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Integration of a high share of variable RES in the Cyprus power system
Project summary - version 1.6

Administrative arrangement: SI2.211494

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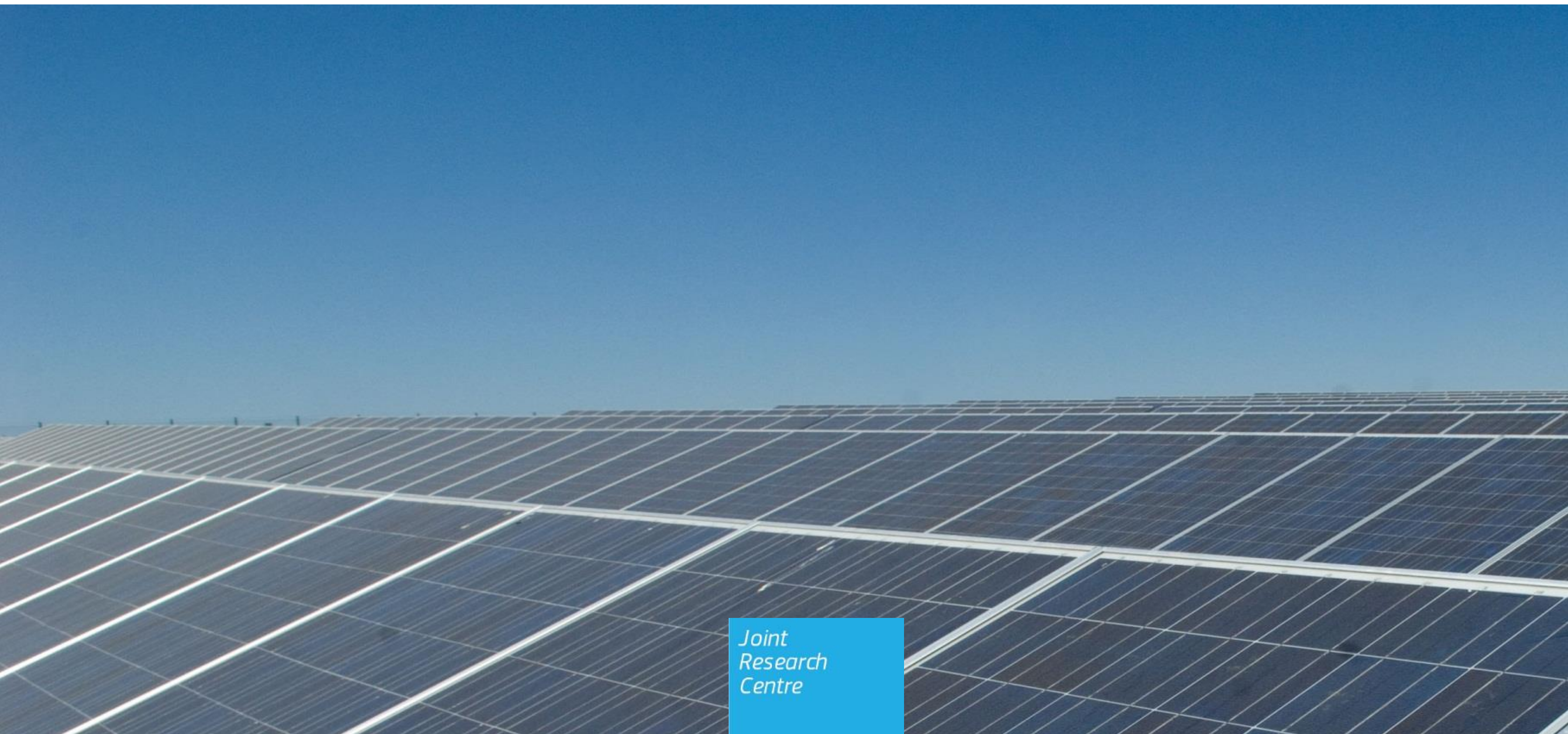

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Electricity in Cyprus – project summary

This report is presenting the final results for the project "Technical assistance for assessing the current state of the transmission and distribution electricity systems and proposing optimum solutions for increasing the amount of Renewable Energy Sources (RES) generation that can be fed on the electricity system". The main objective of the project is to support the Government of Cyprus to establish a comprehensive medium- to long-term policy for the optimum penetration of renewable energy in the electricity system until 2030. The main findings of the research are summarized in this document.

Administrative arrangement:

SI2.211494

Project acronym:

CYPRUS RES-GRID

Project title:

Technical assistance for assessing the current state of the transmission and distribution electricity systems and proposing optimum solutions for increasing the amount of Renewable Energy Sources (RES) generation that can be fed on the electricity system

This report is presenting the

Summary of the project results

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List of acronyms

BAU: Business as usual

BESS: Battery Energy Storage System

CCGT: Combined cycle gas turbine

CERA: Cyprus Energy Regulatory Authority

CSP: Concentrating solar plant

DR: Demand response

DSO: Distribution system operator

EAC: Electricity Authority of Cyprus

EC: European Commission

EU: European Union

FCR: Frequency containment reserve

FRR: Frequency restoration reserve

GT: Gas turbine

HFO: Heavy fuel oil

HV: High voltage

ICE: Internal combustion compression ignition engine

IRENA: International Renewable Energy Agency

JRC: Joint Research Centre

KTH: Royal Institute of Technology in Stockholm

LV: Low voltage

MECIT: Ministry of Energy, Commerce, Industry & Tourism

MV: Medium voltage

OLTC: On Load Tap Changer

PCC: Point of common coupling

PSP: Pump storage plant

PV: Photovoltaic

RE: Renewable Energy

RES: Renewable Energy Sources

ROCOF: Rate of change of frequency

RR: Replacement reserve

SCADA: Supervisory control and Data Acquisition

STEAM: Steam turbine

TSO: Transmission system operator

U/G: Underground (cable)

VO&M: variable operation and maintenance

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- Savvas Papadouris from EAC-distribution

1 INTRODUCTION

1.1 PROJECT DESCRIPTION

This report is a deliverable of the administrative arrangement n° SI2.211494 between DG-JRC and DG-EMPL for the project "Technical assistance for assessing the current state of the transmission and distribution electricity systems and proposing optimum solutions for increasing the amount of Renewable Energy Sources (RES) generation that can be fed on the electricity system". The main objective of the project is to support the Government of Cyprus to establish a comprehensive medium- to long-term policy for the optimum penetration of renewable energy in the electricity system until 2030. A special aspect of this project is that the long-term scenarios for the Cyprus power system were provided as input to the JRC by MECIT. Initially the long-term scenarios were foreseen to be based on the outcome of the MECIT-IRENA collaboration [16], which was available by end 2014. However, due to significant changes in some parameters, mainly the significant change in fuel prices forecast, the long term scenarios were further updated by MECIT (based on simulations by KTH) two times during the project. The second version of the long-term scenarios was available in September 2015 and was used as basis to the JRC generation dispatch (UCED) simulations presented in December 2015. After this meeting and following CERA's recommendations to include also new conventional units in the planning model, a third version of the long-term scenarios had to be simulated by KTH and was delivered to JRC in May 2016. The iterations between KTH and JRC simulations and the need to develop a detailed generation dispatch (UCED) model were time consuming activities which were not initially foreseen in the project. Finally, the JRC work plan was adapted to integrate these constraints and it was agreed to replace the work concerning the Electricity market design and implementation by the UCED model design and analysis.

In its final version, the project is divided into four activities, as shown in Figure 1, with a view to perform a technical assessment of the Cyprus electricity system (power infrastructure). This report is presenting a summary of all activities.

Activity 1 concerns mainly the collection of required data needed to perform the other activities. The main deliverable is a database with key parameters concerning distribution, transmission and generation of power.

