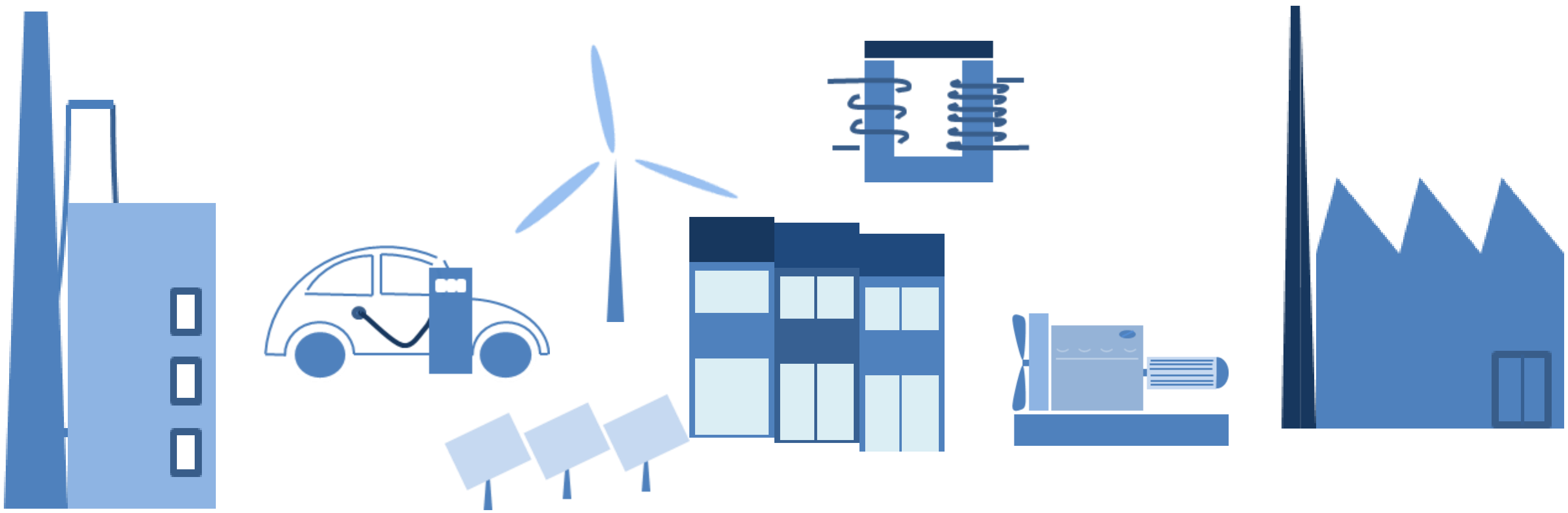
Energy Informatics in Energy Lab 2.0 – A Research Platform for the Energy Transition

Prof. Dr. Veit Hagenmeyer

Institute for Automation and Applied Informatics (IAI)



Energy Lab 2.0

- Large-scale research infrastructure to investigate future energy systems based on renewable energies
- Embedded in Helmholtz Research programs „Renewable Energies“, „Energy efficient materials“ and „Storage and cross-linked Infrastructure“
- Combines experiments with multi-scale simulation and big data
- Investment from 2015-2019: 25 Mio. €* no manpower
- Funding: Helmholtz Association, BMBF, State of Baden-Württemberg

Scientific Questions

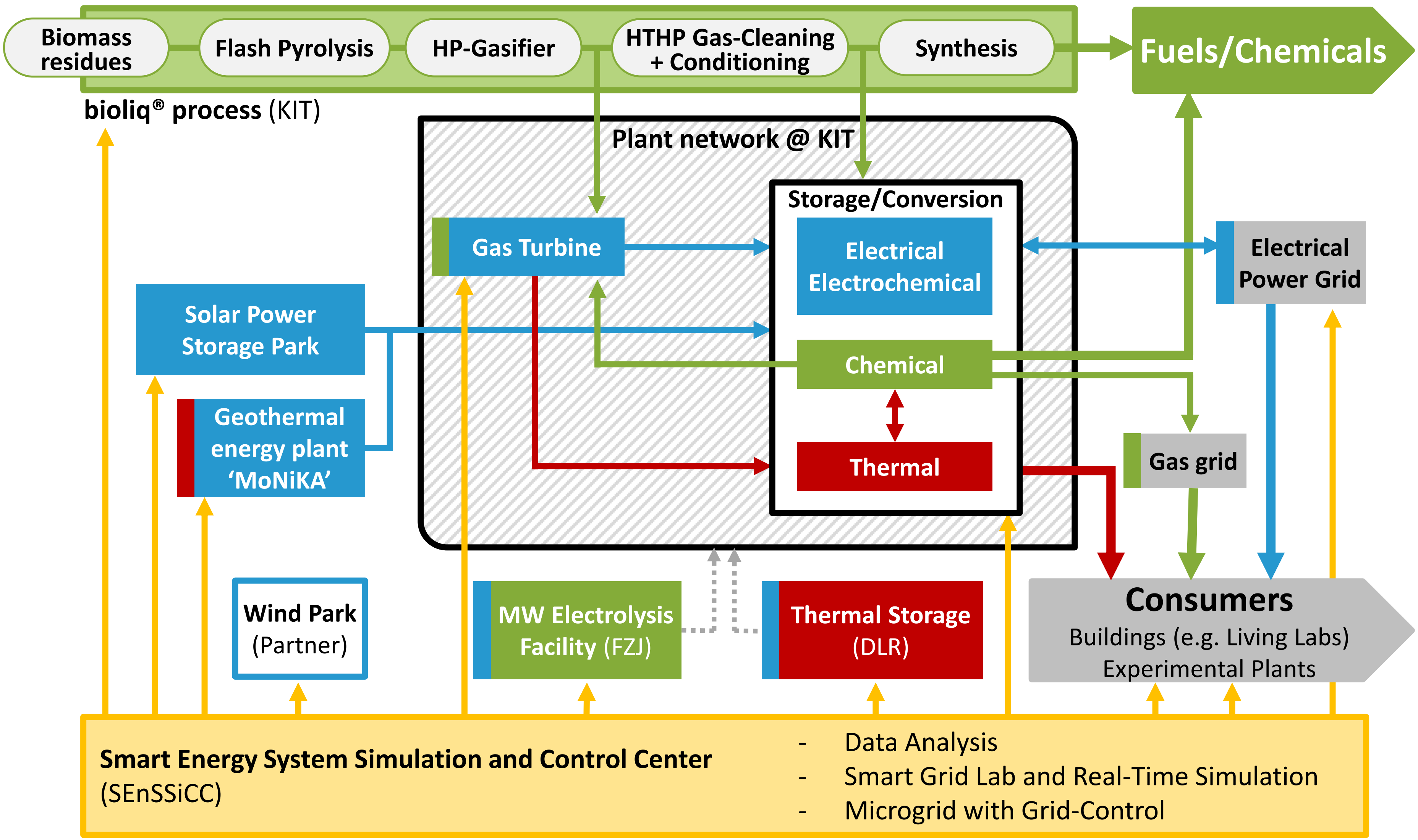
- How can we compensate the role of decreasing availability of rotating masses ("spinning reserve") by **energy system services** based on decentralized components?
- How can we achieve this by establishing a parallel **energy information network**? What kind of information grid is necessary for this task?
- What are the appropriate **grid topologies** for a scenario of mainly decentralized power generation from renewable sources?
- How can we discover and effectively exploit **load flexibility** in integrated decentralized energy networks? (power - gas - heat - ...)

Accompanying Projects

- HGF large investment “Living Lab Energy Campus (LLEC)” Development of an integrated infrastructure for the investigation of future sustainable local energy systems based on decentralised and renewable energies at FZ Jülich and KIT Campus North
- HGF Initiative Energy System 2050 (ES2050) Research topic “Toolbox with Databases”
- HGF-Impuls- und Vernetzungsfonds Energy System Integration
- BMBF Project “Neue EnergieNetzStrukturen für die Energiewende” (Kopernikus ENSURE)
- BMBF Project “Energy system integration & sector coupling using the research infrastructures Energy Lab 2.0 and Living Lab Energy Campus as examples (SEKO)”
- BMWi Project SINTEG c/cells

