Joint Research Centre

the European Commission's in-house science service

Serving society
Stimulating innovation
Supporting legislation

Grid integration of variable RES in Cyprus

Stamatios Chondrogiannis

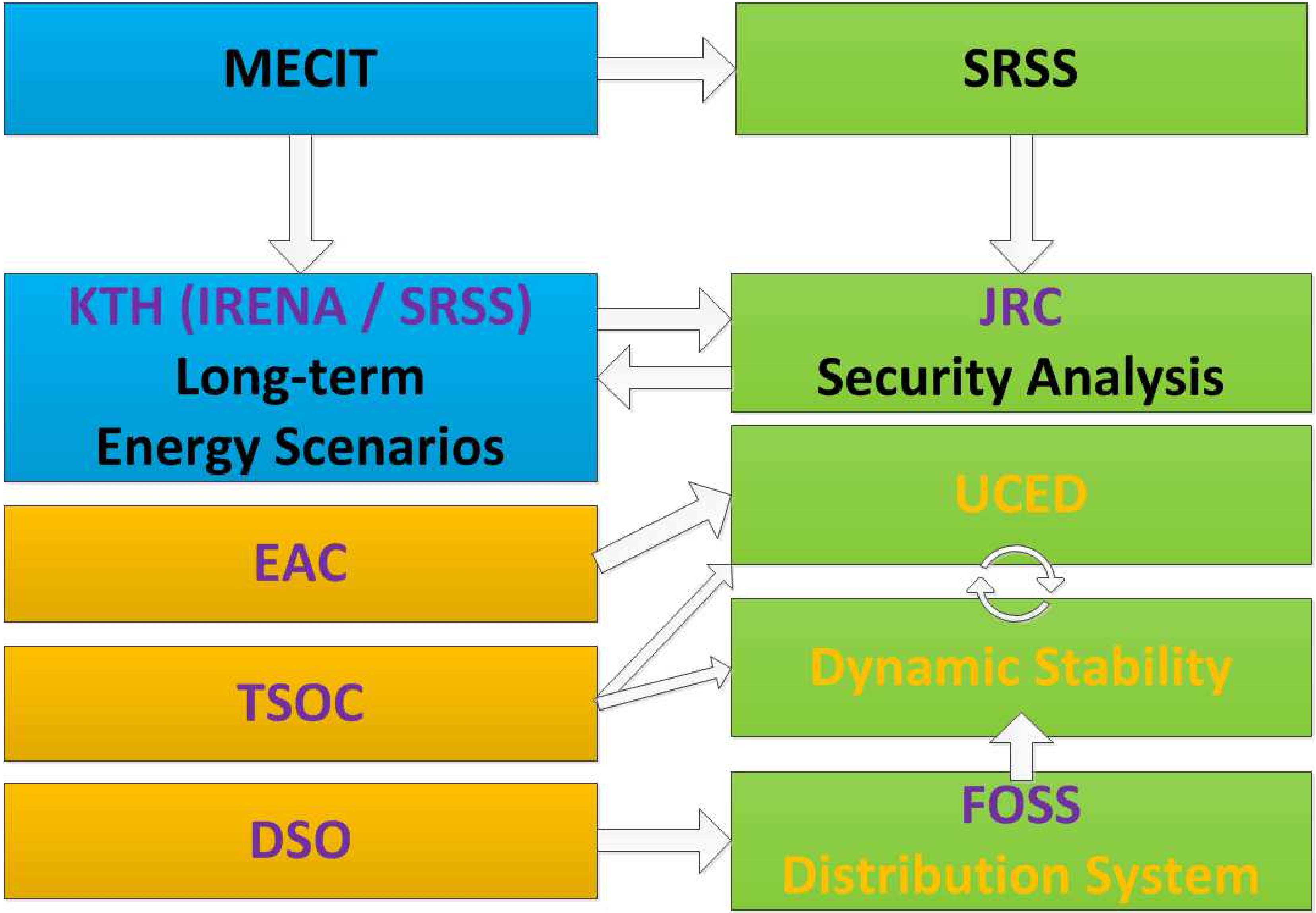
Michel Vandenbergh

Nicosia, Cyprus, 23.11.2017

ETIP SNET South Eastern Region Workshop

European Commission

Context and Goals



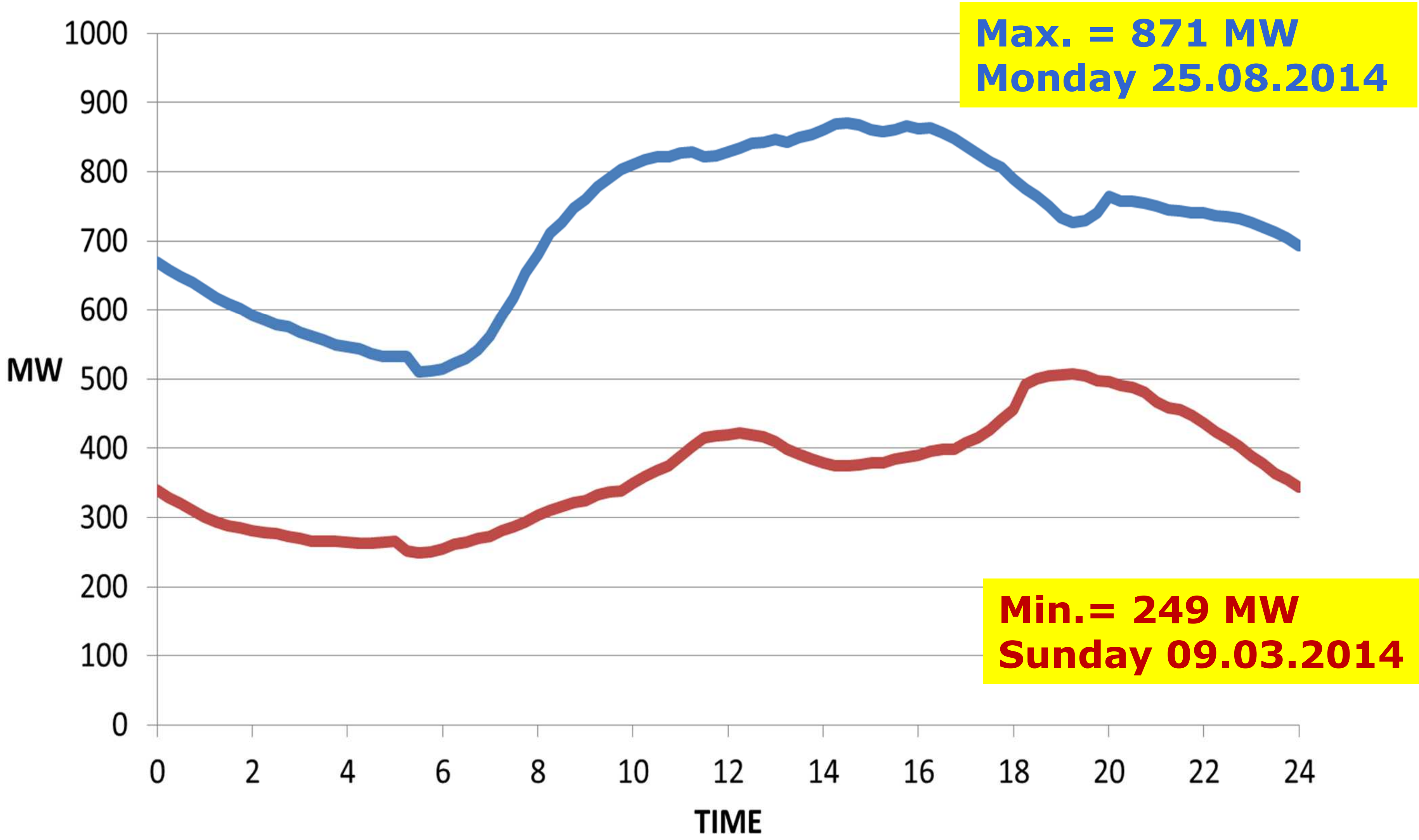
CYPRUS POWER SYSTEM

- 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

:opyright PLATTS for the underlying grid; Copyright INEA - January 2015

European Commission

HIGH DAILY AND SEASONAL FLUCTUATION OF THE LOAD



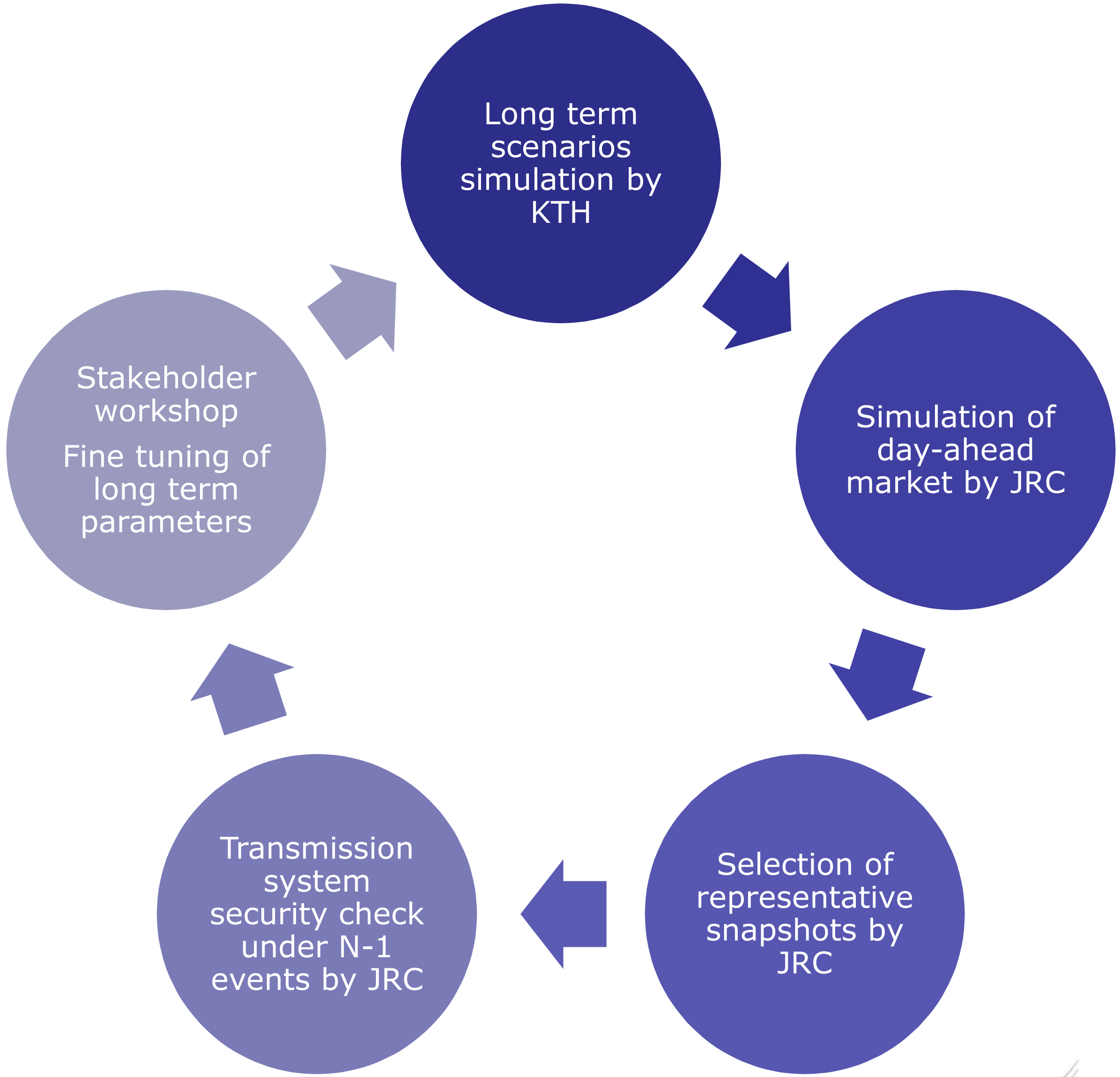
European Commission

EXISTING GENERATION FLEET

	STEAM	STEAM2	ICE	CCGT	GT
Unit power (MW)	130	60	16.7	220	37.5
No. of units	3	6	6	2	5
Fuel type	Heavy oil	Heavy oil	Heavy oil	Diesel	Diesel
Efficiency (%)	40%	31%	42%	50%	29%

