Grid integration of variable RES in Cyprus

Stamatios Chondrogiannis
Michel Vandenberghe

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ETIP SNET South Eastern Region Workshop
Context and Goals

MECIT

KTH (IRENA / SRSS)
Long-term
Energy Scenarios

EAC

TSOC

DSO

SRSS

JRC
Security Analysis

UCED
Dynamic Stability

FOSS
Distribution System
CYPRUS POWER SYSTEM

- Isolated power system (PCI Euroasia interconnector not studied)
- Very good solar resource (1700 MWh/MWp)
- Average (low) wind resource (1350 MWh/MW)
- High dependence on energy imports
- Strong grid
HIGH DAILY AND SEASONAL FLUCTUATION OF THE LOAD

Min. = 249 MW
Sunday 09.03.2014

Max. = 871 MW
Monday 25.08.2014
## EXISTING GENERATION FLEET

<table>
<thead>
<tr>
<th></th>
<th>STEAM</th>
<th>STEAM2</th>
<th>ICE</th>
<th>CCGT</th>
<th>GT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit power (MW)</strong></td>
<td>130</td>
<td>60</td>
<td>16.7</td>
<td>220</td>
<td>37.5</td>
</tr>
<tr>
<td><strong>No. of units</strong></td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td><strong>Fuel type</strong></td>
<td>Heavy oil</td>
<td>Heavy oil</td>
<td>Heavy oil</td>
<td>Diesel</td>
<td>Diesel</td>
</tr>
<tr>
<td><strong>Efficiency (%)</strong></td>
<td>40%</td>
<td>31%</td>
<td>42%</td>
<td>50%</td>
<td>29%</td>
</tr>
</tbody>
</table>

- High electricity prices due to imported liquid fuels (Heavy oil, Diesel). Indigenous natural gas shall be exploited in future.
- CCGT is efficient and offer flexibility (operation in 2+1, 1+1, 1+0), but not used much because Diesel fuel is more expensive than Heavy oil.
- Generation flexibility constraints for complying with emissions limits (NOx, SOx) for ICE units (and open-cycle GTs)
- Relatively big power plants (130 MW) compared to load ➔ system has to react fast to recover after contingencies.
INTEGRATION STUDY METHODOLOGY

- Long term scenarios simulation by KTH
- Simulation of day-ahead market by JRC
- Selection of representative snapshots by JRC
- Transmission system security check under N-1 events by JRC
- Fine tuning of long term parameters by JRC
- Stakeholder workshop
## LONG-TERM SCENARIOS

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Demand level</th>
<th>Oil price</th>
<th>Natural Gas price</th>
<th>Availability of Natural Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>Baseline Efficiency</td>
<td>High</td>
<td>Very high</td>
<td>2020</td>
</tr>
<tr>
<td>A2</td>
<td>Baseline Efficiency</td>
<td>Low</td>
<td>Low</td>
<td>2020</td>
</tr>
<tr>
<td>A3</td>
<td>Extra Efficiency</td>
<td>High</td>
<td>Medium</td>
<td>2020</td>
</tr>
</tbody>
</table>
### Long Term Scenarios Under Investigation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Base 2014</th>
<th>A1 High RES</th>
<th>A2 Low fuel price</th>
<th>A3 Energy saving</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2020 2030</td>
<td>2020 2030</td>
<td>2020 2030</td>
</tr>
<tr>
<td>Demand</td>
<td>GWh</td>
<td>3925</td>
<td>4641 5897</td>
<td>4641 5897</td>
<td>3851 4476</td>
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<tr>
<td>Fuel cost NG</td>
<td>EUR/GJ</td>
<td>-</td>
<td>13.8 21.7</td>
<td>1.1 1.5</td>
<td>6.9 10.8</td>
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<tr>
<td>PV+CSP capacity</td>
<td>MW</td>
<td>61</td>
<td>432 1577</td>
<td>221 580</td>
<td>189 374</td>
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<tr>
<td>Wind capacity</td>
<td>MW</td>
<td>147</td>
<td>175 775</td>
<td>175 175</td>
<td>175 175</td>
</tr>
<tr>
<td>Conventional generation</td>
<td>MW</td>
<td>1414</td>
<td>1414 1282</td>
<td>1414 1282</td>
<td>1414 1066</td>
</tr>
<tr>
<td>Pump storage 130MW-8h</td>
<td>Units</td>
<td>0</td>
<td>0 1</td>
<td>0 1</td>
<td>0 1</td>
</tr>
<tr>
<td>Battery storage 1MW-2h</td>
<td>Units</td>
<td>0</td>
<td>11 61</td>
<td>0 2</td>
<td>23 69</td>
</tr>
<tr>
<td>Battery storage 50MW-0.3h</td>
<td>Units</td>
<td>0</td>
<td>1</td>
<td>1 1</td>
<td>1 1</td>
</tr>
</tbody>
</table>
PART 1 – UCED STUDIES

