Potential for Interconnection of Isolated Power Systems with ENTSO-E Network Example of Cyprus Power System

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***Abstract*— When it comes to isolated power systems on the ENTSO-E perimeter, many aspects need to be addressed both on technical, economic and political level. From system development prospective in scope of TYNDP project, ENTSO-E conducts every 2 years various studies in order to identify the prospective system needs and clarify the benefits of building new interconnectors and substations, reinforcement of the existing interconnection lines. In this regard isolated systems should be kept on the radar and investigated even with more cautiousness and with more details considered.**

The system investment needs in order to reach pan-European energy network with all Member States sufficiently interconnected and secured against sudden supply disruptions were in the past, and still are today substantially high.

This can be confirmed preliminary by the TYNDP 2016 Common Planning Studies results and as a final stage by the CBA results for the various infrastructure projects and with the results of Identification of the System Needs process results as a stage of TYNDP 2018.

Meanwhile considering the planned evolution of RES in ENTSO-E as it is addressed by various pan-EU goals and the ENTSO-E developed Scenarios, it makes it important to handle the operation of the isolated systems in terms of stability and security.

Keywords-components: RES; stability; capacity; Scenario

I. Interconnection Targets and Analysis Conducted by ENTSO-E

Preliminary based on the European Council decision from 2002, the 10% electricity interconnection targets have provided political support in order to address the evolution of the generation mix at the pan EU perimeter based on the ENTSO-E TYNDP 2016 and identify the key cross-border needs. As the consequence, implementation of PCI projects has improved the interconnection levels throughout the EU in the last decade.

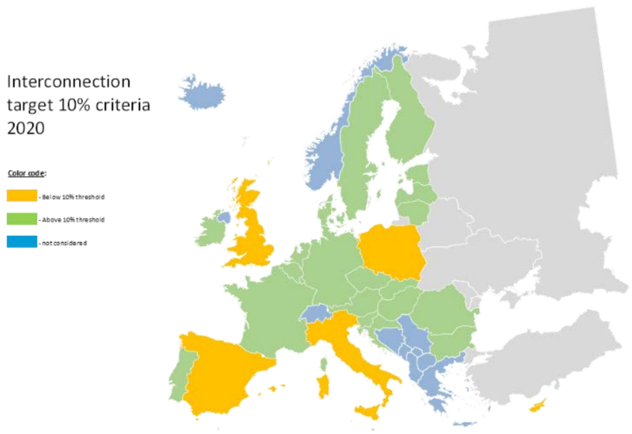

Figure 1 Expected Interconnection Levels by 2020 (source: http://tyndp.entsoe.eu/tyndp2018/power-system-2040/)

Nowadays, 17 Member states have reached the 10% targets. Seven Member States – Bulgaria, Germany, France, Ireland, Italy, Portugal and Romania – are on the path to reaching the 10% target by 2020 through the completion of PCIs currently under construction. However, additional efforts are needed to integrate the Iberian Peninsula (interconnectors Portugal-Spain and Spain-France) , South Eastern Europe (Cyprus) as well as Poland and Ireland (the Celtic interconnection with France is planned to be the first connection link between Ireland and the EU continent).

Table 1Member States' interconnection levels in 2017 and 2020 (source: https://ec.europa.eu/energy/sites/ener/files/documents/communication_on_infrastructure_17.pdf)

Country	Interconnection levels in 2017	Expected interconnection levels in 2020
AT	15%	32%
BE	19%	33%
BG	7%	18%
CY	0%	0%
CZ	19%	23%
DE	9%	13%
DK	51%	59%
EE	63%	76%
ES	6%	6%
FI	29%	19%
FR	9%	12%
UK	6%	8%
EL	11%	15%
HR	52%	102%
HU	58%	98%
IE	7%	18%
IT	8%	10%
LT	88%	79%
LU	109%	185%
LV	45%	75%
MT	24%	24%
NL	18%	28%
PL	4%	8%
PT	9%	21%
RO	7%	15%
SE	26%	28%
SI	84%	132%
SK	43%	59%

According to 2014 March and June European Councils conclusions, which stressed the need to ensure the full participation of all Member States in the internal energy market, the European Council called upon the Commission in October 2014 to report regularly to the European Council with the objective of arriving at a 15% target by 2030, as proposed by the EC.

The EC established an Expert Group, composed of 15 experts from all over Europe, to advise on the ways to achievement of the 15% interconnection targets by 2030. The Expert Group concluded its report last September and it has been issued last November.

The report of the Expert Group studied the challenges brought by the constantly changing energy sector. Its' recommendation in assessing the need for developing further interconnection capacity addressed different thresholds and approaches to reflect in a more detailed way the up to date energy realities of the Member States and the purpose interconnectors follow in supporting the implementation of the internal energy market, fostering the RES integration and improving the SoS on pan-European perimeter.

According to the Expert Group, Member States, TSOs/promoters, regulators and European institutions should take actions in case of any of the following thresholds is triggered:

- Efficient internal energy market should be interpreted in competitive electricity prices throughout EU. Member States should strive for minimising differences in wholesale market prices. New interconnectors shall be kept in priority if the price difference is exceeding threshold of 2€/MWh Member State borders, regions or bidding zones. The higher the price difference, the higher are the interconnection needs.

- The peak demand shall be met through the combination of national capacity and imports for every Member State. In case the nominal transmission capacity of interconnectors is below 30% of their peak load, Member State should investigate options of further interconnector possibilities.

- The further integration of RES shall not be blocked by the insufficient export capacity. RES for any Member State should be optimally at the pan-European level. Countries for which the interconnectors' nominal transmission capacity is below 30% of installed renewable capacity should study the options of further infrastructure development.

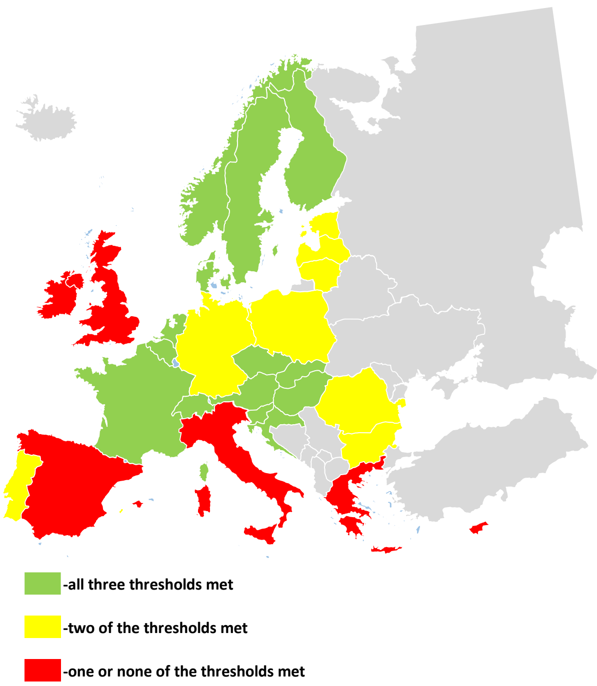

Figure 2 Expected Interconnection Levels by 2030 (source: https://ec.europa.eu/energy/sites/ener/files/documents/report_of_the_commission_expert_group_on_electricity_interconnection_targets.pdf)

As it could be derived from the Figure above, even when using 2020 nominal capacities of interconnectors (P= √3*U*Inom.) and the prospective 2030 RES generating capacities and loads from TYNDP 2016 for the computations, some Member States still are left without the targets being reached. This is especially applicable for the isolated systems like Cyprus, Sardinia (Italy), Corsica (Italy), Greece, Crete (Greece), Great Britain, Ireland.