- ❑ 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



European Commission

LONG-TERM SCENARIOS

Scenario	Demand level	Oil price	Natural Gas price	Availability of Natural Gas
A1	Baseline Efficiency	High	Very high	2020
A2	Baseline Efficiency	Low	Low	2020
A3	Extra Efficiency	High	Medium	2020

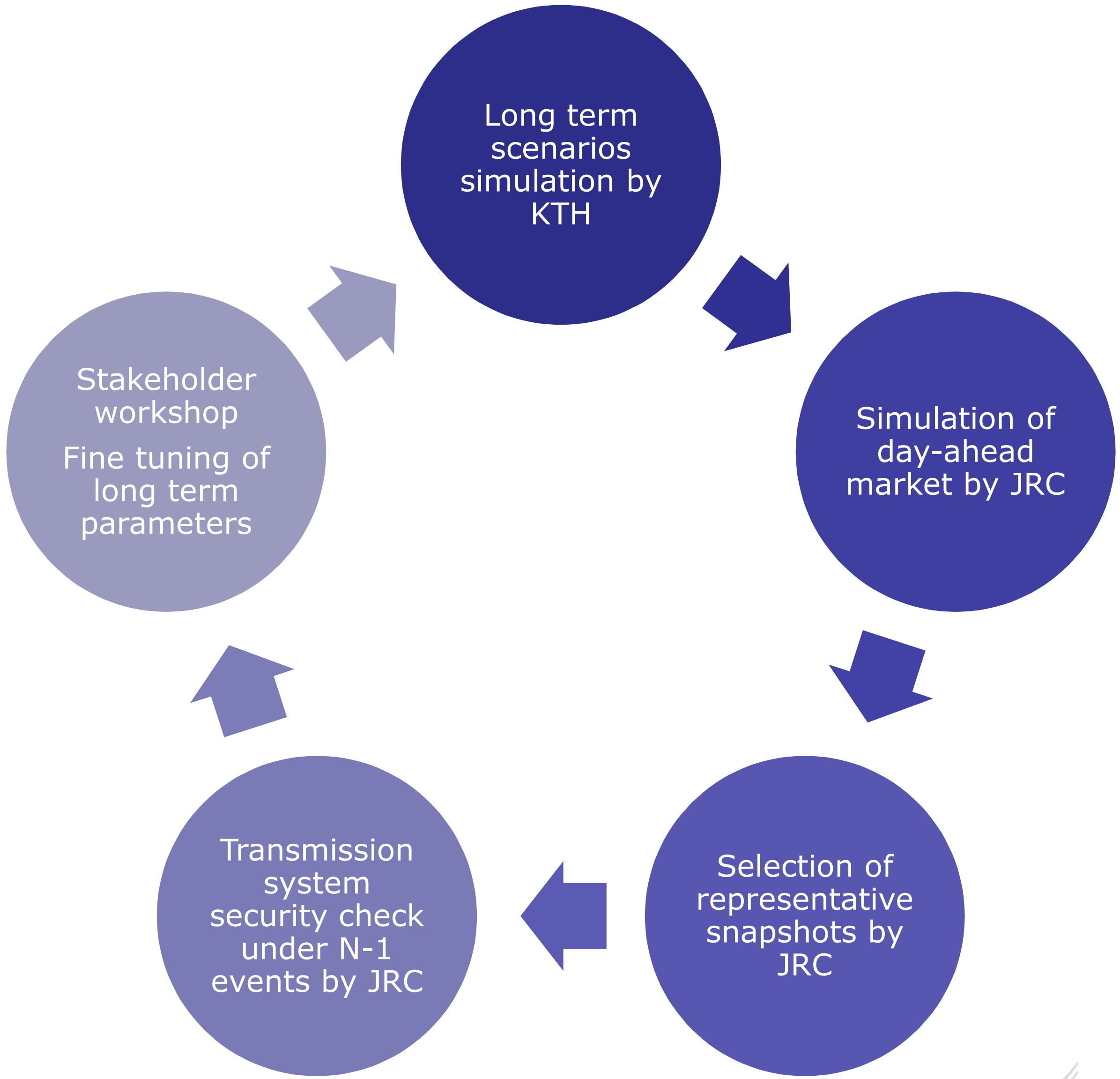
European Commission

LONG TERM SCENARIOS UNDER INVESTIGATION

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

European Commission

PART 1 – UCED STUDIES



European Commission

MODELING THE DAY-AHEAD MARKET

- **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**

European Commission

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

European Commission

SYSTEM CONSTRAINTS (2/2)

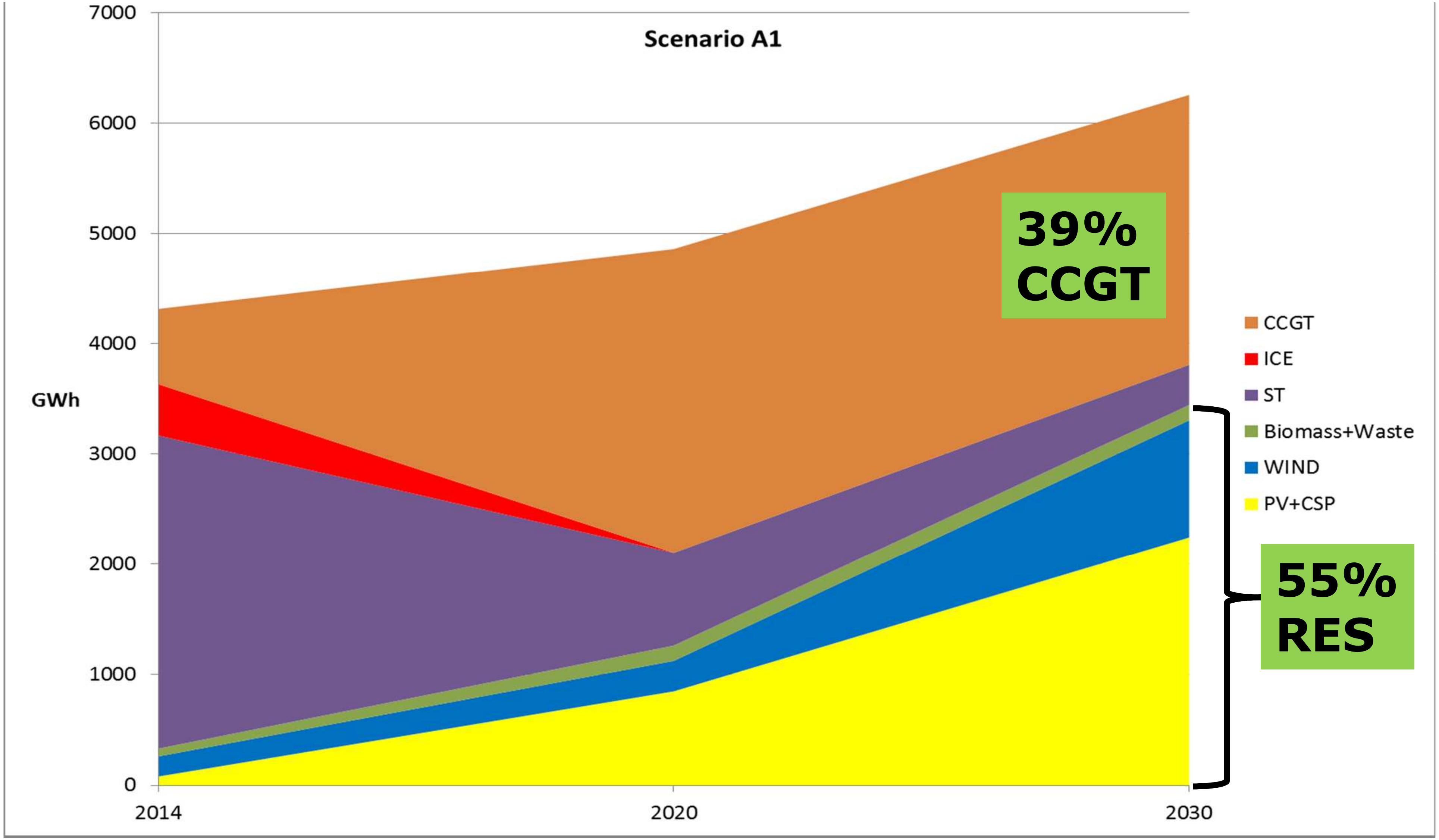
- **Replacement reserves (RR): must be available within 4 hours**

- **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.

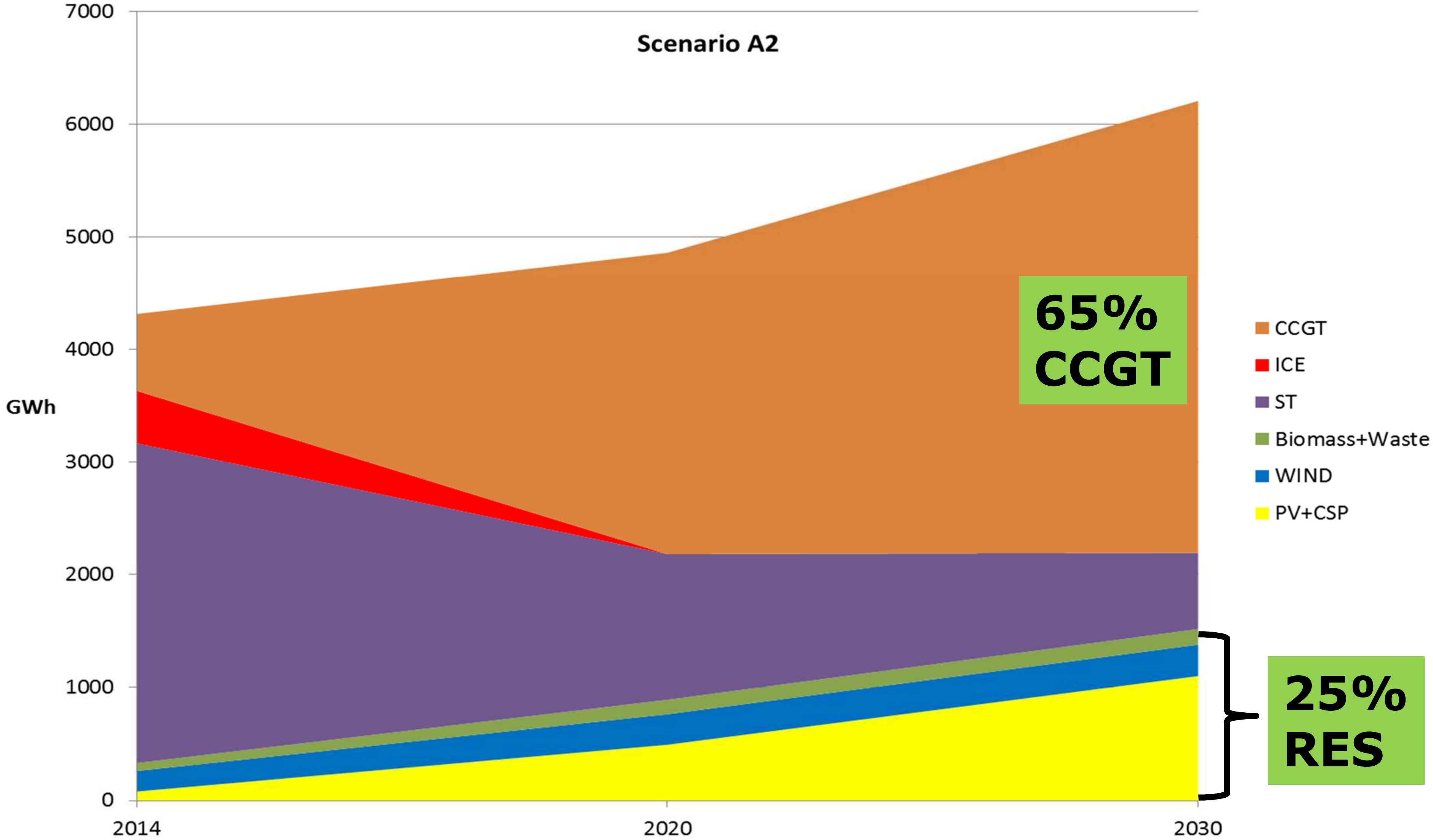
- **Reserves for RES forecasting errors.**
  - Two scenarios for the energy availability of RES at each hour: normal RES scenario and low RES Scenario with -50% Wind and -10% PV.
  - The commitment of CCGT and STEAM units is the same in both Scenarios