- Long term scenarios simulation by KTH
- Simulation of day-ahead market by JRC
- Selection of representative snapshots by JRC
- Transmission system security check under N-1 events by JRC
- Stakeholder workshop
  Fine tuning of long term parameters
Assuming a perfect competition, the problem is to find an optimal combination of on/off decisions (=unit commitment) and power levels (=dispatch) for all generating units across a time horizon of 24h. The decisions must minimize the variable generation cost and respect the defined constraints.

- 365 day optimizations
- Time step = 1 hour
- Simulation for years 2020 and 2030
- No grid model (one node approach)
- Modeling of individual generators (CCGT can be operated as 1+0, 1+1, 2+0, 2+1)
- Software = PLEXOS, solver = XPRESS-MP
UCED SYSTEM CONSTRAINTS (1/2)

- **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 (FCR):**
  - frequency is recovered at 49.5Hz inside 1min,
  - incident1 = loss of the generating unit with the largest loading,
  - incident2 = loss of 5% of load

- **Frequency restoration reserves (FRR):**
  - frequency must restore inside 20min,
  - incident1 = loss of the generating unit with the largest loading,
  - incident2 = loss of 5% of load
SYSTEM CONSTRAINTS (2/2)

- **Replacement reserves (RR):** must be available within 4 hours

- **Max. ROCOF < 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 scenarios for the energy availability of RES at each hour: normal RES scenario and low RES Scenario with -50% Wind and -10% PV.
  - The commitment of CCGT and STEAM units is the same in both Scenarios.

- **No unserved energy is allowed**
Simulation result: energy mix scenario A1 (high RES)

- 39% CCGT
- 55% RES
Energy mix in scenario A2 (low fuel price)

- **65% CCGT**
- **25% RES**
Energy mix in scenario A3 (Energy saving)

- **65% CCGT**
- **25% RES**
With the availability of natural gas, CCGT units are becoming the major energy providers.

Baseload is reduced to 132 MW (= 2 CCGT in 1+1 at minimum power)

CCGT is operated as a flexible unit: more ramping, part load operation, start/stop, switching from 2+1 to 1+1
UCED RESULTS – Renewable energy

- RES energy share: from 18 % (A2-2020) to 55 % (A1-2030).

- Curtailed RES energy: ~ 1% (exception: 17 % in scenario A1-2030).

- Curtailed RES power: up to 1 GW in scenario A1-2030!

- RES penetration leads to increased number of hours of low cumulative inertia in the System
PROPOSED OPTIONS FOR MORE FLEXIBILITY

- **Energy storage capacity**
  - Pump storage for provision of PV peak shaving and ancillary services
  - Battery storages with fast response to frequency events
  - CSP with thermal storage to shift in time delivery of solar energy

- **More flexible demand**
  - Demand response from water heating, cooling, desalination, EV's,…
  - New strategies supporting high PV generation during daytime

- **More flexible thermal generation fleet**
  - More FCR provision by spinning units (tuning of dead bands in controllers, operation below rated power)
  - Faster start procedure for non-spinning reserve
  - Lowering minimum stable generation level (ICE, GT)
  - Operating Steam units with fixed pressure (instead of sliding)
PART 2 – POWER SYSTEM SECURITY STUDIES

- Long term scenarios simulation by KTH
- Stakeholder workshop
  Fine tuning of long term parameters
- Simulation of day-ahead market by JRC
- Transmission system security check under N-1 events by JRC
- Selection of representative snapshots by JRC
- Fine tuning of long term parameters
SCOPE OF SYSTEM SECURITY STUDIES

• Input: UCED results for different Scenarios
• Investigate whether the dispatches are secure
  ➢ Load flow studies:
    1. Normal steady-state conditions
       (line loadings, voltage profile)
    2. Steady-state conditions after a N-1 contingency
       (congestions)
  ➢ Dynamic studies:
    1. Loss of largest infeed
    2. Loss of largest load (2030, pumped-hydro)
    3. Short-circuits in critical lines of transmission grid
The Transmission Network reflected in the regions north of the ceasefire line, in which the Republic of Cyprus does not exercise effective control, is what was installed before July 1974.
TRANSMISSION SYSTEM MODEL
FACTORS OF UNCERTAINTY