Energy Lab 2.0 – Components in Interaction

Karlsruhe Institute of Technology

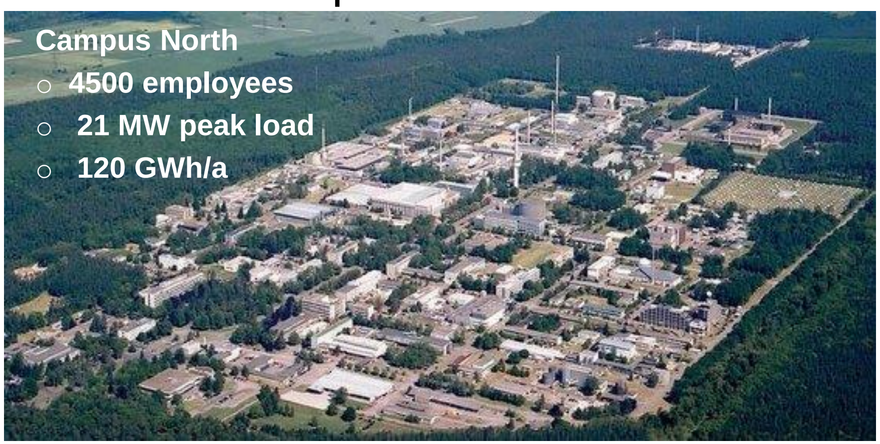


Existing Infrastructure

Bioliq Plant

1 MVA Photovoltaic Experimental Field

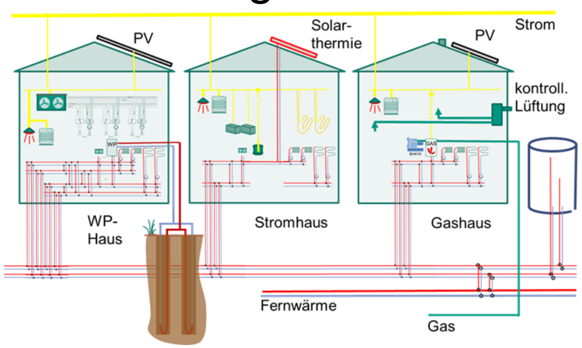
KIT as prosumer



Energy Smart Home Laboratory

Infrastructure under Construction

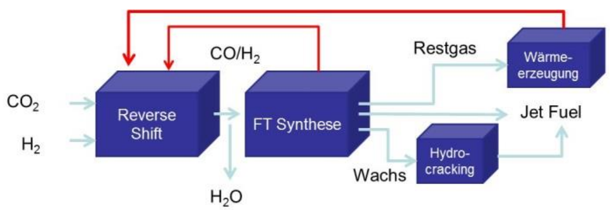
Living Labs



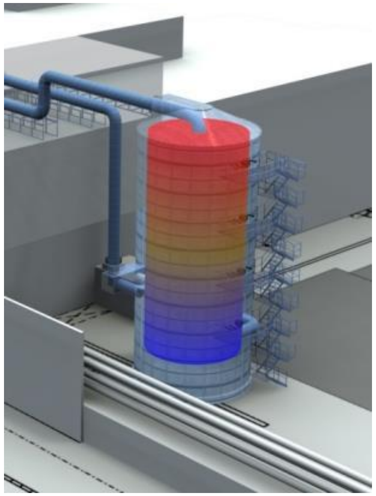
1,5 MWh Battery Storage

Quelle: Younicos

Jet Fuel Synthesis

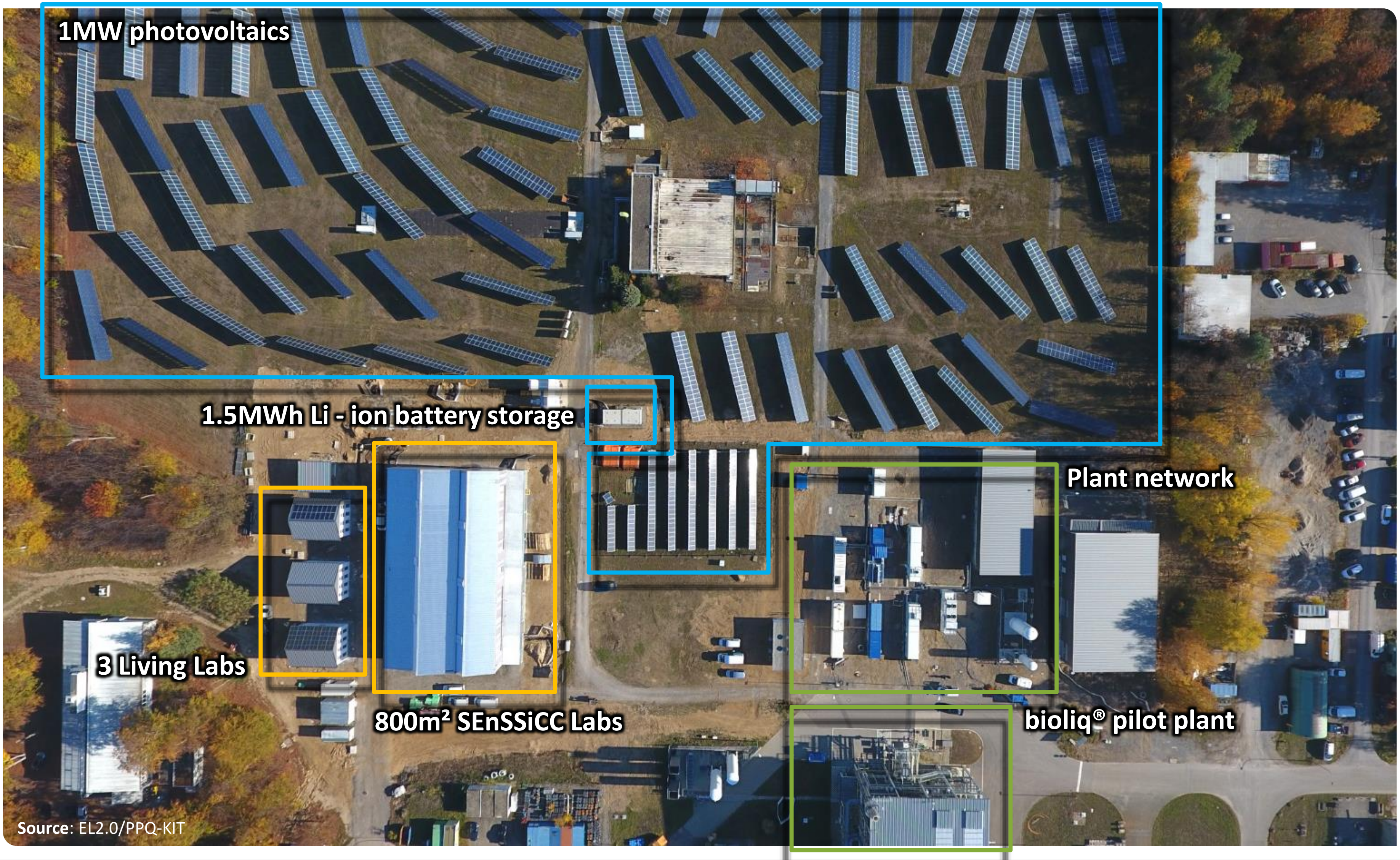


Thermal Energy Storage

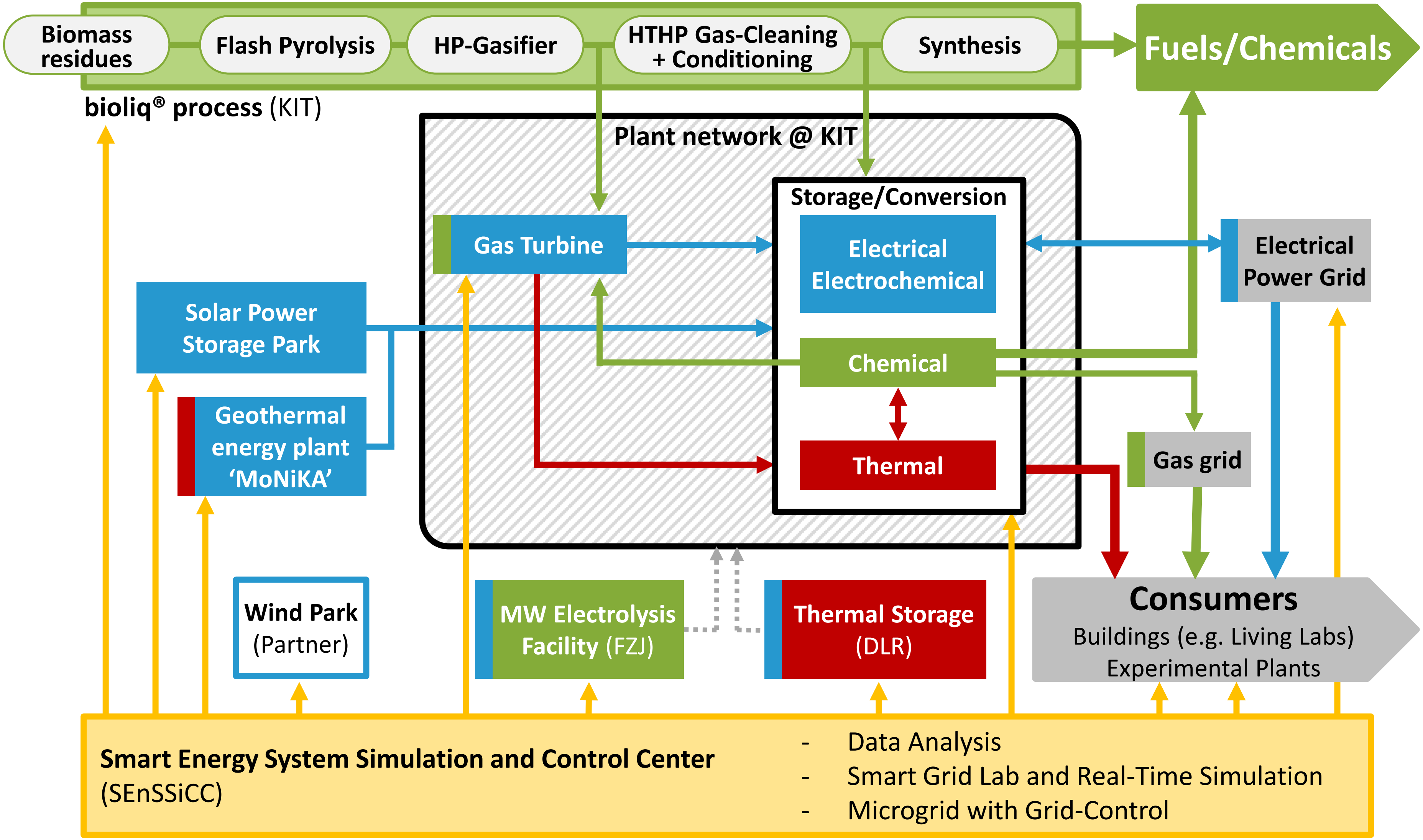


Location at KIT

Location at KIT

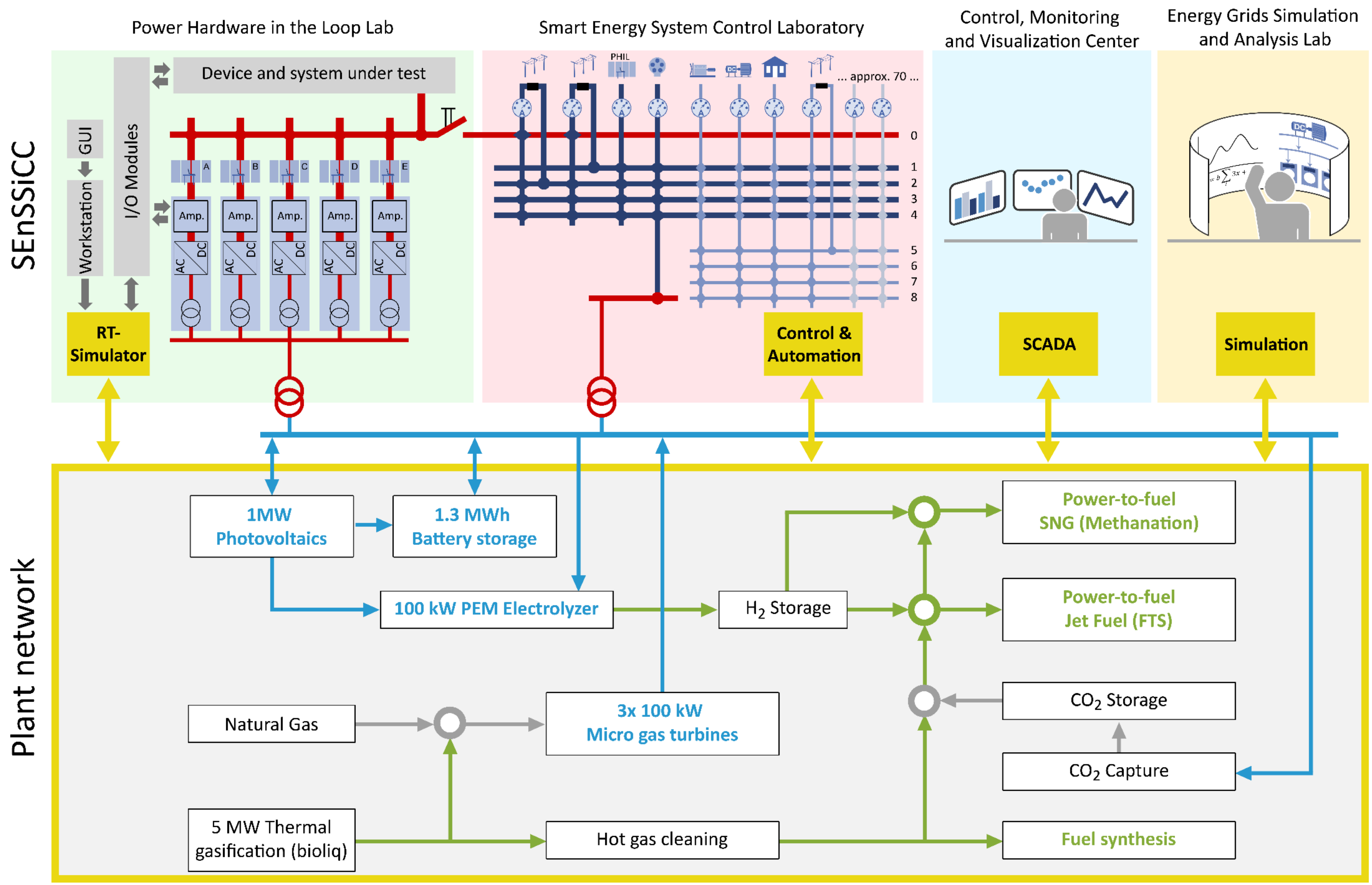


Energy Lab 2.0 – Components in Interaction



Energy Lab 2.0

Schematic set-up



Source: Pic courtesy of EL2.0/IAI/KIT

Smart Energy System Simulation and Control Center

Main components:

- Control, monitoring and visualisation center