- **No unserved energy is allowed**

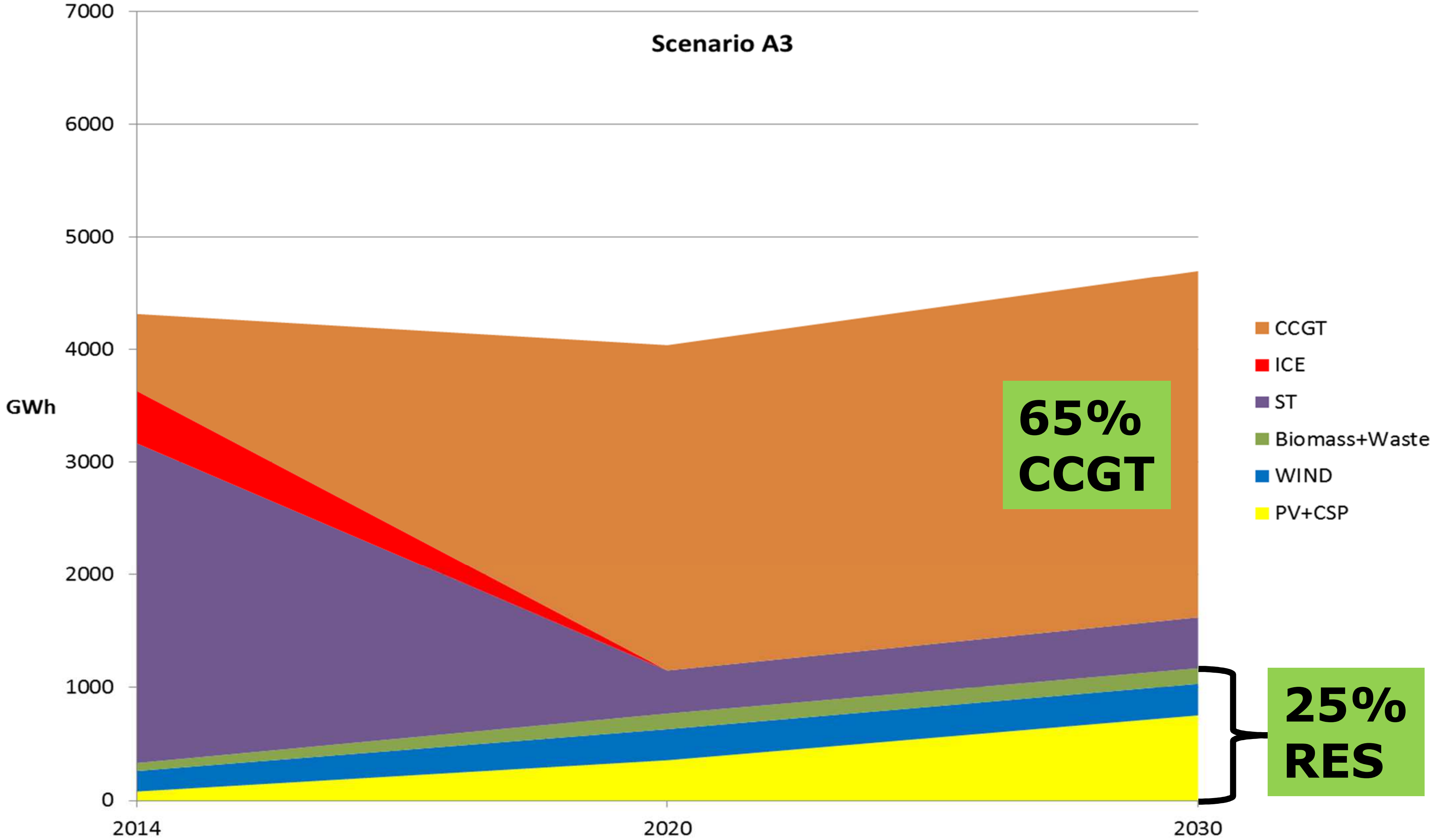
Simulation result: energy mix scenario A1 (high RES)



Energy mix in scenario A2 (low fuel price)



Energy mix in scenario A3 (Energy saving)



UCED RESULTS – Conventional generation

- 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).**

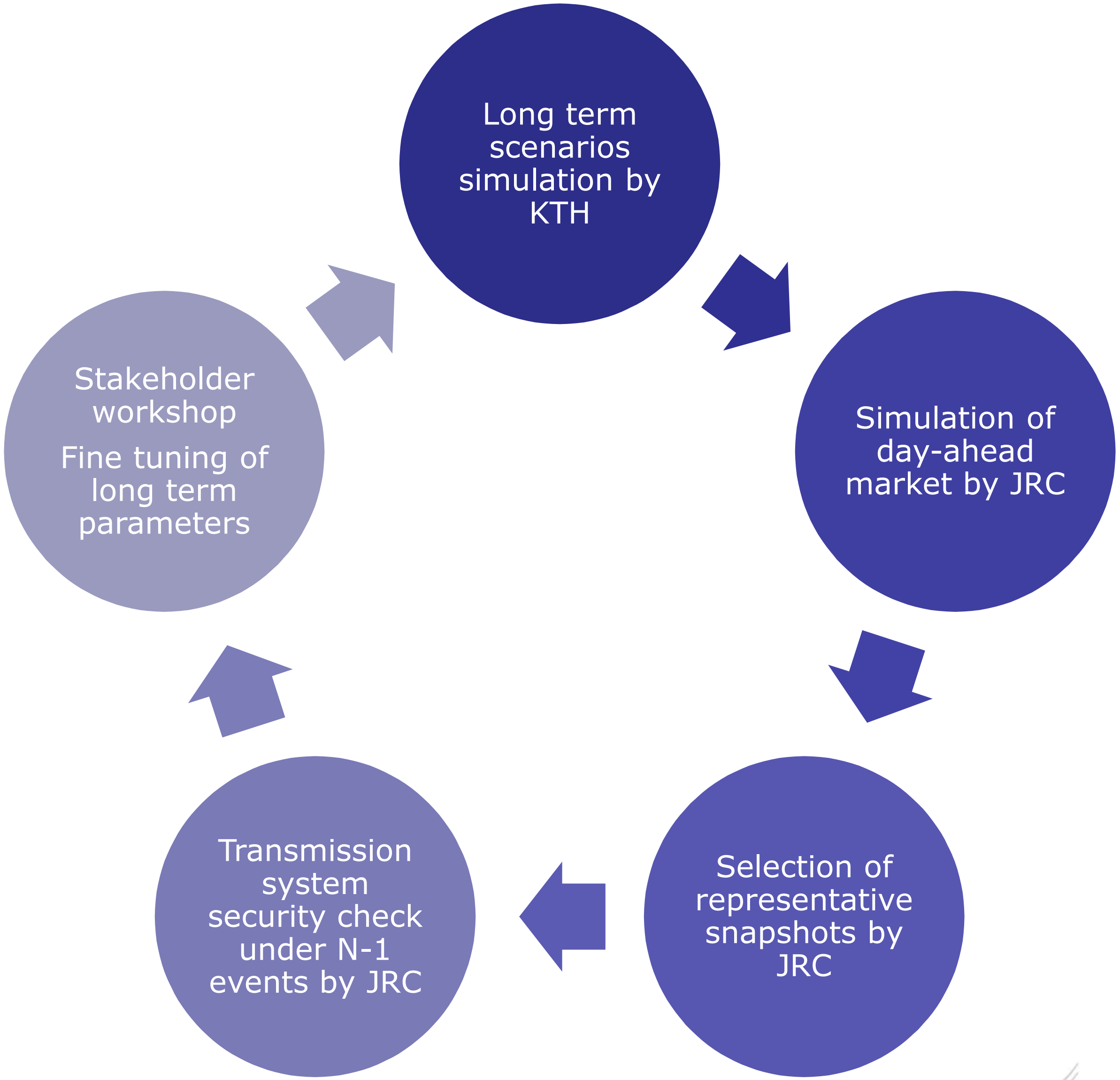
- ❑ **Curtailed RES power: up to 1 GW in scenario A1-2030 !**

- ❑ **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



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**

European Commission

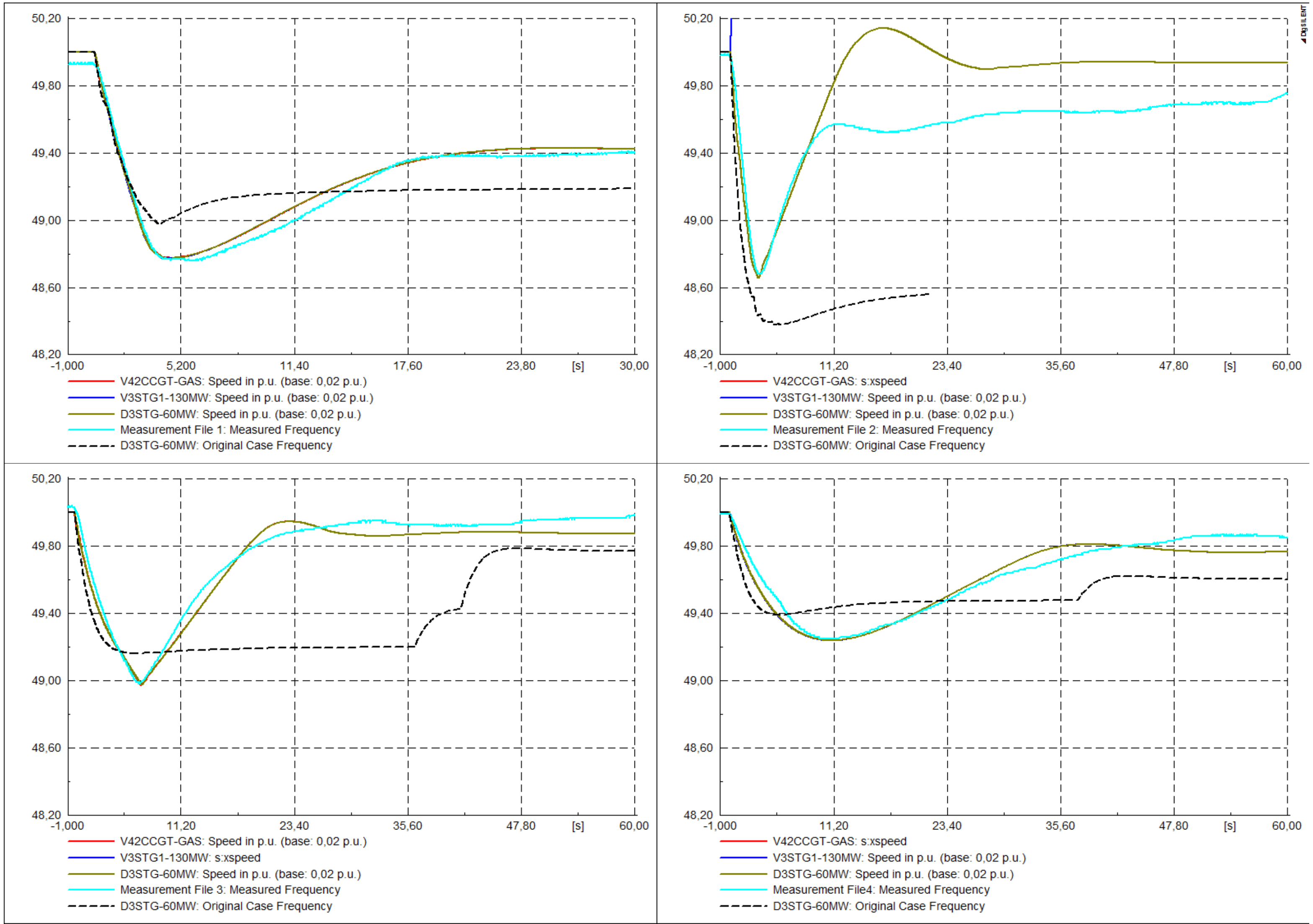
TRANSMISSION SYSTEM MODEL
FACTORS OF UNCERTAINTY

1) **Conventional units AVRs**
   - 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