1) Conventional units AVR
   • AVR models of conventional units not evaluated.
   • System model not evaluated against actual response of System under short-circuits

2) Spatial distribution of new capacity
   • PV – of particular importance for 2030
   • Wind farms - of particular importance for 2030, High-RES Scenario
   • New CCGT
   • Small BESS

3) Spatio-temporal development of demand (P, Q)
   • More uncertainty for 2030

4) Dynamic load model
   • Significant impact on behaviour of System after short-circuit clearance
EVALUATION OF DYNAMIC MODEL OF TS

Particular effort to governor models
Significant improvements achieved
No problems found.
The Grid is capable of handling steady-state flows in both normal and N-1 contingency conditions.
DYNAMIC ANALYSIS
LOSS OF LARGEST INFEED

BESS Enhanced Frequency Response important for compliance

22/04/2020 21:00, Scenario A2.
Total Load: 510,5MW. Loss of 88.1MW (17,2%)
DYNAMIC ANALYSIS
Short-circuit fault. Low RES

Inability of voltage recovery under fault. System collapse

24/03/2020 22:00 Scenario A3. Load 416.9MW. RES 0%
System recovers successfully after clearance of short-circuit

24/03/2020 22:00 Scenario A3. Load 416.9MW. RES 0%
Re-dispatch: V50CCGT-STEAM off. V1STG-130MW on
DYNAMIC ANALYSIS
Short-circuit fault. High RES

Cascading failure initiating with small PV tripping. System collapse

11/06/2030 11:00 Scenario A1. Load 1043.7MW. RES 85%
Large-scale voltage instability. Complex phenomenon.

Studies indicate that can be a serious issue particularly for 2030 (high load, high RES situations).

May lead in 2030 in significant RES curtailment for dynamic security reasons.

Further investigation requires addressing the factors of uncertainty in transmission model.

CCGT AVR models
1) N-1 security under loss of largest infeed secured under:
   • Full utilisation of conventional units capabilities
   • Imposition of an Inertial constraint
   • BESS with Enhanced Frequency Response

2) For 2020 no big challenges are shown

3) For 2030 dynamic behaviour under serious short-circuit faults (close to Vassilikos P.S) becomes critical. Envisaged Scenarios cannot be condoned without further work

4) As things stand, policy option for prioritisation of small dispersed PV after 2020 should be reconsidered
TRANSMISSION SYSTEM SECURITY ANALYSIS RECOMMENDATIONS

1) Modelling effort should be continued and enhanced. Conventional unit models should be validated by tests which should include both governors and AVR

2) If 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

3) Imposition of stricter technical requirements (i.e. ride-through capability) to distributed generation may be necessary
1) Existing electricity distribution system
   A. Spatial and temporal modelling of the electrical demand
   B. Analysis of distribution grid control techniques
   C. Identification of reference LV networks

2) Possible scenarios in development of distribution grids
   A. Spatial and temporal modelling of PV generation
   B. Evaluation of existing grid hosting capacity for PV
   C. Impact of EVs penetration in distribution system

3) Smart Grid technologies for higher share of RES and EVs
   A. Analysis of the ongoing Smart Grid projects in Cyprus
   B. Potential for Demand Response
Spatial and temporal modelling of electrical demand

- Biomass generation for reference year 2014
- Wind generation for reference year 2014
- PV generation for reference year 2014

Net load for reference year 2014 from SCADA

 Aggregate load for reference year 2014

Scaling factors (IRENA) and Demand Decomposition

Aggregate and S/S load for year 2020
Aggregate and S/S load for year 2030
Identification of reference LV feeders

1. Macroscopic analysis of LV demand in Cyprus on a postal code basis
2. Navigation in ArcGIS to representative areas
3. Extraction of representative line and customers’ characteristics for LV feeders
4. Modelling the representative LV feeders of CY Distribution Network in DIgSILENT v. 15.2 format
PV grid hosting capacity of Distribution System

- Steady-state analysis on six typical distribution grids
- Monte-Carlo simulations regarding PV location
- Different control techniques \([pf=1, pf=0.95, \cos \phi (P)]\)
  - Enhanced voltage control can address voltage constraints
  - Urban networks demonstrate higher hosting capacity
    without the need for reinforcements
  - Strategic allocation of new PV installations increase considerably the overall hosting capacity
- The current Distribution System does not pose barriers for high distributed PV deployment
OVERALL CONCLUSIONS

Main Contributions of the Project:
• Development of a detailed UCED model
• Development of an evaluated Transmission System dynamic model incorporating all new technologies
• Soft-linking of the two models for Power System Planning
• Examination of possible barriers in the Distribution System