In Activity 2, the current TSOC dynamic system model is first updated to define the reference system. Models for future components are developed and added to allow the simulation and analysis of the power system in 2020 and 2030 for different scenarios.

Activity 3 concerns first the realization of reference distribution grid models and then the simulation of the impacts due to the large integration of PV, electric vehicles and demand response. It should be noticed that Distributed Storage was not investigated in Activity 3 because this technology was included only at the very end of the project (May 2016) in the long-term scenarios provided by MECIT.

Activity 4 concerns the detailed modelling of unit commitment and economic dispatch of the generation fleet (one node system model), which dispatch results are used as input for the transmission model (activity 2).

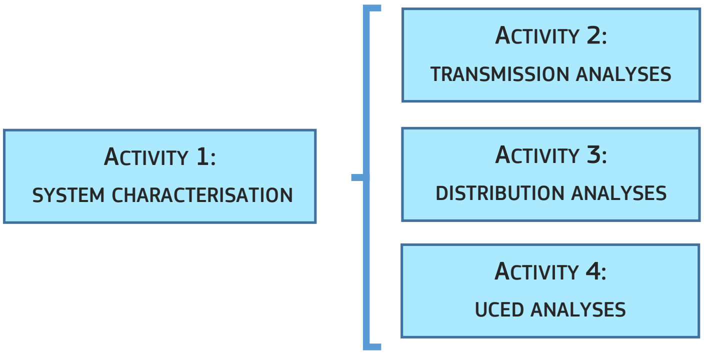

Figure 1 – Project activities

1.2 SCENARIOS FOR THE INTEGRATION OF RES IN THE POWER SYSTEM

The Cyprus power system has the typical characteristics corresponding to isolated Mediterranean island grids: no grid connection to a neighbour country, heavy dependence on liquid fuel imports (HFO, Diesel), low inertia requiring fast response in case of events, high fluctuation of the load during the day and between seasons (250-950 MW). The present generation fleet includes STEAM, CCGT, Internal Combustion Compression Ignition Engines (henceforth “ICE”) and GT units, which are located in 3 sites (Vasilikos, Dhekelia and Moni). Operational constraints are set on some generators for complying with emissions limits (NO_X, SO_X). In general, the conventional generators have not been designed for a very flexible operation that might be required in the future.

Cyprus is also characterized by an abundant solar energy resource during the whole year. The average global solar irradiation resource on an optimally tilted PV module is reaching 2000 kWh/m^2. Wind energy is another variable RES option for electricity generation. The wind energy resource is however quite limited over the island of Cyprus, with an annual average wind speed below 4 m/s (at 10 m above ground level) in the majority of areas.

More information about the power system and the potential use of RES can be found in activity 1 reports [1] and [2].

MECIT, with the assistance of Royal Institute of Technology of Sweden KTH, has defined three long term scenarios for the integration of variable RES (solar+wind) in the power system. The parameters of the scenarios are presented in Table 1. All scenarios foresee the availability of natural gas for future power generation for the studied period 2020-2030. The technical impacts of these three possible evolutions of the power system are analysed in details in the project.

Scenario A1 (High oil and gas prices) combines baseline energy efficiency demand with high gas and oil prices. Very high levels of RES are expected to be integrated in the system. With high levels of intermittent renewables, several storage technologies become also cost effective. A new CCGT (216MW, same characteristics as existing units) becomes available from 2024. Gas is becoming available for power generation in 2020.

Scenario A2 (Low oil and gas prices) combines baseline energy efficiency demand with low gas and oil prices. In this scenario, the renewable energy technologies are getting competitive only in the latest years of the planning horizon. A new CCGT unit becomes available from 2024.

Scenario A3 (Energy saving) combines extra energy efficiency demand with BAU gas and oil prices. With a lower demand level, there is no need to build any additional conventional units.

Scenario		Base	A1		A2		A3	
Year		2014	2020	2030	2020	2030	2020	2030
Fuel cost NG	EUR/GJ		13.8	21.7	1.1	1.5	6.9	10.8
Fuel cost HFO	EUR/GJ		18	28.2	11.1	15.2	18	28.2
Fuel cost diesel	EUR/GJ		19.6	29.8	12.8	16.8	19.6	29.8
Vasilikos Gen	MW	836	836	836	836	836	836	836
Dhekelia Gen	MW	450	450	102	450	102	450	102
Moni Gen	MW	128	128	128	128	128	128	128
New CCGT unit	MW			216		216		
Total conventional Gen	MW	1414	1414	1282	1414	1282	1414	1066
Trans. Wind	MW	144	173	773	173	173	173	173
Dist. Wind	MW	2	2	2	2	2	2	2
Total Wind	MW	147	175	775	175	175	175	175
Trans. PV	MW	0	181	310	42	42	40	40
Dist. PV	MW	61	151	1167	79	438	99	234
Total PV	MW	61	332	1477	121	480	139	274
CSP Tower	MW	0	50	50	50	50	0	50
CSP Dish	MW	0	50	50	50	50	50	50
Total CSP	MW	0	100	100	100	100	50	100
Dist. Biomass	MW	10	30	30	27	30	30	30
Waste	MW	0	9.5	9.5	9.5	9.5	9.5	9.5
Dist. Fossil	MW	19	0	0	0	0	0	0
Storage Hydro 130MW-8h	Units	0	0	1	0	1	0	1
Storage Li-Ion 1MW-2h	Units	0	11	61	0	2	23	69
Storage CSP 50MW-0.3h	Units	0	1	1	1	1	1	1
Demand Response 50MW[1]	Units	0	1	1	1	1	1	1
Demand	GWh	3925	4641	5897	4641	5897	3851	4476
Total net generation	GWh	4180	4862	6178	4862	6178	4034	4689

Table 1 – Reference scenario parameters

[1] Demand Response potential has been estimated by JRC based on results of Activity 3 (see [15] and [6])

2 POWER GENERATION AND DISPATCH

This section presents the main dispatch results for the three future scenarios in 2020 and 2030.

2.1 OVERVIEW OF SIMULATION PARAMETERS

The results have been obtained by simulating the Unit Commitment and Economic Dispatch (UCED) for the Cyprus power system with the software PLEXOS® Integrated Energy Model. No grid model is implemented. Full chronology for a reference year with a time step of 1 hour is used. The UCED study [6] shows how the system will optimally run with an already given generation fleet by considering various technical and system constraints as follows:

- Flexibility of conventional generators: minimum up and down time, max ramping, minimum stable level, start-up time based on 3 thermal states
- Frequency containment reserves: frequency is recovered at 49.5Hz inside 1min, incident 1 = loss of the generating unit with the largest loading, incident2 = loss of 5% of load
- Frequency restoration reserves: frequency must restore inside 20min, incident1 = loss of the generating unit with the largest loading, incident2 = loss of 5% of load
- Replacement reserves: must be available within 4 hours
- Max. ROCOF [2] < 0.8 Hz/s
    - Incident = loss of the generating unit with the largest infeed,
    - Dynamic constraint on remaining kinetic energy in the system.
    - Only kinetic energy from synchronous thermal generators is considered.
- Reserves for RES forecasting errors.
    - Two different day-ahead RES forecast error scenarios are considered for the simulations: the "no error" forecast (= no deviation from the reference RES time

[2] In case of losing the largest infeed generator, the remaining synchronous inertia reserve should be large enough to limit the initial frequency gradient (ROCOF) to less than 0.8 Hz/s in absolute values, as specified in [3] . With this constraint, enough time is given for an effective activation of frequency containment reserves (FCR) and load shedding (UFLS) can be avoided.

series) and the RES over-estimation forecast (with -50% Wind and -10% PV). No RES under-estimation scenario is used because RES curtailment is assumed to be applicable.

    - The algorithm solves the UCED problem considering both RES forecast error scenarios. The unit commitment decisions for the start-up and shutdown of large, inflexible thermal generators (i.e. CCGT and STEAM) are made 'upfront' without fully knowing the outcome of the RES availability. For each of the more flexible units (GT, ICE, storage) the commitment decisions can be different depending on the RES forecast error scenario.

