability of generation, in order to assess their influence on grid voltages and frequency.

Both in peak and minimum load scenarios, the cases presented in the following table have been tested.

Tested cases in dynamic analysis.

	HVDC with frequency regulation	*Interconnection with Algeria*
CASE 1	NO	NO
CASE 2	YES	NO
CASE 3	NO	YES
CASE 4	YES	YES

The most important results obtained in this analysis are:

a) power fluctuations do not affect excessively the system performance, as the frequency and voltages variations remain within acceptable ranges thanks to the frequency regulation of the HVDC system and the interconnection to Algeria.
b) lacking one of these two conditions, the situation worsen; when both the above conditions are not met, the situation becomes unacceptable as the frequency goes beyond acceptable limits .
c) No particular differences between peak and minimum load conditions have been noticed (just a slight worsening in minimum load, but leaving the main results unchanged), even if the penetration of non-dispatchable RES generation is remarkably higher in minimum load condition[5].
d) The effect of HVDC frequency regulation is important in both scenarios, particularly if the Tunisian grid is isolated from the rest of Maghreb (also in this case the fluctuations are generally contained in the acceptable limits).

Fault analysis

This analysis consisted of the simulation of three critical situations (three-phase short circuits without fault impedance), each of them having a particular scope:

- Skhira – Maknassy 400 kV : three-phase short circuit on one line used to evacuate the ELMED production;
- Oueslatia – Mornaguia 400 kV : contingency on the south-north backbone of Tunisian system.
- Menzel Jemil – Bizerte 90 kV : contingence in proximity of certain RES power plants.

We point out that the faults near to ELMED power plant cause important oscillations for the whole system.

The relays of frequency derivative protection appear to be a too restrictive condition and their installation is not required either in Italian Grid Code or in Spanish Grid Code. For this reason, the simulations have been run both with and without this protective relay.

The most important results obtained from the analyses are reported below:

a) The frequency derivative protections cause in every simulation the disconnection of all RES generation plants, leading to the loss of a significant generation amount (530 MW). Therefore, we recommend avoiding the installation of frequency derivative protections.
b) Without the frequency derivative protection, the RES power plants remain in service for almost all the contingencies. The fault on the Menzel Jemil – Bizerte line risks causing the disconnection for the intervention of the underfrequency protection of one RES power plant: the nearest. In general, the tree-phase short circuit close to a RES power plant can cause its disconnection.
c) The only difference noticed between peak and minimum load scenarios has been the voltage levels, which are slightly higher in minimum load conditions. However, thanks to the RES power plants' reactive power absorption, they do not exceed the acceptable limits.

[5] The penetration coefficient of non-dispatchable RES generation is the ratio between this production and the total load.

d) The HVDC frequency regulation is important for improving the system performances (in terms of frequency regulation) after a grid fault.

In conclusion, considering the analyses carried out in compliance with the assumptions adopted in our study, a non-dispatchable RES generation equal to 530 MW appears adequate if the thermal production of ELMED power plant is 400 MW in minimum loading conditions. However, if the thermal generation is greater than 400 MW in minimum loading conditions, the non-programmable RES generation shall be reduced according to Tab. E-1.