On the basis of the methodologies defined by the Interconnection Target Group ENTSO-E decided to go further and check the Interconnection Levels at the 2040 time horizon as reached during the Identification of the System Needs process in TYNDP 2018 as explained in the latest report of ENTSO-E named “Completing the map”.

The methodology and the steps of analysis that have been taken to reach the 2040 interconnection levels could be summarized on the Figure 3 below.

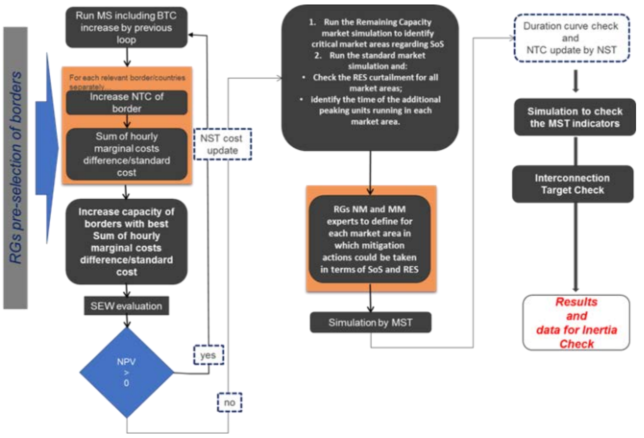

Figure 3 Diagram of Identification of the System Needs Process

As it could be derived from the Figure 3, the transfer capacity increase has been driven by Socio-economic welfare, RES integration and Security of Supply criteria while using the Regional expertise for the 2 latter indicators. The starting point used for the analysis was 2030 time horizon Scenarios from TYNDP 2016 CBA process.

According to the analysis of the Interconnection levels for all 3 2040 Scenarios which were consolidated based on the Identification of the System Needs process: Sustainable Transition, Global Climate Action, Distributed Generation.

For 2040 Sustainable transition:

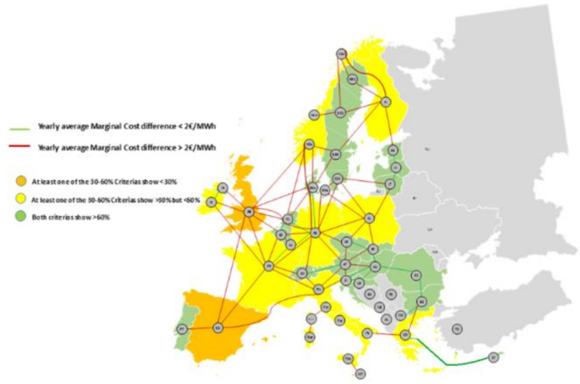

Figure 4 Prospective Interconnection Levels for 2040 ST Scenario (source: http://tyndp.entsoe.eu/tyndp2018/power-system-2040/)

For 2040 Global Climate Action:

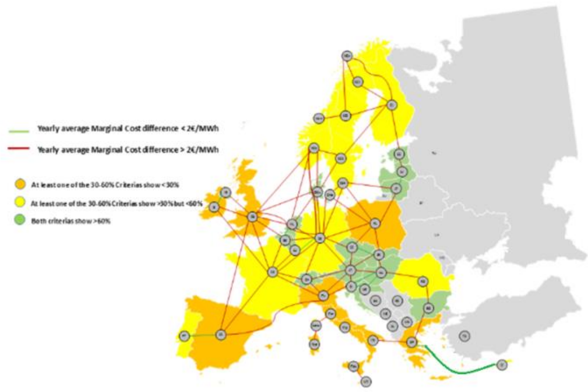

Figure 5 Prospective Interconnection Levels for 2040 GCA Scenario (source: http://tyndp.entsoe.eu/tyndp2018/power-system-2040/)

For 2040 Distributed Generation:

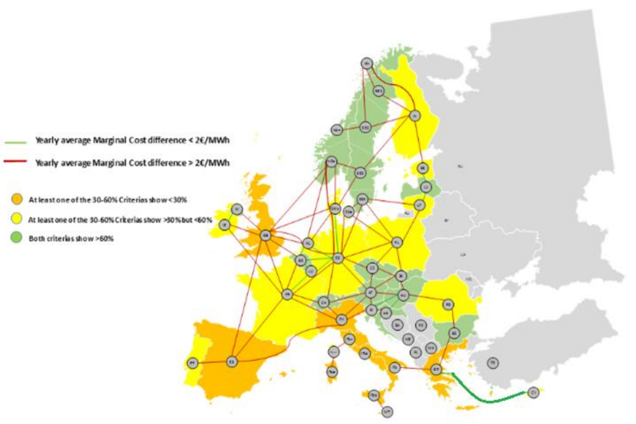

Figure 6 Prospective Interconnection Levels for 2040 DG Scenario (source: http://tyndp.entsoe.eu/tyndp2018/power-system-2040/)

As it may be concluded based on the results of Identification of the System Needs process of TYNDP 2018, Member States shall consider investigation of additional infrastructure investments even on this time horizon. This is especially applicable for the South-East region, Iberian Peninsula, Great Britain, Ireland. In high RES penetration Scenarios the interconnection possibilities should be evaluated for the interconnections with Cyprus, Baltic States.

It is worth to mention that synchronisation of the three Baltic States' electricity grid with the continental European network is also in line with the political priority goals currently supported from the European Commission side.

In this context, the study is currently being carried out by the Transmission System Operators of Lithuania, Latvia, Estonia and Poland with European Network of electricity Transmission System Operators (ENTSO-E).

II. Economic prospectives of interconnection of Cyprus power system

From the TYNDP 2018 prospective it is worth to analyse Regional Group Continental South East (Figure 7) to address the importance of interconnection of one of the largest isolated power systems in ENTSO-E, Cyprus power system.

