IEEE-Power Tech 2025 Tutorial:

Real-Time Simulation and Co-Simulation for Large-Scale Power Grids

The Kopernikus ENSURE Co-Demonstration Platform as a Collaborative Approach

Session 4: **European RMS *PowerFactory* Model**

Dr.-Ing. Uwe Kühnapfel (KIT-IAI)

With funding from the:
Federal Ministry of Research, Technology and Space

Presentation

Dr.-Ing. **Uwe G. Kühnapfel**

Head of Research-Section FG-ESI, Group-Leader SV

Institute for Automation and Applied Informatics (IAI), Karlsruhe Institute of Technology(KIT)

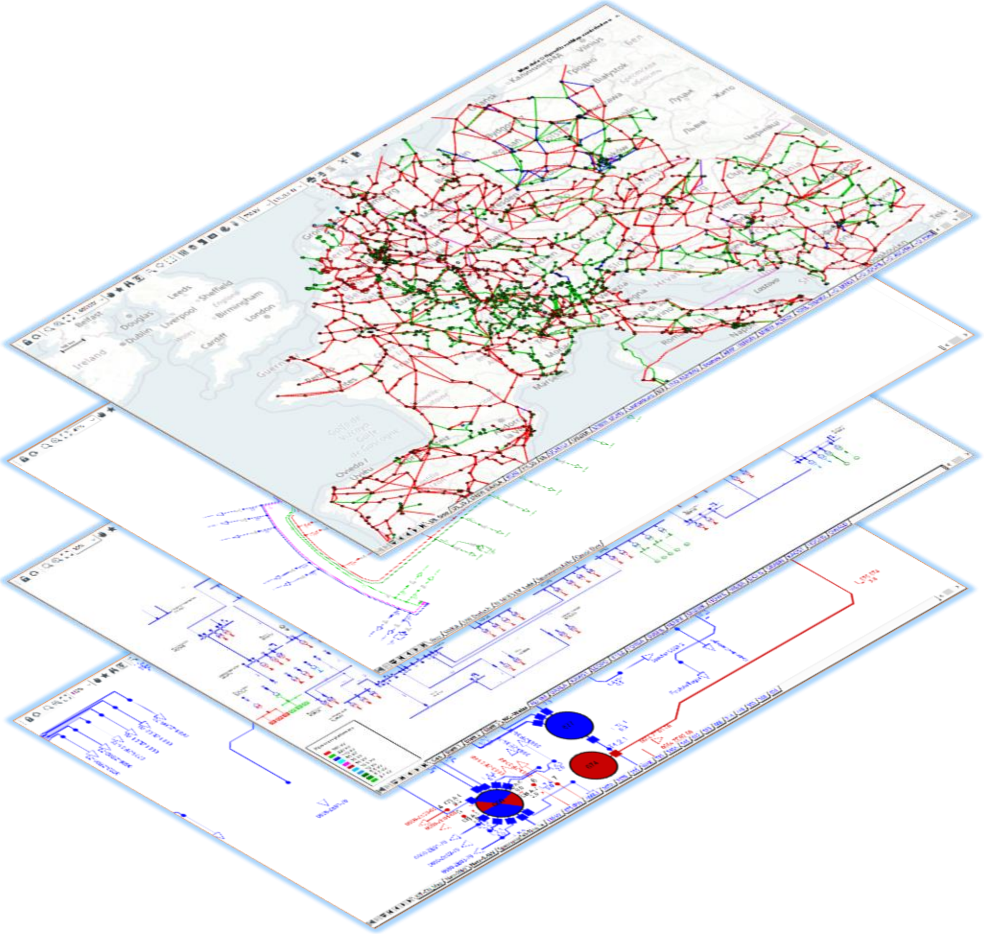
uwe.kuehnapfel@kit.edu

Content

- Grid-Models for Kopernikus-ENSURE
- Transient-Dynamic RMS Grid-Model of the ENTSO-E CE Region
  - Study: Grid-Separation (2021 Croatia, Stabilisation, Re-Synchronisation
- Extension to Distribution Grid Level (110-kV, MV-/LV-Subgrids)
- Dynamical Grid-Models „Re-Bundling“ (Transmission- and Distribution Grids)
  - Study: Short-Circuit Simulation across all Voltage-Levels
- Actual: Study on **“Black-Out”** in **Spain/Portugal**, 28 April 2025
- Summary and Conclusion
- Demo Dynamical Model (*PowerFactory*)

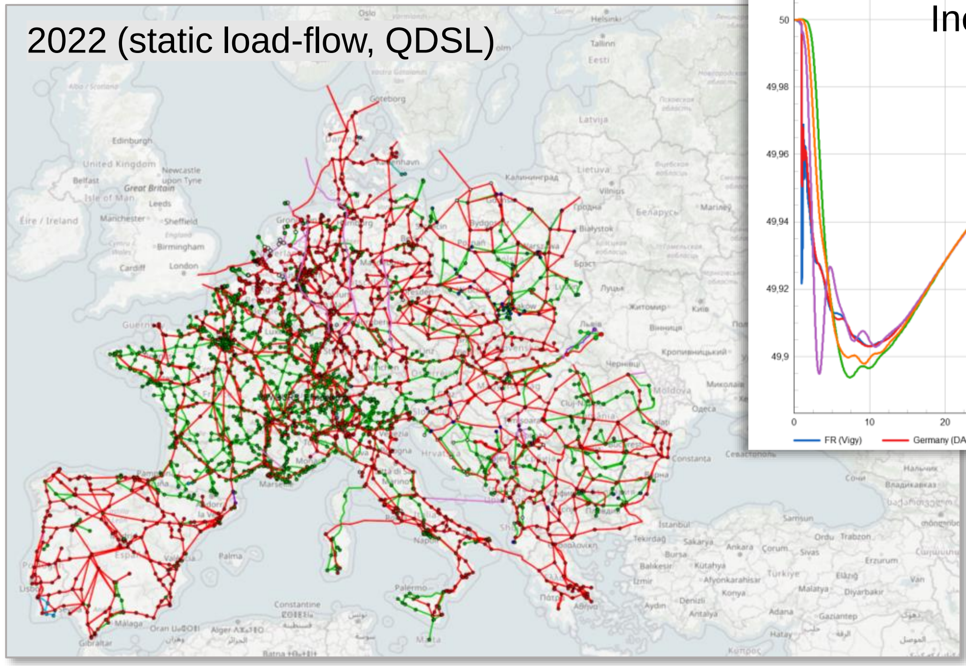
Electricity Grid Models ENSURE-2, -3

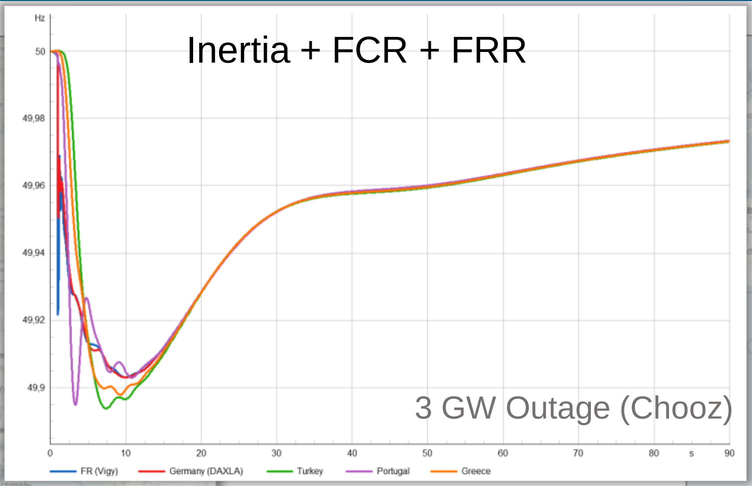
- GE-Grid-Maps Europe (CE-Region, Scandinavia, GB, Ireland)
  own preliminary work (2015, → Geo-Coordinates)
- ENSURE-2: ENTSO-E CE Static Model Germany (Europe),
  Extensions for NEP 2030 (e.g. *NordLink*, Powerplants …)
- 110-kV Region: Control-Zone Transnet-BW,
  since 2024: all 4 Control-Zones DE
- Various HV-/MV-/LS-Models (partly RMS-/EMT dynamic)
  e.g.: KIT-Campus Nord, Quarter KA „Rehbuckel“ (HV, MV, LV)
  Local Substation „N1418“ + 75 Houses, PV-units
  - Load-Flow/ Time-Series (QDSL), stationary short-circuit
  - Large archive of PMU-Data

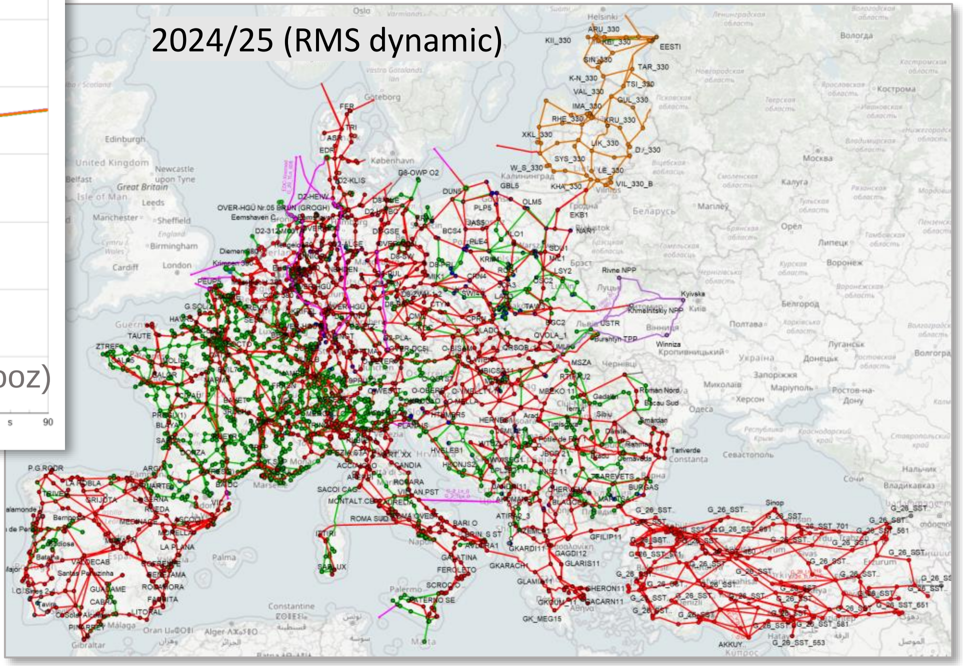


→ **„Re-Bundling“** (opposite of „Un-Bundling“)

ENTSO-E Central European Dynamic Grid Model (CE-Region)



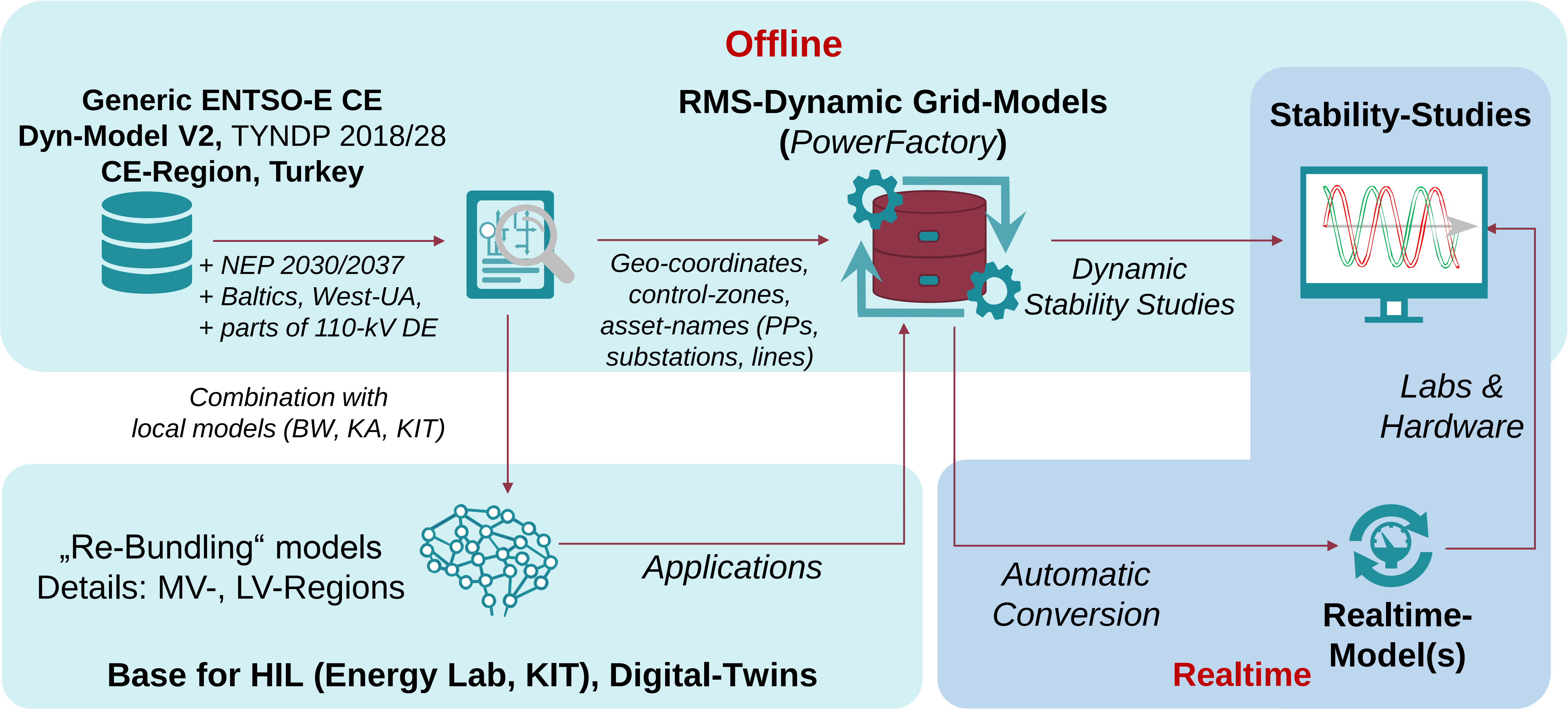




- **Transient-Dynamics RMS Simulation Model** (Base: ENTSO-E with NDA, TYNDP_2018/28), *PowerFactory*
- **Vertical Boundary Grids for "Re-Bundling"** (DE 110-kV → DG Models, 20-/0,4-kV Subgrids)
- Simulates the CE-grid regarding: **Frequency Stability** (Load & Generation Balance**), Short-Circuits, Protection, Reserves (P, Q),** and **"Inter-Area Oscillations"**
- **Extensions KIT** (Geo-Coordinates, Grid-Extension NEP 2026 / 2030 / 2037, regional Extensions (Baltics + West-Ukraine), local Distribution areas …). Total: **> 461.700 Elements** in *PowerFactory*, **+ 654 powerplants** with **Dyn.-Controllers**, 4 Basic Types (Nuclear, Other thermal, Gas, Hydro)

International benchmark
TwinEU – Digital Twin of EU grid (2027, 25 Mio. €)

Tool-Chain (Workflow)



Software Tools used at KIT for Electricity Grid Modelling, -Simulation, -Analysis