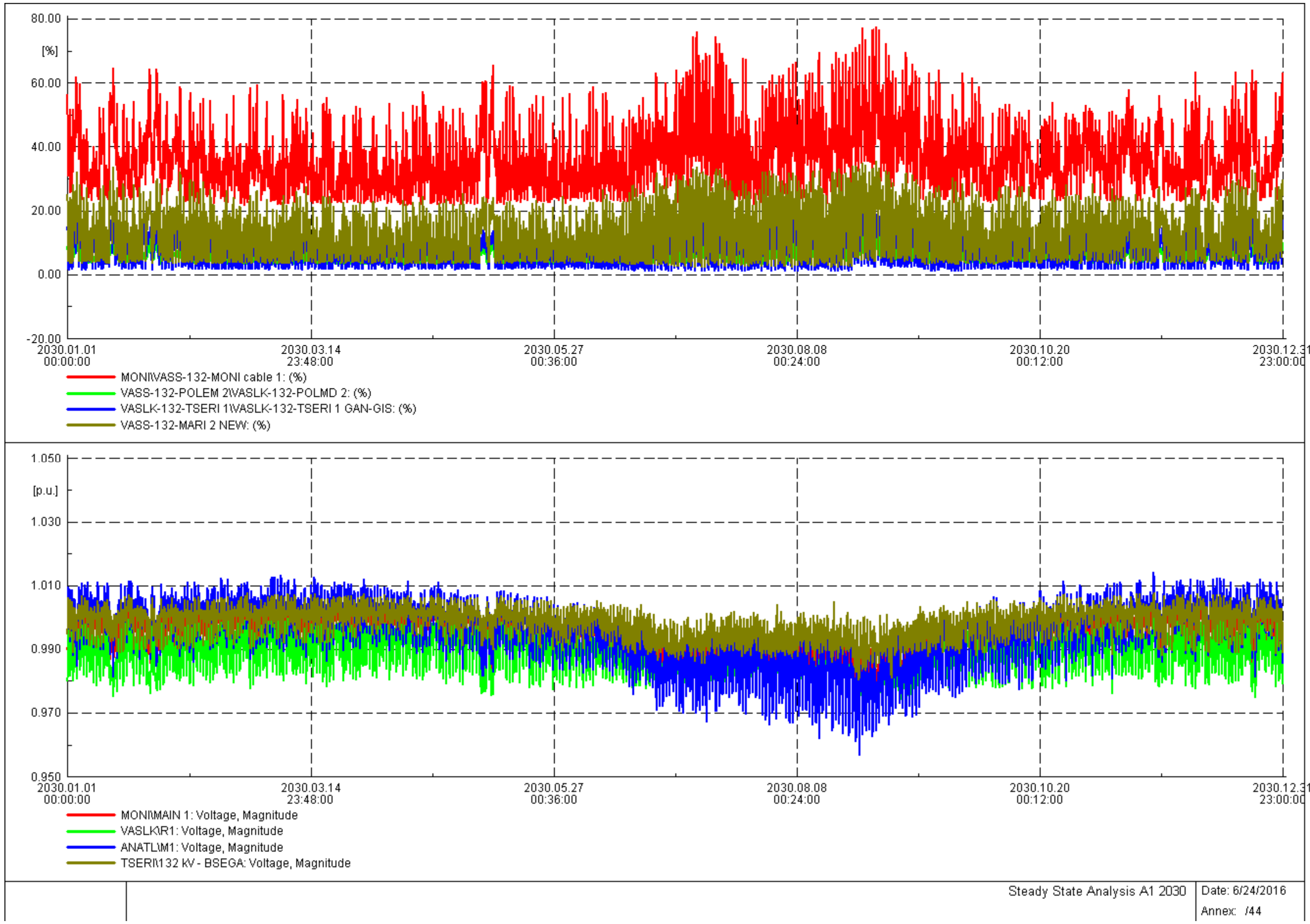
EVALUATION OF DYNAMIC MODEL OF TS

Particular effort to governor models

Significant improvements achieved



LOAD FLOW ANALYSIS



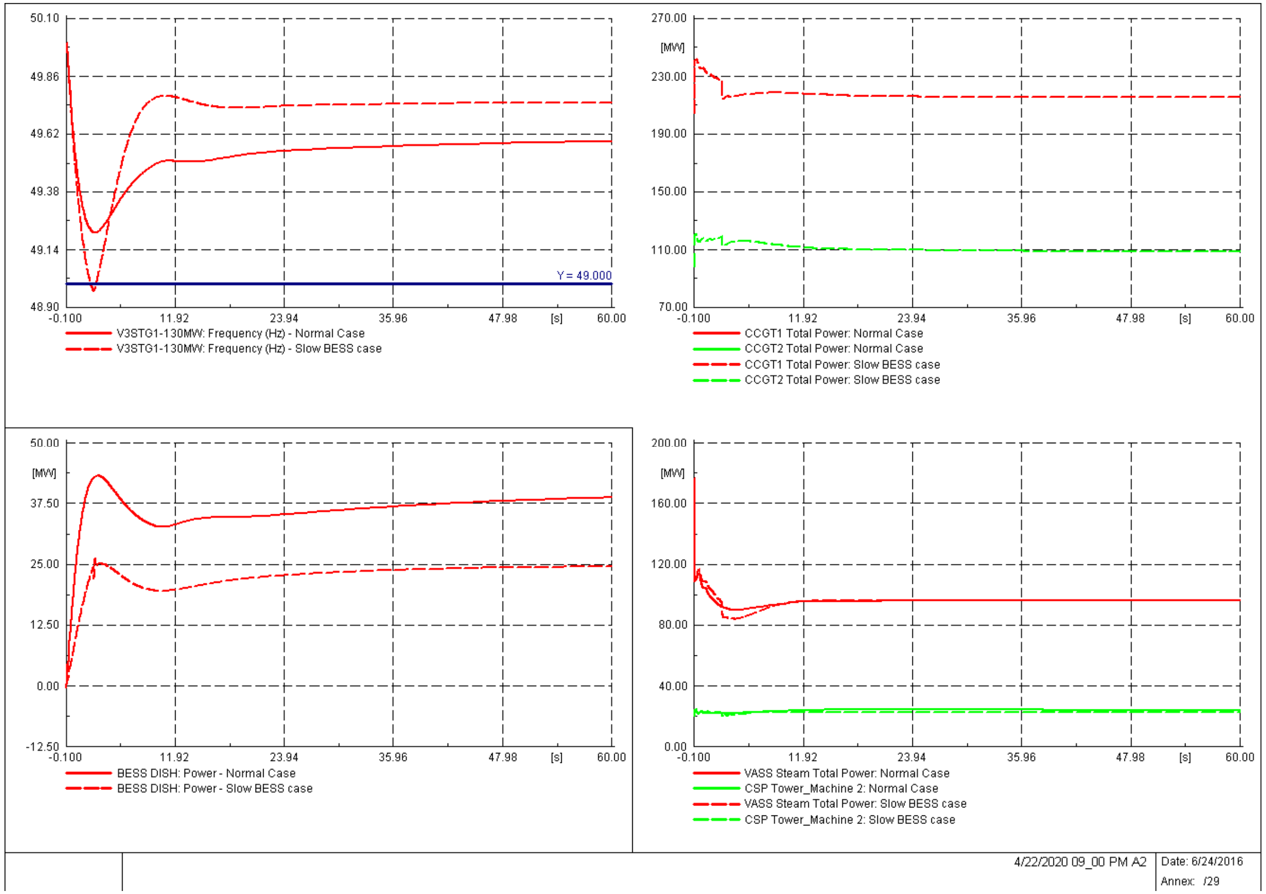
Scenario A1, 2030

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

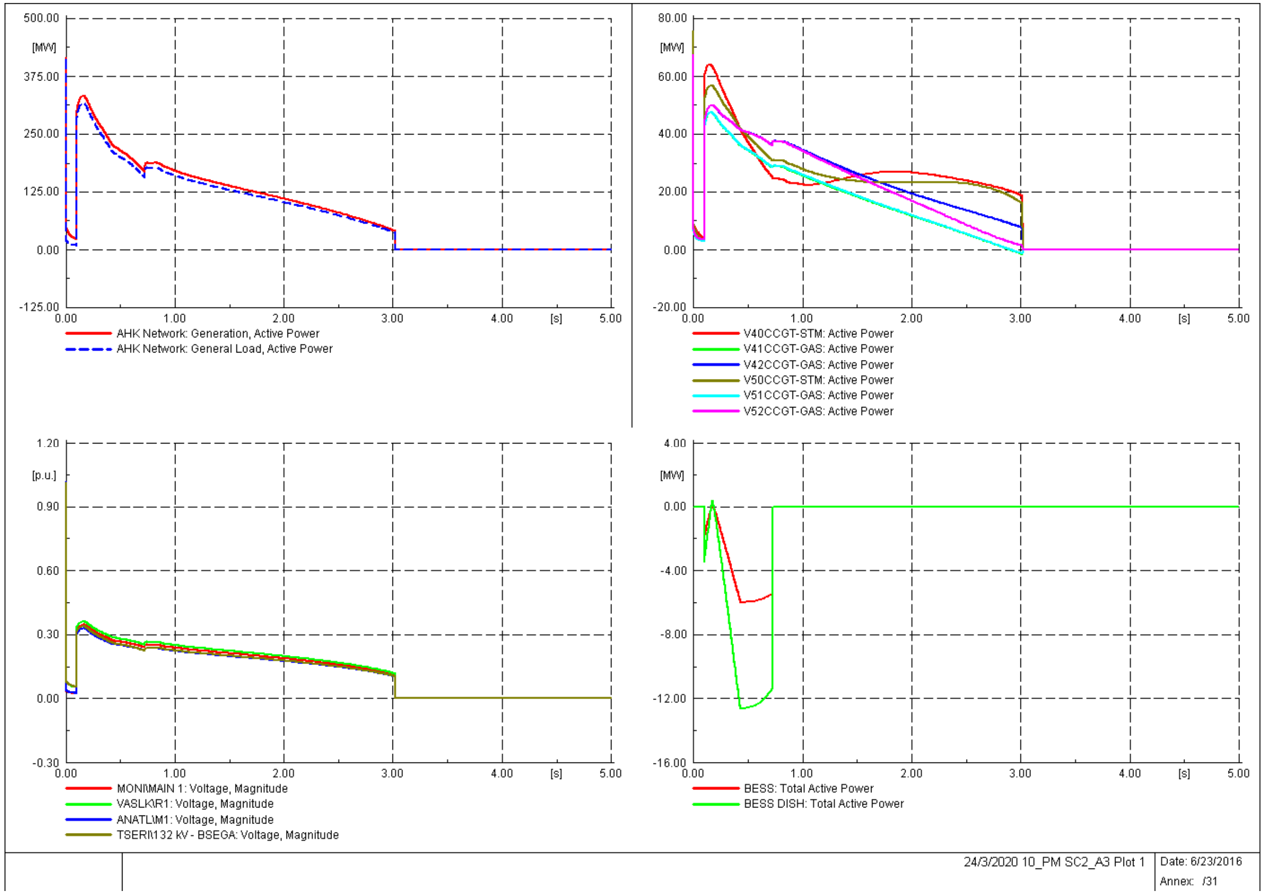
BESS Enhanced Frequency Response important for compliance