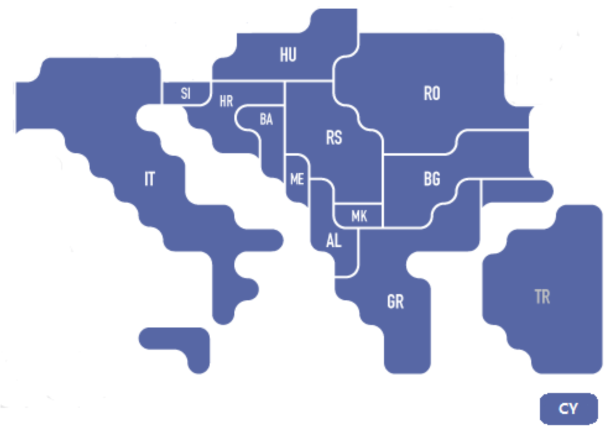

Figure 7 RG CSE Members

In order to address the economic benefit of interconnection of the Cyprus system it is worth to compare the unserved energy according to market simulation results taking into account 2040 generation mix as defined in the TYNDP 2018 Scenarios with 2040 estimated grid, when the system is already interconnected with ENTSO-E network and the situation where 2020 grid exists while the generation mix reflects the 2040 optimized generation fleet.

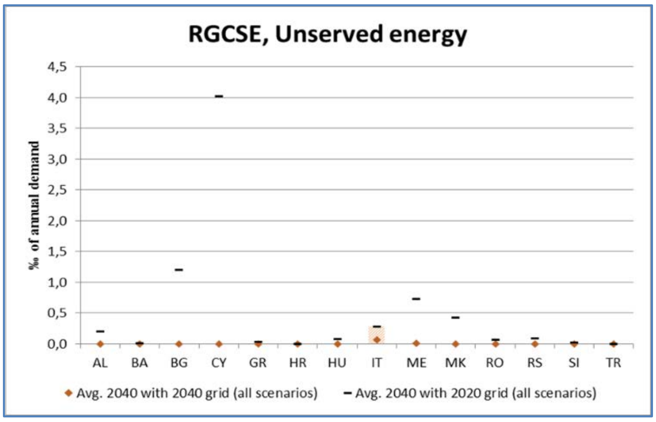

Figure 8 RG CSE Unserved energy 2020 VS 2040 (source: [https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP 2018/rgip_CSE_Full.pdf](https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/rgip_CSE_Full.pdf))

While weighting the unserved energy by native demand, we can see that based on the 2040 forecast, Cyprus may be under serious risk of loss of load. However, the risk completely diminishes after the 2000 MW interconnection is built with ENTSO-E network (Eurasia interconnector).

It is worth mentioning that the marginal cost drops twice in case of interconnection of Cyprus with ENTSO-E compared to the case of no interconnector existing while using the average figures among all the 2030 and 2040 ENTSO-E TYNDP 2018 Scenarios. This is shown in the Figure 9 also in comparison with other countries which are included in the Regional Group CSE included in System Development Committee of ENTSO-E.

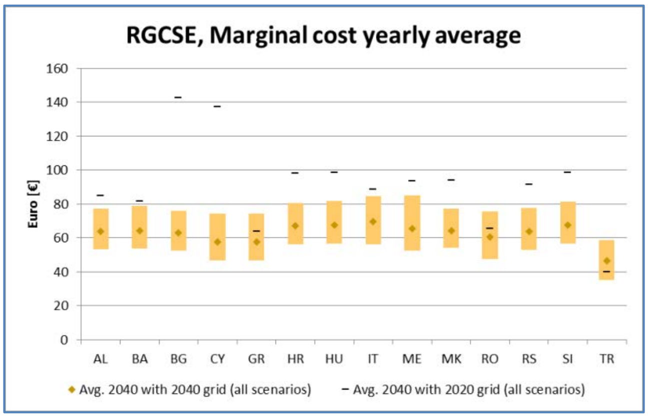

Figure 9 RG CSE Marginal costs 2020 VS 2040 (source: https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP 2018/rgip_CSE_Full.pdf)

In TYNDP 2016 process specific project has been submitted connecting Cyprus. Greece and Israel. The project has received PCI label 3.10. .

The Euro Asia Interconnector consists of a 400 kV DC underwater electric cable and any essential equipment and/or installation for interconnecting the Cyprus, Israel and the Greek transmission networks (offshore). The Interconnector is planned to establish the gross transfer capacity of 2000 MW. The total length of the project is around 832 nautical miles/around 1541 km (approx. 314 km between CY and IL, 894 km between Cyprus and Crete and 333 km between Crete and Athens) and should allow reverse transmission of electricity.

The project has been assessed according to the CBA 1.0. methodology, approved by the EC in February 2015.

The CBA results of the interconnection projects are shown in the Table below.

Table 2 TYNDP 2016 B1, B2, B3, B4, B5 Indicators for Euroasia Interconnector project according to CBA 1.0. methodology (source: https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP %202016/projects/P219.pdf)

Scenario specific CBA indicators	EP2020	Vision 1	Vision 2	Vision 3	Vision 4
B1 SoS (MWh/yr)	N/A	N/A	N/A	N/A	N/A
B2 SEW (MEuros/yr)	360 ±40	660 ±100	580 ±90	1010 ±150	1120 ±170
B3 RES integration (GWh/yr)	750 ±50	4080 ±820	4070 ±810	3260 ±650	3010 ±600
B4 Losses (GWh/yr)	1250 ±125	1100 ±110	1100 ±110	1225 ±122	2050 ±205
B4 Losses (Meuros/yr)	54 ±5	59 ±6	51 ±5	73 ±7	137 ±14
B5 CO2 Emissions (kT/year)	±100	-5600 ±800	-6800	-2300 ±300	-1300 ±200

Project showed serious benefits in terms of Socio-Economic welfare (B2, MEuro/year) mainly due to Security of Supply component as is expected to solve the adequacy issues in the long term in Cyprus, which in high RES penetration Vision 4 from TYNDP 2016 reaches 1120 ± 170 MEuro/year.

Also project according to the CBA results fosters the integration of the renewable energy sources of around 3010 ± 600 GWh/year, consequently this leads to reduction of the CO_2 emissions in the Vision 4 (2030 time horizon) in TYNDP 2016 by 1300 ± 200 kT/year.

Therefore, the interconnection of Cyprus to ENTSO-E already based on the CBA results from TYNDP 2016 and the analysis conducted during the TYNDP 2018 Identifications of the System Needs process may be considered beneficial both financially and environmentally.

III. Evolution of the Generation Mix in Cyprus

It is worth to point out the energy mix development in Cyprus according to the ENTSO-E Scenarios.