- Energy grids simulation and analysis laboratory
- Smart energy system control laboratory

Main methodologies:

- Big Data, machine learning, artificial intelligence
- Advanced control and optimization methods
- Reliable, safe and secure software systems

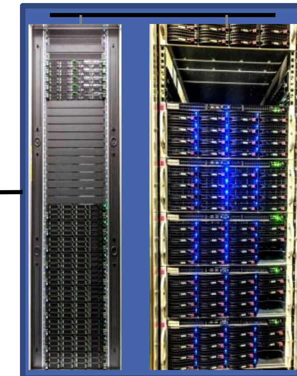
Control, Monitoring and Visualization Center (CMVC)

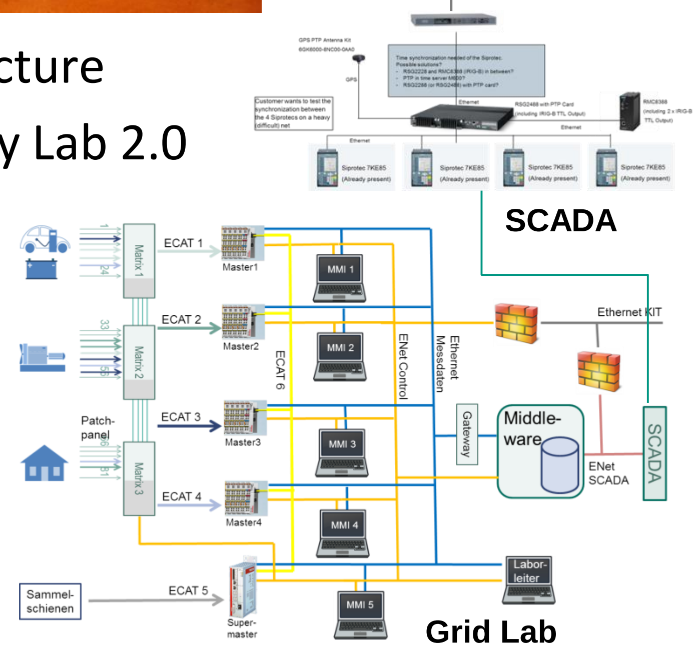
Karlsruhe Institute of Technology

- Should look like a real grid control center for operators
- Combines own research solutions for monitoring, control and visualization of grid simulations with commercial control center software and a SCADA communication infrastructure
- Integrates grid lab hardware and external Energy Lab 2.0 plants
- Research on new control center software components and architectures, latest communication technology and risks, tools for demand side management, demand response, grid utility operations