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

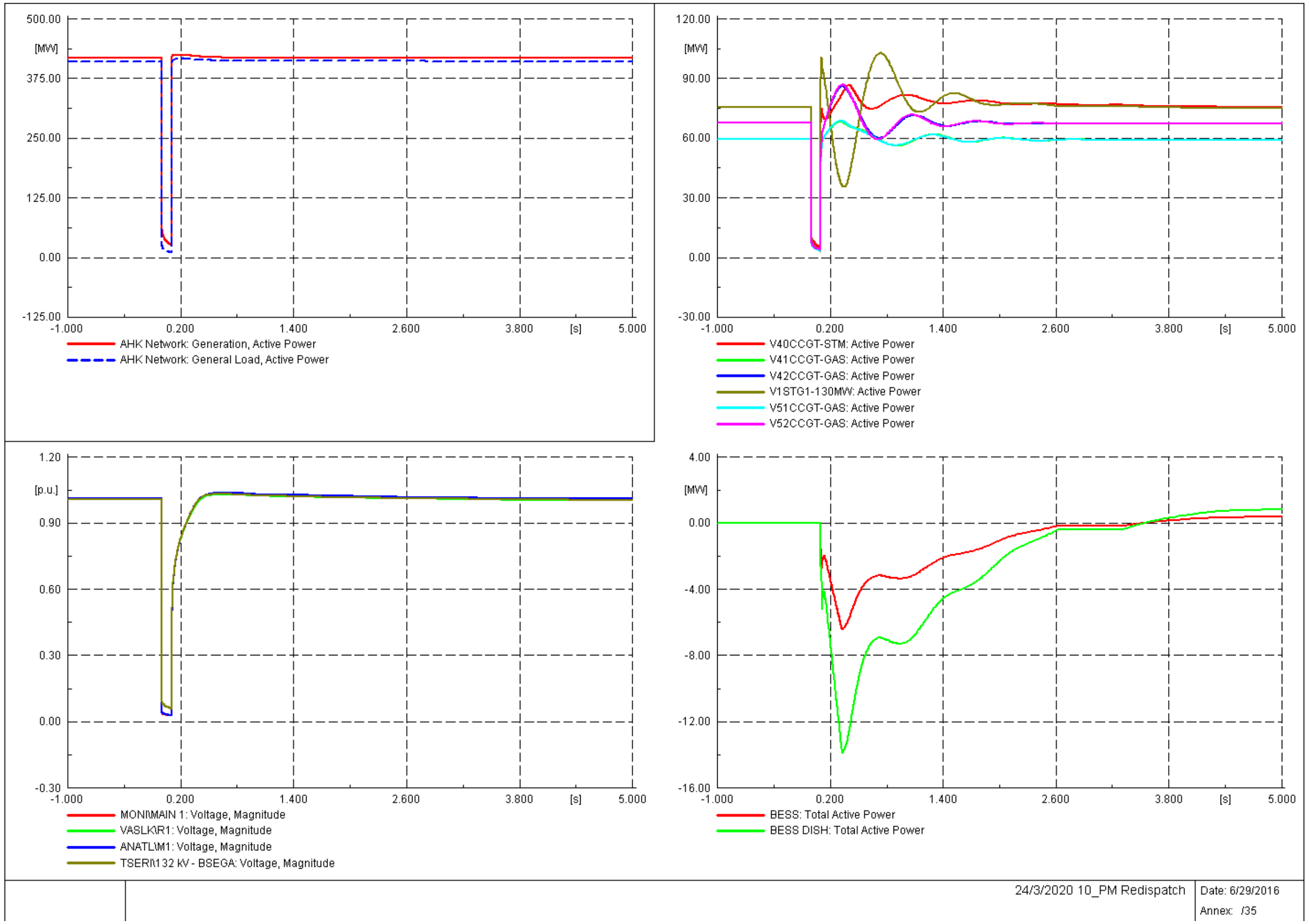


24/03/2020 22:00 Scenario A3. Load 416.9MW. RES 0%

European Commission

IMPORTANCE OF CCGT AVR MODELS VALIDATION

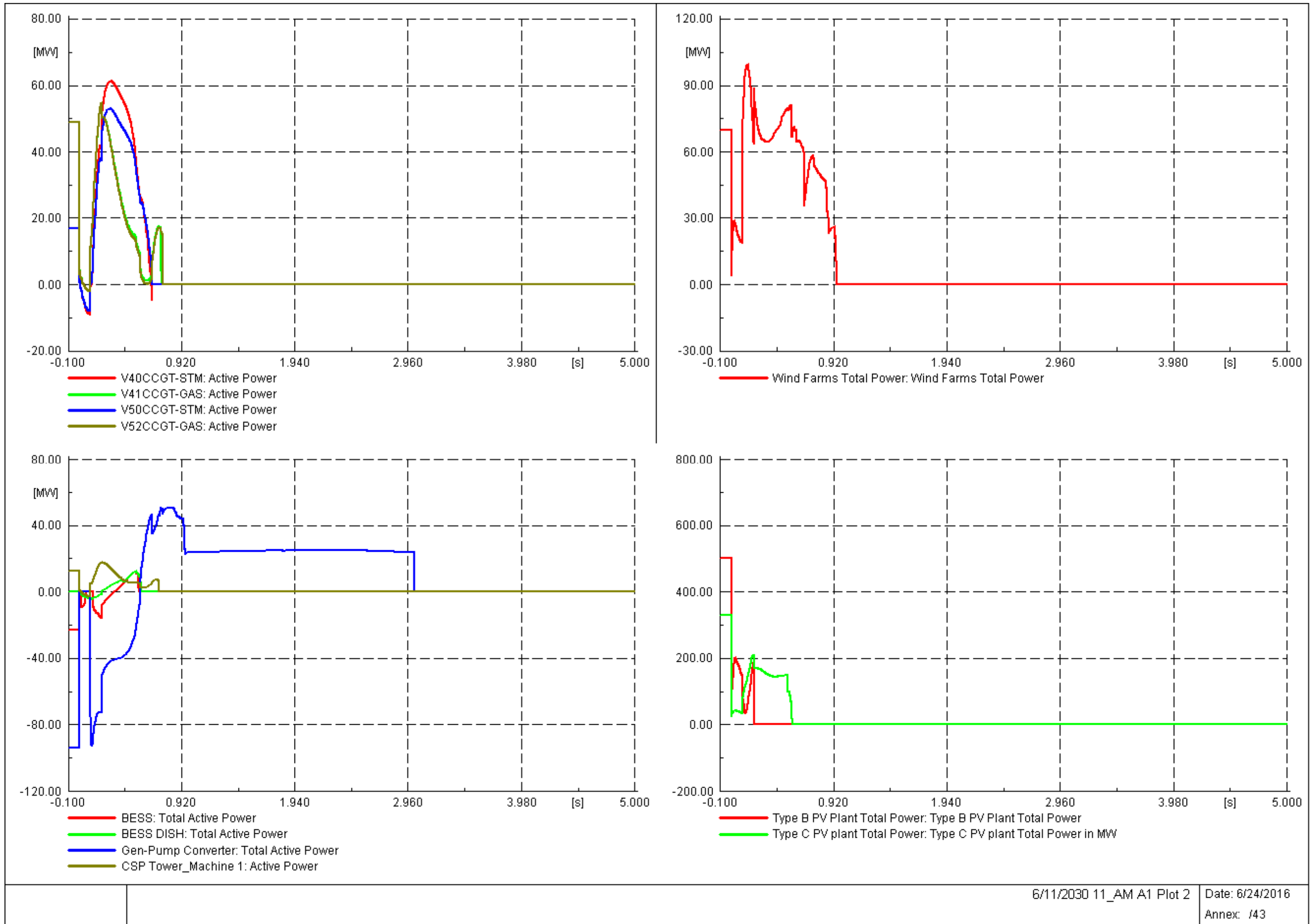
System recovers successfully after clearance of short-circuit



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%

European Commission

DISCUSSION ON TRANSIENT INSTABILITY

- **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

TRANSMISSION SYSTEM SECURITY ANALYSIS CONCLUSIONS

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) As things stand, policy option for prioritisation of small dispersed PV after 2020 should be reconsidered