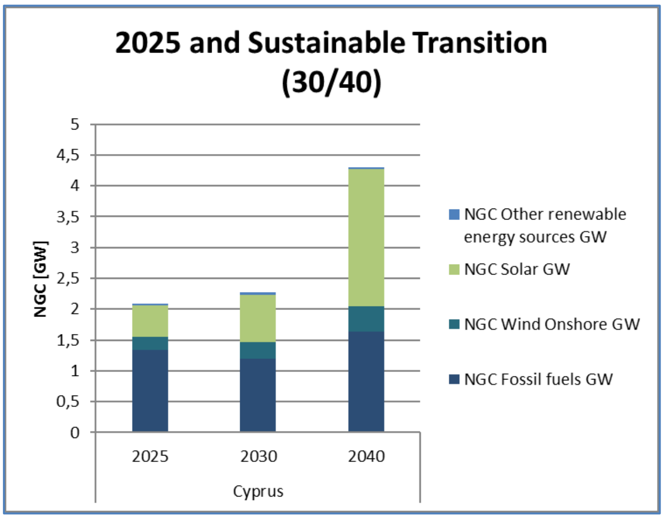

Figure 10 NGC Evolution in Cyprus for Other RES, Solar, Wind Onshore, Fossil fuels – 2025 BEST, 2030 ST, 2040 ST ENTSO-E TYNDP 2018 Scenarios

As it can be seen on the Figure 10, Cyprus Net Generating Capacity faces exponential increase for the solar technology, especially between 2030 and 2040 time. Even for the most conservative ENTSO-E Scenario Storyline – Sustainable Transition, the increase accounts for 1,44 GW of additional solar generation capacity which is almost 3 times as much as in 2030 Sustainable Transition and almost 4 times as much as in 2025 Best Estimate Scenario.

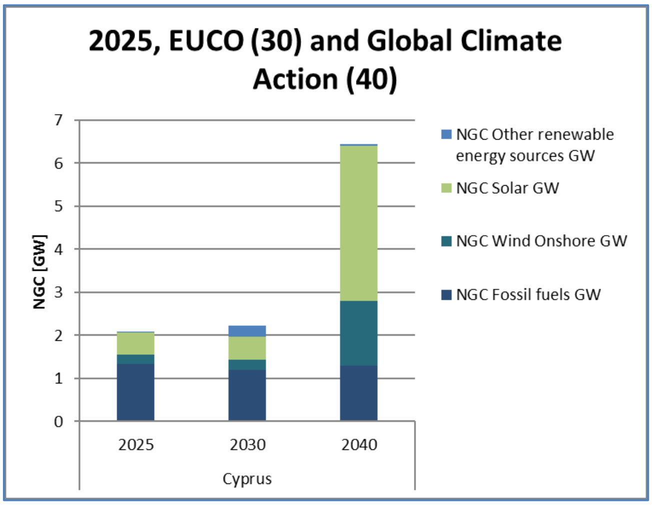

Figure 11 NGC Evolution in Cyprus for Other RES, Solar, Wind Onshore, Fossil fuels – 2025 BEST, 2030 EUCO, 2040 GCA ENTSO-E TYNDP 2018 Scenarios

As it can be clearly seen in Figure 11, in one of the "greenest" ENTSO-E Scenario the highest increase in Solar Net Generating Capacity in Cyprus between 2030 and 2040 can be observed, reaching the difference of 3,06 GW which is 6 times higher than in 2030 European Target Scenario in 2040 Global Climate Action and almost the same ratio compared to 2025 Best Estimate. At the same time, an increase of 1,3 GW in Wind Onshore Net Generating Capacity is reached between 2030 EUCO and 2040 Global Climate Action Scenarios which is 5 times accounts for 5 times increase in this case.

Last but not least, the 2040 Distributed Generation ENTSO-E Scenario, as depicted in the Figure 12 below, shows also considerable increase in Solar NGC (almost 1 GW) and at the same time the highest increase of Wind Onshore Net Generating Capacity among all the ENTSO-E Scenarios between 2030 and 2040 time horizons (1,3 GW) while moderate increase between 2025 and 2030 for Wind NGC however considerable increase in Solar NGC (0,49 GW).

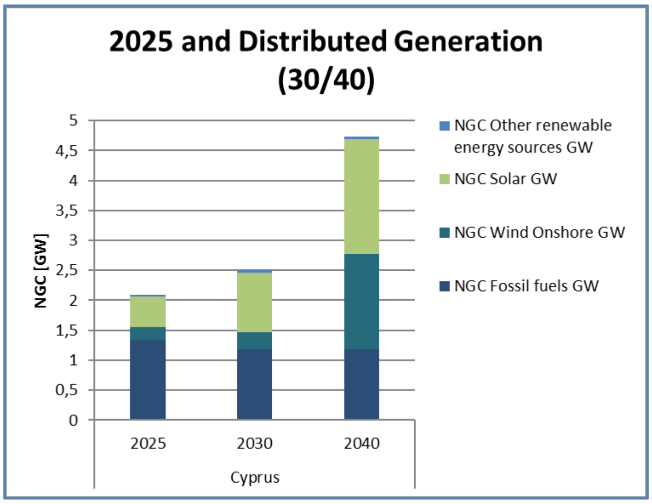

Figure 12 NGC Evolution in Cyprus for Other RES, Solar, Wind Onshore, Fossil fuels – 2025 BEST, 2030 DG, 2040 DG ENTSO-E TYNDP 2018 Scenarios

As a conclusion, the evolution of average between all the 2025, 2030 and 2040 Scenarios is visualized in the Figure 13.

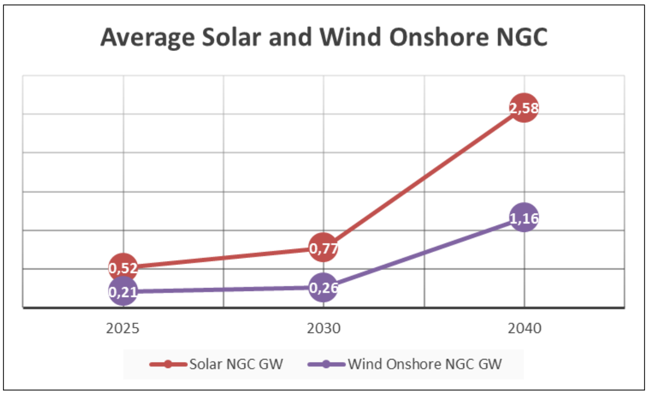

Figure 13 Average Solar and Wind Onshore NGC between 2025 and average of all 2030 and 2040 ENTSO-E TYNDP 2018 Scenarios

As it can be summarized based on the Figure 13, there is considerable increase of Solar and Wind Onshore generation expected by 2030 and 2040 time horizons which is based on the ENTSO-E TYNDP 2018 Scenarios built based on the EU targets and other justified pan-EU assumptions.