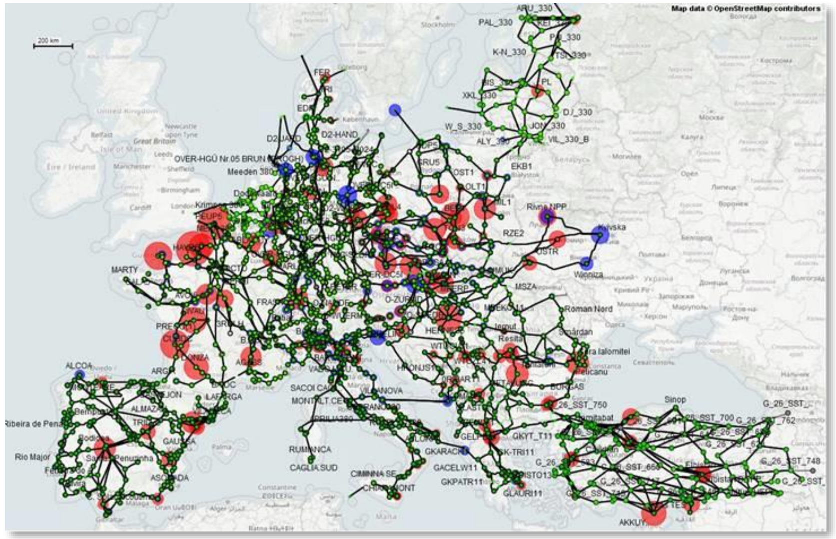
	PF Powerflow	OPF Optimal Powerflow	SC Short Circuit	TS Transient Stability	EMT Electro-magnetic Transients	PHIL Real time simulation	OS Open Source
GridLAB-D	✓						✓
Matpower* / MatDyn*	✓	✓	✓	✓			✓
OpenDSS	✓		✓	✓			✓
(Open) Modelica*, Dymola			✓	✓			(✓)
PyPSA	✓	✓					✓
panda**power**	✓	✓	✓				✓
Matlab / Simulink / Simscape	✓		✓	✓	✓		
NEPLAN (ABB)	✓	✓	✓	✓			
PSS SINCAL (Siemens)	✓	✓	✓	✓			
DIgSILENT PowerFactory	✓	✓	✓	✓	✓		
INTEGRAL-7	✓	✓	✓	✓			
PSCAD (Manitoba Hydro)	✓	✓	✓	✓	✓		
RSCAD (RTDS), Hypersim (Opal-RT)	✓	✓	✓	✓	✓	✓	

* With own extensions to Matpower (PV, Wind) and MatDyn (PV, Wind)
All listed tools are licensed and available at the Energy Lab

Transient-Dynamic Study *Grid Separation*

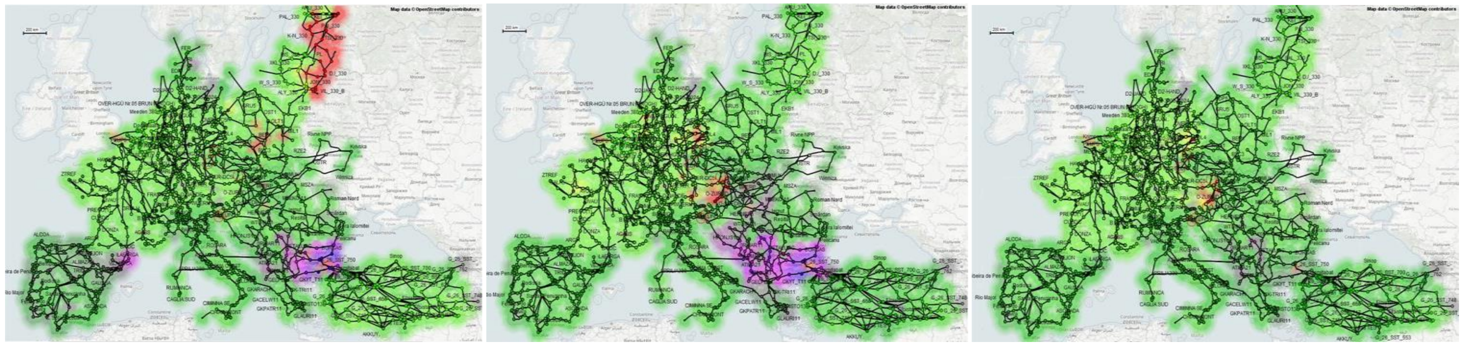
Study **Grid Separation** (example), refers to event* at 8.1.2021 (initial event Croatia → CE-Region)

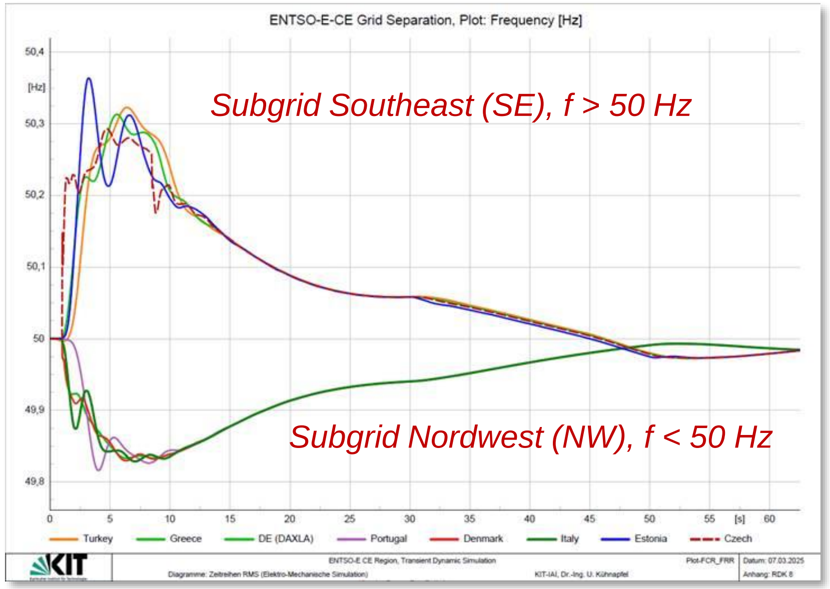
- Initial Situation: Grid separation into 2 large regions: Northwest (NW) und Southeast (SE) at t = 1 s, along borders DE-PL, DE-CZ, AT-CZ, AT-HU, AT-SI, IT-SI, Adria (total load ~ 350 GW)
- Heavily unbalanced generation > 4 GW (+/-) → large flows occur in both regions
- NW stabilises, SE requires PP-emergency shutdowns and TSO-load measures (pumped hydro) 6-10 s
- t = 30 – 58 s: TSO load shedding (Aluminium factories, other Industrial), initiates Re-Synchronisation.
- FCR-FRR, Frequency diagrams of the 2 regions cross 2 times, i.e. at t~48 s and t~63 s.
- At 2nd crossing Re-Synchronisation is done (power switches at Injector-Lines are closed).
  After ~20 s of „Reverse TSO-Load Actions“ is balanced again …



Voltage-Stability:

t = 3 s   t = 11 s   t = 21 s





* Ref.: https://www.entsoe.eu/news/2021/07/15/final-report-on-the-separation-of-the-continental-europe-power-system-on-8-january-2021/

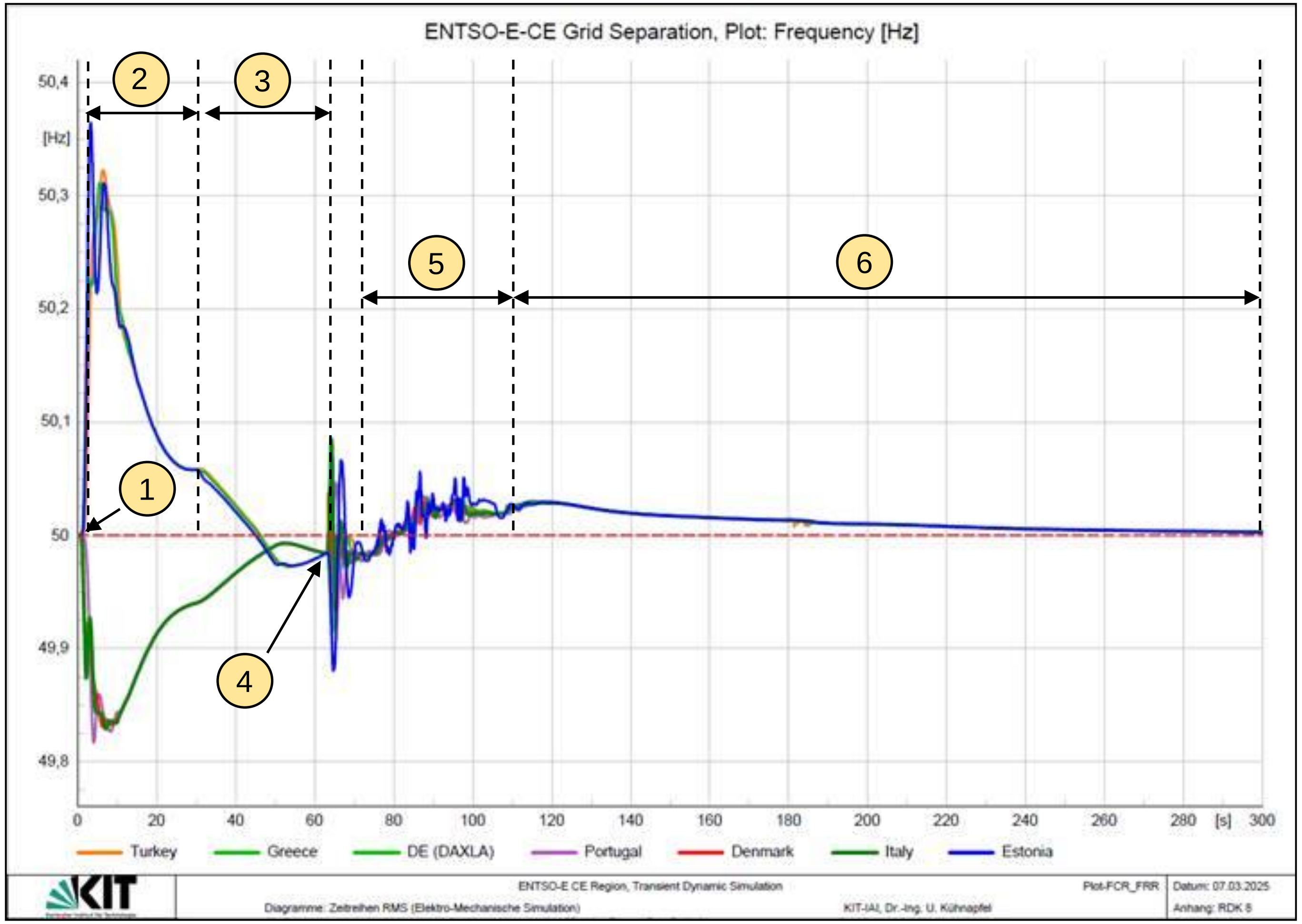
Transient-Dynamic Study ***Grid Separation***

Complete series of phases in the study. Simulated time: 300 s from event “Grid-Separation”

➢ 1 Separation 2 Stabilisation 3 Frequency adaption 4 Re-Synchronisation 5 Load re-activation 6 FRR → 50 HZ

„Lessons learned“:

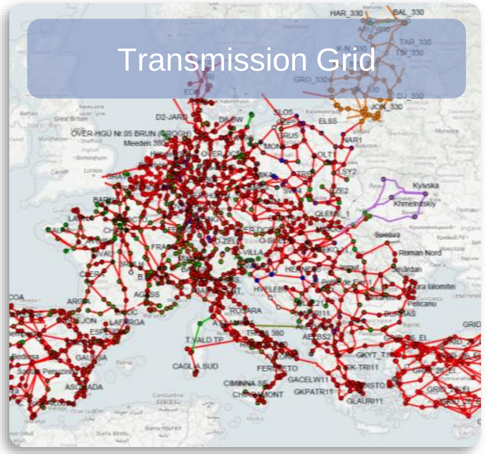
- Computation time ~2,5 hours (factor: 1:25 to 1:40) on Win10-notebook. Depending on dynamics parameter setup, e.g. adaptive step-width, damping factor
- No static generators (voltage sources) at all in the model for FCR/FRR simulation
  i.e. no Ward-elements, no PV or Wind-PP elements
- Static generators (RE) are replaced by „Dynamic Loads“ (i.e. negative P for generators, pos. P for consumers)
- Method works as well in RSCAD (RTDS)

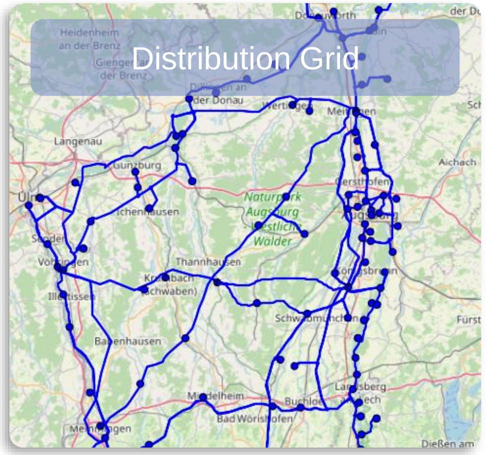


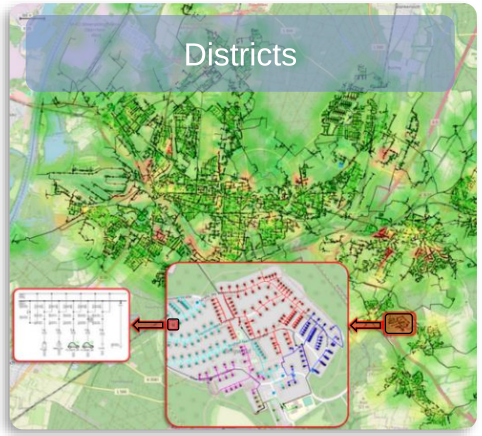
Helmholtz-ESD, ST 2.2: Selected Results
„The water tank in which the fish „ENSURE“ swims …“

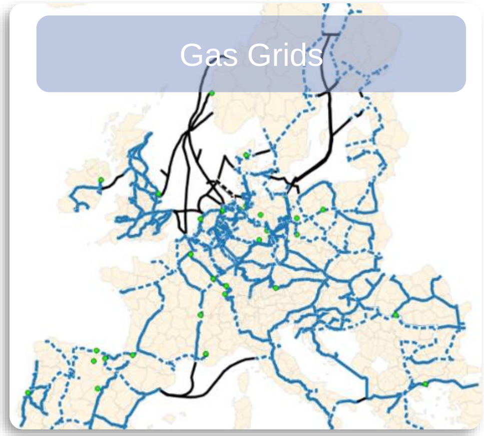
Helmholtz-Program Energy System Design (ESD)

- Energy Lab (Hardware, Digital-Twins, IT-Server, …)
- Simulation models
    - Electricity: Transmission, Distribution (110-kV, MS-/NS)
    - Gas: Transmission, Distribution (EBI-VDGW-KIT/ITC)
    - Heating (District Level)
- Energy-Sector Coupling, Test Facilities + Replicas
- Experimental-Campus (KIT-CN)
- Co-Operation with FZ-Jülich, DLR-Oldenburg, HZ-Berlin
- RESUR: Coupling TG / districts via Pyro5 → model **privacy** (HGF-financing due to UA-war, bundling of resilience research)