Control Room

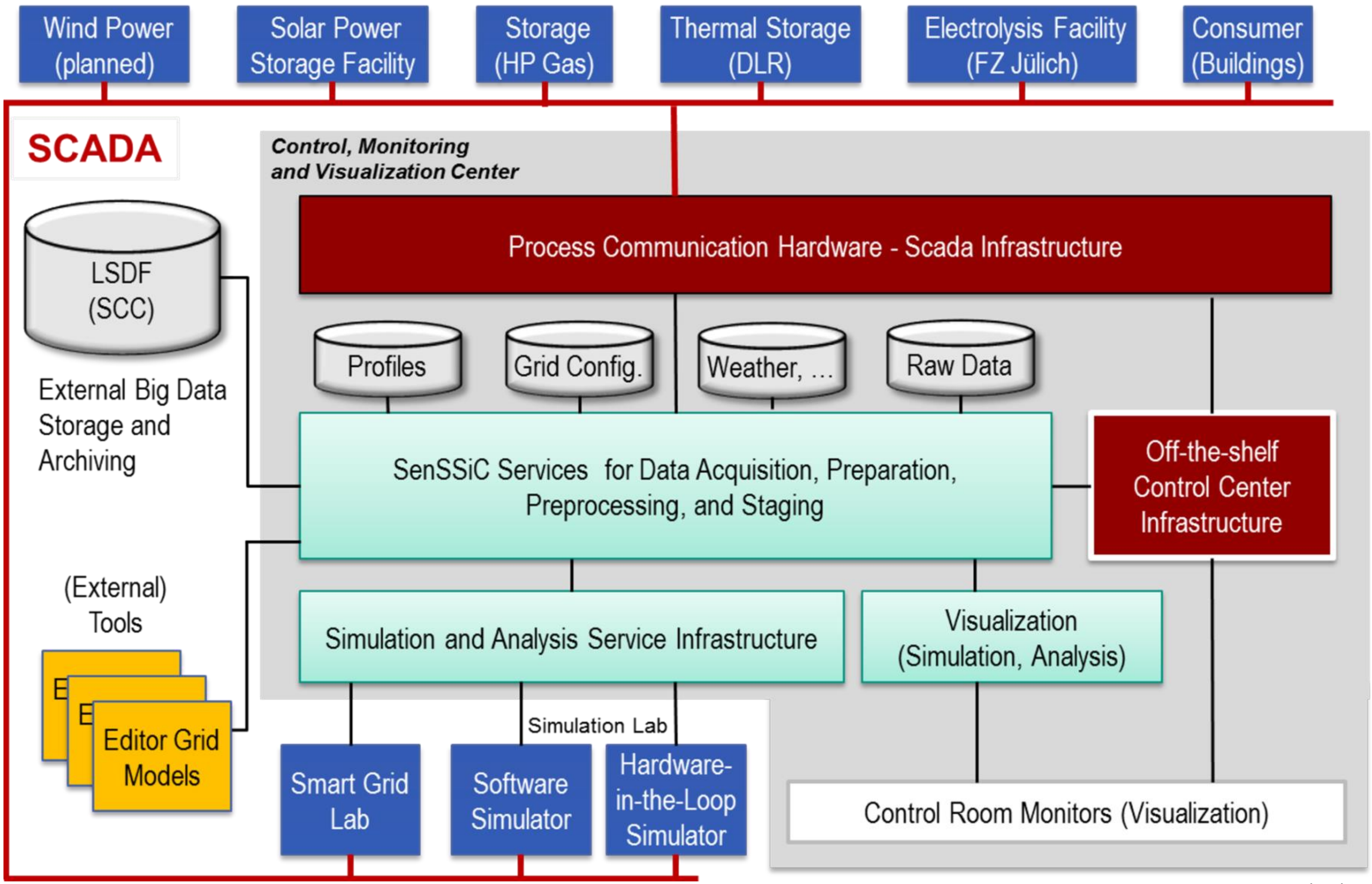
Data & Compute Center





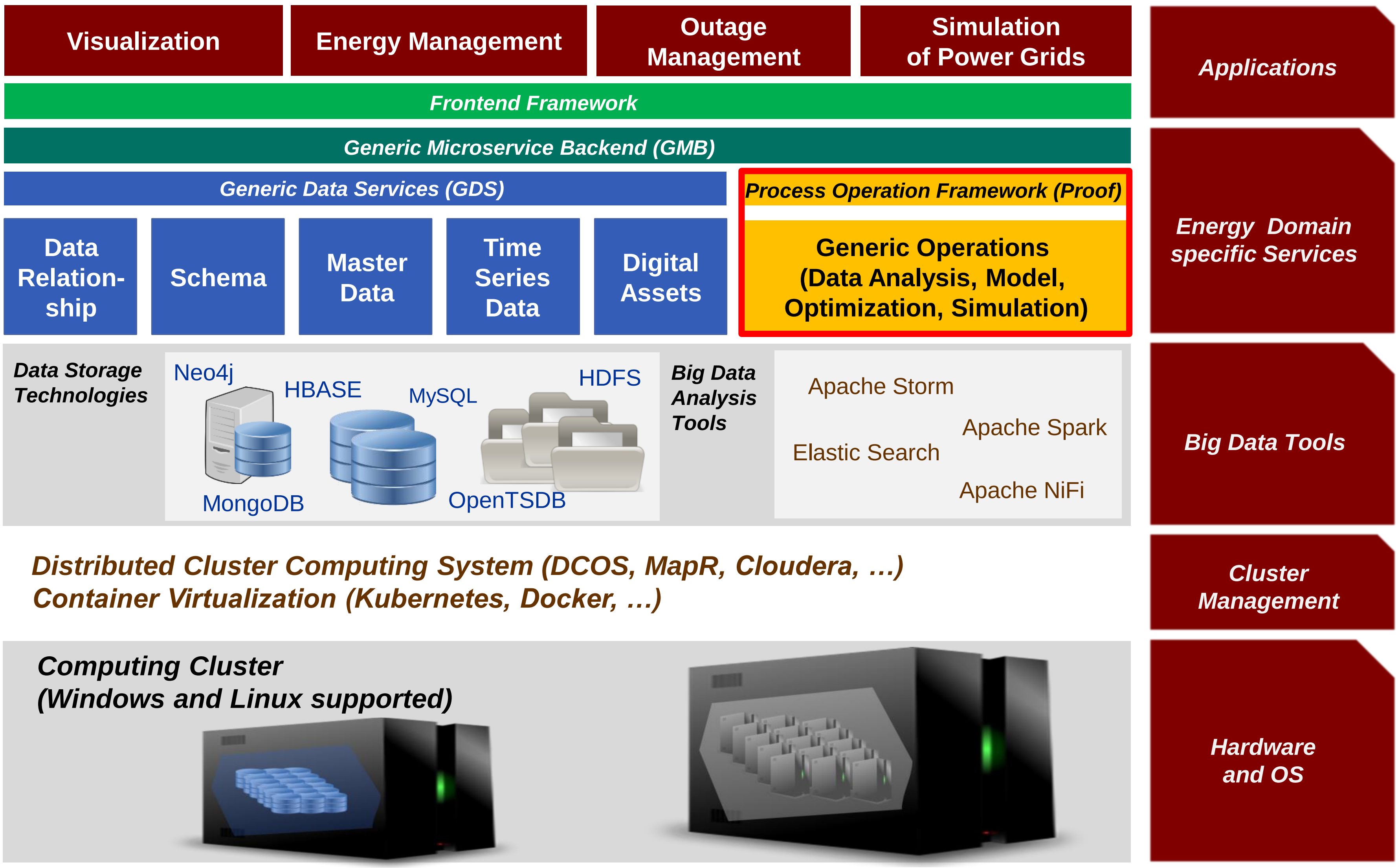
Control, Monitoring and Visualization Center

SCADA and basic concepts



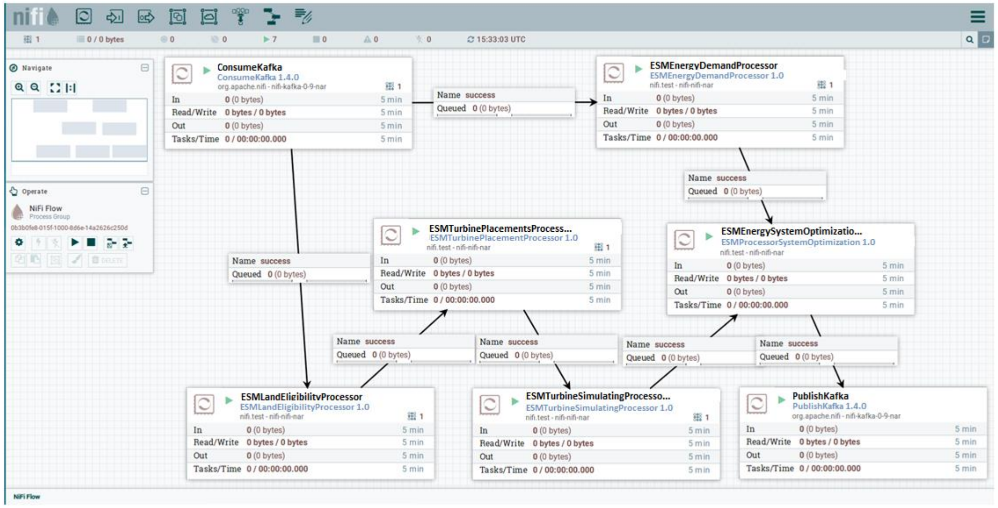
Source: Pic courtesy of EL2.0/IAI/KIT

Data and Compute Platform



Process Operation Framework (PROOF)

- Allows to define processing workflows which integrate different applications running on the cluster
  - Different simulators can be run on separate machines but can perform a co-simulation within a workflow
    - E.g. physical models of technical plants (photovoltaic field, storage)
    - Models of energy networks (power network, heating network)
    - Economical models
  - Applications for data forecasting (weather or energy consumption forecasting) can be integrated
  - Control logic can be added
  - Interfaces to real hardware can be added
  - Tools for optimization can be integrated too
- Data exchange on high level using real-time message infrastructure (Apache Kafka)

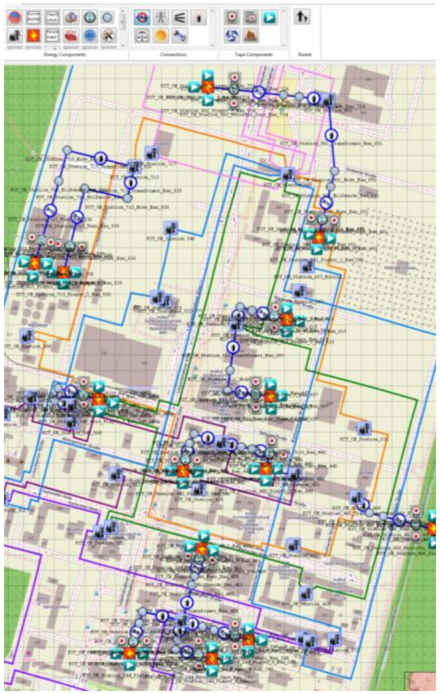


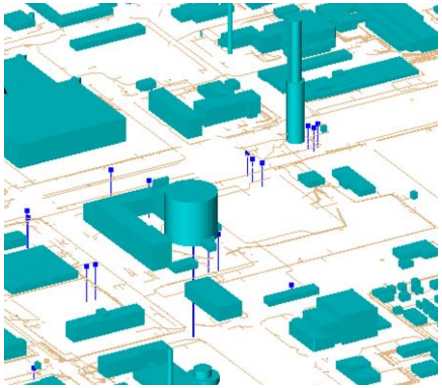
- Will allow simulation and analysis of smart grid operation for different types of smart grids

Energy Grids Simulation and Analysis Lab

Focus

- **Electricity Grids**
  - Grid modeling, simulation & analysis, measurements and monitoring in the PHIL and Microgrid labs as well as at KIT
  - co-simulation E-Grid ↔ weather data
  - Additionally: E-Transmission Grid BW, Germany, Europe → Scenario 2050 Germany & Europe
- **Heat / (Natural) Gas / Air**
  - 3D-building and -area models + gas/heat grids (*CityGML, gbXML, IFC*)
  - co-simulation buildings ↔ heating,
  - semantic modeling, standardization work within OGC (Open Geospatial Consortium)
- **Big Data & Databases**
  - Generic data services, Data-Life-Cycle Lab, energy data archiving & retrieval
  - data-security & procedures





Source: Pics courtesy of EL2.0/IAI/KIT

Energy Grids Simulation and Analysis Lab

Software tools

Simulation-Software (commercially & open-source)

- GridLAB-D , OpenDSS
- PSCad
- **DigSiLENT-PowerFactory**
- NEPLAN (ABB)
- PSS/E (Siemens; SINCAL, NETOMAC)
- INTEGRAL7 (RWTH-Aachen / Mannheim)
- Matlab, Simulink, **MatPower**
- **OpenModelica**
- **eASiMOV (inhouse development)**