In order to incorporate in the Cyprus Ten Year Development Plan the analysis for the euroasia interconnector the TSOC needs to have a valid application from the promoter. Although, this interconnection project is at a mature stage still the application is not submitted yet. For the above reason, the Cyprus Ten Year Development Plan is studied based on the case of isolated condition situation.

Therefore, to handle such large-scale RES penetration, Cyprus power system should be studied in detail and prepared to operate in such future realities.

For these purposes Cyprus TSO has conducted detailed study to investigate the maximum possible RES penetration in the Cyprus Electricity System while ensuring the secure operation of the System and without allowing mandatory curtailment of RES output. The results of this study are described in the following chapters.

The aim of the current study is presented in Section IV, whereas Section V examines the input data and the assumed parameters adopted in the study. A detailed description of the methodology is examined in Section VI. The results are presented in Section VII, followed by the discussion of results and conclusions in Section VIII.

IV. THE AIM OF THE STUDY

As mentioned in the chapter III and as already witnessed during the past decade, electricity generation from Renewable Energy Sources (RES) is taking a significant share of the Global Electricity Generation. This especially applies in the European Union, mainly due to the RES' penetration targets set by the European Commission, which are successfully integrated in the ENTSO-E developed target and conservative Scenarios as well as the increasing private initiatives. RES penetration in the electricity system is increasing exponentially, especially technologies such as Photovoltaics (PV), Wind Farms, Biomass and Solar Thermal Power Generation Plants, which are now considered to be reliable and attractive to investors, even without subsidies.

Nevertheless, as most of those technologies are characterised as Variable Renewable Energy Sources (VRES), their generation profile is dependent on the prevailing weather conditions. Furthermore, the high cost of energy storage systems is a deterrent for their use, meaning VRES are a non-dispatchable generation technology. In that meaning, VRES technologies cannot accommodate the option to vary their generation profile. It should be noted that their output can be decreased (curtailed), however the primary energy source is then lost and can not be used at a later stage. According to the ENTSO-E investigations done during the Identification of the System needs process while comparing the situation of 2020 grid and 2040 generation mix and the 2040 grid and 2040 generation mix the value of curtailment among all the TYNDP 2018 Scenarios reaches maximum of 2,47 TW in some hours of the year and 1,04 TWh\year on average.

The aim of the study was to investigate:

A. Secure Operation of Cyprus Power System

The fundamental parameter of the study is the Secure Operation of the System under both Steady State and Dynamic Operation.

The Steady State security assessment of the system is based on the assumption that after a disturbance, the transition from one operating state to another occurs without any instability phenomena being observed in any part of the Electricity System.

Dynamic system security assessment evaluates the stability and quality of the transition processes from the pre-disturbance to the post-disturbance operating state. Thus, it is ensured that the System will remain stable after a disturbance and that transient phenomena resulting from this disturbance are manageable and do not cause any instability problems. To assess Dynamic System Security four parameters related to the System Operation were studied:

Rotor Angle Stability: The ability of connected synchronous machines in an Electricity System to remain synchronised during normal operation and especially after a disturbance. This depends on the ability to conserve or restore the balance between electromagnetic and mechanical torque on all synchronous machines on the system.

Frequency Stability: The ability of an Electricity System to maintain the system frequency within specified limits after a disturbance which results in an imbalance between aggregate generation and aggregate demand.

Voltage Stability: The ability of an Electricity System to maintain the voltage at all busbars within acceptable limits under normal operating conditions, and more importantly after a disturbance. The main cause of voltage instability is inability to maintain reactive power balance in the System.

Harmonic Distortion: Harmonic currents or voltages at frequencies which are a multiple of the fundamental system frequency, and which are generated due to non-linear characteristics of power systems and loads.

For the four parameters described above, the maximum allowable RES penetration was determined for a range of selected Demand scenarios. For each individual scenario the minimum number of synchronised conventional generating units was set.

B. Maximum RES penetration

RES penetration was investigated in steps corresponding to different demand scenarios each with its own synchronised generation mix, taking into account the steady state and dynamic security assessment.

RES penetration scenarios were based on the revised 2020 RES Action Plan of the Ministry of Energy, Commerce, Industry and Tourism (MCIT).

The annual RES curtailment was estimated based on the demand scenarios, RES penetration and minimum synchronised conventional Generation requirements so as to ensure system security.

V. CONSTRAINTS/ASSUMPTIONS

A. Constraints

The Cyprus Electricity System is an isolated system without any energy storage facilities. This is crucial, because it means that Demand must always equal generation for the system to be in balance.

Minimum synchronized generation mix requirements have been set by TSO-Cyprus, to ensure the secure Operation of the System. Furthermore, the requirements for FCR, FRR, RR and the additional reserves due to wind and solar generation are set based on the Spinning Reserve policy.

Due to the constitution of the System, under frequency stages have been set which trigger load rejection in case of loss of generation due to a fault.

All Power generation takes place at three conventional Power Stations owned by the Dominant Participant (Electricity Authority of Cyprus), and include the following types of generation units:

- Steam Turbines
- Combined Cycle Gas Turbines
- Open Cycle Gas Turbines
- Internal Combustion Engines (ICE)

Finally, the inertia of the load connected to the System is taken into account in the analysis of under frequency events.

B. Assumptions

The study assumptions are:

- The current conventional generation capacity remains unchanged.
- The Transmission System evolution is as per the Ten Year Development Plan.
- Demand is based on the approved Ten Year Forecast of TSO-Cyprus.
- Maximum RES Generation is based on the National Action Plan 2015-2020. More specifically, for the year 2020, the installed RES capacity will consist of 258 MW PV, 175 MW wind and 15 MW biomass.
- N-1 generation loss due to a fault, that is only one generation unit may be lost at a time.
- The loss of the biggest generation unit connected to the Electricity System (130MW) is likely to trigger the Under frequency Load Rejection plan.
- RES generation takes priority in unit commitment over Conventional Generation.
- RES generation is not affected by under frequency/ over frequency events.
- RES protection systems operate correctly.
- Conventional generation unit commitment priority is as specified by the Electricity Authority of Cyprus, except where security reasons necessitate a different unit committment priority.

Furthermore, the following assumptions apply for Harmonic Distortion Analysis:

The System does not have any harmonic sources other than PV connected to the Distribution System.

The level of harmonic infeed is similar for all PV systems because they are all installed at roughly the same longitude.

There is zero dc infeed from the PV system inverters.

VI. METHODOLOGY

A. *Simulations*

Two software tools, DIgSILENT Powerfactory® and Matlab Simulink, were used for the dynamic modeling of system operation during loss of generation events. PowerFactory is a commercial power system analysis software application for use in analysing generation, transmission, distribution and industrial systems. Matlab Simulink® is a block diagram environment for multidomain simulation and Model-Based Design.