- No unserved energy is allowed in all scenarios, even if this might be economically viable in some cases.

Finally, it is important to mention that the simulation model was designed primarily to integrate realistic technical constraints (reserves, inertia, ramping, uncertainty of RES forecast, etc). Economical parameters having no or only a limited impact on the final dispatch results were approximated based on best available data.

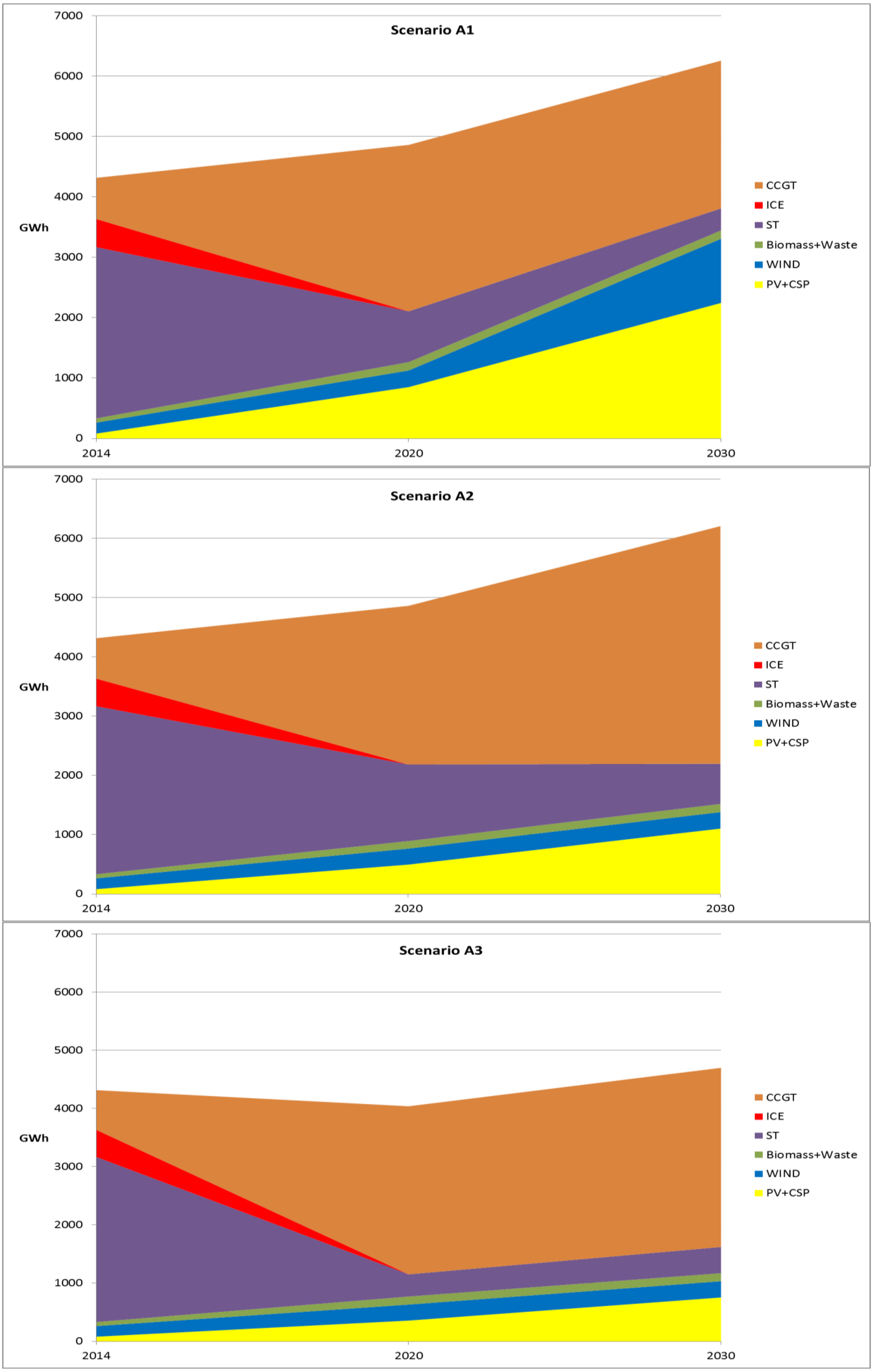

Figure 2 – Evolution of the energy mix for the 3 scenarios

2.2 EVOLUTION OF ENERGY MIX

The analysis of the evolution of the energy mix per generator category indicates significant changes (Figure 2):

- The share of renewable energies varies between 18.4 % (scenario A2 in 2020) and 55.1 % (scenario A1 in 2030). The high RES share in scenario A1-2030 corresponds also to a high RES energy curtailment level of 701 GWh (= 16.9 % of theoretical maximum infeed of RES). The power to be curtailed in this scenario can reach very high levels of up to 1 GW. For other years and scenarios, the RES energy curtailment is small with a maximum of 1.1 %.

- With the availability of natural gas, CCGT units are becoming the major energy providers in the system. CCGT units are operated as a flexible base load. With a high share of solar energy concentrated during the daytime, a more flexible operation (ramping, start/stop, part load operation, switching from 2+1 to 1+1) is required for the CCGT units (Figure 3).

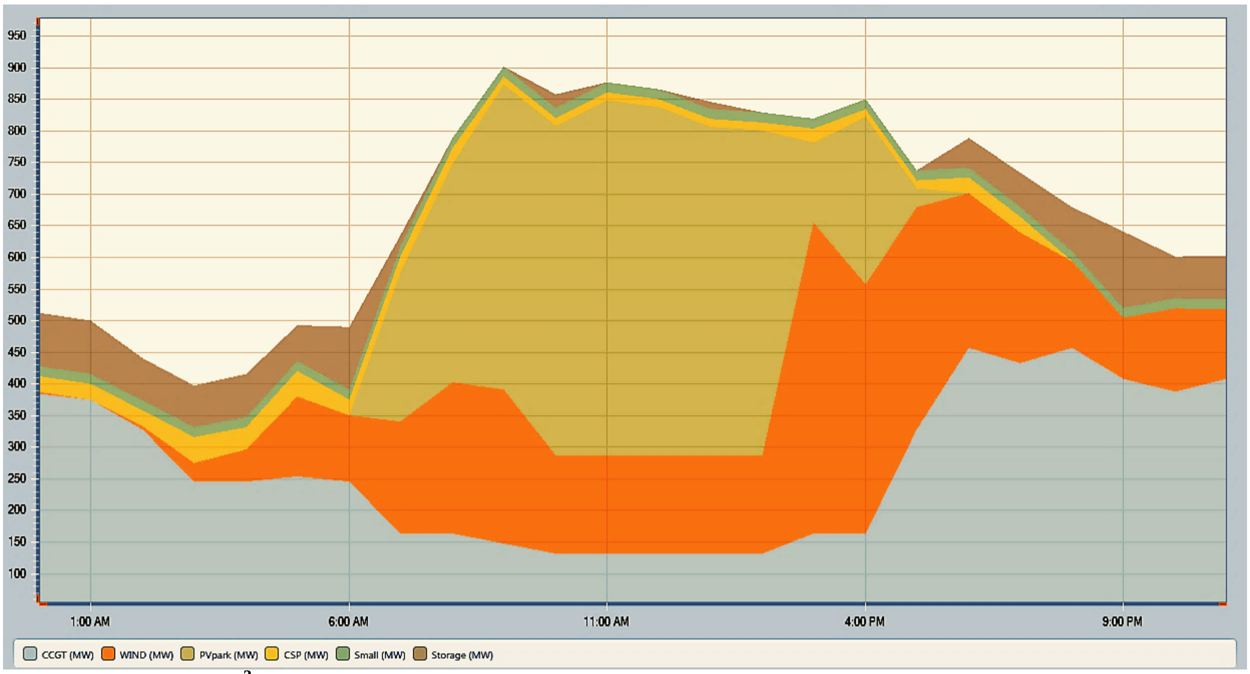

Figure 3 - Power mix[3] (MW) on day 20.02 (scenario A1-2030)

- During high RES penetration situations, the constraint to limit the initial ROCOF following a contingency is met with the inertia corresponding to two CCGT units both in a 1+1

[3] Category "Small" include biomass and waste units, which are not controlled and have a fixed power.

configuration. The minimum stable operation for these two CCGT units corresponds to a base load of 132 MW.