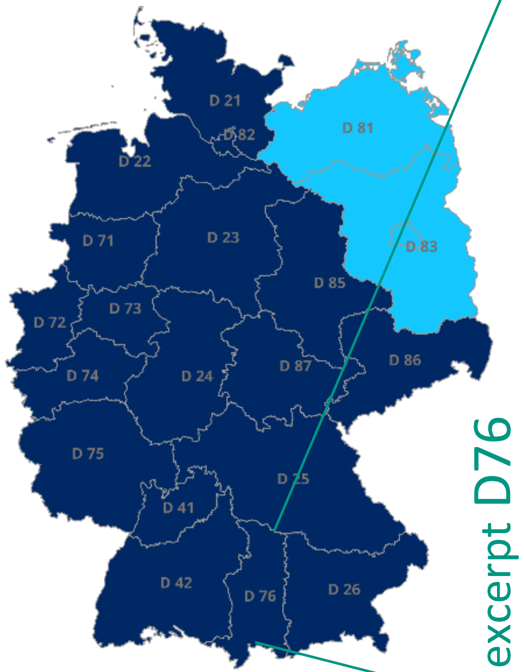




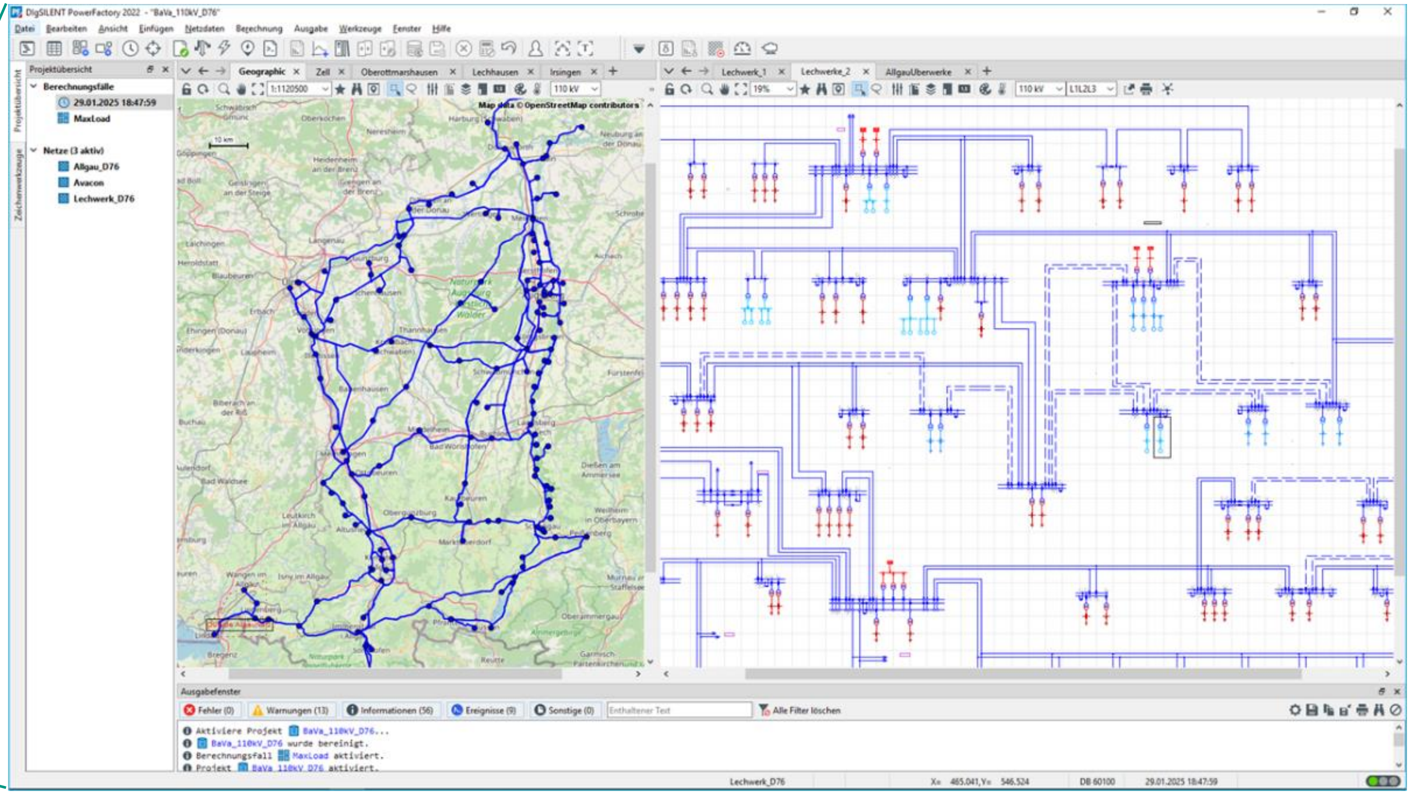
[1] Kühnapfel, Uwe et. al., On the Art of Electric Power System Modelling and Simulation … , ISBN: 978-3-031-69030-3
[2] Weber, Moritz et. al. IEEE Transactions on Smart Grid, DOI: 10.1109/TSG.2024.3406765
[3] Dindar, Burak et. al. IEEE PES APPEEC, DOI:10.1109/APPEEC57400.2023.10562006

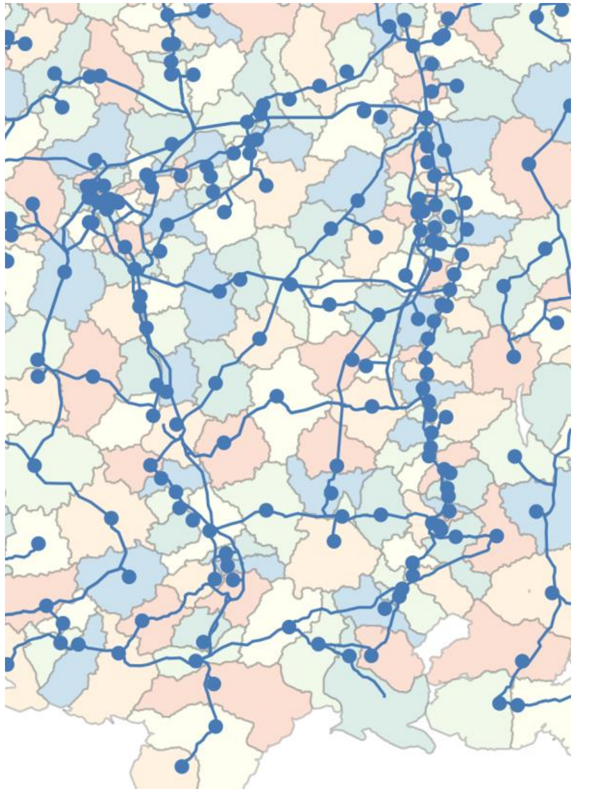
„Re-Bundling“
Modelling 110-kV Grid Germany

- In DE the main integration-layer for „large“ wind- and solar-plants. Layers 1-4 modelled (MS-buses)
- In the meantime 100% finished, structured according TG-zones, assignment according LAU-1 („Verbandsgemeinden“)



excerpt D76





- Aggregated RE-units from „Marktstammdatenregister“ (Source: BNA), Loads from Statista (population)
  → Excel-Tables and PF-interface via Phyton scripting (Pyro5)

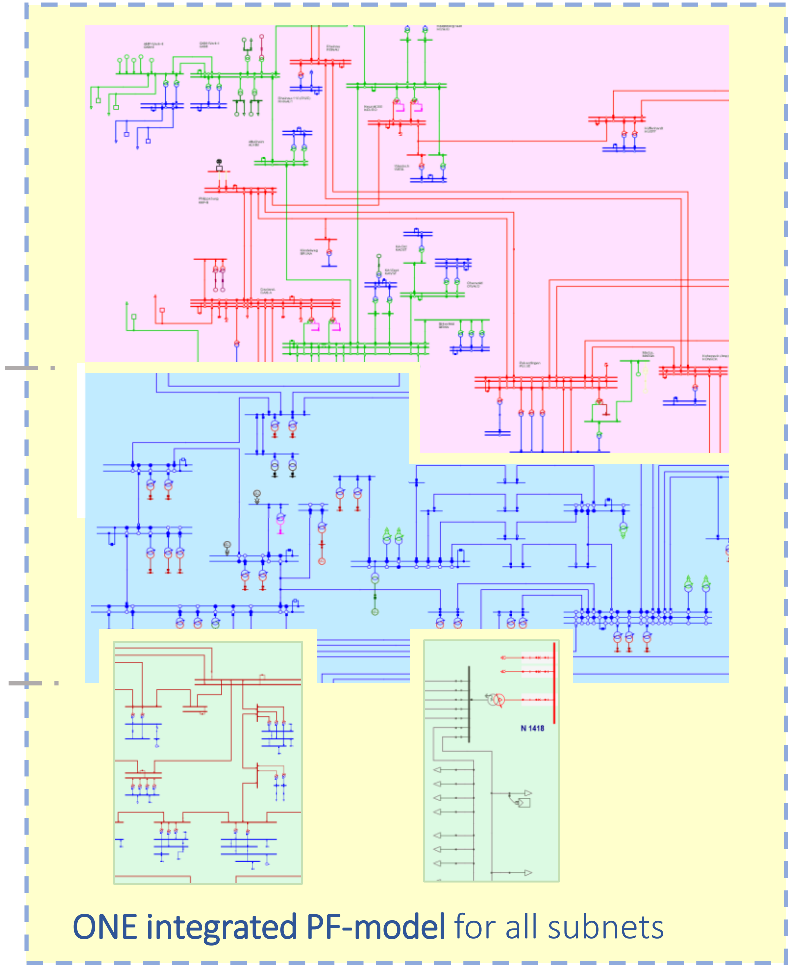
Grid Re-Bundling
Close versus Soft Grid Connections

(a) Close Coupling

TSO
EHV
HVDC

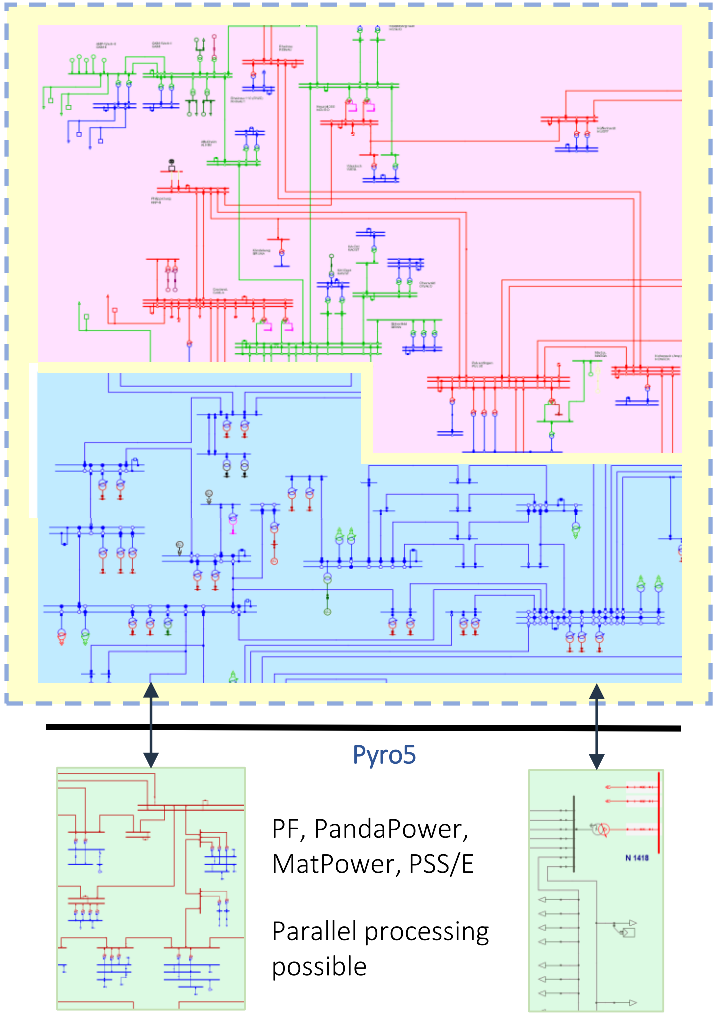
DSO
HV (110kV)

DSO
MV / LV
City-Works



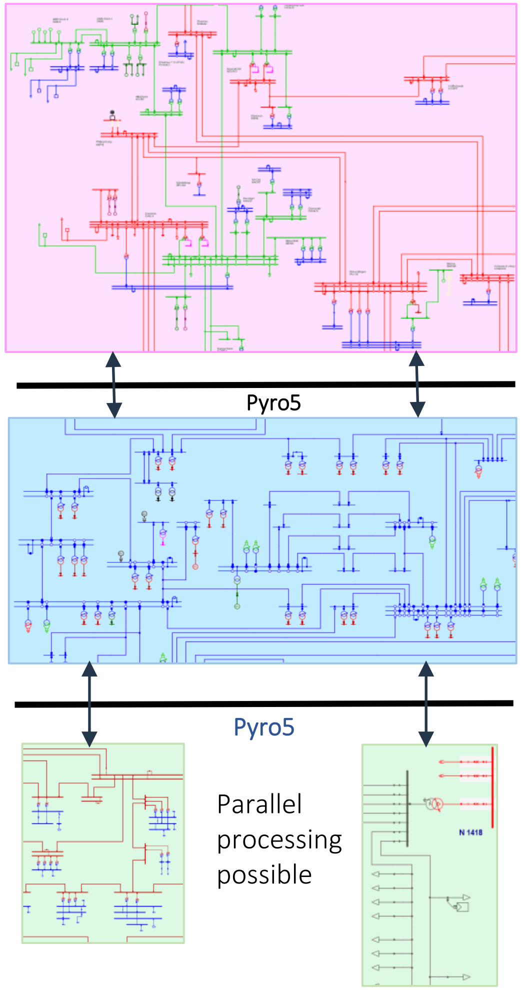
RMS-Dynamics for all Subgrids

(b) Moderate Coupling (e.g. RESUR)