TRANSMISSION SYSTEM SECURITY ANALYSIS RECOMENDATIONS

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

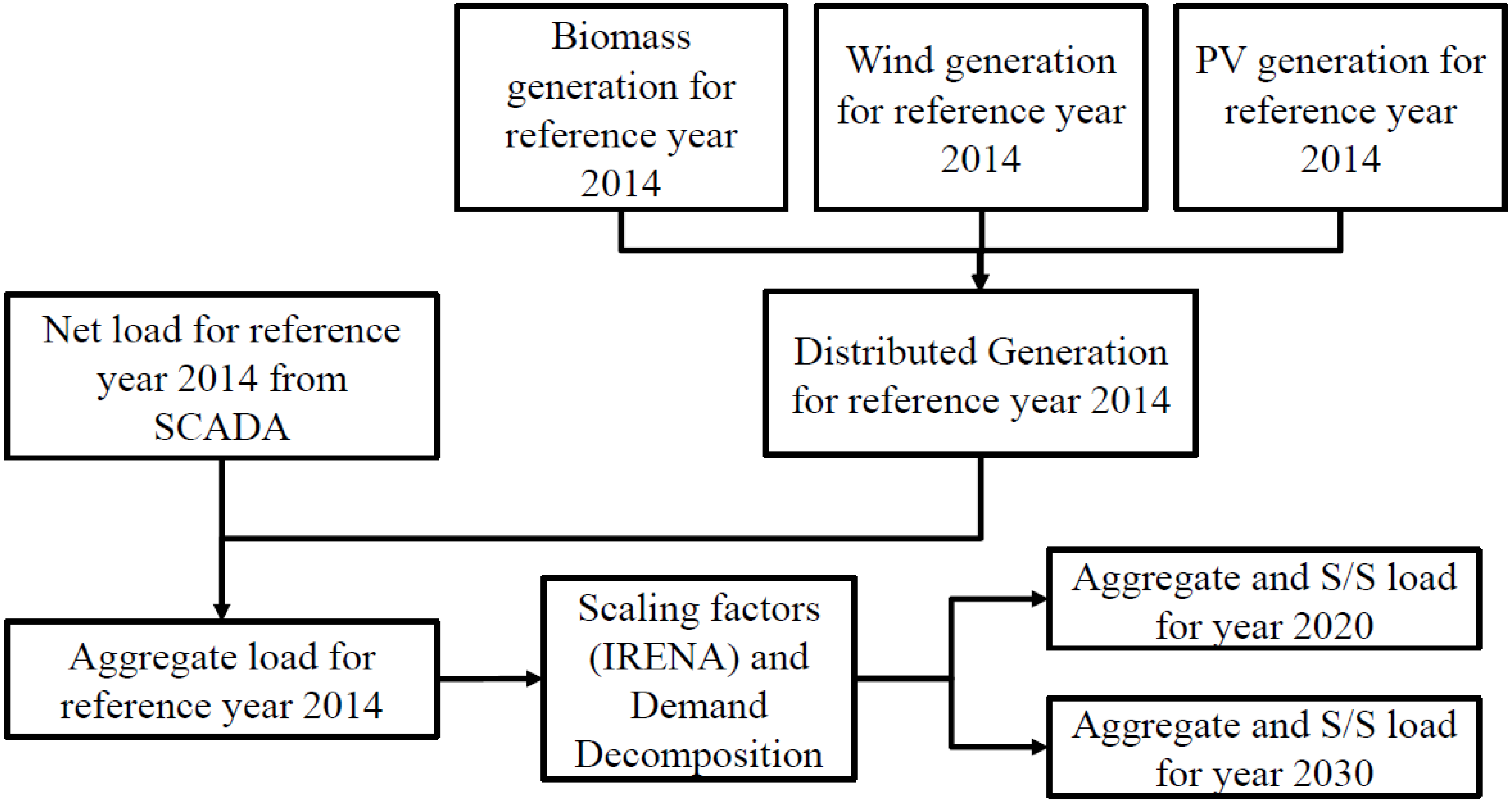
European Commission

DISTRIBUTION SYSTEM STUDIES

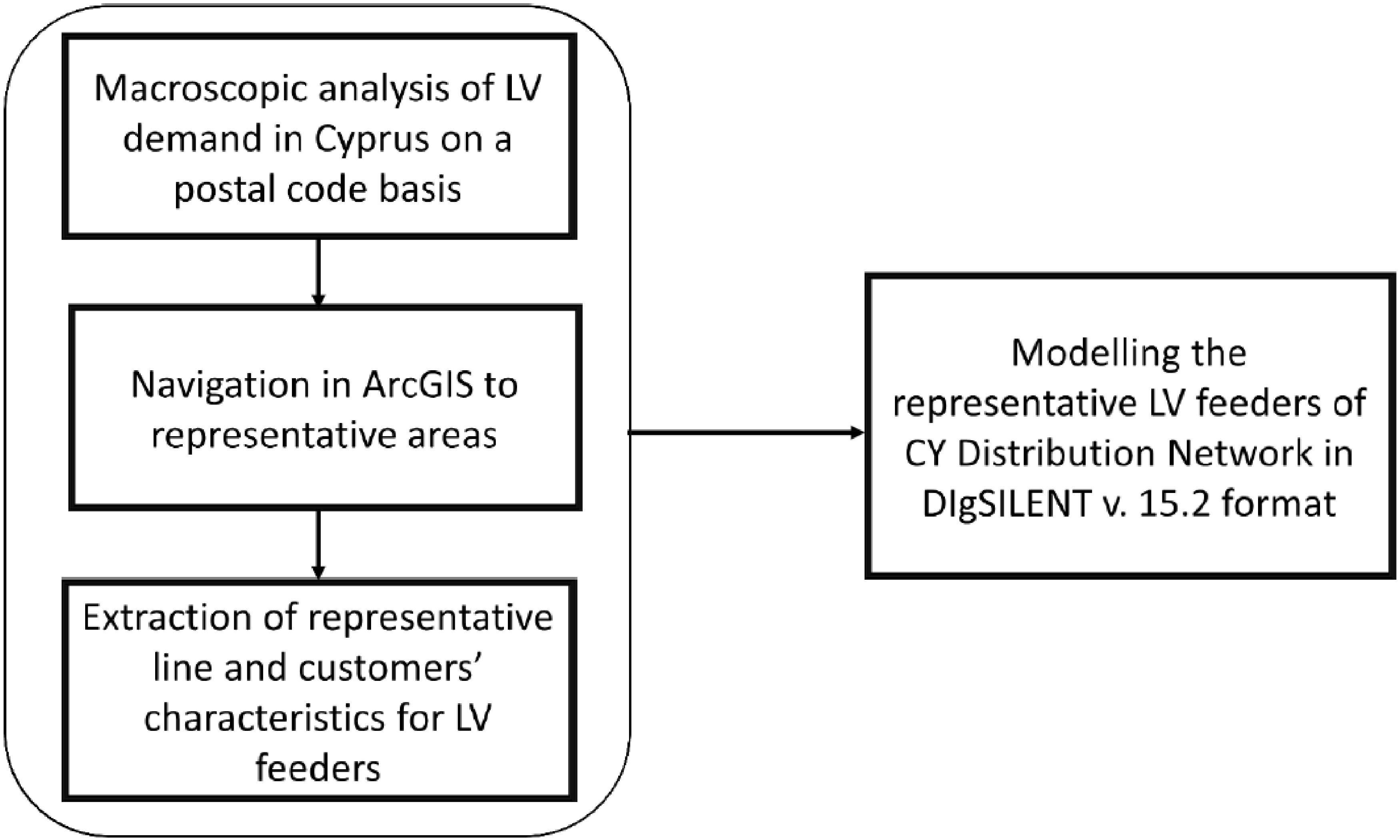
1) Existing electricity distribution system
   A. Spatial and temporal modelling of the electrical demand
   B. Analysis of distribution grid control techniques
   C. Identification of reference LV networks
2) Possible scenarios in development of distribution grids
   A. Spatial and temporal modelling 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

European Commission

Spatial and temporal modelling of electrical demand



Identification of reference LV feeders



European Commission

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, cosφ(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