- GT's and ICE units have no energy contribution at all. These units are used for providing reserve services only. It is interesting to notice that this is an economical optimum result, since natural gas is not available to any of these units, which use more expensive fuel like HFO or diesel.

2.3 USE OF STORAGE UNITS

Three different storage technologies with different characteristics in terms of conversion efficiency, stand-by losses and flexibility are foreseen to be available in the future: thermal CSP, pump hydro and battery. Different technical sizing are also possible for each storage unit (power/energy ratio, maximum capacity, dynamic response of the converter), that will have an important impact on the unit capability to provide energy shifting as well as ancillary services.

The pump hydro unit (Kouris) is the largest storage unit used in the model in terms of power and energy. It is most suitable for storing the cheap power available during daytime because of the excess of RES and to release this energy during night time for reducing the fuel consumption of conventional generators.

The big battery storage unit BESS-CSP (50MW-0.3h) is characterized by a very small energy/power ratio. This technology is capable of very fast ramping and is most suitable for providing fast FCR reserve. Athough not considered in the JRC simulations, it is expected that this unit could also be a very good candidate to provide a combination of fast FCR and virtual inertia.

Compared with BESS-CSP, the distributed battery storage units (BESS-SMALL) are characterized by a higher Energy/Power ratio and is therefore more suitable to energy shifting.

The CSP tower includes a thermal storage which charging depends on the solar radiation. Only the discharge power level and schedule is controllable for this storage. The service offered by this unit cannot be compared to the three previous bi-directional storage categories.

2.4 RESERVE PROVISION

In 2020 and 2030, the largest contributor of reserve FCR+ are the storage units with a share of more than 60 % for scenarios A1 and A3, and more than 40 % for scenarios A2. The rest of FCR provision comes mainly from CCGT gas turbines, the Vassilikos Steam units, and the CSP tower.

Main contributors to reserve FRR+ are the STEAM, ICE, CCGT and Pump Storage units. RES without storage, do not contribute to FRR+. Demand response is providing between 4% and 8 % of the total FRR+.

Before their de-commissioning, Dekhelia Steam units with low run-up rates are suitable for providing more than 90% of replacement reserve (RR2) needs, which have to be delivered within 4hours. In 2030, the RR2 is shared by many unit categories: GT, ICE, CCGT, storage. Demand response is providing some replacement reserve as well.

2.5 DEMAND RESPONSE

Smart grid technologies can be implemented to control identified deferrable loads (water desalination, water pumping, air conditioning, water heating, future electric vehicles, etc.) for matching their consumption profile with the availability of intermittent RES. A significant potential for demand response (DR) has been identified in Cyprus.

In high RES scenarios in 2030, UCED simulation show that load activation by Demand Response takes place mainly during daytime, when cheap PV energy is available. This is a very different strategy compared to what is applied today in Cyprus and thus further analysis is recommended, as mentioned in section 4.4. . The main point is that currently the daytime cost of electricity is governed by demand, while in 2030 the studies show that it will be governed by RES (mainly PV) high output.

3 TRANSMISSION SYSTEM ANALYSIS

3.1 METHODOLOGICAL APPROACH

After deliberations with stakeholders the following key technical issues have been identified for the integration of RES into the Cyprus power system:

- Minimum Stable Generation Level of Conventional Units in relation to the generating units required to provide frequency regulation Ancillary Services and "spinning" reserves.
- Low system inertia during low demand periods in conjunction with the fact that the loss of a single generator corresponds to a considerable percentage of the total generation in the system due to the large unit size employed in Cyprus
- Variability of RES generation and high ramp-up/ramp-down rates required to cope with this variability
- Weakening of the Under Frequency Load Shedding (UFLS) scheme because of the introduction of distributed generation (thus reducing the net load shed on Medium Voltage Feeders)
- Which levels of RES curtailment (if any) are required for securing the dynamic stability of the system ?
- What is the cost of ancillary services (e.g. provision of FCR, FRR) required for achieving the Frequency Quality Targets ?

The methodology proposed for assessing the dynamic security of the future Cyprus power system is described in report [3]. It was applied during the study with minor adaptations. More specifically the methodology addresses:

- Major issues for future dynamic security as identified by deliberations with stakeholders
- Considered security standards based on which the security of the future system will be assessed
- Considered metrics for the dynamic response of power generating modules

The different steps of the proposed methodology for the dynamic security assessment are shown in Figure 4.

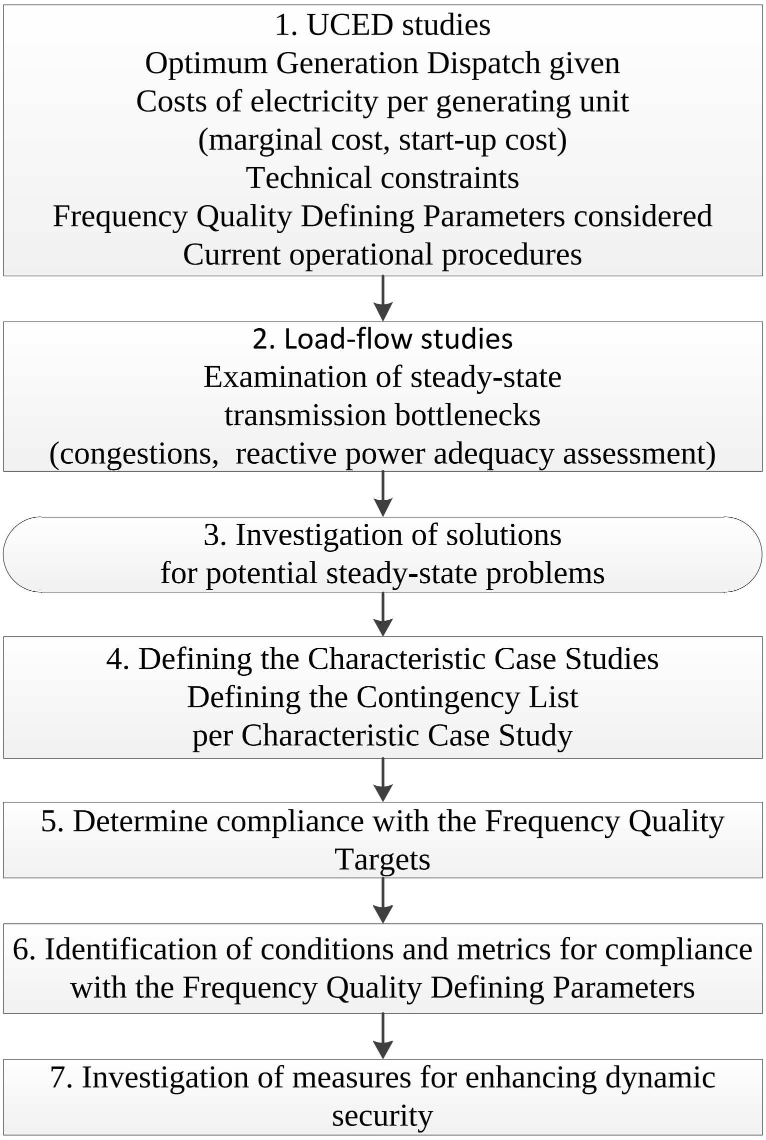

Figure 4 - Flow-chart of dynamic security assessment study

In the first step of the methodology, UCED studies provide realistic "snapshots" of the state of the power system in future Scenarios (up to 2030) under the considered Frequency Quality Targets. Moreover, these snapshots should permit an investigation whose results will be on the safe side. UCED results can also include RES curtailment, if needed to comply with the Frequency Quality Targets.