All available at the Energy Lab 2.0 – Simulation Lab

Energy Grids Simulation and Analysis Lab

The German Grid

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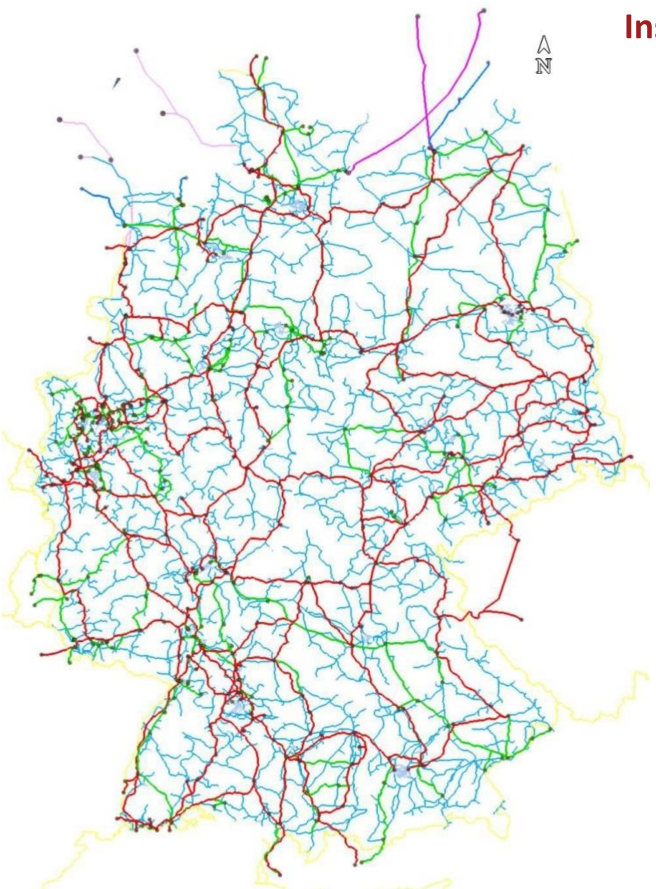
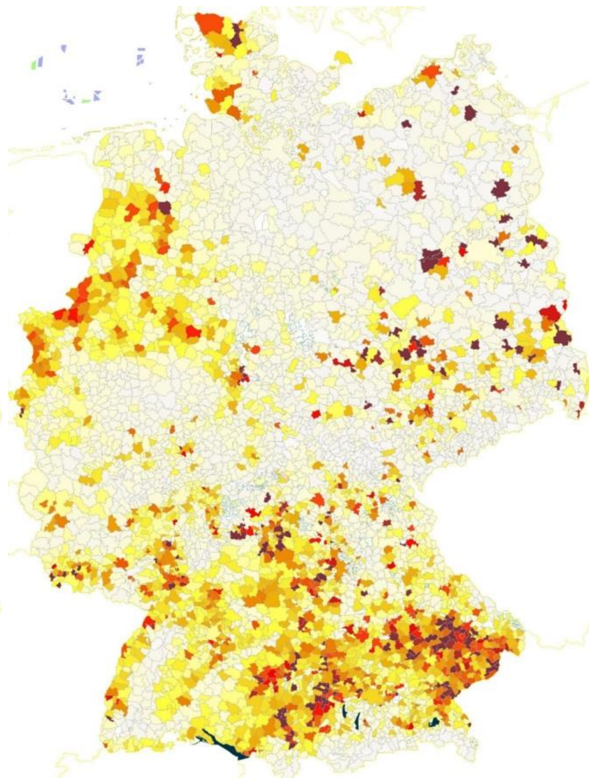
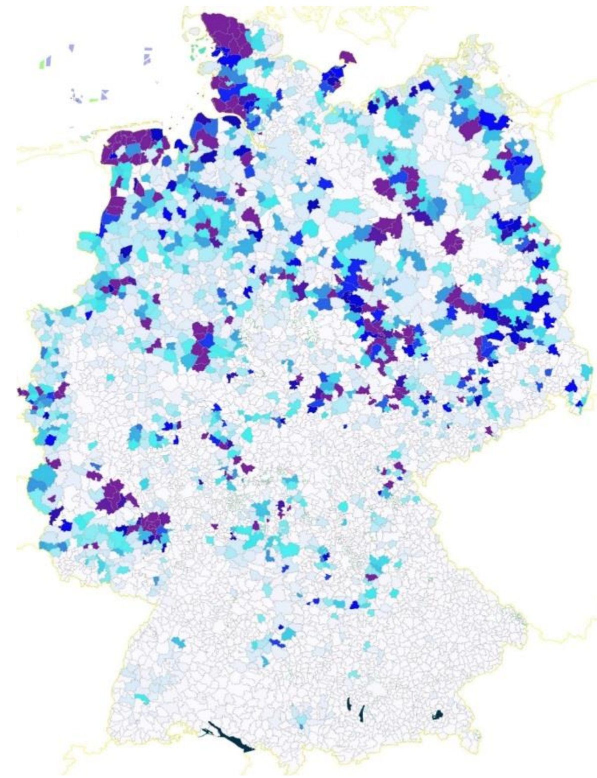


Installed PV-Generator density (peak)



0 ... ≥ 400 kWp/km^2

Installed Wind-Generator density (peak)



0 ... ≥ 100 kWp/km^2

TN, 110 kV AC- & HVDC grid Germany

including HV ground cables. The grid model consists of stations, overhead lines & ground cables, RE & conventional generators and a population-based load model (communities at LAU-1 level: 4541 regions).