Twitter: @EU_ScienceHub

LinkedIn: european-commission-joint-research-centre

YouTube: JRC Audiovisuals

Vimeo: Science@EC

European Commission

APPENDIX 1

FROM DYNAMIC STABILITY TO DYNAMIC PERFORMANCE

European Commission

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

European Commission

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

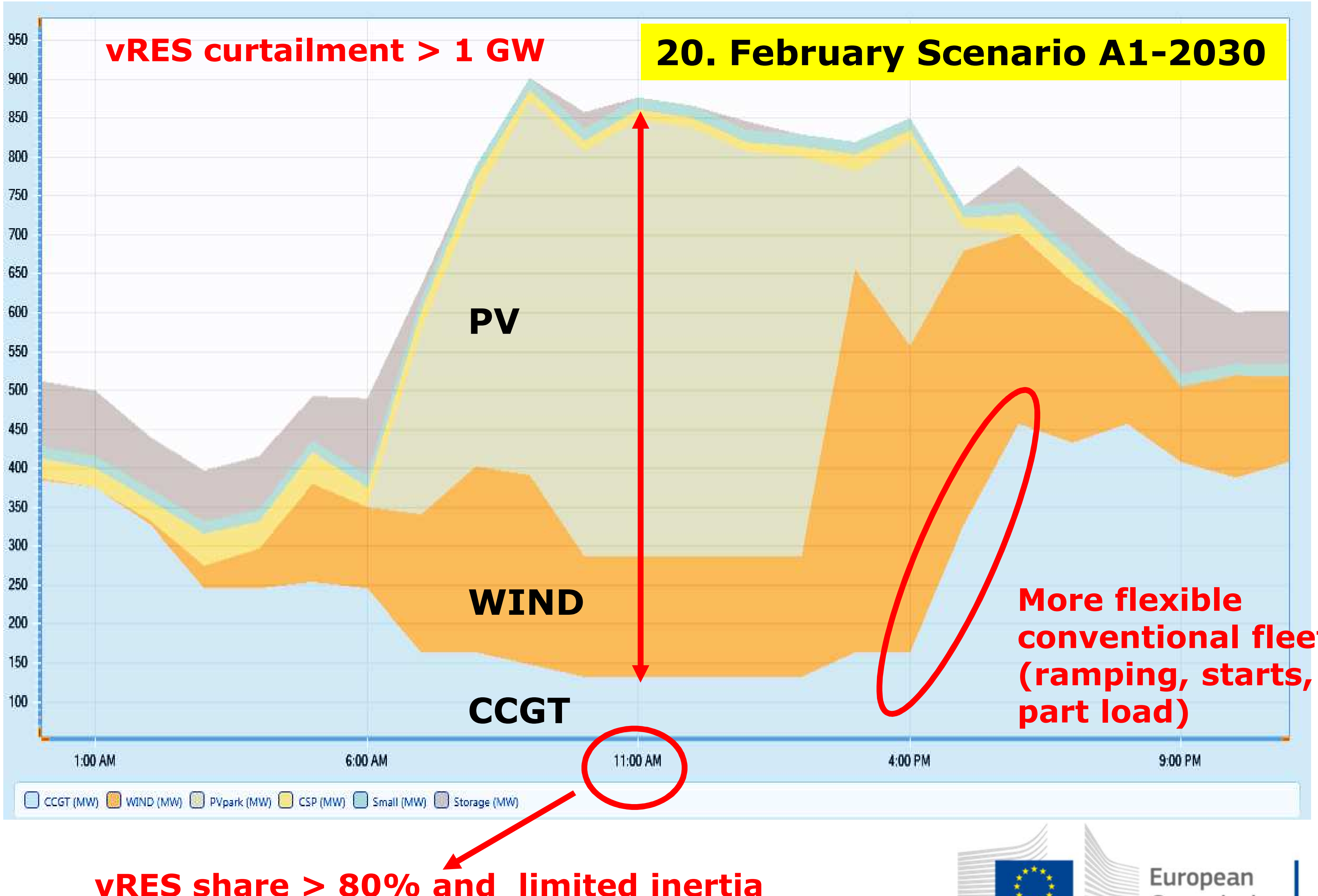
European Commission

APPENDIX 2

CHALLENGES FOR RES INTEGRATION

European Commission

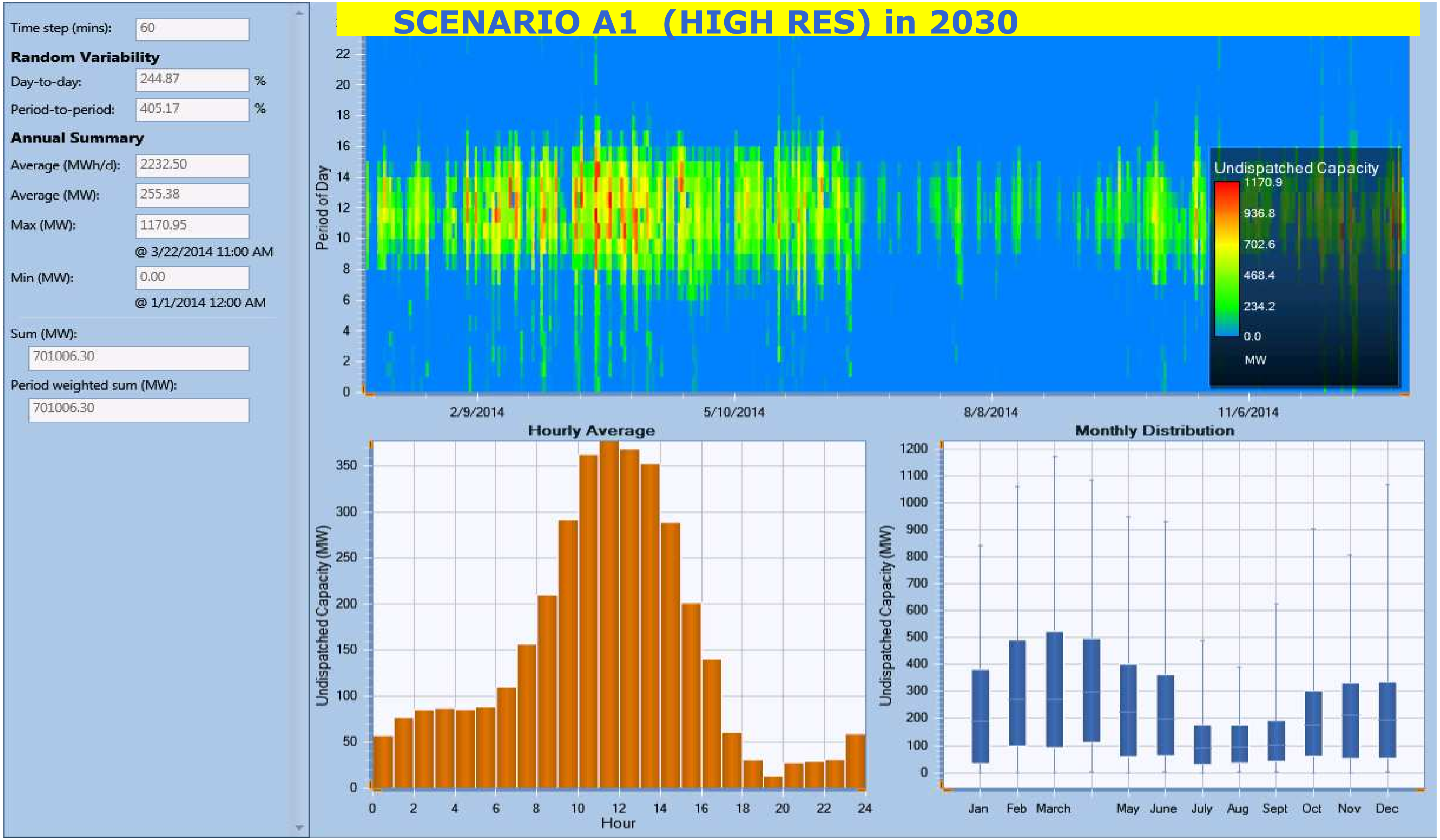
CHALLENGES FOR A SECURE INTEGRATION OF RES



APPENDIX 3

Detailed UCED RESULTS

RES CURTAILMENT

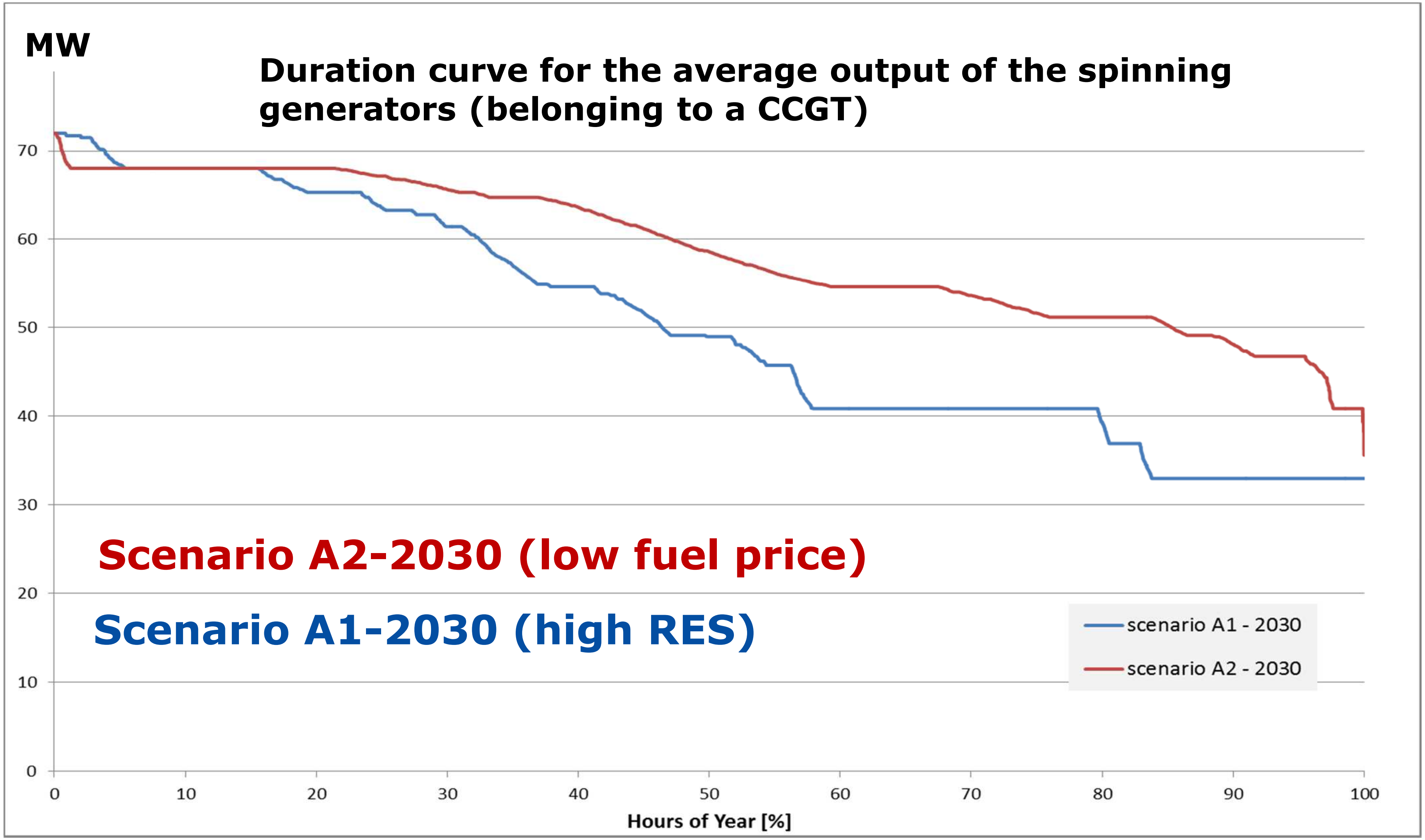


Max power curtailment = 1170 MW

Annual RES energy curtailed = 701 GWh (17%)

European Commission

CCGT PARTIAL LOADING

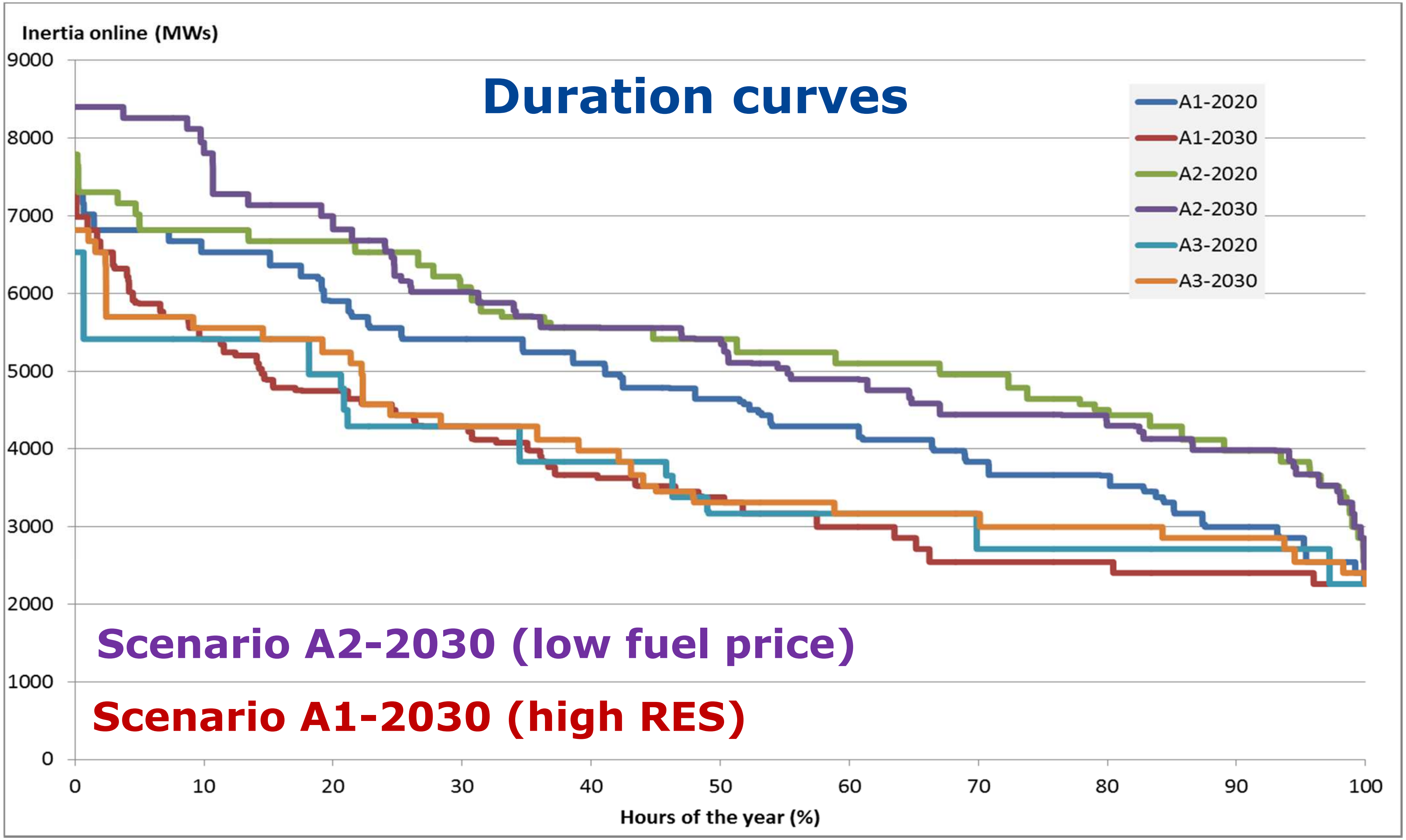


INCREASING FLEXIBILITY BY STORAGE

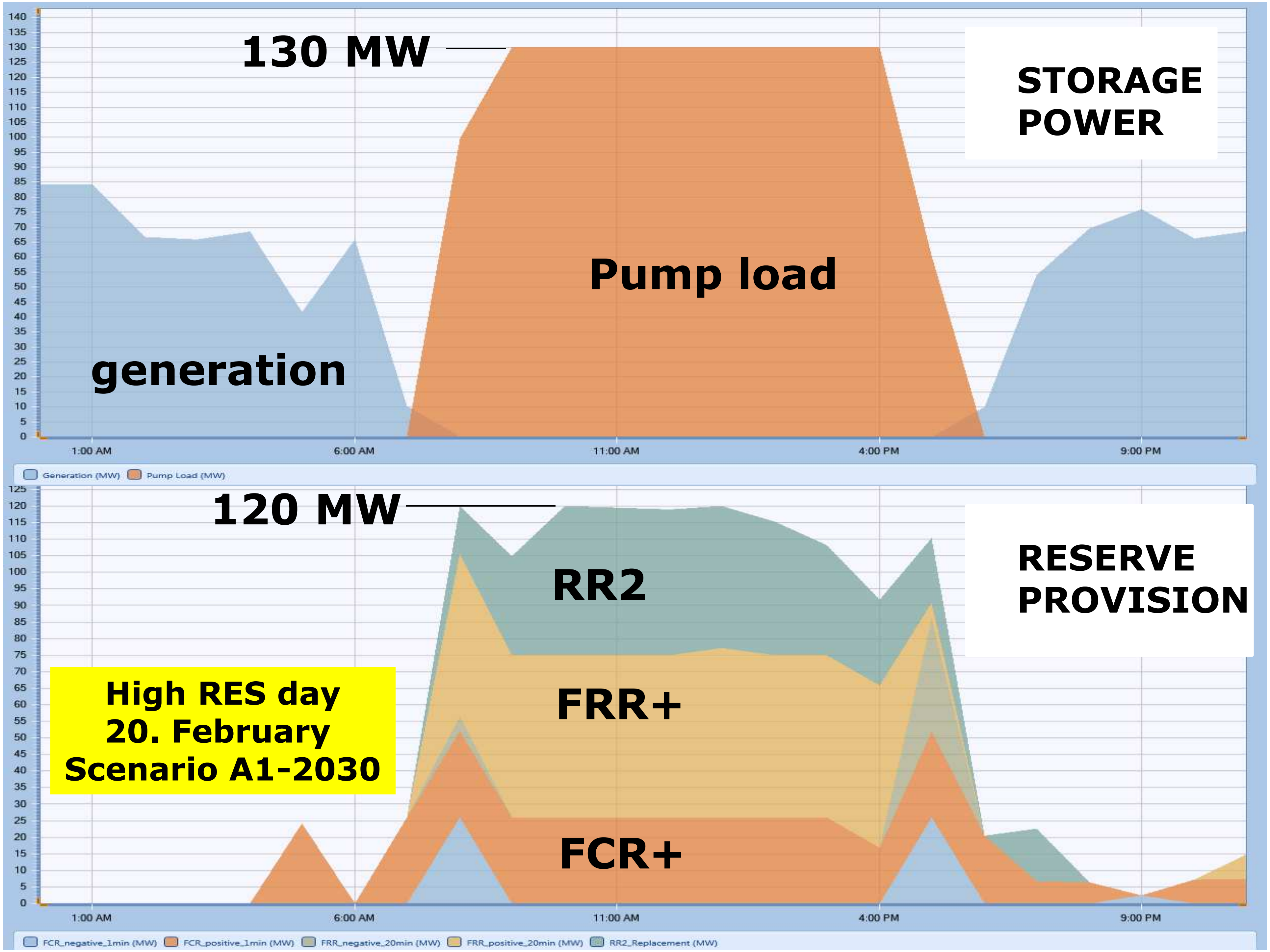
		Hydro 130 MW 8h	**Battery 1** 50 MW 0.3 h	**Battery 2** 61 MW 2 h
Reservoir cycling	cycles	228	876	683
Capacity factor generation	%	20.8	3.0	15.6
Capacity factor FCR+	%	10.1	32.4	29.6
Capacity factor FRR+	%	15.6	0.7	3.6
Capacity factor RR2	%	11.7	0.4	3.0