Both software have been used extensively in the past for modelling the Power Systems of Cyprus and their results have been verified against real events of loss of generation or load.

B. *Demand Profile*

The first step of the study was to estimate the demand curves for the period under investigation. Aggregate Consumption (GWh) and Peak Load (MW) were obtained from the ten year forecast which is published annually by TSO-Cyprus.

Demand time series for 2018, 2019 and 2020 were estimated based on the half-hourly measurements for year 2016, ensuring that the annual aggregate consumption and the peak load were close to the values given in the ten year forecast. These time series were used to estimate the annual RES curtailment. 12 scenarios were used to estimate curtailment, representing the minimum System demand for each calendar month.

Furthermore, dynamic system performance was studied for demand values between 350-1200 MW in 50 MW steps.

C. *RES data*

According to the National Action Plan, the RES mix will consist of PV, Wind, Biomass and Solar Thermal units. As the generation profile of Solar Thermal systems is similar that of PVs, it was assumed that the two technologies are the same. Thus, the study considered the worst case penetration scenario, since the possible storage capacity of Solar Thermal Systems was not included[1]. The per unit generation profile for every RES technology was estimated for a year (in half-hourly steps) and then for every scenario, the actual generation profile was calculated based on the installed capacity for that scenario.

PV generation time series were based on the generation profile of the existing systems, which is turn estimated through measurements from selected PVs that are connected to the SCADA.

Wind generation time series were based on the generation profile of existing Wind Farms, as recorded through the SCADA.

As no generation profile for biomass is available, it was assumed that biomass station output is constant and equal to the capacity factor of existing units.

Furthermore the maximum allowed RES penetration for specified Demand levels was investigated through a dynamic system performance analysis.

D. *Conventional Generation Unit Commitment*

Conventional Unit Commitment is determined based on demand, so that after taking into account RES generation and requirements for Reserves, Generation and Demand are balanced. The minimum level of Conventional Units for varying Demand levels is determined through the dynamic system performance analysis.

It should be emphasized that the Minimum Conventional Generation in the System is determined by the technical characteristics of the Generation Units. Curtailment is estimated based on this minimum conventional generation limit.

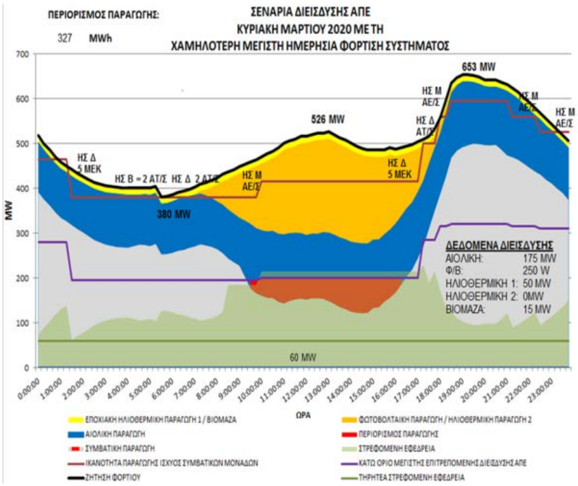

Table 1: RES penetration curtailment scenarios at minimum load

Dynamic system performance analysis determines the number and type of Conventional Generation Units required for the secure operation of the System.

E. *Frequency and Rotor Angle Stability Investigation*

The dynamic performance of the parameters related to an under frequency event was investigated; these are inertia, rate of change of frequency, frequency recovery time, frequency minimum, and the frequency containment reserve of the System.

Under minimum synchronised conventional generation conditions as determined earlier for each scenario, the effects of the loss of the biggest synchronised generation unit were investigated using the two software tools (Powerfactory and MatLab).

The study determined the maximum RES penetration for each demand scenario. Operation was considered secure where the system frequency recovers to 49,5Hz within 20 seconds from the occurrence of the under frequency event. It should be noted that operation of the under frequency stages was included in the analysis.

F. *Voltage Stability Investigation*

To begin with, PVs were allocated to the busbars of every Transmission Substation, in order to study locally per substation the impact of reactive power in the System. Allocation took place based on the JRC Study (Integration of

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[1] It is noted that the licensed Stations will use Stirling Engines without storage and Concentration Systems with storage

a high share of variable RES in the Cyprus power system 2016).

PV inverters were modelled based on the current DSO instruction. According to this instruction, the inverter reduces power factor linearly when generated output exceeds 40% of rated, by increasing reactive power absorption up to a power factor of 0.9 at maximum generated output.

Three Demand scenarios, 420 MW, 655 MW and 1145 MW, were investigated which are considered representative of the minimum, average and maximum demand of the system respectively.

Additionally, Voltage stability was investigated for an N-2 event along the backbone Transmission System. That is, after a fault resulting in the loss of a double circuit, the System continues to operate reliably.

The aim of the simulation was to determine the maximum allowed RES penetration for each of the three Demand scenarios.

Powerfactory was used for System modelling and simulation.

G. Harmonic Distortion Evaluation

To begin with, PVs were allocated to the busbars of every Transmission Substation, in order to study locally per substation the impact of reactive power in the System. Allocation took place based on the JRC Study (Integration of a high share of variable RES in the Cyprus power system 2016).

Harmonic modelling of PV system inverters was based on existing PV measurements and also on the maximum allowed harmonic distortion as per the relevant clauses of the Cyprus Transmission and Distribution Rules and IEC 61727.

Three Demand scenarios, 420 MW, 655 MW and 1145 MW, were investigated which are considered representative of the minimum, average and maximum demand of the system respectively.

Detailed harmonic analysis for the above scenarios took place for the 132kV and the 11/22kV busbars at a selection of Transmission Substations, for the maximum possible PV penetration and for the maximum allowed voltage harmonic distortion according to the Cyprus Transmission and Distribution Rules, while also considering the N-1 and N-2 criteria.

The aim of the simulation was to determine the maximum allowed RES penetration for each of the three demand scenarios.

Powerfactory was used for System modelling and simulation.

VII. RESULTS

A. Frequency and Rotor Angle Stability Investigation

The worst-case scenario for under frequency events is the one with the fewest synchronized conventional units (4 steam turbines in two separate power stations), which results in the least inertia and frequency containment reserve.

Under worst case scenario, the loss of the biggest unit while operating at maximum load combined with the rest of the synchronised units operating at minimum load results in the maximum percentage loss of generation and therefore the operation of more stages of the Under frequency Plan.

Wind production improves System response as it results in less output (and hence lower percentage loss) from conventional Units.

Photovoltaic generation affects the System inertia and therefore the frequency minimum, the rate of change of frequency and the frequency recovery time.