Impact of the project – Opportunities identification:
• Better utilisation of assets (conventional units)
• Initiatives for enhanced observability of transmission and distribution system (PMUs, PV production)
• Identification of criticalities (small PVs) and solutions (battery storage with enhanced frequency response)

Lessons learned:
• In small isolated systems UCED has to incorporate in detail balancing reserves and inertial response
• Under high RES penetrations long-term energy planning has to take into account dynamic security constraints
THANK YOU FOR YOUR ATTENTION

Stay in touch

**JRC Science Hub:**  [www.ec.europa.eu/jrc](http://www.ec.europa.eu/jrc)

**Twitter:**  @EU_ScienceHub

**LinkedIn:**  european-commission-joint-research-centre

**YouTube:**  JRC Audiovisuals

**Vimeo:**  Science@EC
APPENDIX 1

FROM DYNAMIC STABILITY TO DYNAMIC PERFORMANCE
From DYNAMIC STABILITY to DYNAMIC PERFORMANCE

- Currently under major N-1 contingencies (i.e. loss of Largest Infeed) automatic load shedding is one of the main defence mechanisms
- TSOC plans to provide an enhanced service to the end-customers
- Compliance with the Frequency Quality Targets defined for IRE Synchronous Area according to the EC Guideline on Systems Operation (SO GL)
- It is noted that compliance with SO GL is voluntary for the case of Cyprus
FREQUENCY QUALITY TARGETS (FQTs) GOAL

• Normal operating conditions: 49.8Hz-50.2Hz

For a negative N-1 Contingency (loss of Generation):
• System Frequency at most down to 49.0Hz
• System Frequency to 49.5Hz within 1 minute
• System Frequency above 49.8Hz within 20 minutes

UFLS activated only under Exceptional Contingencies (N-2 or worse)

For a positive N-1 Contingency (loss of Load):
• System Frequency at most up to 51.0Hz
• System Frequency to 50.5Hz within 1 minute
• System Frequency below 50.2Hz within 20 minutes

FQTs DEFINE CONTINGENCY RESERVES
CHALLENGES FOR A SECURE INTEGRATION OF RES

- vRES curtailment > 1 GW
- 20. February Scenario A1-2030

- More flexible conventional fleet (ramping, starts, part load)
- vRES share > 80% and limited inertia
APPENDIX 3

Detailed UCED RESULTS
Max power curtailment = 1170 MW
Annual RES energy curtailed = 701 GWh (17%)
CCGT PARTIAL LOADING

Duration curve for the average output of the spinning generators (belonging to a CCGT)

Scenario A2-2030 (low fuel price)
Scenario A1-2030 (high RES)
## INCREASING FLEXIBILITY BY STORAGE

<table>
<thead>
<tr>
<th></th>
<th>Hydro 130 MW 8h</th>
<th>Battery 1 50 MW 0.3 h</th>
<th>Battery 2 61 MW 2 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir cycling cycles</td>
<td>228</td>
<td>876</td>
<td>683</td>
</tr>
<tr>
<td>Capacity factor generation %</td>
<td>20.8</td>
<td>3.0</td>
<td>15.6</td>
</tr>
<tr>
<td>Capacity factor FCR+ %</td>
<td>10.1</td>
<td>32.4</td>
<td>29.6</td>
</tr>
<tr>
<td>Capacity factor FRR+ %</td>
<td>15.6</td>
<td>0.7</td>
<td>3.6</td>
</tr>
<tr>
<td>Capacity factor RR2 %</td>
<td>11.7</td>
<td>0.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

**High RES scenario A1 in 2030**
TOTAL INERTIA RESPONSE

Duration curves

Inertia online (MWs)

Scenario A2-2030 (low fuel price)

Scenario A1-2030 (high RES)
STORAGE

POWER

Pump load

generation

130 MW

120 MW

RR2

FRR+

FCR+

RESERVE

PROVISION

High RES day
20. February
Scenario A1-2030
LOAD ACTIVATION BY DEMAND RESPONSE

Daytime load activation <> strategy applied today in Cyprus.