RMS-Dynamics in EHV- and HV-Level Grids

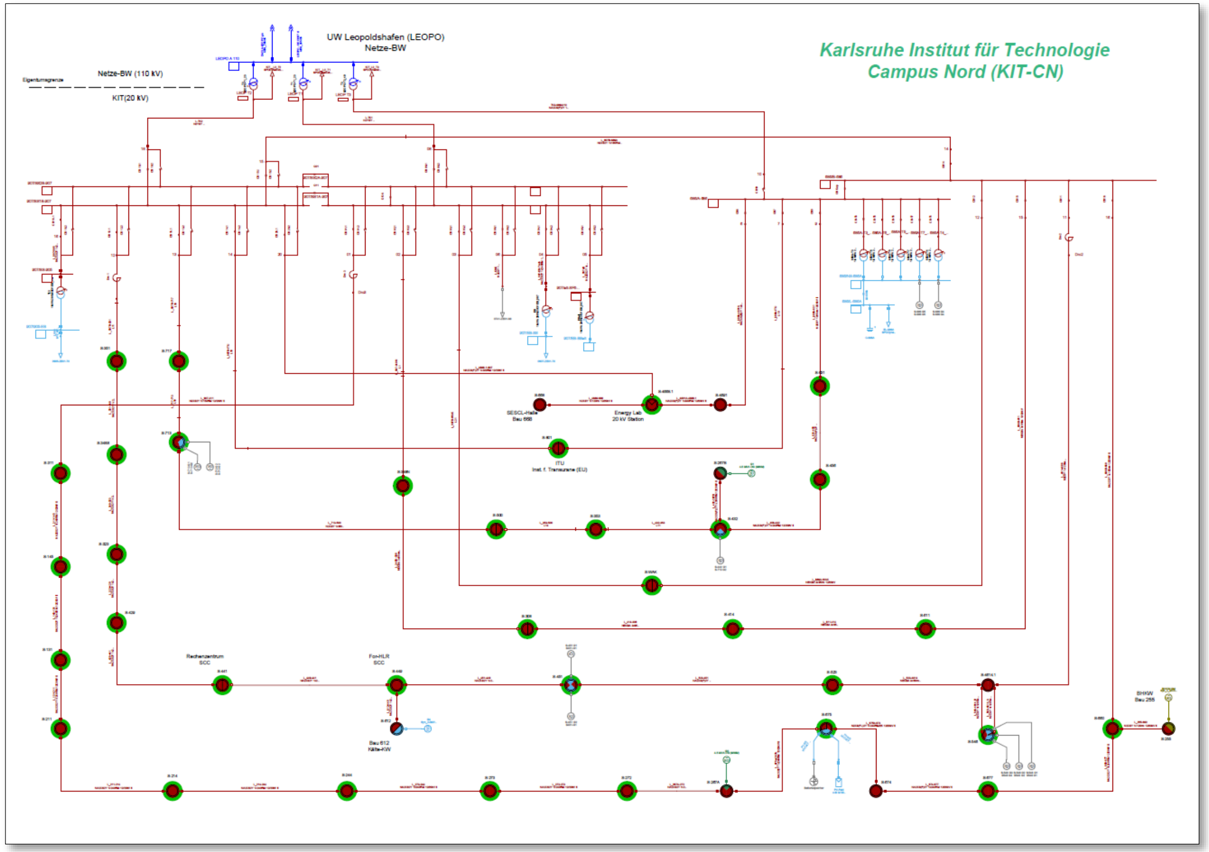
(c) Soft Coupling

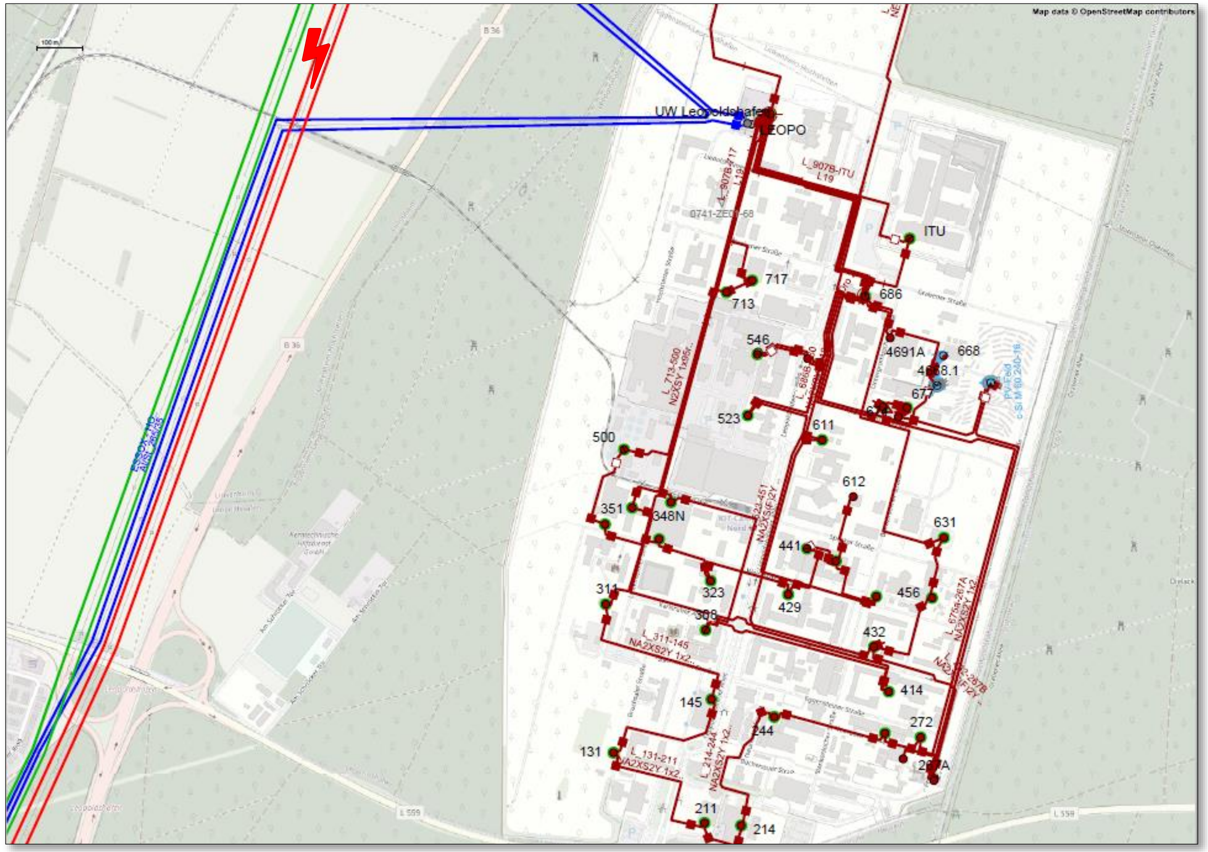


Load-Flow & QDLS

Dynamic Model:
Voltage-layers combined („Re-Bundling“)

- Dyn-Model: ENTSO-E CE + 110-kV (PHILI-DAXL-ALHIM-BRUKA) + KIT-CN (HV/MV/LV)



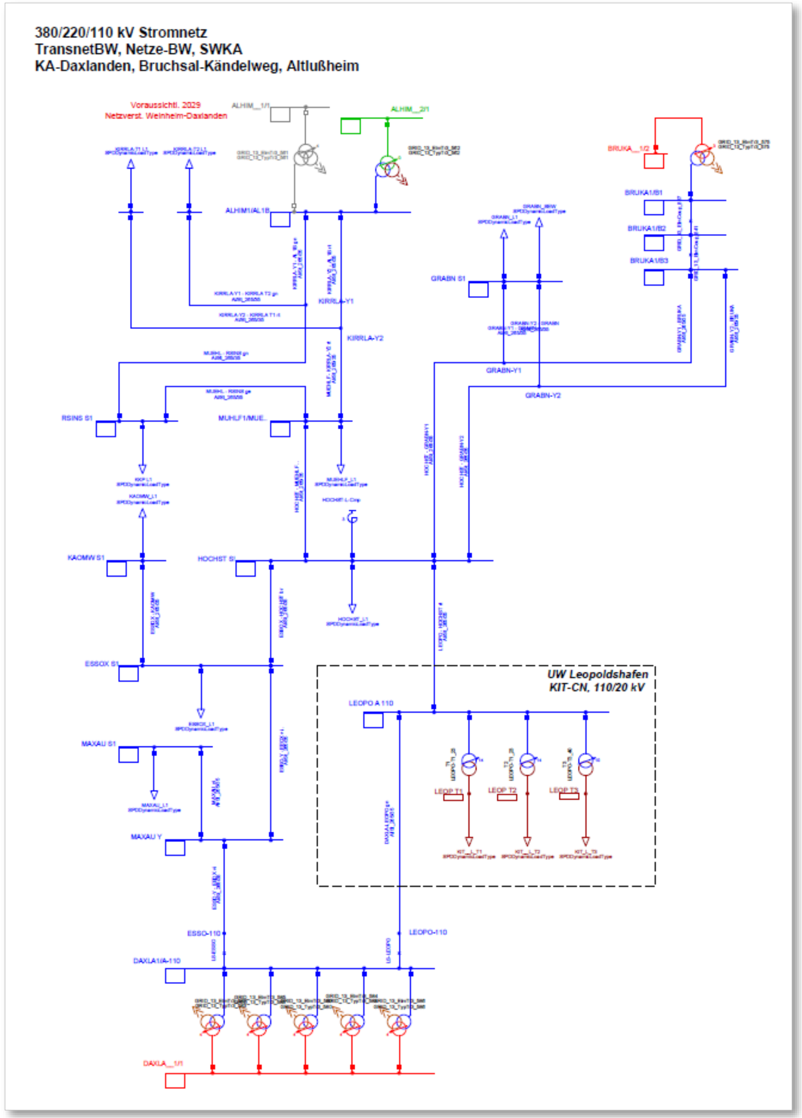


- Grids coupling 110-kV with KIT-CN-grid at HV/MV-transformers at substation UW LEOPO (NetzeBW)
- Replacement of „Ext.-Grid“ in (a) and Load element in (b), connect 20-kV feeders to 110-kV transformers

Dynamic Model:

Voltage-layers combined („Re-Bundling“)

Fig.: 110-kV sub-model, Karlsruhe region with KIT-CN

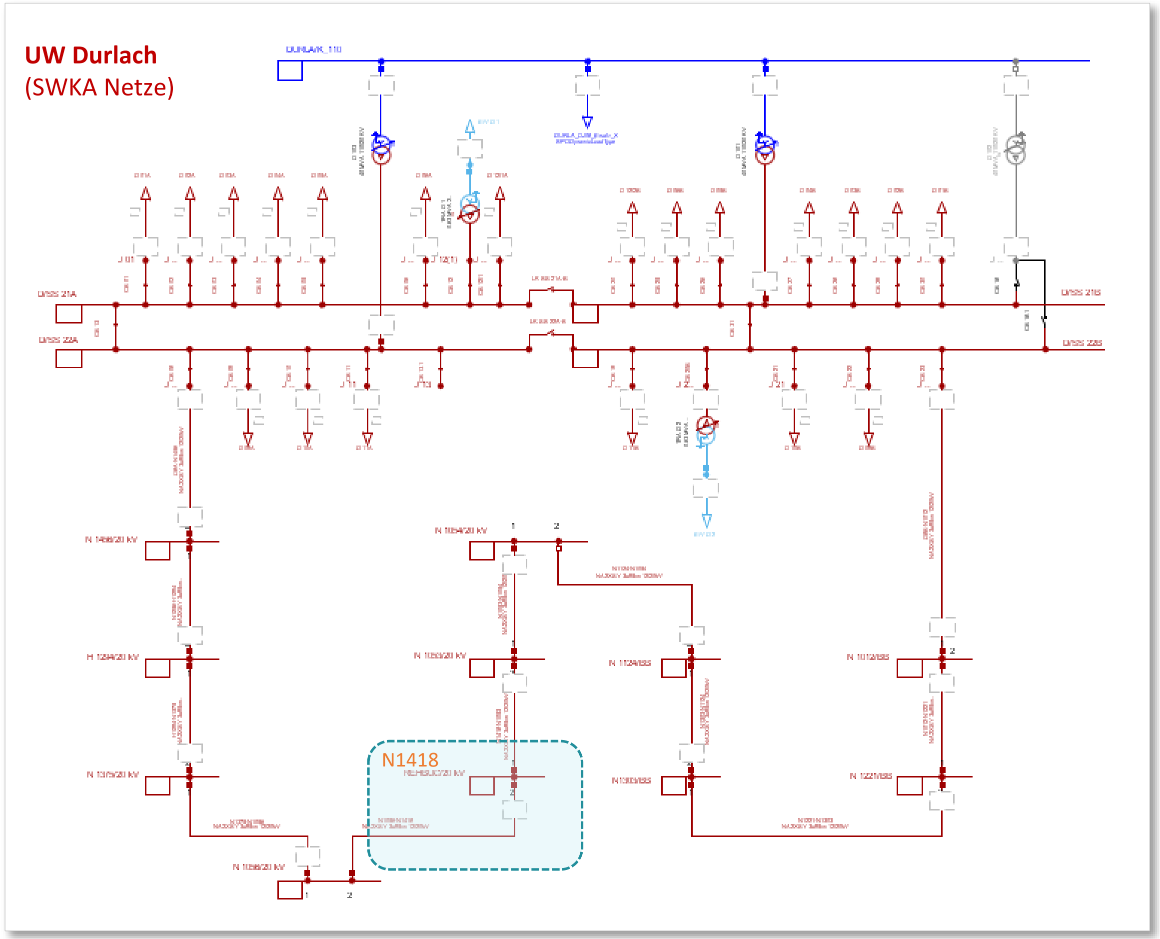


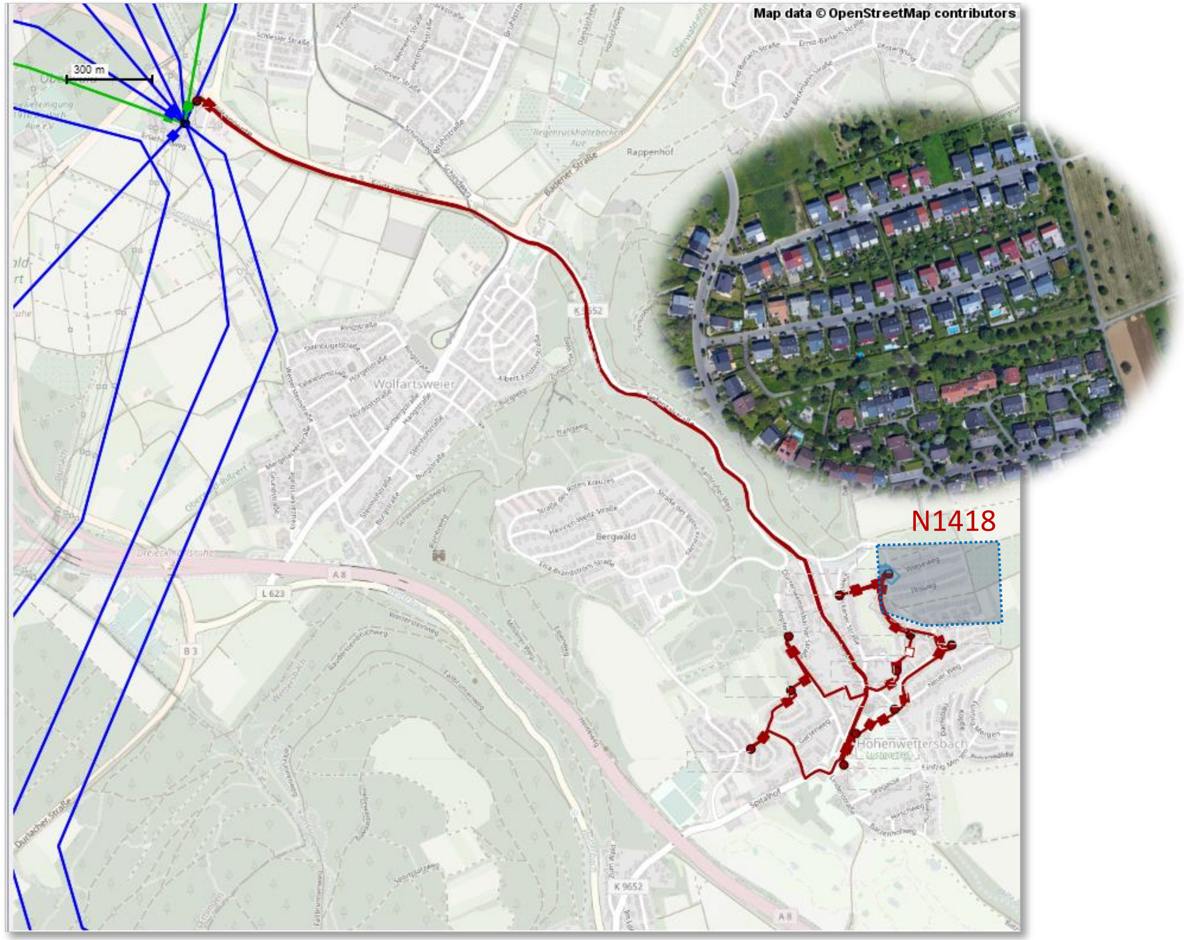
Model Statistics

- 31 Subgrids, **461.722 Elements**
- 10.069 Sites, 21.616 Substations
- 28.118 Buses, 100.571 Switches
- 8.768 Transformers (2W+3W), 19.734 Lines + 2.266 Impedances
- Loads: 12.194 Consumers, 11.343 Constant-Impedance (RE, Converters), 6.179 Constant-Current (RE, HVDC)
- 17.394 SYM-Generators, of them 651 with dyn. Controllers
- 2.048 Reactors/Capacitor Banks (L, C)
- Additionally: STATCOMs, Async.-Machines (KIT-CN)

Dynamic Model “re-bundling”:
Voltage-layers with submodel “Urban-Area”

- Dyn-Modell: ENTSO-E CE (EHV) + 110-kV NetzeBW+SWKA KA (HV)+ 20-kV Cable ring (MV) + Urban grid (LV)