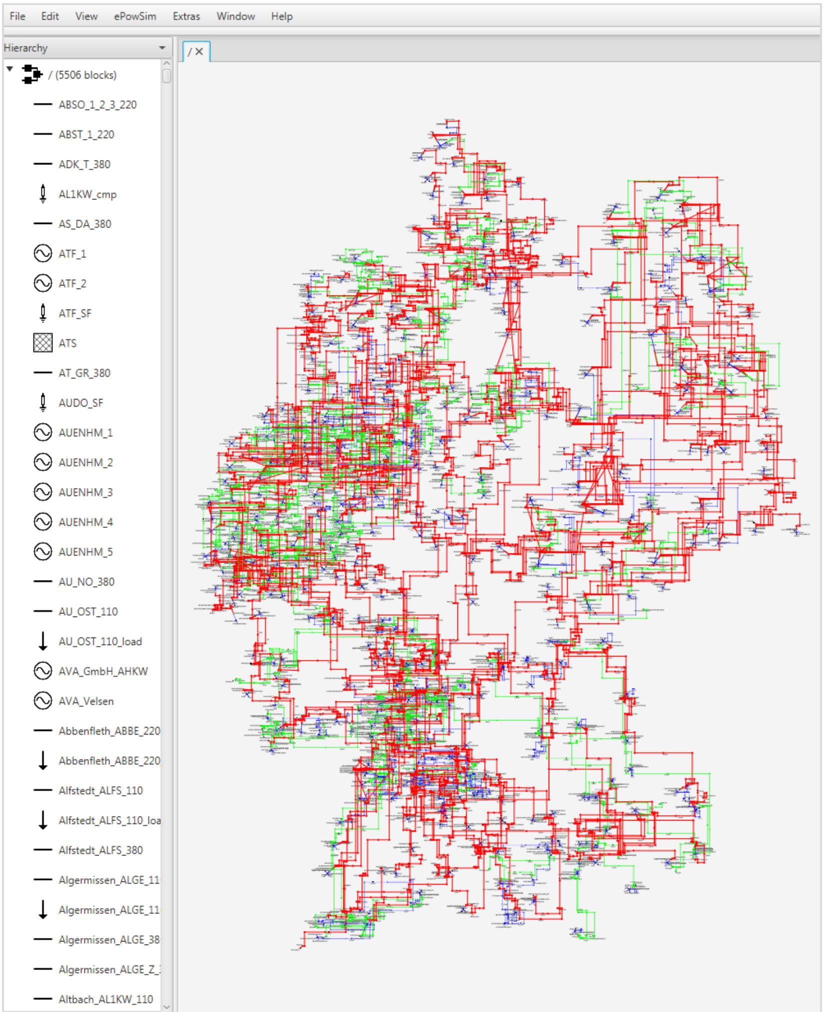
Source: Pics courtesy of EL2.0/IAI/KIT

Energy Grids Simulation and Analysis Lab

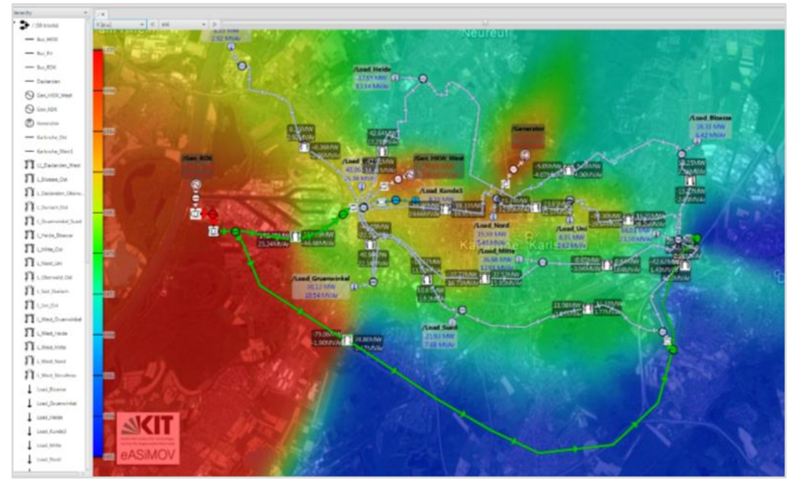
eASiMOV

Karlsruhe Institute of Technology

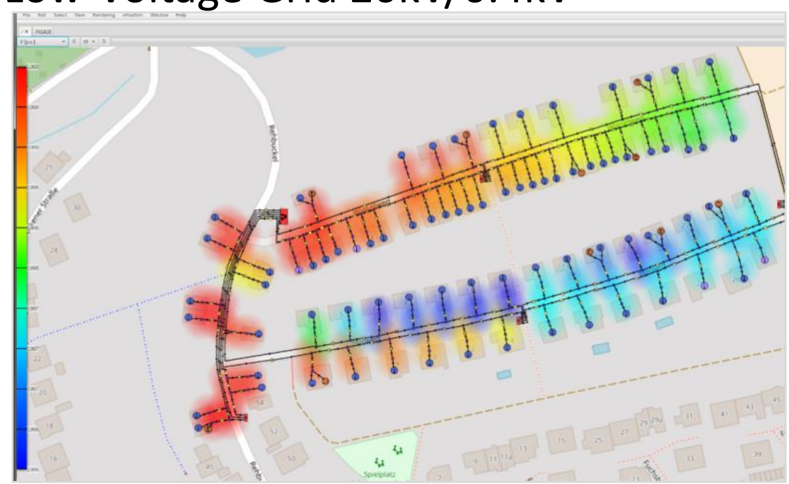
German Transmission Grid



Urban High-Voltage Grid 110kV



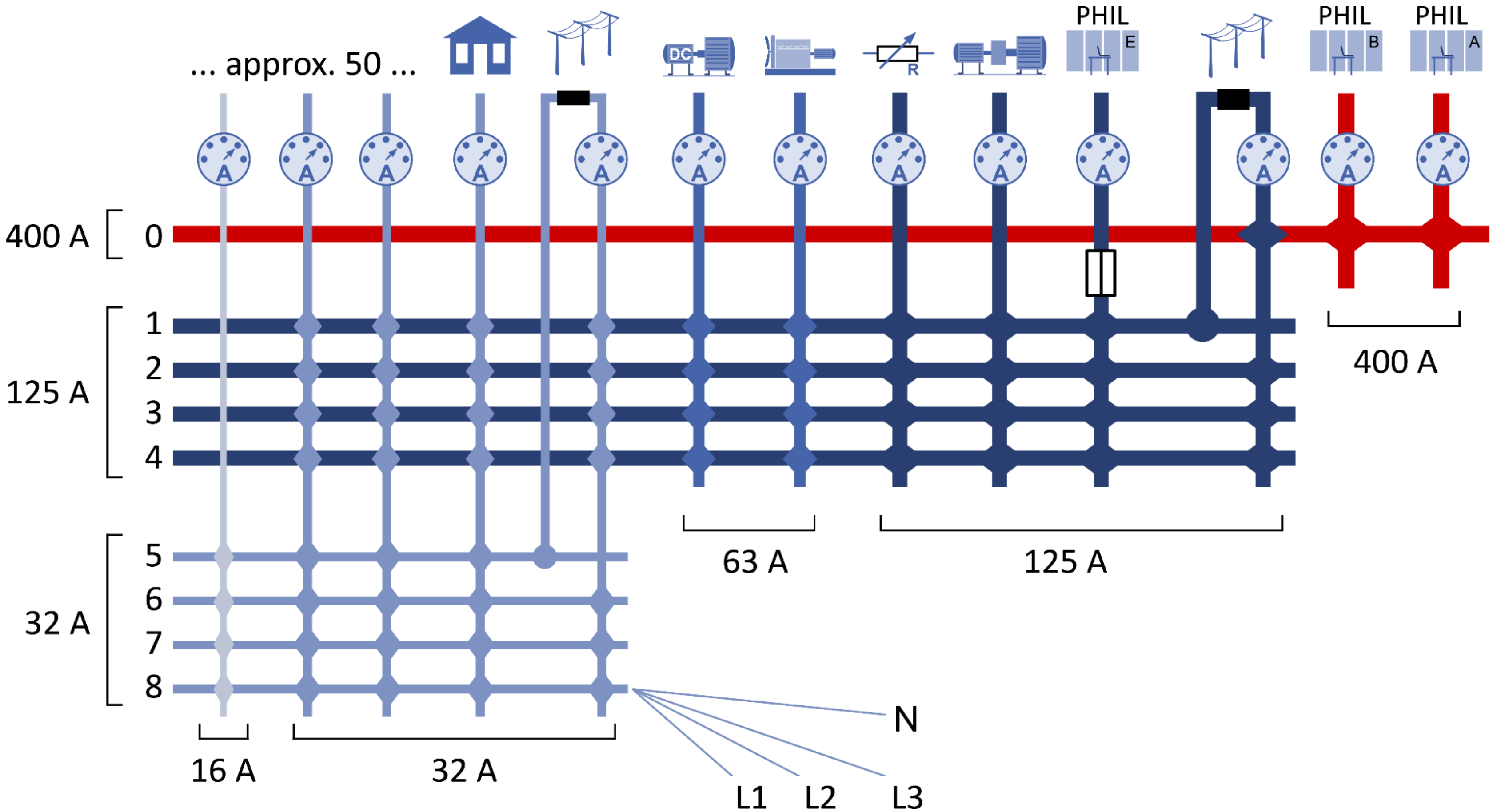
Low-Voltage Grid 20kV/0.4kV



Source: Pic courtesy of EL2.0/IAI/KIT

Smart Energy System Control Laboratory

Switching matrix



Source: Pic courtesy of EL2.0/IAI/KIT

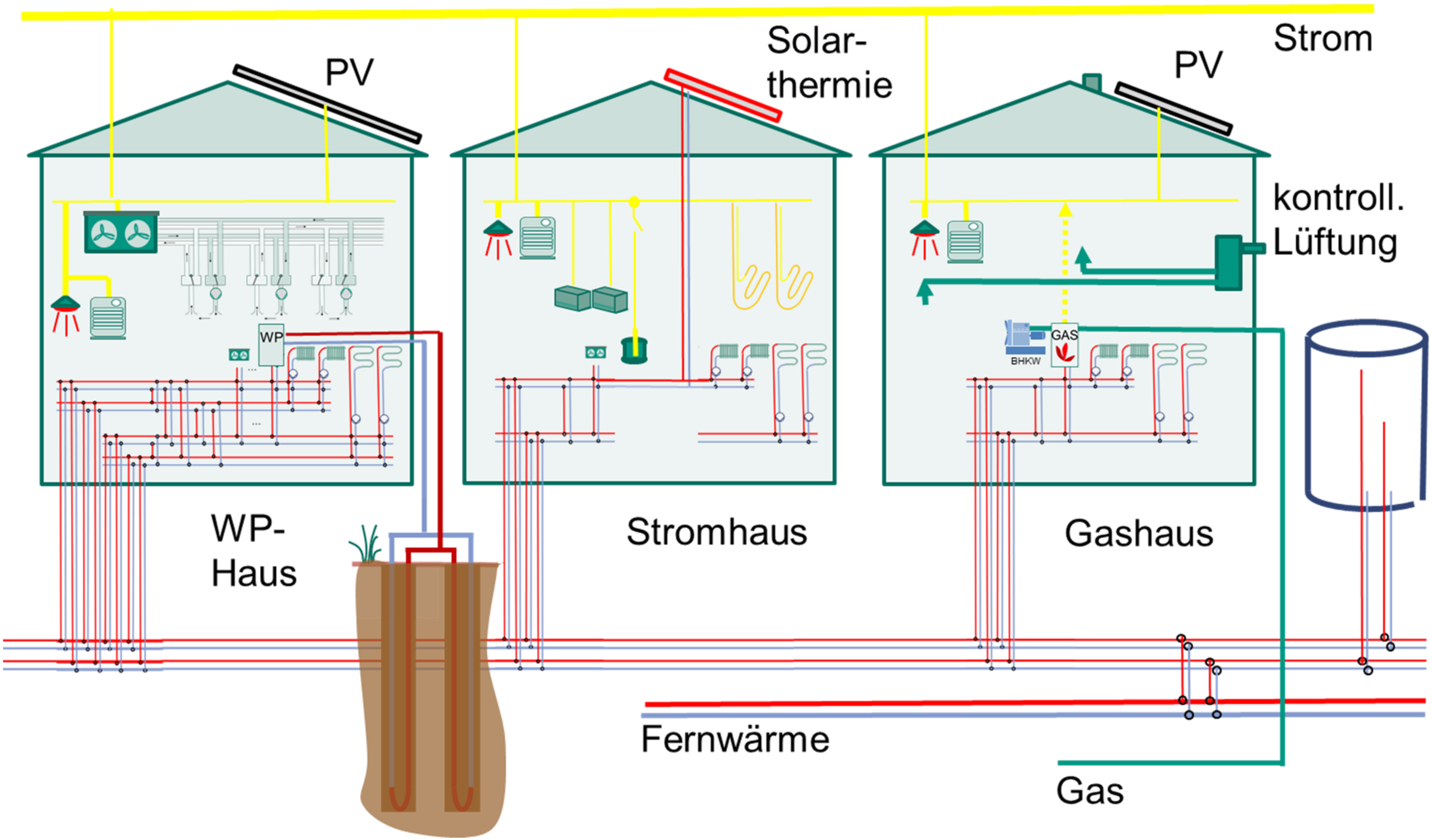
Smart Energy System Control Laboratory

Equipment

Karlsruhe Institute of Technology

- Smart Houses (3)
  - Living labs
- Generators (10)
  - Diesel/Gas generator
  - Micro co-generation plant
  - Photovoltaics and smaller wind turbine
  - Power amplifier
- Reactive power components (5)
  - Capacitors
  - Inductors
  - Phase shifters
  - FACTS (Flexible AC Transmission System)
- Prosumers (5)
  - Supercaps
  - Battery storage
  - Storage power station
- Consumers (10)
  - RLC load
  - Asynchronous machine with oscillating weight
  - DC motor with PWM interface
  - Car charging station
  - Power-to-heat
  - Hardware in the loop consumer
- Other (5)
  - Passive nodes (Connectors for wiring)
  - Grid connection components (Transformer/RONT)
  - Measurement equipment and programmable IEDs
  - …

Smart Energy System Control Laboratory



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Main methodologies:

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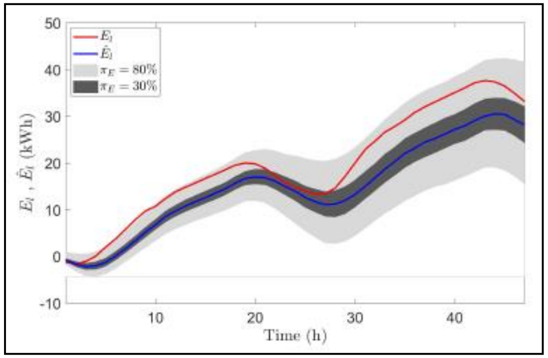
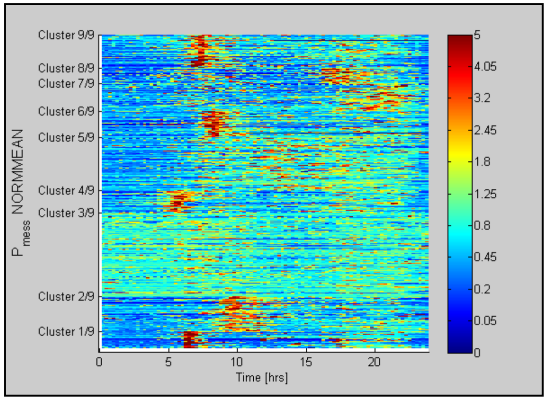
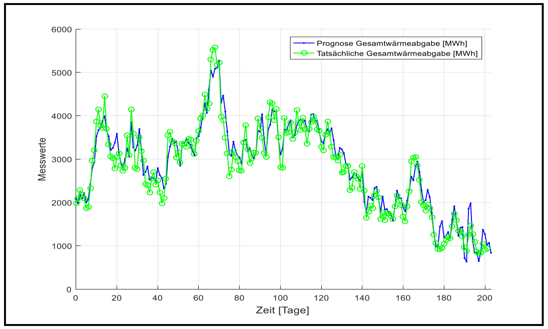
- Reliable, safe and secure software systems

Big Data, machine learning, AI

- Method development and test:
  - Interval forecasts
  - Forecasts with limited input variables (weather)
  - Cluster-based analysis
  - Test of big data environments (Apache Spark)
  - Comparison with standard algorithms & tools
- Application scenarios:
  - "Production mode" of KIT Campus North energy system (Collecting, archiving, and analyzing time series data of all routine operations
  - Experimental campaigns in "Smart energy system and control laboratory"
- Transfer of algorithms to industry, e.g.
  - District heating network of Stadtwerke Karlsruhe (routine use since 2015)
  - Steam, power and heat (BASF)