High RES scenario A1 in 2030

TOTAL INERTIA RESPONSE

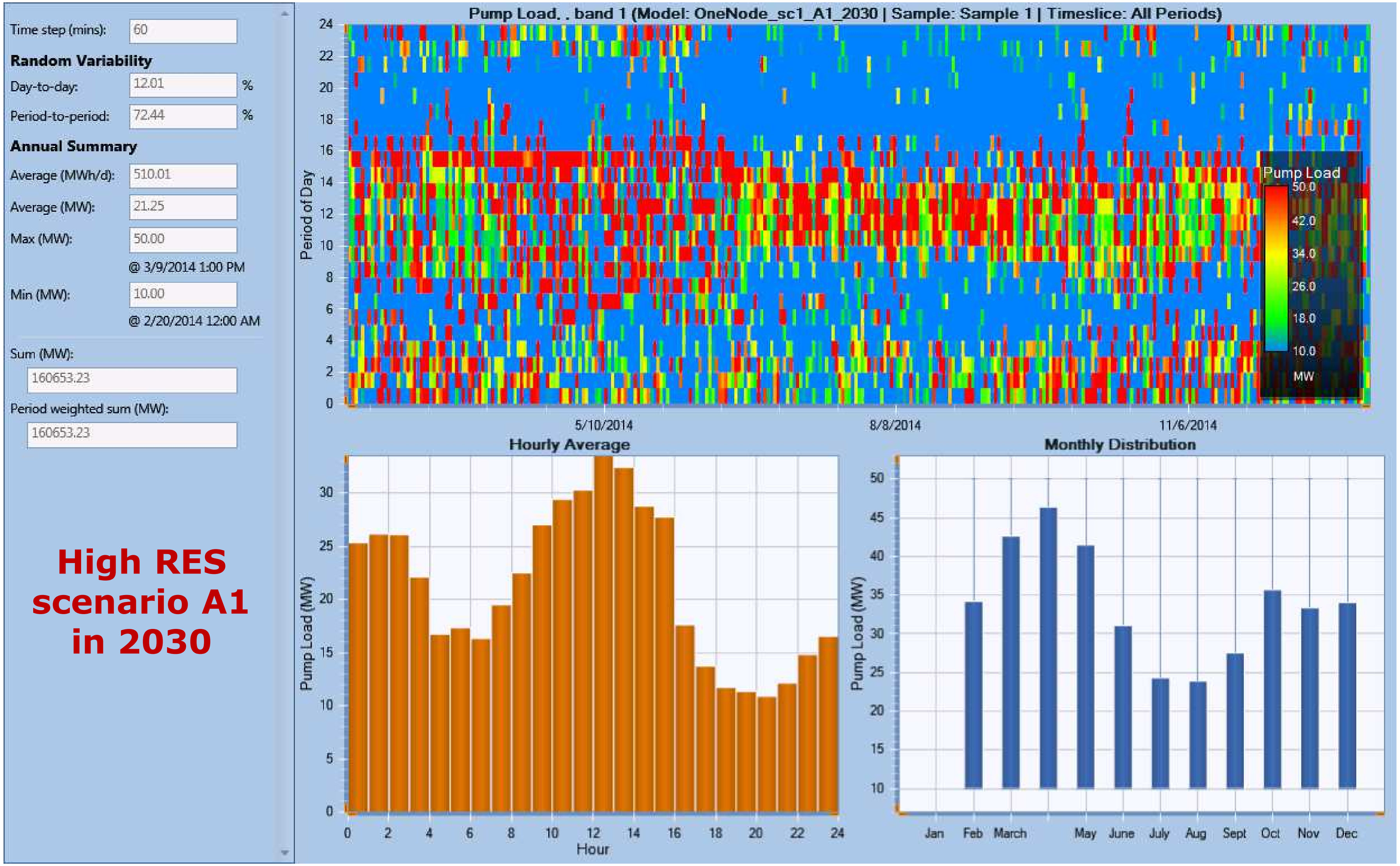


European Commission



130 MW
STORAGE POWER
Pump load
generation
1:00 AM
6:00 AM
11:00 AM
4:00 PM
9:00 PM
Generation (MW)
Pump Load (MW)
120 MW
RESERVE PROVISION
RR2
FRR+
FCR+
High RES day
20. February
Scenario A1-2030
FCR_negative_1min (MW)
FCR_positive_1min (MW)
FRR_negative_20min (MW)
FRR_positive_20min (MW)
RR2_Replacement (MW)

LOAD ACTIVATION BY DEMAND RESPONSE



Daytime load activation <> strategy applied today in Cyprus.

European Commission

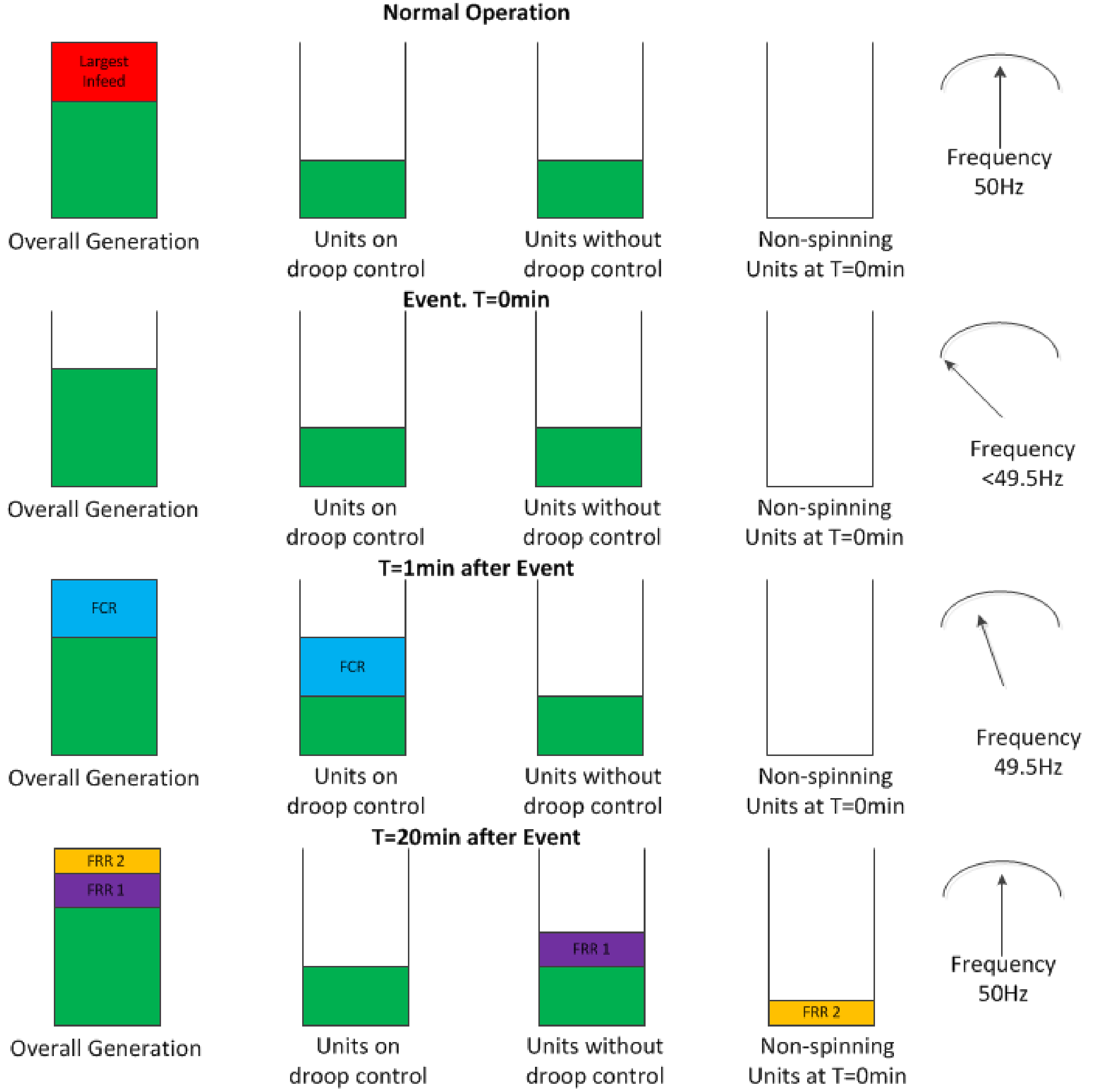
APPENDIX 4

Relationship between UCED and Dynamic studies

European Commission

UCED AND SECURITY STUDIES

UCED



Security studies

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

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	**Scope: Determination of critical "snapshots" of the system in Future Scenarios**
2. Load-flow studies Examination of steady-state transmission bottlenecks (congestions, reactive power adequacy assessment)	**Are steady-state problems expected?**
3. Investigation of solutions for potential steady-state problems	**How can we solve potential steady-state problems?**
4. Defining the Characteristic Case Studies Defining the Contingency List per Characteristic Case Study	**What are the critical cases and faults for dynamic performance?**
5. Determine compliance with the Frequency Quality Targets	**Is the system capable of facing the critical faults?**
6. Identification of conditions and metrics for compliance with the Frequency Quality Defining Parameters	**Can we define constraints for compliant dynamic performance?**
7. Investigation of measures for enhancing dynamic security	**What are our options?**

European Commission

TRANSMISSION SYSTEM MODEL - 1

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)

European Commission

TRANSMISSION SYSTEM MODEL - 2

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

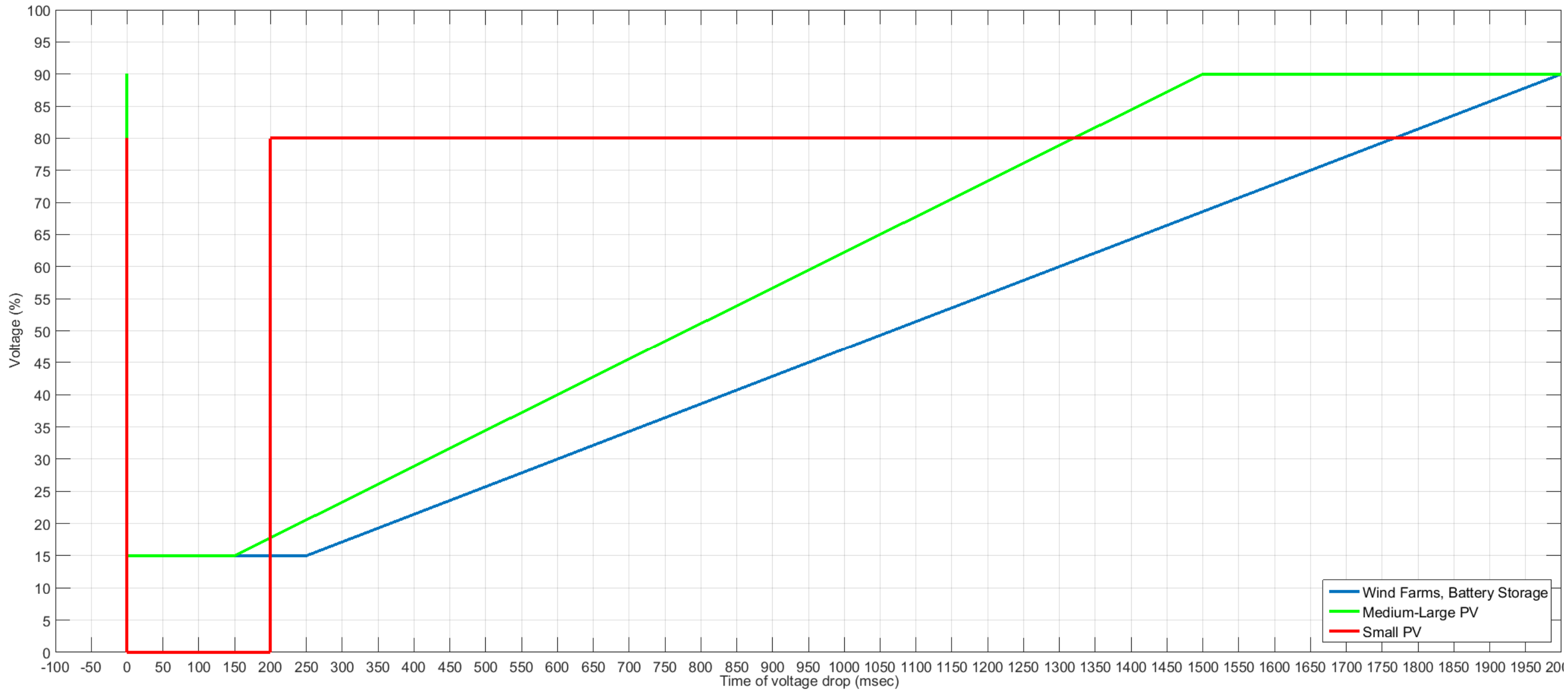
Short-circuits in the transmission network is the critical Event

European Commission

APPENDIX 6

FAULT RIDE-THROUGH CAPABILITY EXPLANATION

FAULT RIDE-THROUGH CAPABILITIES



- **Fault ride-through capability does not mean that plant can remain connected under any voltage drop/duration**

	Voltage (%)		
	50%	**35%**	**25%**
Small PV	TRIP	TRIP	TRIP
Medium-Large PV	OK	TRIP	TRIP
Wind farms, BESS	OK	OK	TRIP

Behaviour under a voltage drop lasting 600ms