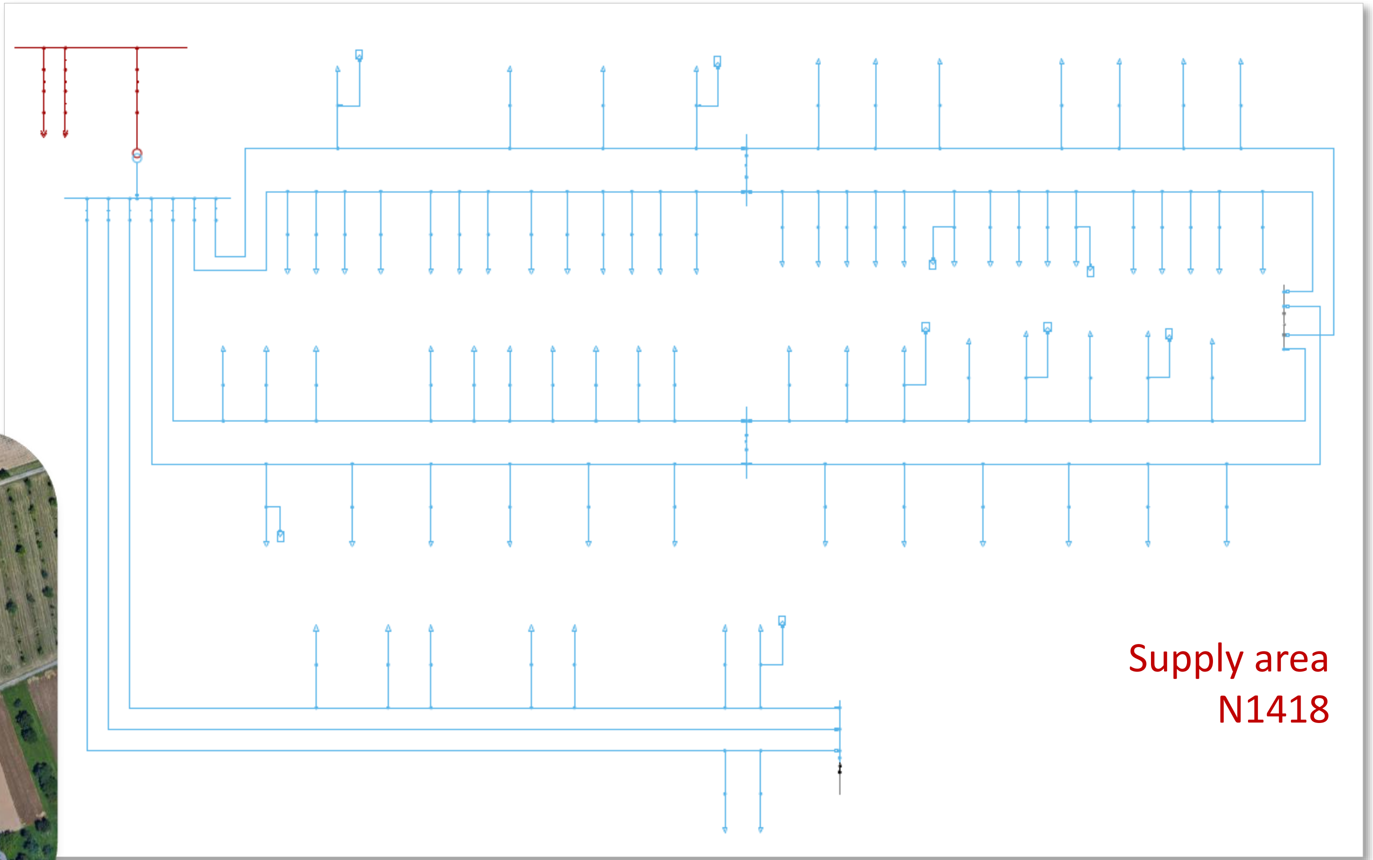




Dynamic Model “re-bundling”:
Voltage-layers with submodel “Urban-Area”

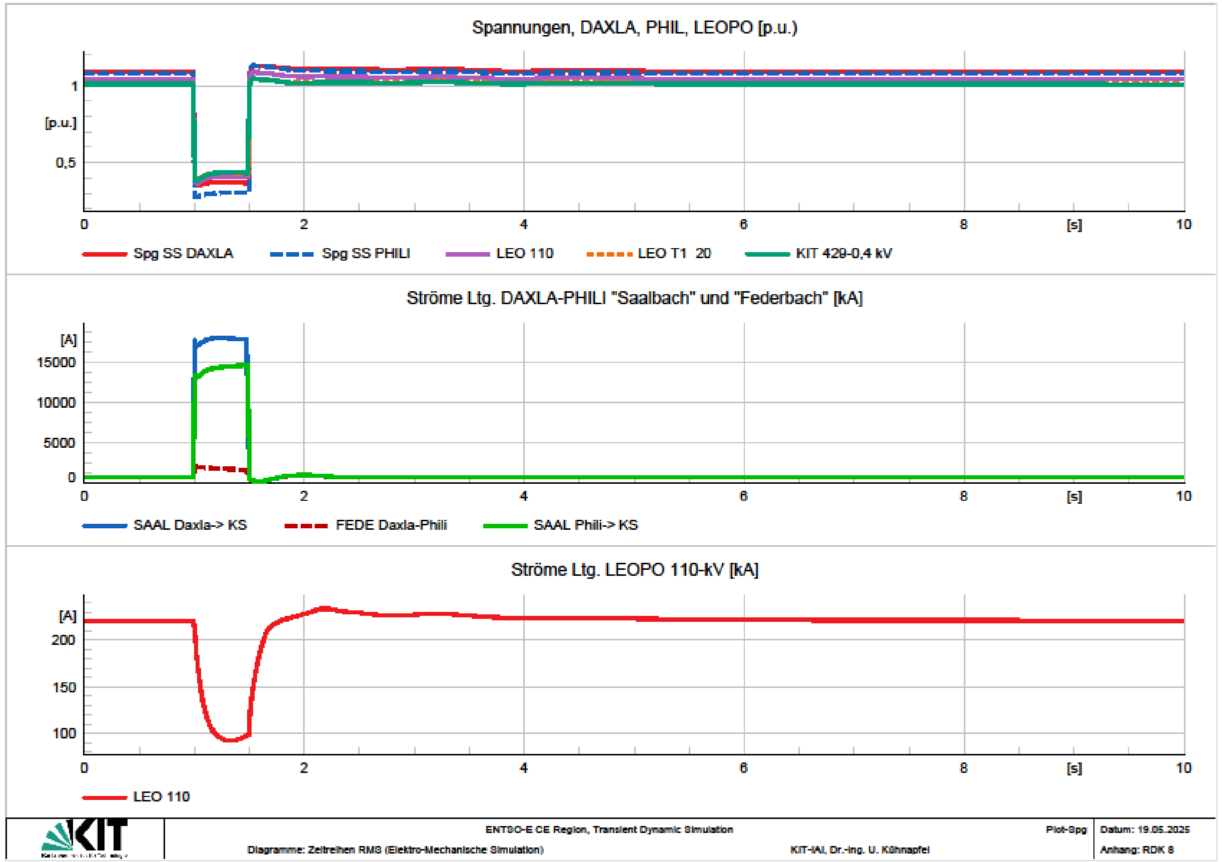
- Dyn-Model: ENTSO-E CE (EHV) + 110-kV NetzeBW+SWKA KA (HV) + 20-kV Cable ring (MV) + Urban grid (LV)

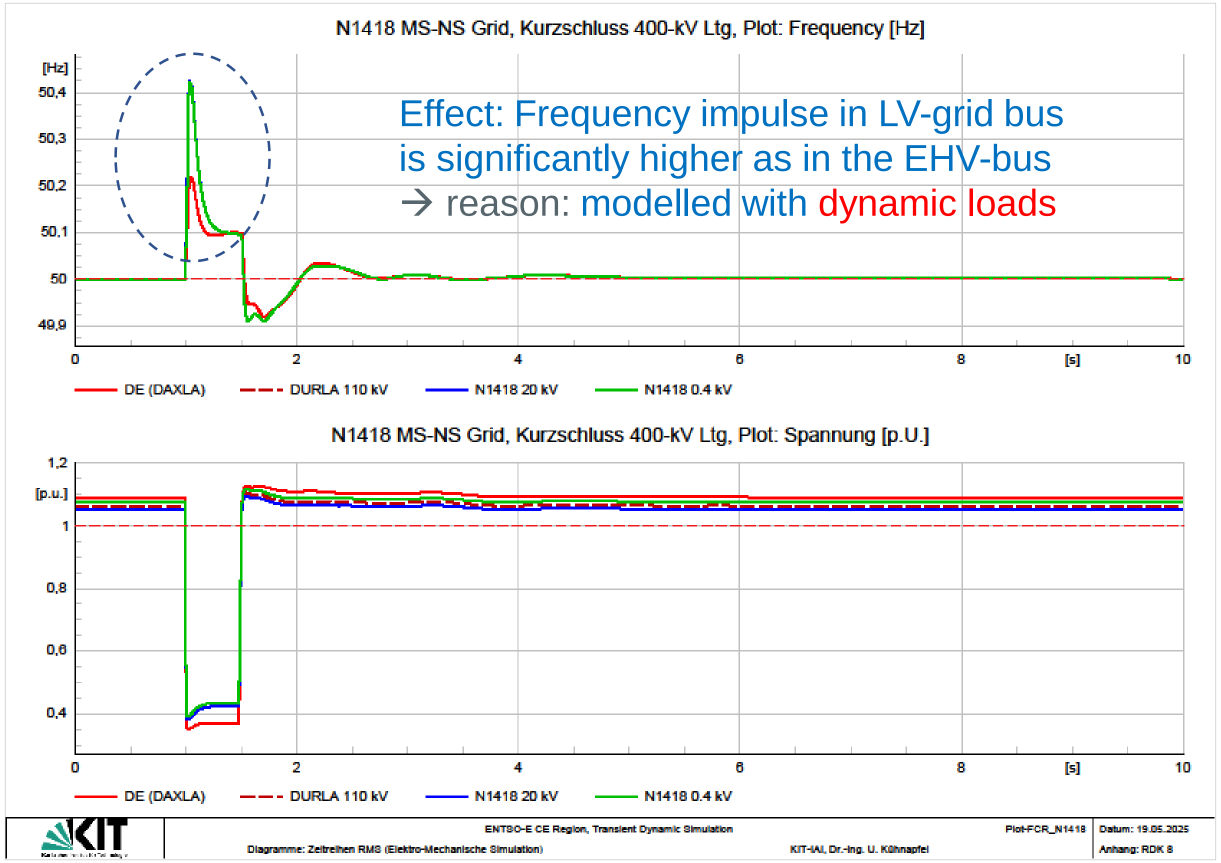
- Urban area with mixed type of housing, 9 PV-units
- Switch cubicles for flexible Grid-Topologies
- 6-week PMU-data from 20-kV substation and from 110-kV station UW Durlach (25 kHz, 7 channels)
- Modelled from grid operator diagram (SWKA-Netze)
  Detailed 20-/0.4 kV transformer data (630 kVA)



Case-Study: ***Short-Circuit Event***
All voltage layers combined

- „Event“: 3p-short-circuit on 380-kV line „*Saalbach*“. Sensors (voltage, frequency, …) across ENTSO-E-CE area

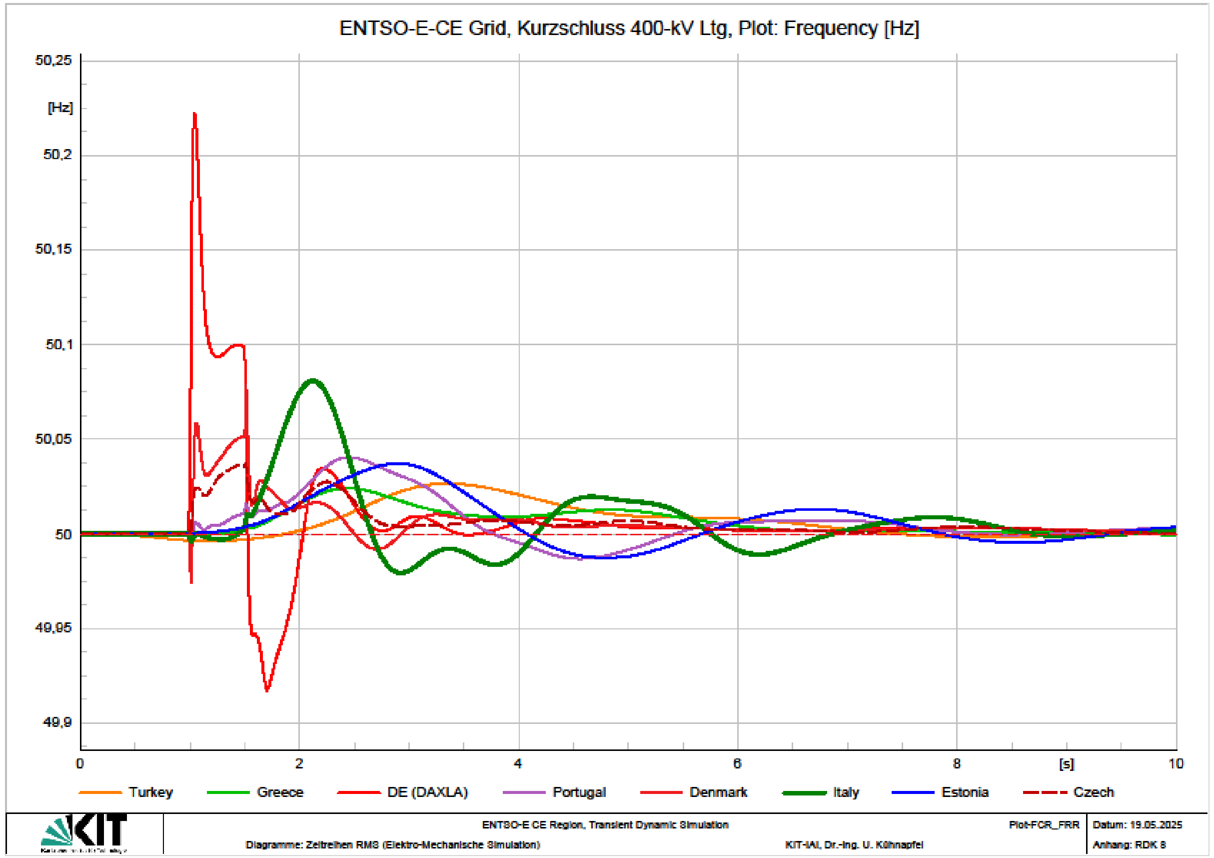


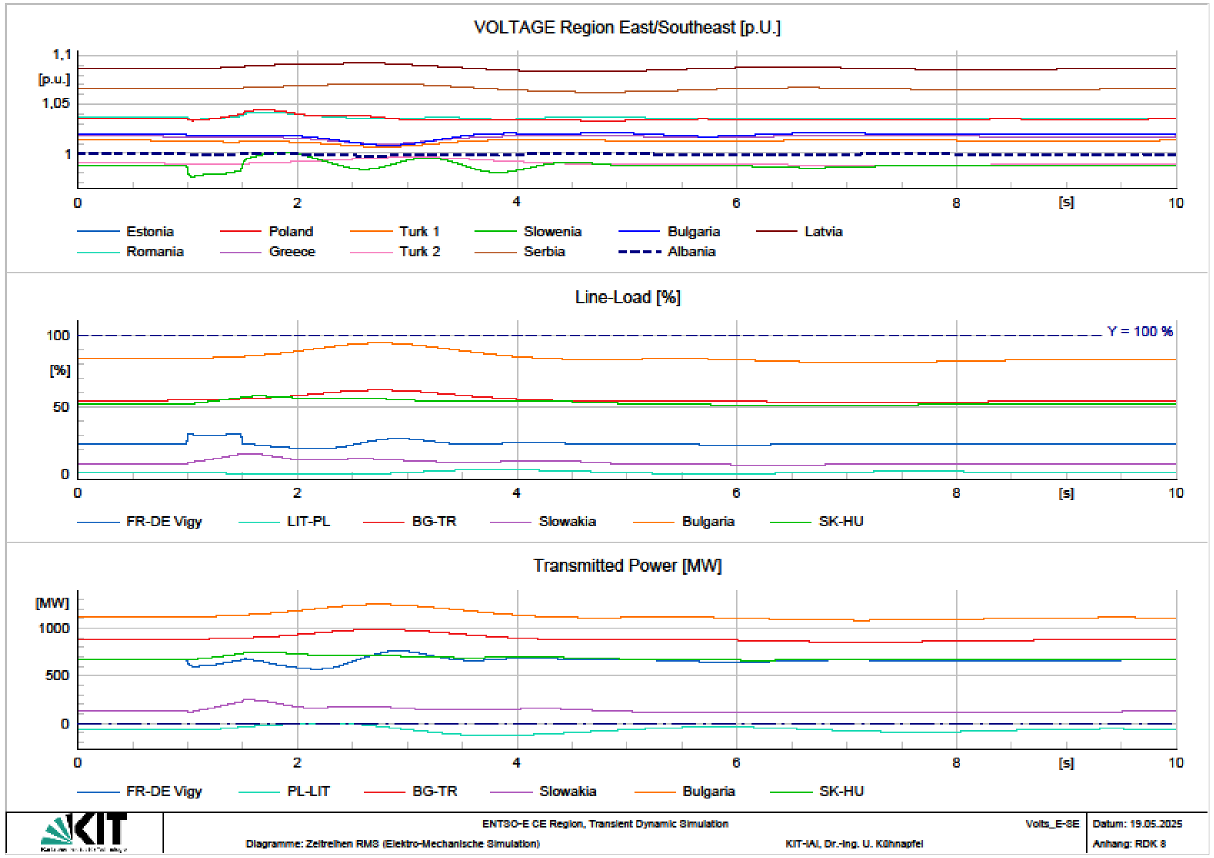


Problem: Frequency spikes in LV due to load-dynamics (mot. / inductive loads)
Question: how „valuable“ are LV frequency-time-series → Transferability to EHV-grid (transmission)
Activity: Academic wide-area frequency-monitoring networks (→ Derived metrics for grid stability)