The coordinated operation of the Under frequency Plan supports frequency recovery to 49.5HZ within 20 seconds from the beginning of the under frequency event, thus Dynamic Stability is successfully simulated.

Finally, the analysis and evaluation of rotor angle stability has not indicated any issues with the dynamic operation of the System.

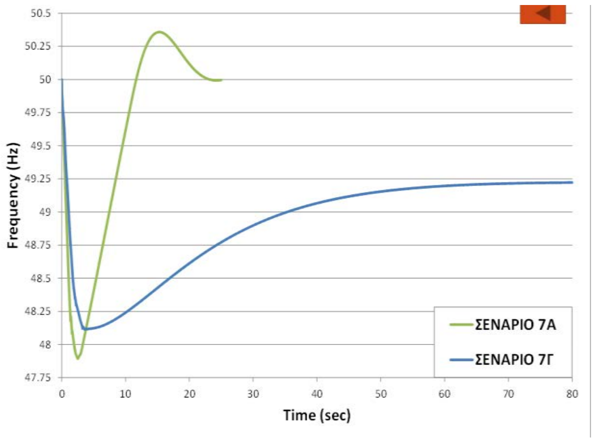


Table 2: Frequency Stability Investigation scenarios

B. Voltage Stability Investigation

The results for the three demand scenarios are:

Maximum demand. Simulations have shown that the maximum allowed PV penetration is 455MW. It should be noted that under an N-2 condition, voltage drop at 132kV busbars is up to 10%, which is the maximum permitted according to the Transmission and Distribution Rules. For 455 MW PV generation there is 200 MVAr reactive power absorption at the same time. Thus system operation is negatively affected, as during maximum demand there is increased demand for reactive power.

For average and low demand where the maximum allowed PV penetration is 455 MW and 200 MW respectively, there were no significant voltage issues. The characteristic pf curve as a function rate of change of PV Power is seen in Table

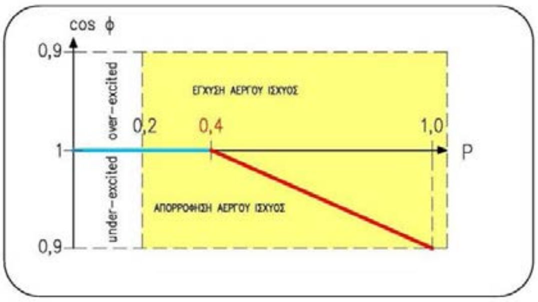


Table 3: Characteristic pf curve as a function rate of change of PV Power

C. *Harmonic Distortion Evaluation*

Simulation using the maximum harmonic distortion permitted by the Cyprus Transmission and Distribution Rules and IEC 61727 results in a significantly higher harmonic voltage distortion at the 132kV and 11kV busbars than simulation using inverter models built from measurements at existing PVs.

In the first case, the maximum allowed PV penetration is significantly reduced, with the limit being 250 MW, 200 MW and 150 MW for maximum, average and minimum demand respectively.

In the second case, the maximum allowed PV penetration is increased to 520 MW for all scenarios.

It is noted that according to Cyprus-TSO measurements at the Wind Farm Connection Points, harmonic distortion is within the limits specified in the Cyprus Transmission and Distribution Rules.

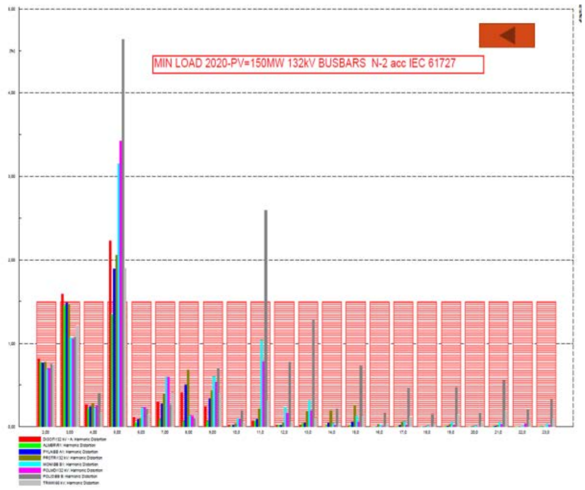


Table 4: Harmonic distortion results.

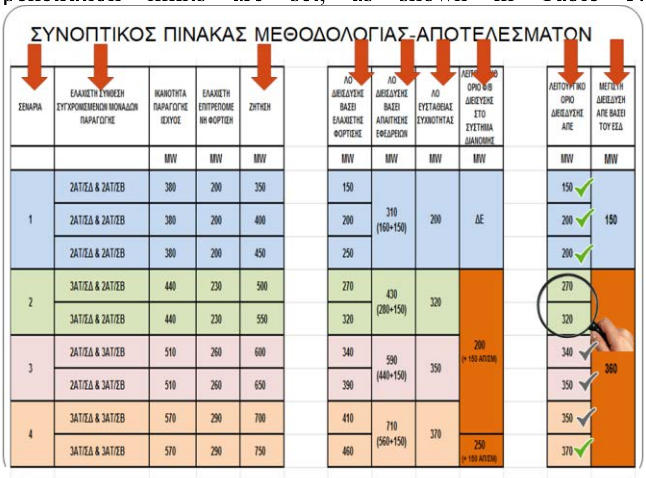
D. *Determination of Operational Limit for Secure System Operation*

The maximum permitted operational limit for PV and other RES penetration was evaluated based on the dynamic system performance analysis and the minimum conventional generation requirements for various Demand scenarios.

Voltage stability and harmonic distortion were the limiting factors in setting the allowed PV limit. Based on the evaluation of the factors, the Operational Limit for voltage stability must not exceed 455MW, while for harmonic distortion according to IEC 62717 which gives worst case results, the maximum allowed PV penetration is 150 MW, 200 MW and 250 MW for low, average and high load. Therefore, harmonic distortion determines the operational limit.

The total RES penetration limit was determined based on PV penetration, the minimum allowed conventional unit output, the System reserves and the frequency stability analysis. Based on these limits, a maximum allowed RES penetration was determined for different system demand levels in 50 MW steps.

Finally, all data were collated in a table, where for every Demand step, the PV and the other RES maximum penetration limits are set, as shown in Table 5.