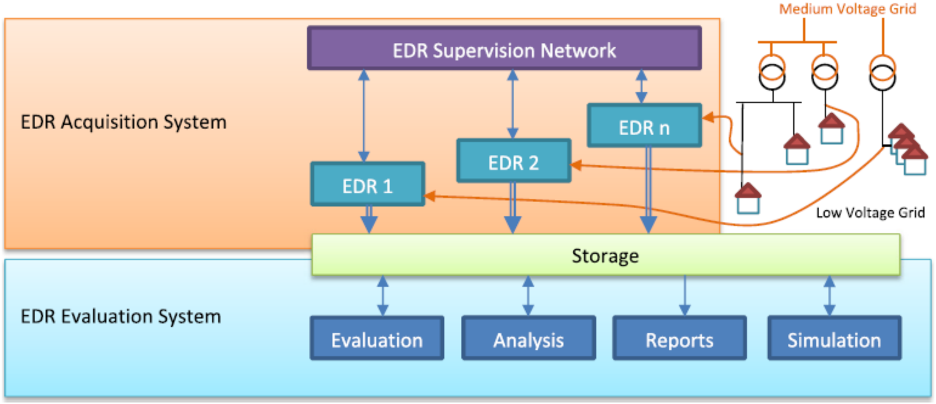


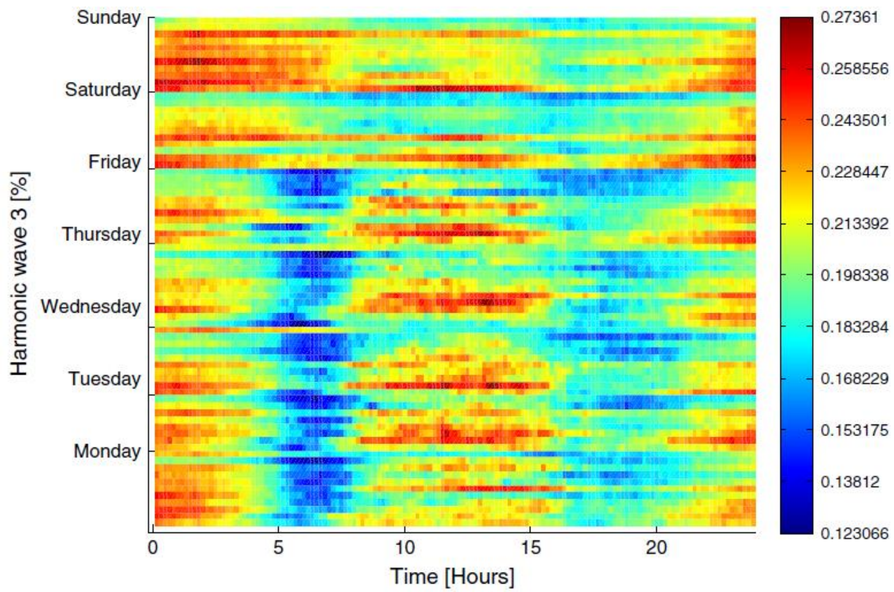




Example: Production Mode (EDR)

- Permanent collection of three phase current and voltage data (sample frequency 12.8 kHz) with Electrical Data Recorders (EDR)
- Archiving (19,3 GByte per EDR and day)
- Extracting information (e.g., higher harmonic waves)
- Analysis and visualization:
  - Generating building profiles
  - Dynamic analysis of special events

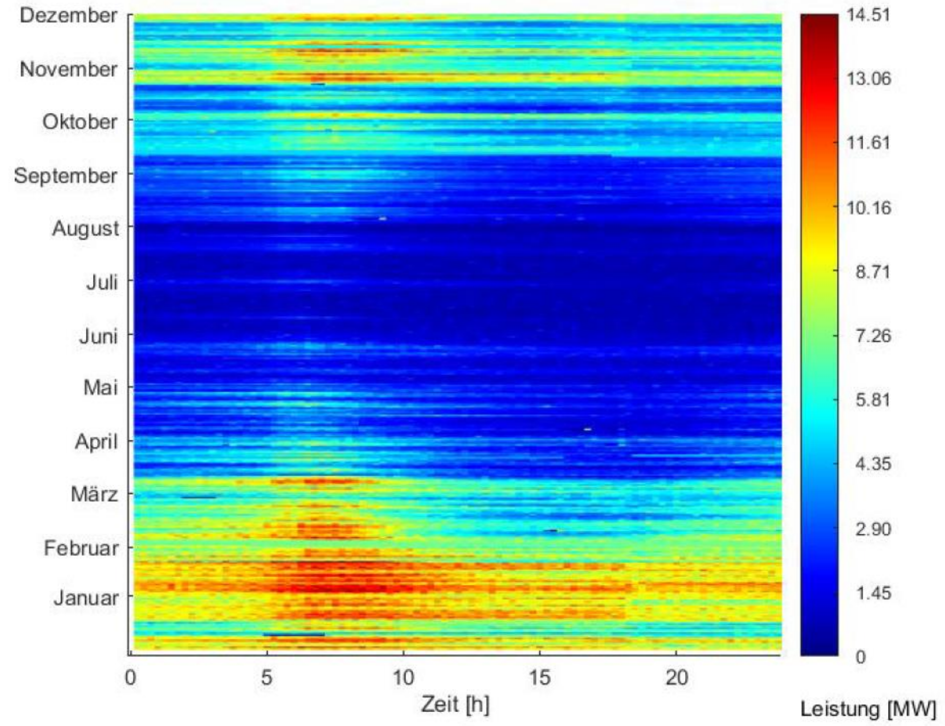




Maaß, H.; Cakmak, Hü. K.; Bach, F.; Mikut, R.; Harrabi, A.; Süß, W.; Jakob, W.; Stucky, K.-U.; Kühnapfel, U. G. & Hagenmeyer, V.: Data Processing of High Rate Low Voltage Distribution Grid Recordings for Smart Grid Monitoring and Analysis. *EURASIP Journal on Advances in Signal Processing,* **2015**

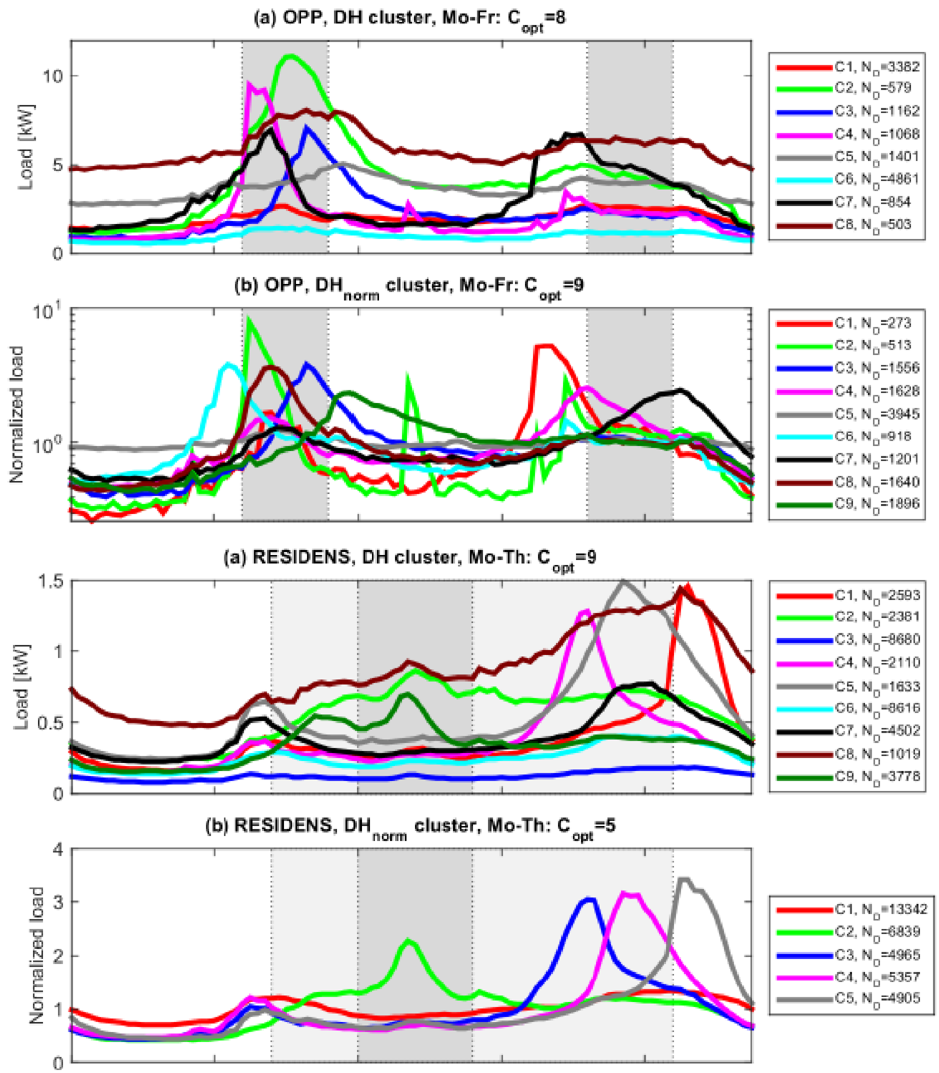
Example: Production Mode (EDR)

- KIT Campus North:
  smart meter data since 2006,
  15 minutes sampling time
- Heat: 170 smart meter
- Power: 563 smart meter
- Under development (together with Facilty Management)
  - Forecasting
  - Detailed analysis (clustering etc.)