Case-Study: ***Short-Circuit Event***
All voltage layers combined

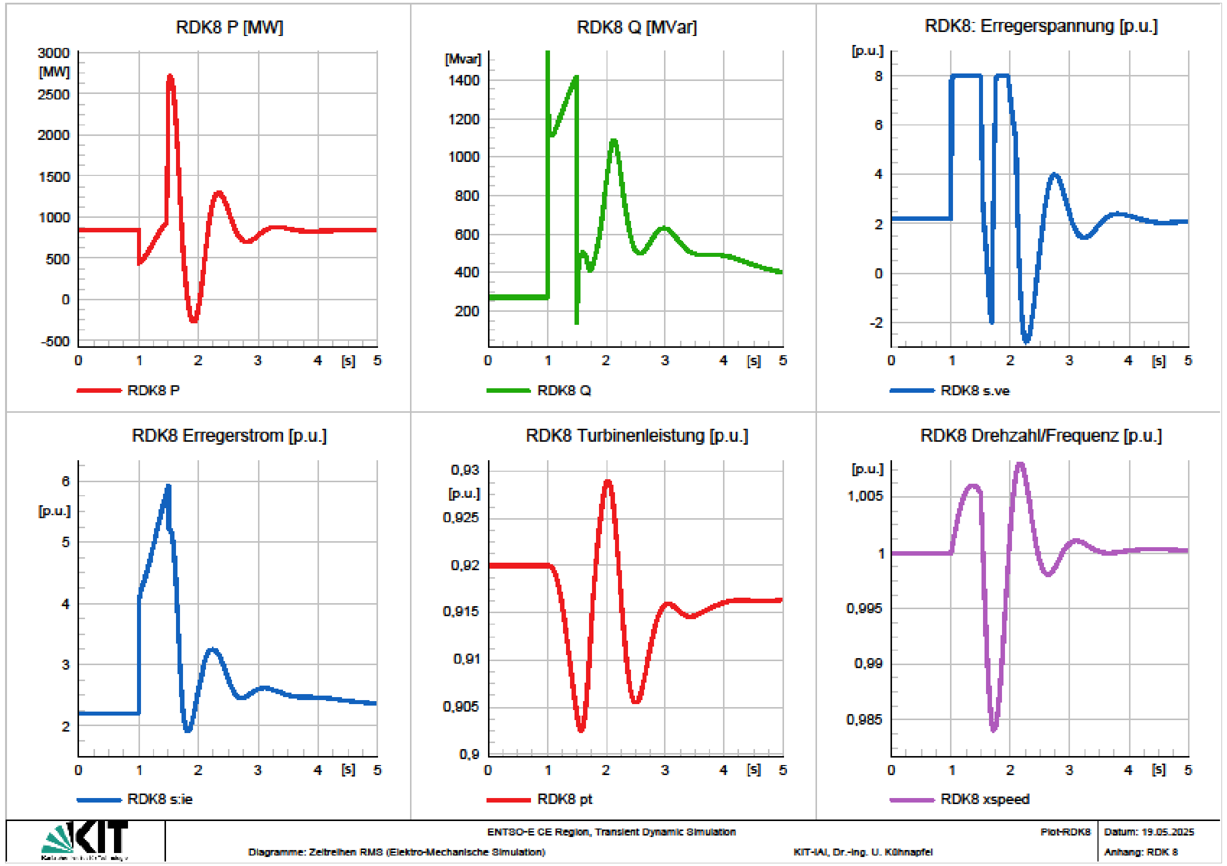
- Frequency, voltage, active power in transmission grid across Europe

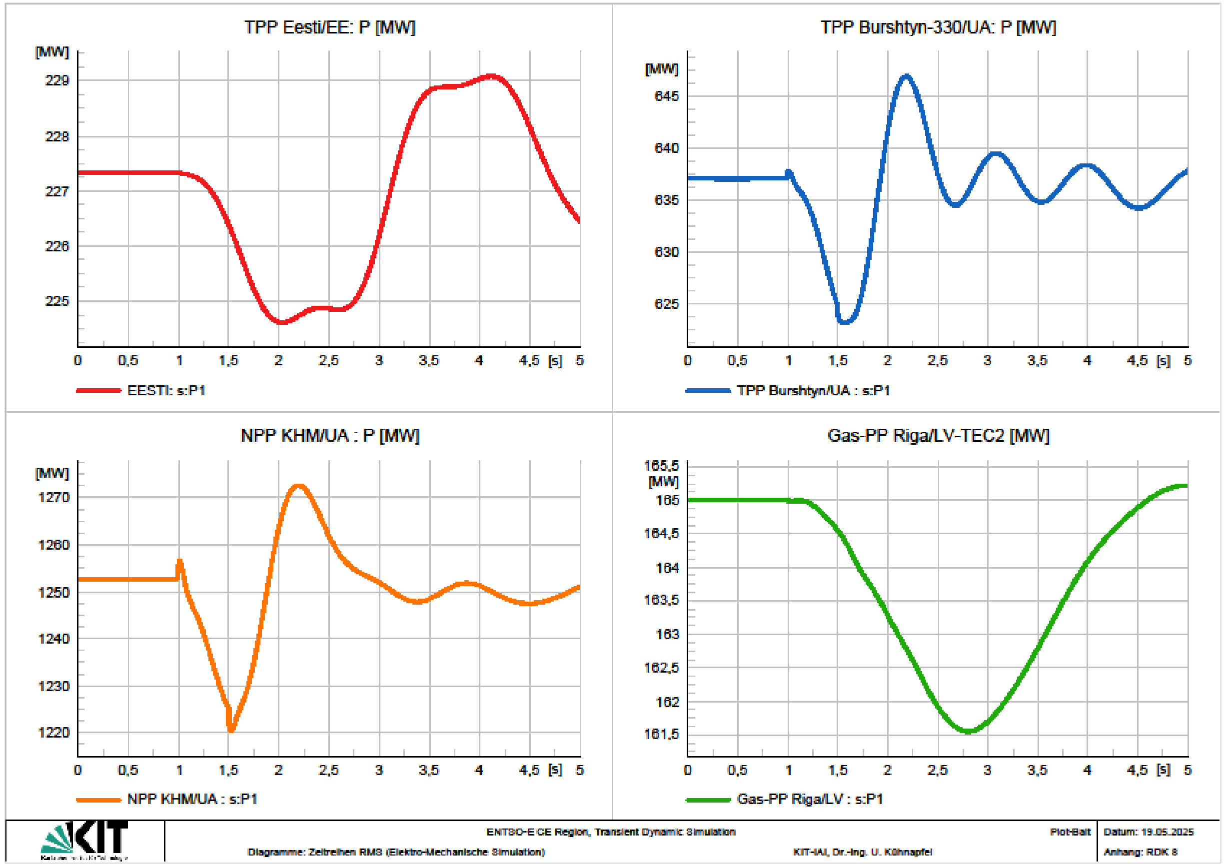




Case-Study: ***Short-Circuit Event***
All voltage layers combined

- Power plants: RDK8 (located close to disturbance), 4 power plants far distant from disturbance





Case-Study: ***Iberian Blackout (28. April 2025)***
Dynamic grid-model, **parameter setup**, simulations

Background: On 28 April 2025 at 12:33 CET, the power systems of Spain and Portugal suffered a total blackout.

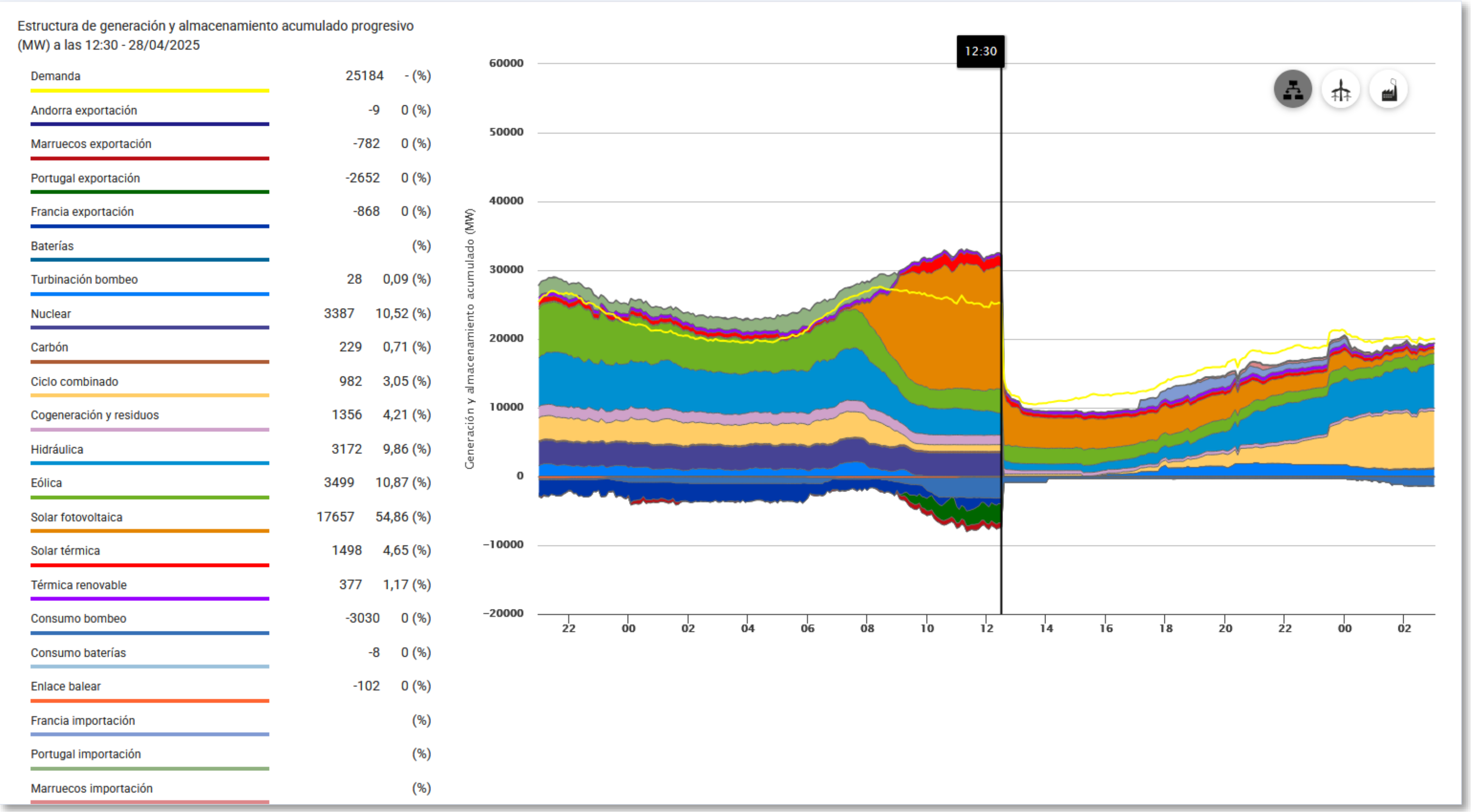
- High media resonance and public interest
- Well covered in “data-communities”
- Our motivation:
  - Evaluation of our dynamic model
  - Develop a “workflow”
  - Derive rules for grid stability (inertia, minimum grid reserves, …)
  - Curiosity and “to have fun”

Known facts

– + 2 GW outage of generation within 17 seconds, starting in areas Granada, Badajoz, Sevilla

– Outage of +20 GW within next 8 seconds

→ complete system-collapse within 25 seconds



Source: TSO REE, Spain (https://demanda.ree.es/visiona/peninsula/demandaau/acumulada/2025-04-28)

Case-Study: ***Iberian Blackout (28. April 2025)***

Dynamic grid-model, **parameter setup**, simulations

POWERTECH KIEL 2025 · IEEE PES Power & Energy Society® · pels IEEE POWER ELECTRONICS SOCIETY Powering a Sustainable Future · IEEE

Workflow

1. Impedances at border-nodes (short circuit calc.), full model
2. Isolation of "area-of-interest" (ES, PT, power Injectors)
3. Setup of
   - Loads (consumption, imports, exports)
   - Generation (per class, per unit if known)
   - Define Events (Switches, Outages, Load ramps)
4. Simulation runs (calc. 75 sec. for real 20 sec. period, ~4:1)
5. Comparison with frequency plots, analysis, model modification

Setup of Power Generation: mapping to specific power plants (units)

Actual Generation per Generation Unit

28/04/2025

SELECT ITEM(S)

Select all · Unselect all · Generation · Consumption

Unit Name	Unit Code	Type	Generation (MW)	Consumption (MW)
SOTO 5	18WSRI5-12345--5	Fossil Gas	86.00 (VARY)	
CAMPGIB2	18WCAMGI20-12-CC	Fossil Gas	168.00 (VARY)	
CASTEJON 1	18WCTJON1-123-CJ	Fossil Gas	0.00 (VARY)	
VANDELLOS	18WVAN2-12345-BA	Nuclear	1043.60 (VARY)	
ECT3TG2	18WECT3TG2-123-Q	Fossil Gas	0.00 (VARY)	
ALG3TG2	18WALG3TG2-123-2	Fossil Gas	134.80 (VARY)	
BES5 TG2	18WBES5TG2-123-W	Fossil Gas	0.00	
ASCO 2	18WASC2-12345-B3	Nuclear	1004.00 (VARY)	
VLLRINO 6B	18WVRN6B-12345-Z	Hydro Pumped Storage		0.00 (VARY)
ARC3TG2	18WARC3TG2-12-CY	Fossil Gas	0.00	