The capability of the transmission system to operate under the steady-state security parameters (bus voltages and line flows) given the yearly dispatches found in UCED studies are examined in the second step "Load flow studies". Solutions are investigated in case that steady-state operational parameters exceed their normal operation range.

For the dynamic analysis critical “snapshots” (“Characteristic Case Studies”) along with respective contingencies are first identified. The Characteristic Case studies cover different levels of demand (low, middle and high) in combination of different levels of instantaneous RES penetration (low, middle and high). The examined contingencies cover mainly the loss of the largest Infeed and 3-phase bolted faults in the lines forming the main transmission corridors. Contingency analysis, as well as frequency and rotor angle stability are then examined for these critical cases and faults in the power system. The scope of the exercise is to calculate metrics, specifically cumulative inertia in the system and frequency containment capability of dispatched generating units, and define conditions (such as possibly the necessity of at least two major generation points in the system) that secure compliance with the considered Frequency Quality Targets.

3.2 REFERENCE GRID MODEL 2015

The developed reference grid model is based on the latest version of the TSOC operational model. It is a static (steady state) and dynamic simulation model for the Cyprus power system in the DIgSILENT PowerFactory software.

As part of the project, the existing simulation model for the Cyprus power system was revised and evaluated by JRC and DIgSILENT. The work was executed in two steps. Firstly, load flow results were compared with snapshots of the SCADA state estimator to validate the steady state model. Secondly, electromechanical transient (RMS) simulations were compared against recorded disturbances in the system.

The validation of the steady state model can be summarized as follows:

- The comparison between load flow results for the given operation scenario and the corresponding snapshot of the system obtained from the SCADA state estimator confirms the validity of the simulation model for the purpose of steady-state calculations.

- Percent deviations of voltages at main busbars and active and reactive power flows are within the tolerance margins of the intrinsic error of the SCADA.

The validation of the dynamic model can be summarized as follows:

- The revision of the dynamic model was done based on information collected during onsite visits to the power plants.

- The revision of the dynamic model focused on the speed governors, prime movers and mechanical characteristics of the generator machines. These models influence the frequency response of the system and therefore play an important role in the analysis of the system operation under increasing penetration of variable renewable energy, as foreseen in future scenarios.

- The revision of the models for voltage regulators and generator exciters was limited to a plausibility check. The involved stakeholders, however, agreed that these models adequately represent the actual voltage response of the machines.

- Modifications are proposed for the speed governors and the turbine models at Vasilikos and Dhekelia power plants. As the collected information about the actual controllers was not available in full details, the proposed changes are essentially adaptations of the standard IEEE dynamic models to better fit the characteristic of these power plants.

- No revision was undertaken for the dynamic models of Moni power plant nor for the black start gas turbine at Vasilikos since no data were available for these machines at the time of this study. Moreover, these units did not participate in any of the events considered for validation.

- With the proposed changes to the dynamic models at Vasilikos and Dhekelia, simulation results show good agreement with the recorded frequency response of the system for the reference disturbances. The enhanced model reasonably reproduces the real frequency behaviour (tolerance of actual frequency was in the range of ±5%) of the system and it was agreed by the involved stakeholders to be the best model that can be achieved based on available information. Further tuning of the model might be required and extensive power plant tests can be made in order to improve the above frequency behaviour . Still, the new, evaluated model has been a noticeable improvement, a fact acknowledged by TSOC.

- As far as the load model is concerned, the simulation of the event on 01.08.2015, shows that the voltage dependency of the active power noticeably influences the dynamic frequency response of the system. For this particular case, employment of a constant impedance load model led to better agreement between simulation result and the actual frequency recording during the Event. However, the constant impedance model cannot be generalized for all system conditions analysed based on currently available data.

3.3 FUTURE GRID COMPONENTS

In future scenarios, it is assumed that technical solutions aiming at achieving more operation flexibility will be available. In order to be able to simulate the Cyprus Power System in future scenarios, these future grid components have been added to the reference grid model. The reference simulation model described in previous section has been expanded for the time horizon 2016 – 2030, by incorporating the new power plants and their dynamic models according to the chronology. The model makes use of PowerFactory's network variations to incorporate the system expansion plan as the expected commissioning year for the time horizon 2016 – 2030. Three study cases were developed, corresponding to the transmission grid in the Reference Year (2014), in 2020, and in 2030 as follows:

a) Study case A1: system configuration in Reference Year
    - Upgrade of the representation of existing wind farm by including dynamic controllers (Agia Anna 20MW, Alexigros 31.5MW, Koshie 10.8MW, Orites 82MW, Aeolian 10.8MW)

b) Study case A2: system configuration for year 2020
    - Kellia and Sanida Wind farms
    - Activation of Under-Frequency control at all wind farms
    - 2 synchronous generator units of 25MW each at S/E Trimiklini, corresponding to the 50MWe CSP plant (with tower solar receiver)
    - Biomass generation at SS/EE Alambra, Athienou, Dhekelia, Ergates (2), Kophinou, Orunta, Pyrgos
    - HVDC terminal at S/E Kophinou. This corresponds to the Cyprus-side terminal of the Euro-Asia interconnector. Yet, in the conducted studies it was always non-operational (out of service status), since the aforementioned interconnector was not part of the examined Scenarios on the evolution of the Cyprus Energy system.
    - Type C PV plants at all 66 or more kV SS/EE. Type C PV plants represent the aggregation of all PV plant of capacity larger than 150kW connected to the respective substation.
    - Type B PV plants at all lower voltage SS/EE (only over-frequency control activated). Type B PV plants represent the aggregation of all PV plant of capacity lower than 150kW connected to the respective substation.

c) Study case A3: system configuration for year 2030

- Connection of a 48MW and a 18MW wind farm at the Klaudia SS.Biomass generation at SS/EE Ayos Nikolaos, F.I.Z., Larnaka, Latsia, Mari
- Connection of the Pump-Hydro generation station at S/E Ypsonas. The pump-hydro plant is considered to employ variable speed technology (DFIG generator), making it capable of offering frequency containment response in both generator and pump-load mode.
- 2nd HVDC link at S/E Kophinou (out of service status)
- Activation of Under-Frequency control at all Type B PV plants

3.4 STEADY STATE SECURITY ANALYSIS

Using the previously described model, the power system security has been investigated by examining normal conditions and specific contingencies (single loss of a generator that is committed and single disconnection of one of the lines forming the transmission backbone).

Steady-state analysis under normal conditions did not reveal any problems in the system such as congestions and/or a voltage profile beyond the acceptable range as defined in the Grid Code. For all years and scenarios, the largest line loading was identified in the pathway/route of Moni-Vassilikos, specifically the cables entering into the Moni Power Station.

Under contingency the main problem identified concerns the congestion in the remaining line connecting Vassilikos to Moni, specifically the cable entering Moni Power Station, after the loss of the parallel line when Vassilikos Power Station injects a large amount of power. This problem can be easily solved with the upgrading of the short cable in question, a project already undertaken by TSOC according to the latest discussions in the Advisory Committee.

3.5 DYNAMIC SECURITY ANALYSIS

For dynamic studies the following events have been examined:

1. Loss of largest infeed.

2. Loss of largest load when it is larger (in absolute values in MW) than the largest infeed. This is applicable for the storage plants, especially for the pumped-hydro in 2030, during midday when it operates in pump mode for storing the cheap energy from the variable RES high production

3. 3-phase bolted fault at the middle of one of the lines connecting Moni to Vassilikos Main, cleared after 100ms with the disconnection of the faulted line. This fault was examined in detail because previous investigations showed that it is the most critical one. A reason for this criticality is that Vassilikos power station is the node in the network with the most concentrated generating units and power injection, even more if natural gas becomes available which makes these units the most cost effective among the conventional ones.