High RES scenario A1 in 2030
APPENDIX 4

Relationship between UCED and Dynamic studies
UCED AND SECURITY STUDIES

**UCED**

**Normal Operation**
- Overall Generation
  - Largest Infeed
  - Units on droop control
  - Units without droop control
  - Non-spinning Units at T=0min

**Event, T=0min**
- Overall Generation
  - Units on droop control
  - Units without droop control
  - Non-spinning Units at T=0min

**T=1min after Event**
- Overall Generation
  - FCR
  - Units on droop control
  - Units without droop control
  - Non-spinning Units at T=0min

**T=20min after Event**
- Overall Generation
  - FRR 1
  - FRR 2
  - Units on droop control
  - Units without droop control
  - Non-spinning Units at T=0min

**Security studies**

- Load flow studies
  - Line loading
  - Voltage profile
- Dynamic studies
  - Short-circuits
- Dynamic studies
  - Frequency nadir
  - Time of restoration
  - Contingency analysis
  - Congestions

European Commission
**METHODOLOGY**

1. **UCED studies**
   Optimum Generation Dispatch given Costs of electricity per generating unit (marginal cost, start-up cost) Technical constraints Frequency Quality Defining Parameters considered

2. **Load-flow studies**
   Examination of steady-state transmission bottlenecks (congestions, reactive power adequacy assessment)

3. **Investigation of solutions**
   for potential steady-state problems

4. **Defining the Characteristic Case Studies**
   Defining the Contingency List per Characteristic Case Study

5. **Determine compliance with the Frequency Quality Targets**

6. **Identification of conditions and metrics for compliance with the Frequency Quality Defining Parameters**

7. **Investigation of measures for enhancing dynamic security**

**Scope:**
Determination of critical “snapshots” of the system in Future Scenarios

- Are steady-state problems expected?
- How can we solve potential steady-state problems?
- What are the critical cases and faults for dynamic performance?
- Is the system capable of facing the critical faults?
- Can we define constraints for compliant dynamic performance?
- What are our options?
1) TSOC’s Transmission Grid having 10-year development plan incorporated (220kV down to 11kV)

2) Automatic load shedding scheme de-activated
   - Current settings not compliant with considered Frequency Quality Targets

3) Conventional units
   - Dynamic response capabilities of units are fully exploited.

4) Battery storage
   - Fault ride-through capability
   - Enhanced frequency response

5) Pumped-hydro plant
   - Frequency response also in pump mode (variable speed DFIG-based plant)
6) Wind farms
   - Fault ride-through capability
   - Full frequency response (over-frequency and under-frequency)
   - No synthetic inertial response

7) Small PV (<150kW)
   - No fault ride-through capability
   - Frequency response only for over-frequency

8) Medium-large PV (≥150kW)
   - Fault ride-through capability
   - Frequency response only for over-frequency - 2020
   - Full frequency response - 2030
APPENDIX 5

CONTINGENCY ANALYSIS
SYSTEM ANALYSIS UNDER EVENTS

1) 84 case studies of different load and RES instantaneous penetration
2) Contingency analysis (steady-state)
3) Dynamic analysis under
   a. loss of the largest infeed
   b. loss of the largest load (2030, pumped-hydro)
   c. 3-phase bolted short-circuit at line Moni-Vassilikos (most critical line) of 100ms duration

- System showed compliant behaviour under 58 case studies
- System showed congestion problems in 13 case studies
- System showed transient stability problems in 13 case studies (1 in 2020, 12 in 2030)

Loss of largest infeed not a problem
Short-circuits in the transmission network is the critical Event
CONTINGENCY ANALYSIS

• Critical contingency: Disconnection of a line connecting Moni to Vassilikos Main
• Congestion to the remaining line connecting Moni to Vassilikos Main (cable entering Moni)
• Under Cases of high Vassilikos Power Station total output
  - \(~650\text{MW}~\) for 2020 under all Scenarios
  - \(~720\text{MW}~\) for 2030, Scenario A3
  - \(~820\text{MW}~\) for 2030, Scenario A1 and A2
• Problem can be easily solved with upgrade of the cables
• If not, minimal impact to Vassilikos P.S. annual energy output (<1%)

Curtailment of Vassilikos P.S. for N-1 steady-state security (GWh)
25/08/2020 16:00, Scenario A2 Normal condition
Total Load: 959.8 MW. Vassilikos P.S.: 764.1 MW
25/08/2020 16:00, Scenario A2 After disconnection of a line Moni-Vassilikos
APPENDIX 6

FAULT RIDE-THROUGH CAPABILITY EXPLANATION
Fault ride-through capability does not mean that plant can remain connected under any voltage drop/duration.

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Voltage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50%</td>
</tr>
<tr>
<td>Small PV</td>
<td>TRIP</td>
</tr>
<tr>
<td>Medium-Large PV</td>
<td>OK</td>
</tr>
<tr>
<td>Wind farms, BESS</td>
<td>OK</td>
</tr>
</tbody>
</table>

Behaviour under a voltage drop lasting 600ms