37/182 TO 46/182

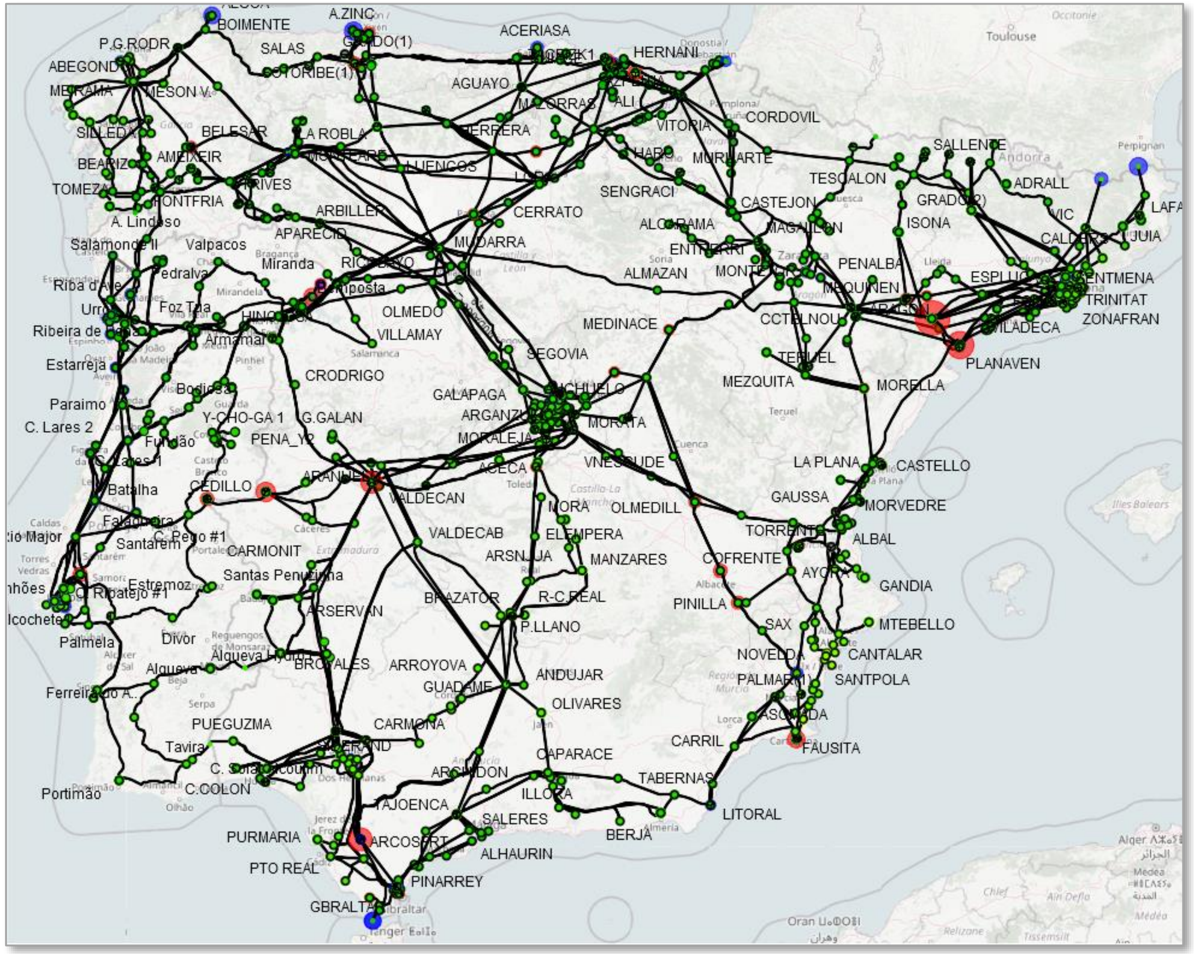
Source: ENTSO-E Transparency Platform (here: Generation per unit, market area Spain (https://newtransparency.entsoe.eu/generation/actual/perUnit?appState={...}), 1-hour data

Case-Study: ***Iberian Blackout (28. April 2025)***

Dynamic grid-model, **parameter setup**, simulations

Basic Dyn-Model „Iberian Blackout“

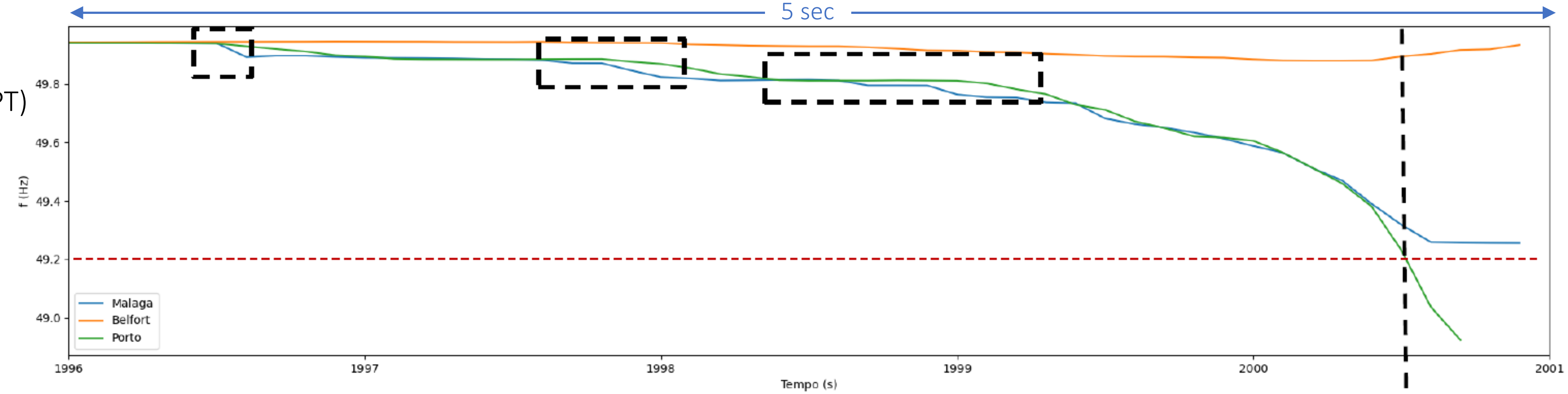
Dyn-Model with calculated Load-Flow (well balanced)



Case-Study: ***Iberian Blackout (28. April 2025)***

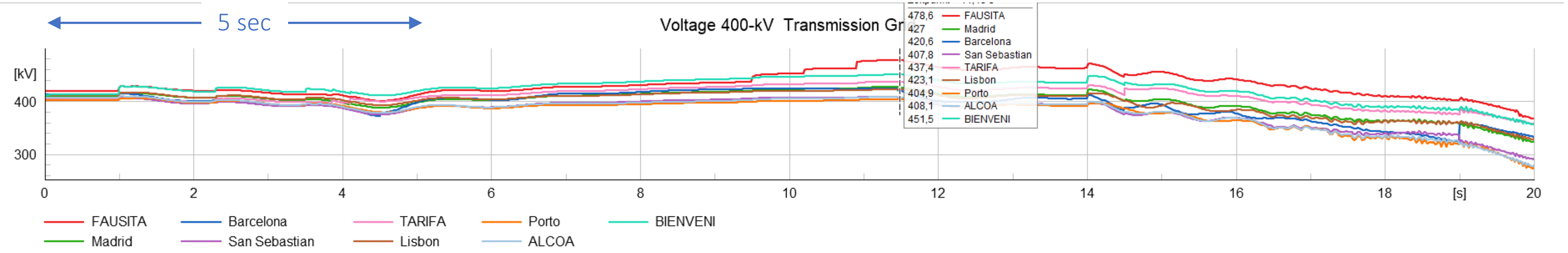
Dynamic grid-model, parameter setup, **simulations**

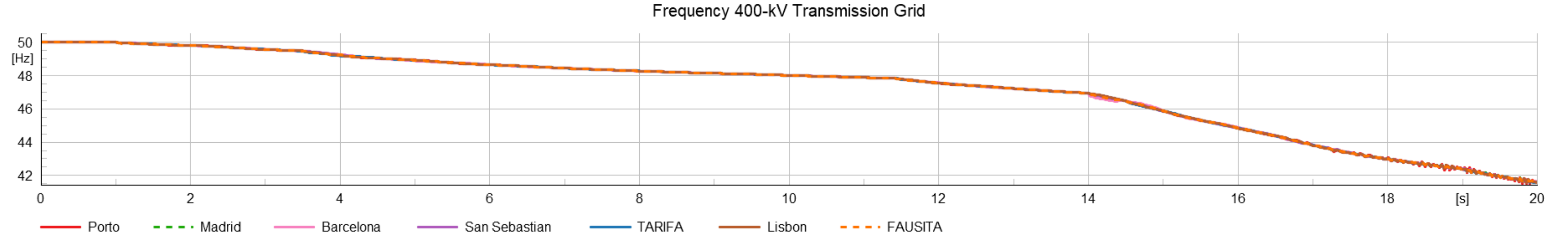
Frequency data (PMU)
(Prof. Joao Pecas Lopes, PT)



Dados sem significado

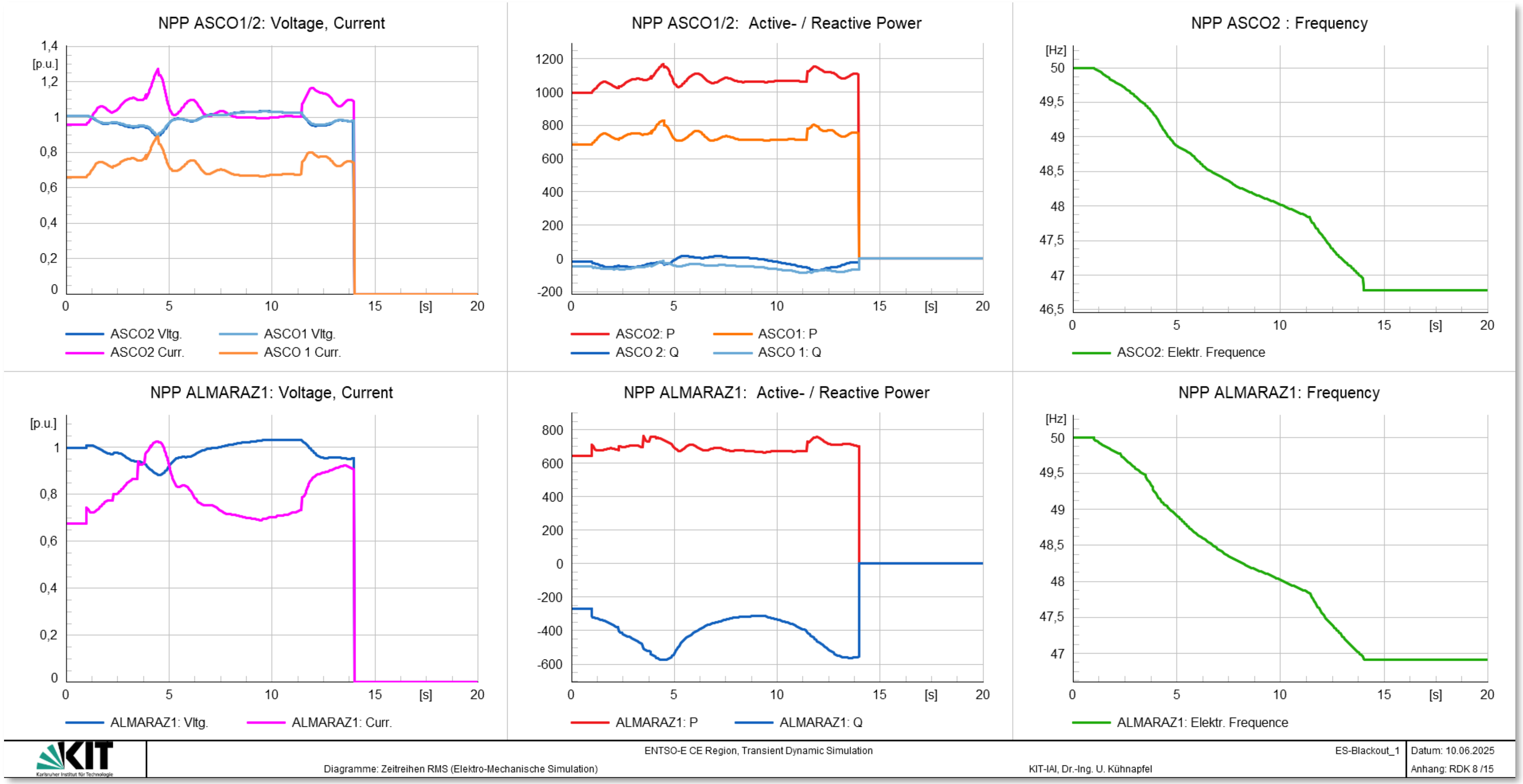
Simulation Results (PF)
(Uwe Kühnapfel, KIT-IAI)





Case-Study: *Iberian Blackout (28. April 2025)*
Dynamic grid-model, parameter setup, **simulations**

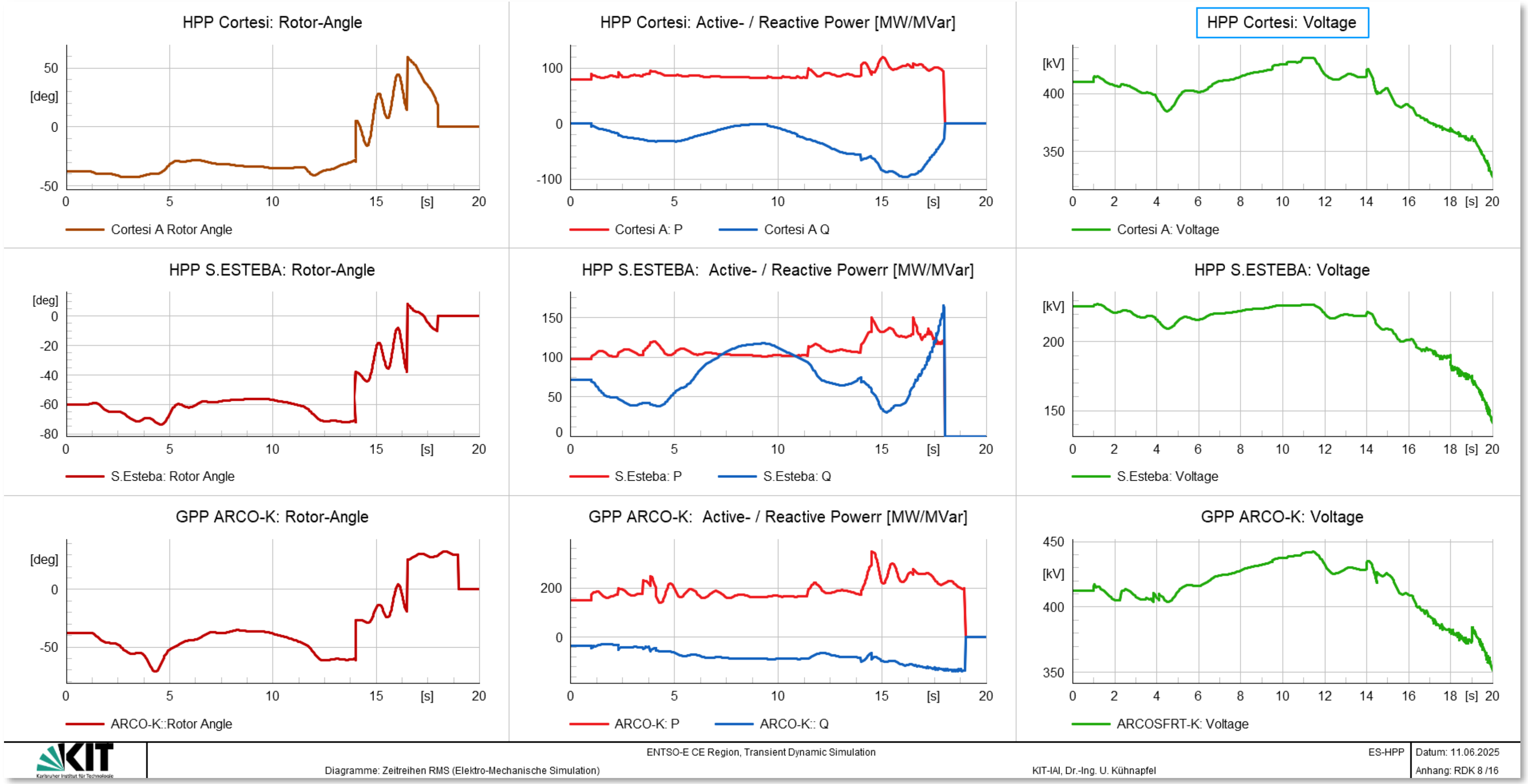
Simulation results: Nuclear Power Plants ASCO 1/2, ALMARAZ, emergency shutoff at t = x + 13 sec.