The System showed compliant behaviour after the single loss of the largest infeed and the largest load for all years and scenarios. It should be taken into account that the dispatches given by the UCED model already secured two important conditions by incorporating respective constraints:

1. The initial Rate of Change of Frequency under the loss of the Largest Infeed should be lower (in absolute values) than 0.8Hz/sec.

2. The volume of FCR (and also FRR and RR) is enough to cover the single loss of the Largest Infeed and the loss of the 5% of total load.

However, the investigation showed another important factor for the compliant behaviour of the System under the Events examined in this Section (loss of generator or load). That is the installation into the system of Battery Storage capable of providing very fast frequency containment response (primary response). This was demonstrated by comparing system response with and without very fast frequency containment response provided by the BESS. Without fast response, the system frequency drops below 49.0Hz and the UFLS scheme is activated. On the contrary with the fast BESS the frequency nadir stays above 49.0Hz.

The above case study shows that not only the volume of FCR, but also the speed of frequency containment response is of importance. Battery Storage can offer an excellent service in this respect, securing the compliant behaviour of the System under sudden power imbalances, such as the loss of the Largest Infeed.

A significant N-1 loss of load is expected only in 2030, where the pumped-hydro plant can represent at times a concentrated large demand. However, cases of heavy pumping are recorded when the penetration of renewable generation is also increasing. Given that both wind turbines and PV have over-frequency response as required by the Codes, as well as the existence of BESS, there is adequate negative FCR to cope with this Event.

Finally, the studies showed that the most onerous N-1 event, among the examined contingencies, is a 3-phase bolted fault at one of the lines connecting Moni to Vassilikos, cleared after 100ms with the disconnection of the line. This event may lead from UFLS activation as a result of widespread disconnection of Type B PV plant due to the action of their under-voltage protection up to total system collapse.

It is important to mention that the identified voltage instability, and especially the large-scale one, is a complex phenomenon that cannot be attributed to a single factor since different phenomena inter-relate. Moreover, the initial conditions in terms of real and reactive power injections spatial distribution, and tap-changer settings could play an important role but a detailed investigation for every case study examined was beyond of the scope of this work that had to identify potential dynamic stability problems in the envisaged future scenarios for the Cyprus power system.

4 DISTRIBUTION SYSTEM

4.1 SCOPE OF THE RESEARCH

In this activity, the objectives are to analyze in detail the current state and future development of Cyprus power distribution system, and to investigate enabling technologies facilitating the optimum technical and economic integration of distributed generation, storage technologies and electric vehicles. The 3 objectives have been met by conducting 8 focused research studies:

1. Characterization of the existing electricity distribution system
   1.1. Spatial and temporal modelling of the electrical demand in the Cypriot power system [8]
   1.2. Analysis of distribution grid control techniques [9]
   1.3. Identification of reference LV networks [10]
2. Analysis of possible scenarios in the development of distribution grids
   2.1. Spatial and temporal modelling of the distributed generation (solar photovoltaic) [11]
   2.2. Evaluation of existing grid hosting capacity for PV [12]
   2.3. Analysis of the impact of Electric Vehicles penetration on distribution systems [13]
3. Applicability of Smart Grid technologies for enabling higher share of RES and EV's
   3.1. Analysis of the ongoing Smart Grid projects in Cyprus [14]
   3.2. Potential for demand response [15]

Highlights of this research are presented in the following sections.

4.2 EVALUATION OF EXISTING GRID HOSTING CAPACITY FOR PV

The hosting capacity for distributed energy resources and in particular PV defines the acceptable amount of PV systems able to be installed at a specific electricity grid based on local performance constrains which are related to voltage profile, power quality and thermal rating of existing network. The system wide hosting capabilities related to stability and frequency control are not within the scope of the distribution system study.

Substation Name	Category	Firm capacity (MW)	Result type	Min. PV hosting capacity (MWp)	Max. PV hosting capacity (MWp)
Akoursos S/S	Rural	32	extrapolation	10.7	38.0
Alambra S/S	Rural	31	**simulation**	10.3	16.4
Amathous S/S	Rural	40	extrapolation	13.4	47.5
Anatoliko S/S	Rural	16	extrapolation	5.3	19.0
Aphrodite S/S	Rural	16	extrapolation	5.3	19.0
Ayios Athanasios S/S	Rural	40	extrapolation	13.4	47.5
Athienou S/S	Rural	16	**simulation**	8.1	8.8
Athalassa S/S	Rural	32	extrapolation	10.7	38.0
Ayia Napa S/S	Rural	40	extrapolation	13.4	47.5
Ayios Nikolaos S/S	Rural	32	extrapolation	10.7	38.0
Ayia Phyla S/S	Rural	60	extrapolation	20.1	71.2
Commercial Centre S/S	Urban	69	extrapolation	61.6	73.8
Dhasoupolis S/S	Urban	80	extrapolation	71.4	85.6
District Office S/S	Urban	80	extrapolation	71.4	85.6
Dhekelia GIS S/S	Rural	40	extrapolation	13.4	47.5
Episkopi S/S	Rural	16	extrapolation	5.3	19.0
Ergates S/S	Rural	32	extrapolation	10.7	38.0
F.I.Z. S/S	Rural	40	extrapolation	13.4	47.5
Hadjipaschalis S/S	Urban	80	**simulation**	84.3	85.6
Internation Airport S/S	Rural	80	extrapolation	26.7	95.0
Karvounas S/S	Rural	16	extrapolation	5.3	19.0
Kokkinotrimithia S/S	Rural	32	extrapolation	10.7	38.0
Kolossi S/S	Rural	40	extrapolation	13.4	47.5
Kophinou S/S	Rural	32	extrapolation	10.7	38.0
Lakatamia S/S	Urban	40	extrapolation	35.7	42.8
Larnaka S/S	Urban	63	extrapolation	56.2	67.4
Latsia S/S	Rural	40	extrapolation	13.4	47.5
Mari S/S	Rural	30	extrapolation	10.0	35.6
Melizona S/S	Rural	40	extrapolation	13.4	47.5
Old Power Station S/S	Urban	63	extrapolation	56.2	67.4
Omonia S/S	Urban	40	extrapolation	35.7	42.8
Orounda S/S	Rural	16	extrapolation	5.4	19.0
Papacostas S/S	Urban	63	extrapolation	56.2	67.4
Paphos S/S	Rural	80	extrapolation	26.7	95.0
Pissouri S/S	Rural	16	extrapolation	5.3	19.0
Polis S/S	Rural	20	extrapolation	6.7	23.7
Polemidhia S/S	Rural	40	extrapolation	13.4	47.5
Prentzas S/S	Urban	80	**simulation**	71.4	76.2
Protaras S/S	Rural	63	extrapolation	21.0	74.8
Pyla GIS S/S	Urban	40	extrapolation	35.7	42.8
Pyrgos S/S	Rural	15	extrapolation	5.0	17.8
Seminary S/S	Urban	69	extrapolation	61.6	73.8
Sotera S/S	Rural	31.5	**simulation**	28.9	37.4
Stroumbi S/S	Rural	16	extrapolation	5.3	19.0
Strovolos S/S	Urban	63	extrapolation	56.2	67.4
Tembria S/S	Rural	20	extrapolation	6.7	23.7
Trimiklini S/S	Rural	16	extrapolation	5.3	19.0
Xeropotamos S/S	Rural	16	extrapolation	5.3	19.0
Yermasoyia S/S	Rural	32	extrapolation	10.7	38.0
Ypsonas S/S	Rural	10	**simulation**	11.1	20.3
TOTAL		**2014**		**1178**	**2263**

Table 2 – PV hosting capacity range per HV/MV substation

The methodology of this study is first to evaluate the PV hosting capacity of six typical distribution grids of Cyprus and then to extrapolate these results in order to provide an estimation for the whole Cyprus distribution system.