ΣΥΝΟΠΤΙΚΟΣ ΠΙΝΑΚΑΣ ΜΕΘΟΔΟΛΟΓΙΑΣ-ΑΠΟΤΕΛΕΣΜΑΤΩΝ

ΣΕΝΑΡΙΑ	ΕΛΑΧΙΣΤΗ ΣΥΝΘΕΣΗ ΣΥΓΧΡΟΝΙΣΜΕΝΩΝ ΜΟΝΑΔΩΝ ΠΑΡΑΓΩΓΗΣ	ΙΚΑΝΟΤΗΤΑ ΠΑΡΑΓΩΓΗΣ ΙΣΧΥΟΣ	ΕΛΑΧΙΣΤΗ ΕΠΙΤΡΕΠΟΜΕΝΗ ΦΟΡΤΙΣΗ	ΖΗΤΗΣΗ	ΛΟ ΔΙΕΙΣΔΥΣΗΣ ΒΑΣΕΙ ΕΛΑΧΙΣΤΗΣ ΦΟΡΤΙΣΗΣ	ΛΟ ΔΙΕΙΣΔΥΣΗΣ ΒΑΣΕΙ ΑΠΑΙΤΗΣΗΣ ΕΦΕΔΡΕΙΩΝ	ΛΟ ΕΥΣΤΑΘΕΙΑΣ ΣΥΧΝΟΤΗΤΑΣ	ΛΕΙΤΟΥΡΓΙΚΟ ΟΡΙΟ Φ/Β ΔΙΕΙΣΔΥΣΗΣ ΣΤΟ ΣΥΣΤΗΜΑ ΔΙΑΝΟΜΗΣ	ΛΕΙΤΟΥΡΓΙΚΟ ΟΡΙΟ ΔΙΕΙΣΔΥΣΗΣ ΑΠΕ	ΜΕΓΙΣΤΗ ΔΙΕΙΣΔΥΣΗ ΑΠΕ ΒΑΣΕΙ ΤΟΥ ΕΣΔ
		MW	MW	MW	MW	MW	MW	MW	MW	MW
1	2ΑΤ/ΣΔ & 2ΑΤ/ΣΒ	380	200	350	150	310 (160+150)	200	ΔΕ	150	150
	2ΑΤ/ΣΔ & 2ΑΤ/ΣΒ	380	200	400	200				200	
	2ΑΤ/ΣΔ & 2ΑΤ/ΣΒ	380	200	450	250				200	
2	3ΑΤ/ΣΔ & 2ΑΤ/ΣΒ	440	230	500	270	430 (280+150)	320	200 (+ 150 ΑΠ/ΣΜ)	270	360
	3ΑΤ/ΣΔ & 2ΑΤ/ΣΒ	440	230	550	320				320	
3	2ΑΤ/ΣΔ & 3ΑΤ/ΣΒ	510	260	600	340	590 (440+150)	350		340	
	2ΑΤ/ΣΔ & 3ΑΤ/ΣΒ	510	260	650	390				350	
4	3ΑΤ/ΣΔ & 3ΑΤ/ΣΒ	570	290	700	410	710 (560+150)	370		350	
	3ΑΤ/ΣΔ & 3ΑΤ/ΣΒ	570	290	750	460			250 (+ 150 ΑΠ/ΣΜ)	370	

Table 5: RES Penetration Limits

VIII. CONCLUSIONS

According to the EC 2020 10% Interconnectivity targets, Cyprus power system was on the list of EU Members, for which the possibilities of interconnection have been flagged as such that should be investigated. The new criteria developed by the Interconnection Target Group, composed of various stakeholders, including EC and ENTSO-E representatives were utilized and a report has been published in November 2017. As the time horizon considered for investigation was 2020 (Expected Progress 2020 Scenario from TYNDP 2016), the Cyprus – GR was still not included in the investigation, therefore Cyprus was still estimated as the EU Member State, for which the interconnectivity levels should be reached.

ENTSO-E went further and conducted an analysis based on the 2040 TYNDP 2018 Scenarios to check the Interconnectivity levels at more long-term time horizon. The results showed that 2 out of 3 2040 Cyprus reached the interconnectivity targets, however for the 2040 Global Climate Action Scenarios, the adequate interconnectivity levels still were not reached. This, of course is linked to the expectations in terms of RES penetration at the ENTSO-E perimeter and in Cyprus in particular.

According to the studies recently conducted by ENTSO-E in the scope of TYNDP 2018 process (Identification of the System Needs process) and CBA analysis of the project connecting the Cyprus TSO with ENTSO-E from TYNDP 2016 the Cyprus interconnection shows major benefits in terms of integration of the electricity markets (Socio-Economic Welfare) and in terms of environmental benefits (reduction of the CO2 emissions). The marginal costs show a drastic drop on 2040 time horizon when comparing situation with and without planned interconnection of 2000 MW in net transfer capacity.

ENTSO-E developed and simulated Scenarios which are also partially outcomes of the Identification of the System Needs process in TYNDP 2018 showing considerable increase of the Solar and Wind Onshore net generating capacities in Cyprus power system. On average between the Scenarios increase of 3-4 times in both wind onshore and solar generation is observed between 2030 and 2040 time horizons.

Such high RES integration levels require additional investigations to be made in order to check the stability phenomena in the Cyprus power system to maintain the future secure operation of the power system.

For the time being Cyprus TSO performed a detailed study to investigate the stability issue on 2020 time horizon in isolated conditions.

According to the study, steady state operation of the Cyprus electrical power system is not expected to have any significant issues up to 2020 and RES penetration is basically limited by the minimum level of synchronised conventional generation for secure system operation.

Based on the studies for RES penetration, RES production curtailment will be minimal until 2020.

Rotor angle stability investigation has not revealed any issues with the dynamic operation of the System.

Frequency stability investigation has shown that RES penetration and thus the generation makeup affects the inertia of the System which can destabilize the operation of the Under Frequency Plan under certain circumstances.

Voltage stability investigation determined a maximum PV penetration of 455 MW only during high system Demand conditions.

Voltage harmonic distortion evaluation based on measured values determined a maximum PV penetration of 520 MW.

Voltage harmonic distortion evaluation based on the provisions of the Cyprus Transmission and Distribution Rules determined a different penetration limit for each demand scenario.

Based on the results of the study from the viewpoint of various System stability investigations as well as the harmonic distortion evaluation, it can be concluded that RES Penetration as per the Revised National RES Action Plan does not cause any issues with the dynamic and steady state operation of the System, provided that the indicative operational scenarios are applied in conjunction with the System demand level.

Further time horizon investigations according to the ENTSO-E Scenarios and EC targets may be conducted in the future.

IX. DISCUSSION

The maximum difference between the midday and evening winter peak in 2016 was around 250MW. Since installed PV capacity, which today is 90MW, is expected to rise to 258MW by the end of 2020, the maximum difference of 250MW will increase significantly.

The spinning reserve of synchronized conventional units, which will be operating around their minimum permitted load around midday, as well as peak generation units such as open cycle gas turbines, will be used to cover the above difference.

Therefore, RES penetration will result in an uneconomic mode of operation for the conventional base load units.

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[2] Study for the safe RES penetration to the Cyprus Electricity Network in conjuction to the updated RES Development Plan 2015-2020. G. Ashikalis et. al., June 2017, unpublished.

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