Case-Study: ***Iberian Blackout (28. April 2025)***

Dynamic grid-model, parameter setup, **simulations**

Simulation results: Gas PP and Hydro PPs, shutoff at t = x + 17 sec. due to voltage collapse

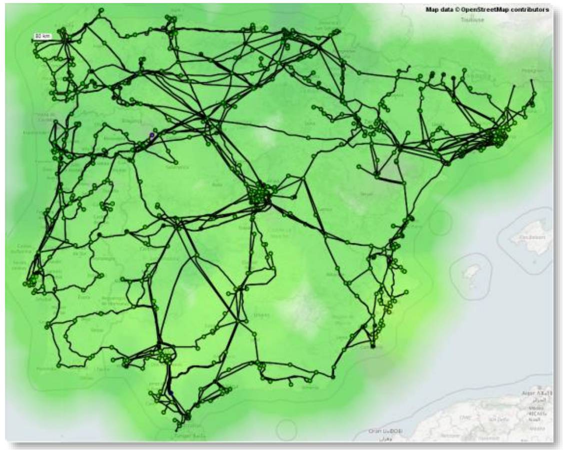


Case-Study: ***Iberian Blackout (28. April 2025)***

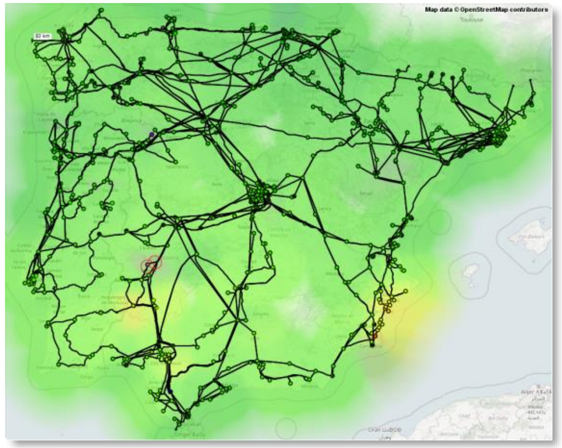
Dynamic grid-model, parameter setup, **simulations**

Voltage-Stability

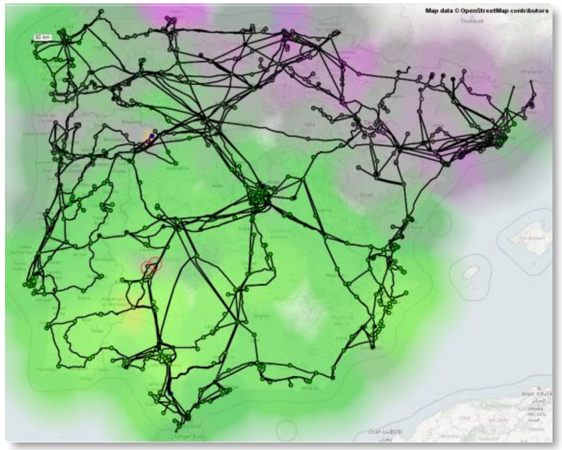
t = 0,5 s (before initial event)



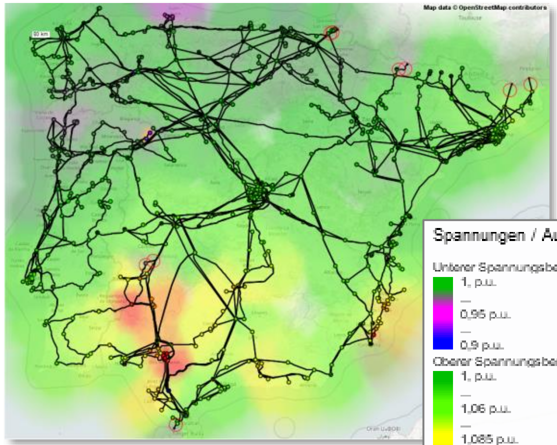
t = 1,25 s



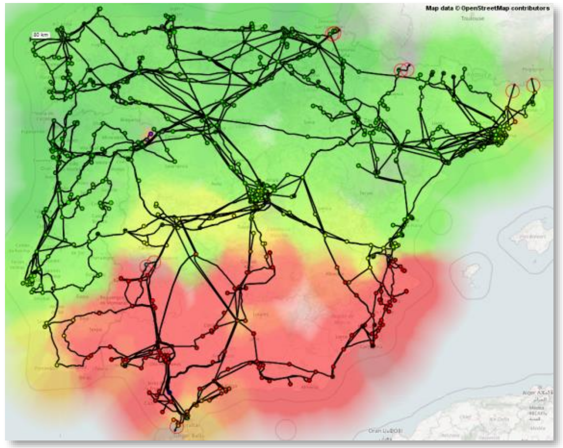
t = 3,5 s



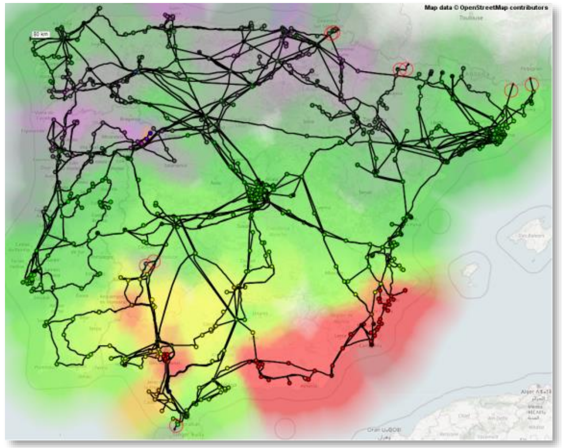
t = 8,0 s



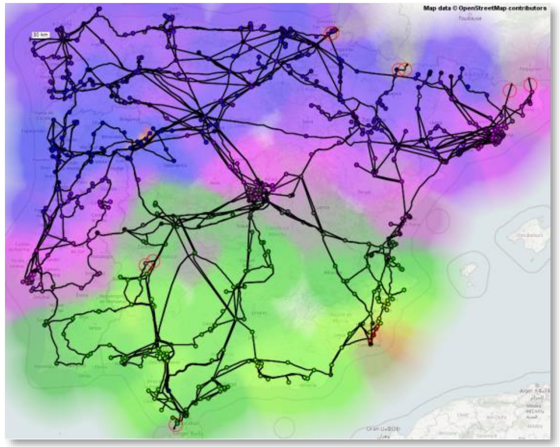
t = 11,4 s



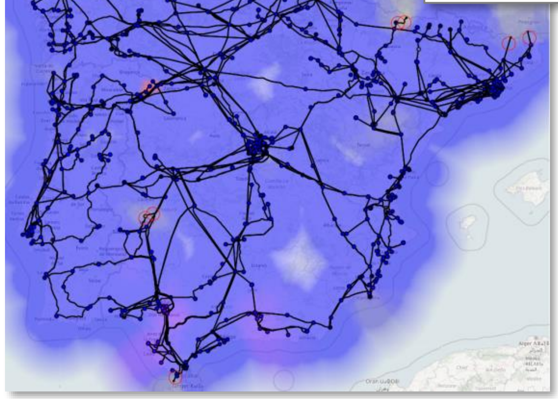
t = 13,9 s



t = 16,0 s



t = 20,0 s (system collapsed)



Summary and Conclusion

- RMS-Dynamical Simulation works in PF even for very large models („Hurra !“)
- Long calculation durations → **model reduction (sub-grids)** for “area-of-interest”
  - Requires **adaption of border nodes (injectors)**
  - **Short-circuit power and impedances for horizontal border grids required**
- Implementation on real-time environment → **requires drastic grid reductions (see Ilya)**

Next Step(s)

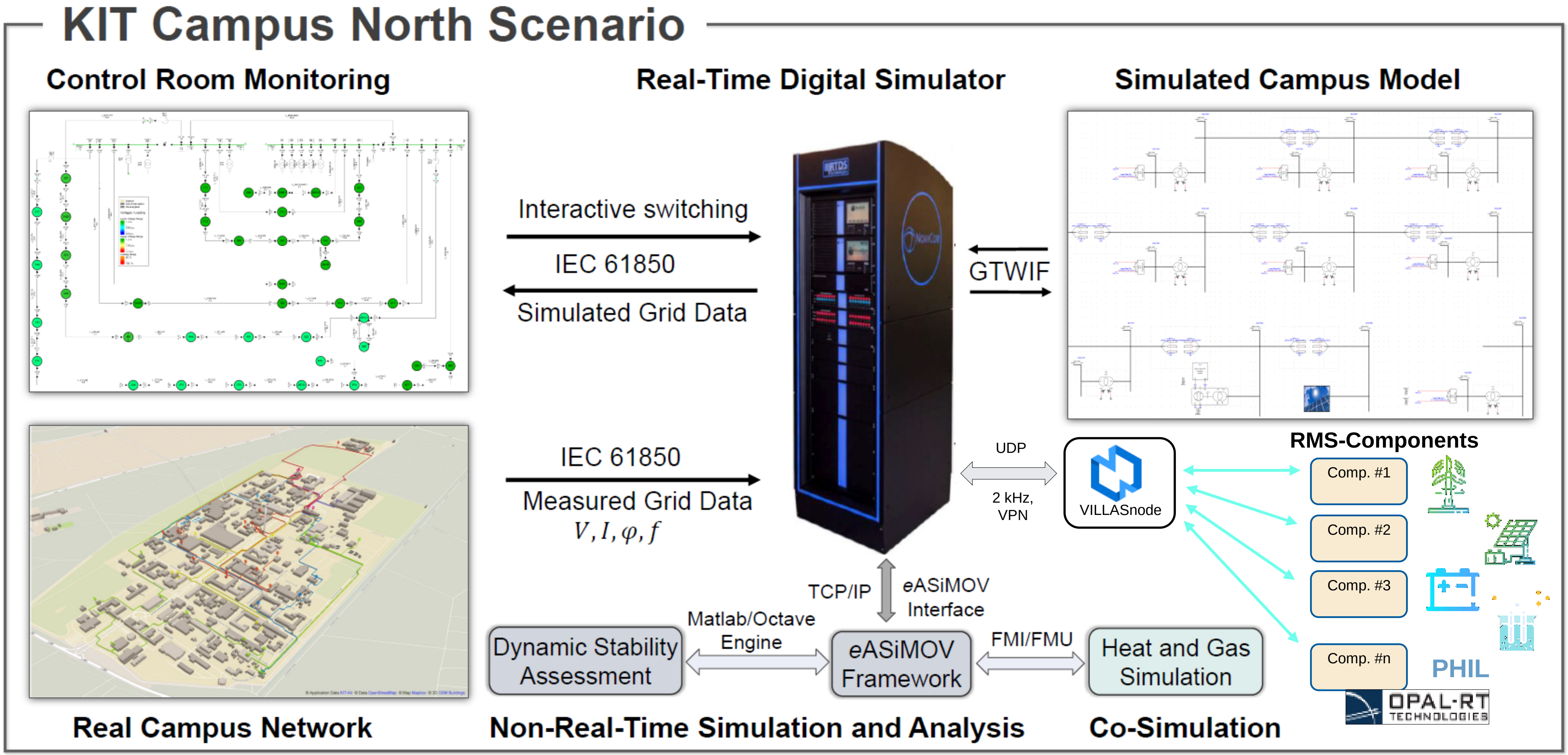
- Further analysis in ES/PT-Blackout study model 28.4.2025, to keep in-line with upcoming new info
- Inter-area oscillations
- Stability studies regarding reserve power (P, Q) and inertia (→ **quantification)**

Thank you, Vielen Dank.

Dr.-Ing. **Uwe G. Kühnapfel**
Institute for Automation and Applied Informatics (IAI)

New Slide

Realtime-Simulation Concept (RMT / EMT)



Baden-Württemberg – AC/DC TG + 110-kV layer „re-bundling“

Model architecture, style:

- Replacement of thermal stations (nuclear, hard coal) 2019 - 2035, to replace: ~ 8 GW
- Max. load in BW today: ~11 GW
- High portion of PV (PPVmax: 7,9 GW)
- Stabilization by 2 HVDC-links, 2x2 GW (ULTRANET, SuedLink A) (2026)
- Modelled to level 4 (HV/MV transf.)

Goals for grid operation

- Security of power supply
- Low rate of Re-Dispatch (PV, Wind)

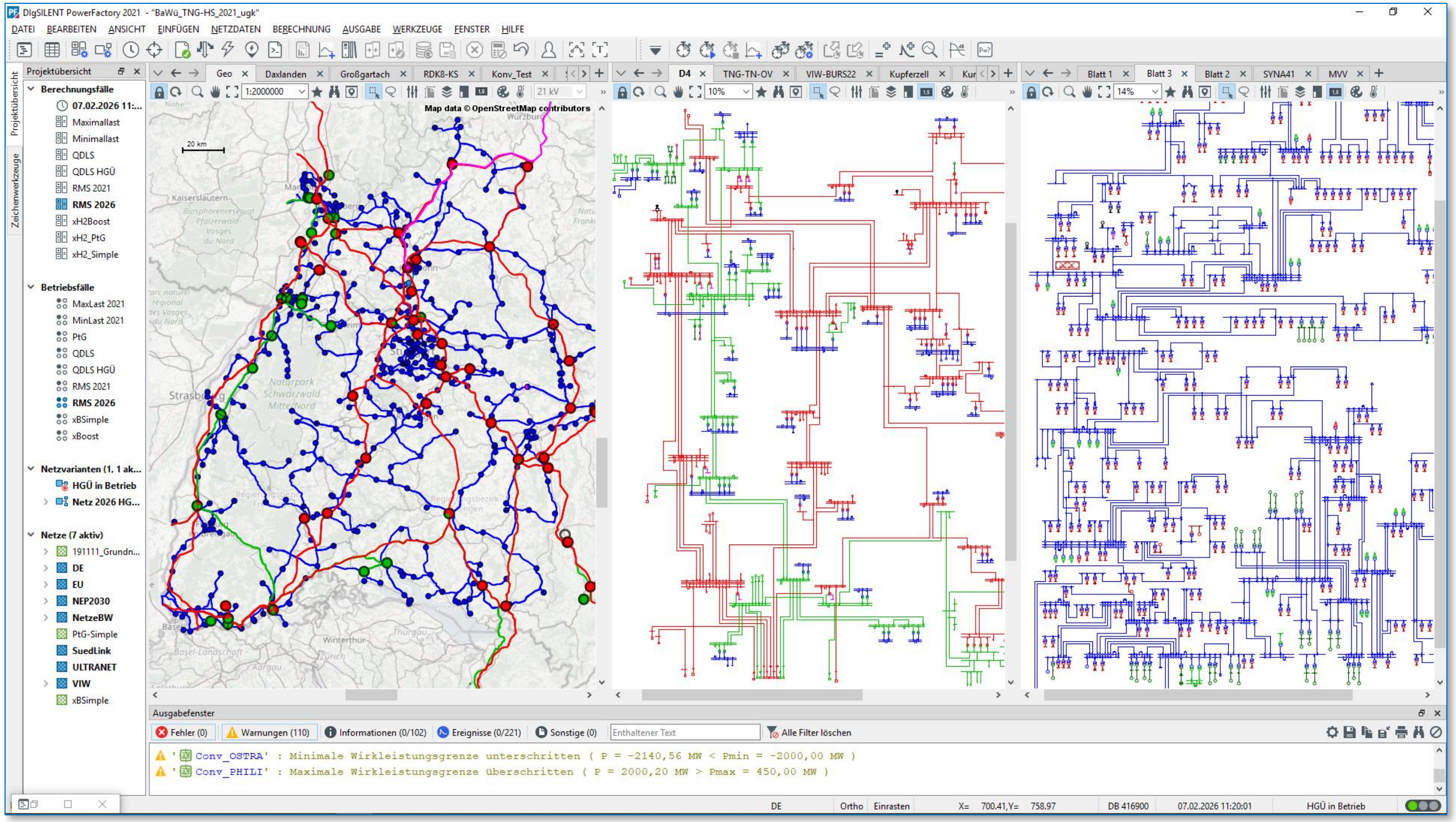


Fig: *PowerFactory*-model Baden-Württemberg (Transmission grid +110 kV layers), Variants: 2022, 2026+. (a) geographic, (b) circuit diagram (Kühnapfel, KIT-IAI)