More specifically, the PV hosting capacity was defined according to the voltage quality and the thermal limits of distribution lines/transformers calculated in steady-state conditions. The hosting capacity of the selected transmission substations has been evaluated under minimum load (demand) conditions to get the worst possible operational conditions, hence results reached are the maximum allowable penetration of PV systems without violating system requirements and quality of supply.

It is important to mention that the PV hosting capacity can considerably increase if proper regulations are formulated that enable to guide the DSO in installing the PV systems strategically according to specific spatial relationship of PV generation. For that reason, several scenarios have been simulated for providing a range of possible PV hosting capacities. Concerning the extrapolation of the results to the whole power system, the hosting capacity is assumed to reach the same percentage of the firm capacity for each rural and urban substation. The firm capacity is defined as its residual amount of capacity (in MW) after an N-1 contingency event (i.e. transformer outage).

From the detailed results in Table 2, the following conclusions can be drawn:

- The substations Athienou and Alambra s/s, supplying rural networks characterized by low capacity overhead lines and long feeders exhibit lower PV penetration capacity (33% to 55% of substation firm capacity) than the average. This means that those rural circuits (long and with low capacity) might require reinforcements to allow more PV installations.
- Substations supplying urban networks have the highest hosting capacities, equivalent to 89 to 118% of the substation firm capacity
- The distribution system in Cyprus is ready to accommodate a higher penetration of PV systems capable of rising to the very high figure equivalent to the firm capacity of transmission substations without violating the operational system requirements and quality of supply. This high figure can be reached with enhanced voltage control through the advanced features of inverters by enforcing them to operate in an under-excited state (absorbing reactive power). The results have shown that penetration levels are not higher with power factor less than 0,95. It is important to notice that if, by applying enhanced

voltage control, the voltage violations can be eliminated, the thermal limit of lines becomes the limiting factor.

- Another option for increasing significantly at distribution level the grid hosting capacity for PV is through a planned deployment of the PV systems. For instance, PV installations in sub-optimal locations such as the end of long feeders or in already saturated areas should be avoided. Adequate planning tools should be made available to assess the impact of existing and future distributed generators on the grid, in order to indicate the best locations for new systems.

- The PV hosting capacity investigated in this study is strictly relevant to the distribution network only and it does not address system wide operational limitations. These are beyond the scope of the distribution system study but despite this, an extrapolation for all the Transmission substations is conducted giving an estimation of the range of PV possible to be installed utilizing the capabilities of the Distribution network and the advanced features of inverters. The aforementioned range is found to be from 1178 to 2263 MWp. It should be made clear that these penetration levels are possible with the Distribution infrastructure as is currently developed and it does not include any possible reinforcements and / or extensions that will be implemented by the DSO from now to 2030.

4.3 ANALYSIS OF THE IMPACT OF ELECTRIC VEHICLES PENETRATION

The current planning and operation of existing electrical power grids is facing fundamental challenges in view of the envisaged decarbonisation of the power industry. In this domain, a key concern is also the widespread integration of Electric Vehicles (EVs) that can lead to an increase in peak demand that is disproportionately higher than the corresponding increase in annual electricity demand, hence the impact of EVs requires further investigation. Furthermore, the transition of the transport sector in the direction of using renewable energy as the energy source, is another major challenge. According to forecasts in IRENA report for the roadmap of Cyprus [16] , 50,000 EVs will be used in Cyprus by 2030 while in 2040 this number is forecasted to be four times higher (200,000 EVs).

In this domain, the steps taken in this analysis starting from the definition of the EV charging profiles that will arise from high penetration levels of EVs in Cyprus, the simulation of the impact of a large integration of EVs and photovoltaic (PV) in the reference grid of Cyprus, are presented. In all simulated cases, specific considerations were taken into account for the EVs plugged-in to the grid such as the quantity of EVs, charging profiles, mode of charging and mobility patterns.

In the study, three charging scenarios were examined.

The first scenario investigates uncontrolled charging in which the EVs are charged based on a charge start time probability profile, emulating the case when most charging occurs at households and workplaces. This scenario represents a worst case for the grid with a full charge needed for each EV, combined to a constant semi-fast charge. Secondly, an uncontrolled charging scenario considering mobility curves is examined, in which the start time of charging and duration of charge is considered able to simulate more realistic average people's driving patterns.

Lastly, a controlled EV charging (smart charging) scenario is investigated, in which the charging of EVs is controlled by the grid operator in order to optimise generation and grid capacity based on the profile of the aggregated per transmission level substation load curves. All three scenarios were simulated initially without PV systems connected to the grid (baseline scenario) and then with a large integration of PV within the investigated grid. For the aforementioned scenarios the main assumption made was that all EVs are equipped with a 36 kWh Li-Ion battery which is expected to dominate the market in the near future.

From the results obtained for the three EV charging scenarios simulated on typical feeders of a reference High Voltage (HV) substation, it is evident that even in the most load demanding case, which is the “Uncontrolled-Full Charging” scenario, no violations of element/voltage limits are observed. The operation of the investigated feeders with a high level of EVs is found to be within the nominal range and within the system limits. More specifically, the voltage levels at low and medium voltage (MV) buses, are slightly reduced and the lines are slightly more loaded in comparison with the base scenario with no EVs. Finally, the results obtained when simulating the “Controlled EV charging” scenario, demonstrated that there is only minor change on the operation of the investigated feeders/substation in comparison to the base scenario with no EVs.

The study also indicated positive synergies when both EVs and PV are integrated into the same MV grid.

4.4 POTENTIAL FOR DEMAND RESPONSE

Demand side management (DSM) is foreseen as a flexible enabling technology for integrating higher shares of renewable energy sources (RES) into existing grids. In particular, DSM includes demand response (DR) measures with potential for enabling a higher share of renewables by shaping the consumption profiles through different policy/regulatory framework techniques.

In this study, information about existing and future deferrable loads is presented (Table 3), including operational parameters like minimum and maximum electrical power, minimum and maximum time off, minimum and maximum time on, average energy consumed per season in Cyprus. The report further describes a DR model and tool that deploys techniques such as peak clipping and load shifting which are the most commonly employed DSM techniques by grid operators. The model operates on the aggregated transmission level substation time series and provides data for the optimization of the load profile based on the selected periods and achievable levels of load clipping and shifting of the prevailing deferrable loads in Cyprus.

Deferrable load category	Units	2014	2020	2030
Residential	MWh	1422	1652	2097
Desalination	MWh	672	-	-
Irrigation	MWh	244	307	362
Electrical storage heaters	MWh	112	121	154
Electric Vehicles	MWh	-	-	359

Table 3 - Identified daily energy for different deferrable load categories in Cyprus

The effects of the main DR techniques of peak clipping and load shifting are investigated for the reference HV substation. For this study, a large integration of EV and PV was also considered in the simulations performed in order to assess the performance of the aforementioned DR techniques. The simulations were performed while applying the aforementioned DR techniques on the load of the reference HV substation, in order to study the effects on voltage quality and line loading in the presence of EV and PV. In the base scenario, no DR techniques are considered. In the next step, the DR techniques of peak clipping and load shifting were enabled in order to reduce the power demand of only deferrable loads by a specific percentage. Furthermore, the two DR techniques are tested while clipping 25 % and 50 % of deferrable loads from peak hours and by also shifting 25 % and 50 % of deferrable loads from peak to off-peak hours. The DR methods are chosen to be applied on the "worst case" (=day with highest mean and max load demand) daily profile of a typical weekday and weekend.

The simulation results for the worst case weekday/weekend clearly demonstrate that by applying DR techniques, the lower level of voltage is improved while the upper level remains relatively unaffected within the limits. Also, by applying DR techniques for the worst case weekday/weekend, the line loading is reduced depending on the DR technique chosen. Furthermore, Peak Clipping performs better than the Load shifting technique for weekday profiles based both on the voltage quality and line loading results. In addition, it is important to note that the load shifting technique performed better than peak clipping based on line loading results for weekend profiles, when a 25 % of deferrable loads is managed. On the other hand, when 50 % of deferrable loads is managed using the Peak Clipping technique for weekend load profiles, the line loading was reduced even more compared to the respective load shifting scenario.

Finally, the results showed that the introduction of DR offered positive results on net load.

It is important to mention that in this study, the benefits of DR have been analyzed only for the distribution system, which was supposed to host a relatively small amount of RES (~150 MW of PV) even in 2030, as specified in project scenarios up to December 2015. In that respect, investigated future DR strategies were not very different compared to what they are today. However, at system level, with in some scenarios up to 10 times more PV power (adding distribution plus transmission levels), the shape of the net load (Demand-RES) profile will be much different with a valley during daytime. In that type of future scenario, new DR strategies need to be developed to take advantage of off-peak electricity price during the day. Hence, opposite to the results from this study, the DR model implemented for the UCED study (see section 2) is meant exclusively to support the whole power system and it was assumed that the maximum DR power was not big enough to create any negative impact on the distribution system (e.g. due to increased loading of the transformers at midday). Finally, this is also indicating that coordinated strategies are needed between TSO and DSO in order to avoid possible conflicting interests for the optimal management of the DR.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 SIMULATION OF FUTURE SCENARIOS

1. **System security is compliant under the loss of largest infeed** under the conditions that:

    a. The FCR contribution of units has been correctly evaluated

    b. The constraint for minimum inertial response is implemented

    c. Battery storage with Enhanced Frequency Response are used

2. **UFLS activation is not needed for N-1 contingencies.** With the proposed Frequency Quality Targets, triggering of the Under Frequency Load Shedding scheme is expected only under Exceptional Contingencies, i.e. N-2 or worse, which is out of scope of the current stage of the JRC study.

3. **In the future, the most critical contingencies in the transmission system may become grave 3-phase faults, especially if small PV installations continue to trip at voltages lower than 80% of nominal.**

4. **A significant amount of PV curtailment takes place in Scenario A1 (high RES) in 2030**. That is quite challenging for the system operation. 17% of the maximum annual PV energy production is curtailed. For some hours more than 1 GW of PV power needs to be curtailed, which could be challenging if most of the PV systems are small units.

5. **CCGT units are becoming the major energy providers as soon as natural gas is available**. CCGTs are however operated with more flexibility than today. Future units will be operated with more ramping, part load operation and switching from 2+1 to 1+1 mode.

6. **Storage units are key components to provide more flexibility in the system**. Storage units are foreseen for providing both energy shifting and fast frequency response. If not enough flexibility can be obtained from the generation and the demand side, storage technology is unavoidable to integrate high shares of RES. Depending on the type of flexibility needs, different storage technologies can be used with significant differences in terms of cycling losses, investment costs, power to energy ratio and reaction speed to frequency events.

7. **Flexibility capabilities of the existing generation fleet could be increased** in terms of ramping, minimum time off and on, start procedure, response speed of controller. Based on what is claimed by manufacturers today, the existing thermal generation units could be operated with more flexibility. However, the economic impact for the power plant operator needs to be better assessed. Increasing significantly the flexibility could increase variable operational costs and/or reduce efficiency.

8. **A minimum PV capacity of 1178 MW can be integrated in the distribution grid.** The PV hosting capacity investigated is strictly relevant to the distribution grid and is limited by voltage quality and thermal limits only. Using a good planning at the construction stage and/or advanced features of inverters, the grid hosting capacity could be doubled.

9. **Optimal management strategies for distributed resources might be different for DSO and TSO.** Solving problems locally (e.g. voltage quality in MV grid) and globally at system level might be conflicting. Possible conflicting interests were identified for demand response strategies and the weakening of UFLS scheme. Smart Grids deployment may offer the required tools for a more integrated approach taking into account both interests of the transmission and distribution systems.

5.2 RECOMMENDATIONS

1. **Policy option for the prioritisation of small dispersed PV after 2020 should be reconsidered.** If however distributed generation is to become a significant part of the generation capacity, systematic verification of its behaviour under normal and abnormal conditions must be undertaken (e.g. for Low Voltage Fault Ride Through, curtailment). Smart Grid deployment could improve the observability and controllability of the small units in the distribution system. However, it is recommended to analyze the costs and benefits for this option.

2. **Demand response potential should be more thoroughly investigated.** Demand response is potentially a very economic way to increase the system flexibility. Therefore, its full potential needs to be carefully investigated. Especially the following demand sectors should be analysed: (a) drinking water production and distribution, (b)water pumping for irrigation, (c) hotel sector, (d) prosumer households (for increasing self-generation).

3. **Modelling effort should be continued and enhanced.** Conventional unit models should be validated by tests which should include both governors and AVRs (Automatic Voltage Regulators). Manufacturer specific information of the actual excitation systems, speed/power controllers and prime movers for the steam and gas turbines at Vasilikos, Dhekelia and Moni should be obtained. Dynamic response of the different load categories also needs to be researched.

4. **Detailed investigation of techno-economic parameters for the flexible operation of CCGT units.** With a high share of solar energy concentrated during the daytime, the modelling results indicate that the system would benefit from a more flexible operation of the CCGT units (more ramping, start/stop, part load operation, switching from 2+1 to 1+1). Operating in the future CCGT units as flexible base load has technical limits and also economic impacts. It highly recommended to investigate as accurately as possible the techno-economic parameters for flexible operation of CCGT units.

5. **Detailed investigation of techno-economic parameters for the flexible operation of STEAM units.** Topics of interest: operation with fixed pressure instead of sliding pressure, speed controller settings, retrofit options.

6. **Intra-day forecast for demand and RES.** Today in Cyprus, there is a significant room for improvement in the operational procedures relating to RES forecasting and dimensioning of

respective reserves. Methodologies should be examined for incorporating short-term (intra-day) forecasting of distributed generation and demand into the secure operation of the Cypriot power system in respect to requirements such as reserve allocation, congestion management etc.

7. **Emission constraints should be defined taking into considerations the impact on RES integration.** In the JRC simulations, pre-defined environmental considerations (limits on NOx, CO and SOx emissions) are adding constraints that significantly reduce the operational flexibility of ICE and GT generators. However, higher operational flexibility has the potential to reduce RES curtailment and reduce the fuel consumption, which would consequently reduce emissions. Instead of defining emissions targets for each of the conventional generators, it is suggested to define in the simulations only a global target for the whole generation fleet.

8. **Curtailment of RES in the High-RES scenario is unavoidable.** According to simulations, in 2030, on some days, more than 1 GW of RES must be curtailed. On a yearly basis, the curtailed RES energy is significant. As RES curtailment will always be cheaper than activation of UFLS (load shedding) to keep the system stable, it is crucial to define with clear rules which economic compensations are available or not for the RES plant investor.

9. **Accurate measurements for the dynamic response of the main components of the power system.** This is absolutely needed to validate the dynamic model.

10. **Additional topics recommended for further investigations in future studies**:

    a. Sensitivity analysis on storage size and type

    b. Simulation of a No Gas scenario. In All scenarios it was assumed that Natural Gas will be available. It is important to study the impact on system operation.

    c. Additional flexibility solutions needed to reduce the RES curtailment to acceptable levels in the high oil price scenario

    d. Include all fixed costs of system components in the UCED simulations to provide realistic levelized electricity costs

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