Example: Experimental Campaigns

- Comparison of customer behavior for different tariffs
- Data of two different campaigns (Residens/Germany and Olympic Peninsula Project OPP/USA)
- Systematic data analysis using preprocessing, clustering and regression methods
- Results:
  - Subgroups of customer behavior
  - Matching of subgroups to different tariffs
  - Quantification of changes

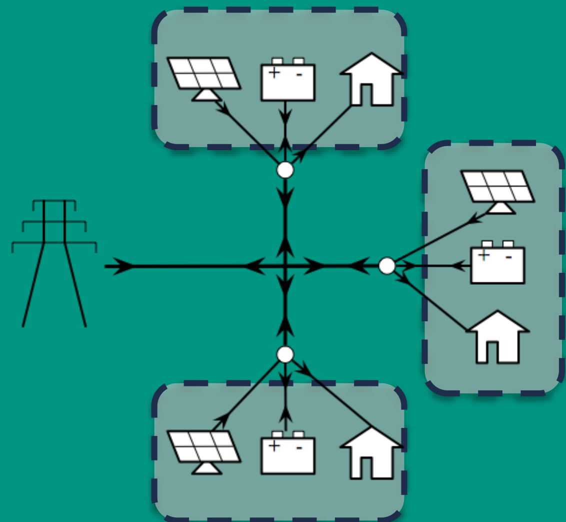


Waczowicz, S.; Reischl, M.; Hagenmeyer, V.; Klaiber, S.; Bretschneider, P.; Konotop, I.; Westermann, D. & Mikut, R. Demand Response Clustering – How do Dynamic Prices affect Household Electricity Consumption? *Proc. IEEE Powertech, Eindhoven,* **2015**

Advanced Control and Optimization Methods
Distributed nominal scheduling via convex optimization

Karlsruhe Institute of Technology

Distributed battery scheduling

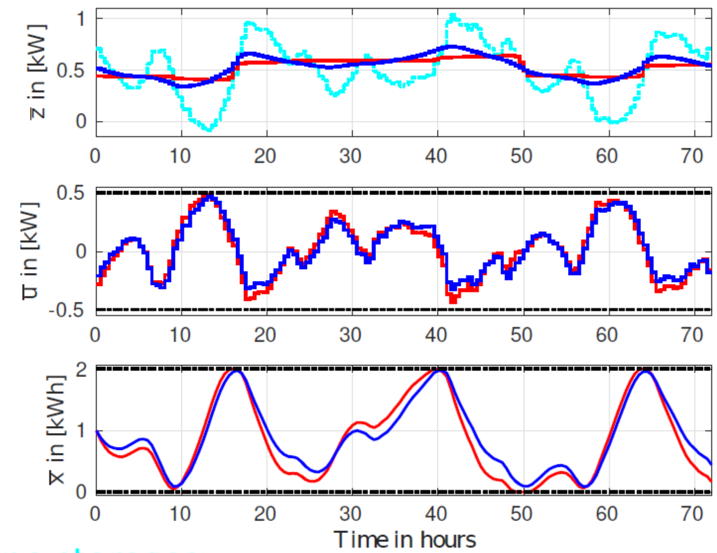


- 300 households, $N = 48$
- PV generation & battery

$\rightarrow$ Convex QP (≈ 40000 variables)

- Tackled via ADMM

[Braun, Faulwasser et al. `16a, `17a]



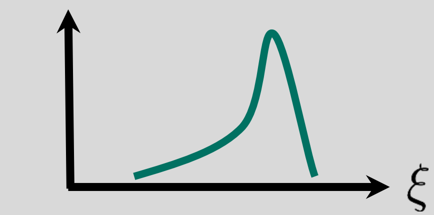
- no storages
- $\sum_{k=0}^{N-1} \|\text{average-grid-load} - \text{average-demand}\|^2$
- $\sum_{k=0}^{N-1} \|\text{avg. rate of change of grid load}\|^2$

→ **Uncertainties**? → Appino et al. `2017

→ Grid topology? **Power flow restrictions**?

Stochastic Optimal Power Flow

$\mathsf{D} \in \mathsf{L}^2(\mathbb{R}^{n_d})$ with ρ_D



$$\min_{\mathsf{U} \in \mathsf{L}^2(\mathbb{R}^{n_u})} \quad \mathsf{E}[J(\mathsf{U})]$$

$$\text{s. t.} \quad f(\mathsf{X}, \mathsf{U}, \mathsf{D}) = 0,$$

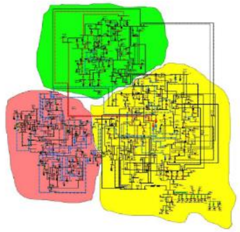
$$\Pr[\mathsf{X} \in \mathcal{E}_x] \geq 1 - \varepsilon_x,$$

$$\Pr[\mathsf{U} \in \mathcal{E}_u] \geq 1 - \varepsilon_u$$

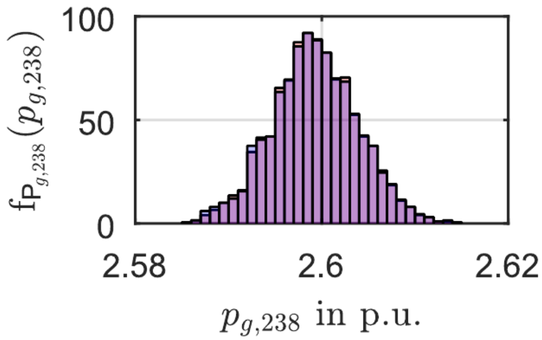
Automatic Generation Control (AGC) $\quad \mathsf{U}^\star(\mathsf{D}) \in \mathsf{L}^2(\mathbb{R}^{n_u})$

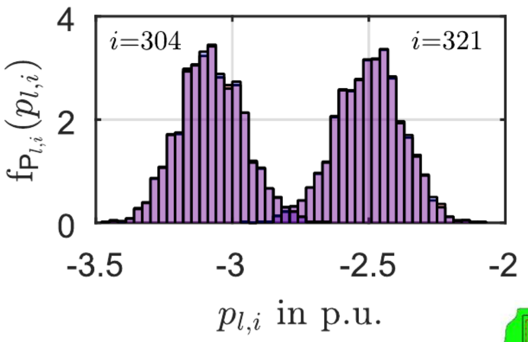
Case study: IEEE 300-bus test system under DC conditions

- 69 generators , 195 loads (of which 9 uncertain)
- 60 tap changers, 304 transmission lines

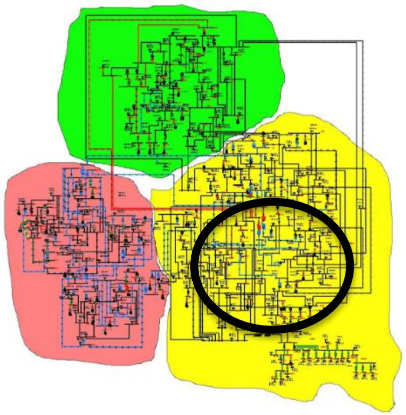


Case study – 300 bus IEEE test system





	μ_{PCE}	μ_{MC}	σ_{PCE}	σ_{MC}
$P_{g,238}$	2.5993	2.5993	0.0047	0.0046
$P_{l,304}$	-3.0761	-3.0758	0.1195	0.1199
$P_{l,321}$	-2.4985	-2.4982	0.1226	0.1229



- Problem size: 3321 variables vs. 600 variables x 2000 samples
- Computation time: 1.7s vs. 217.9s

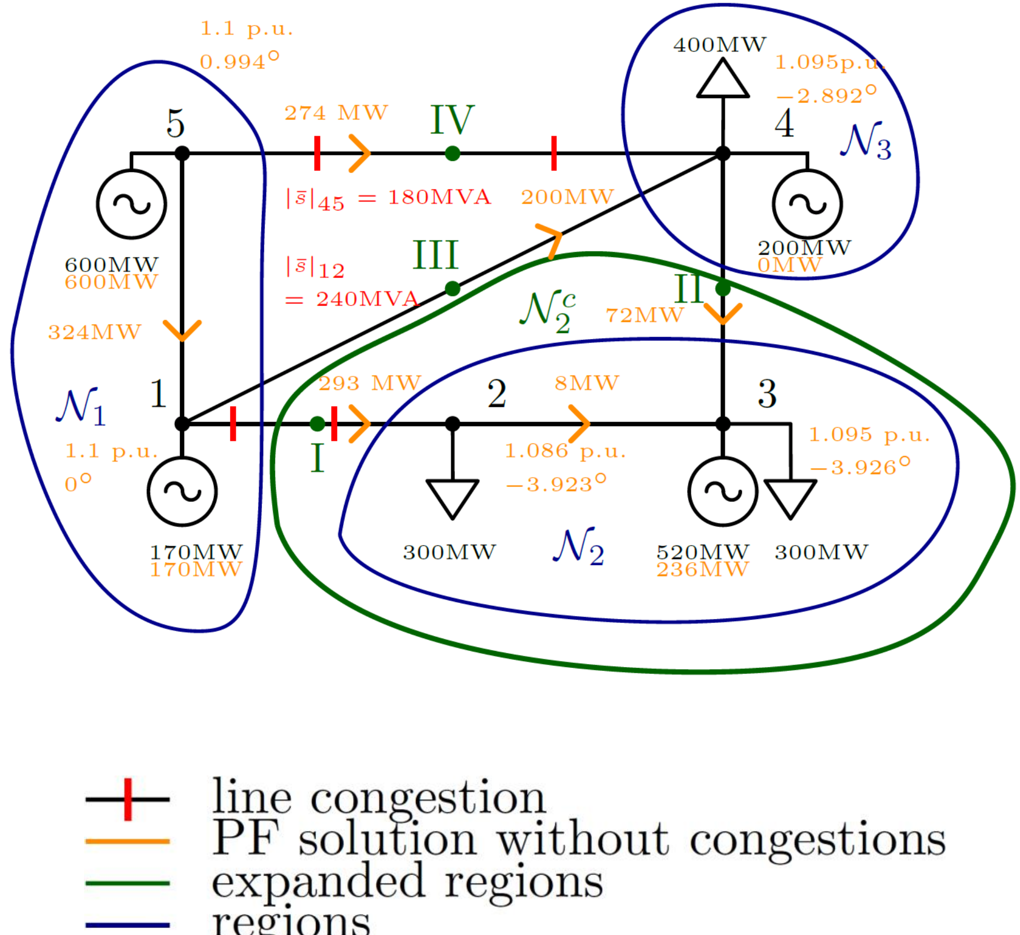
→ **Efficient solution** to large class of uncertain problems

Mühlpfordt, T.; Faulwasser, T.; Roald, L., Hagenmeyer, V.. Efficient Solutions to DC-OPF with correlated Non-Gaussian Uncertainties
IEEE CDC **2017**

Distributed solution to nominal OPF?

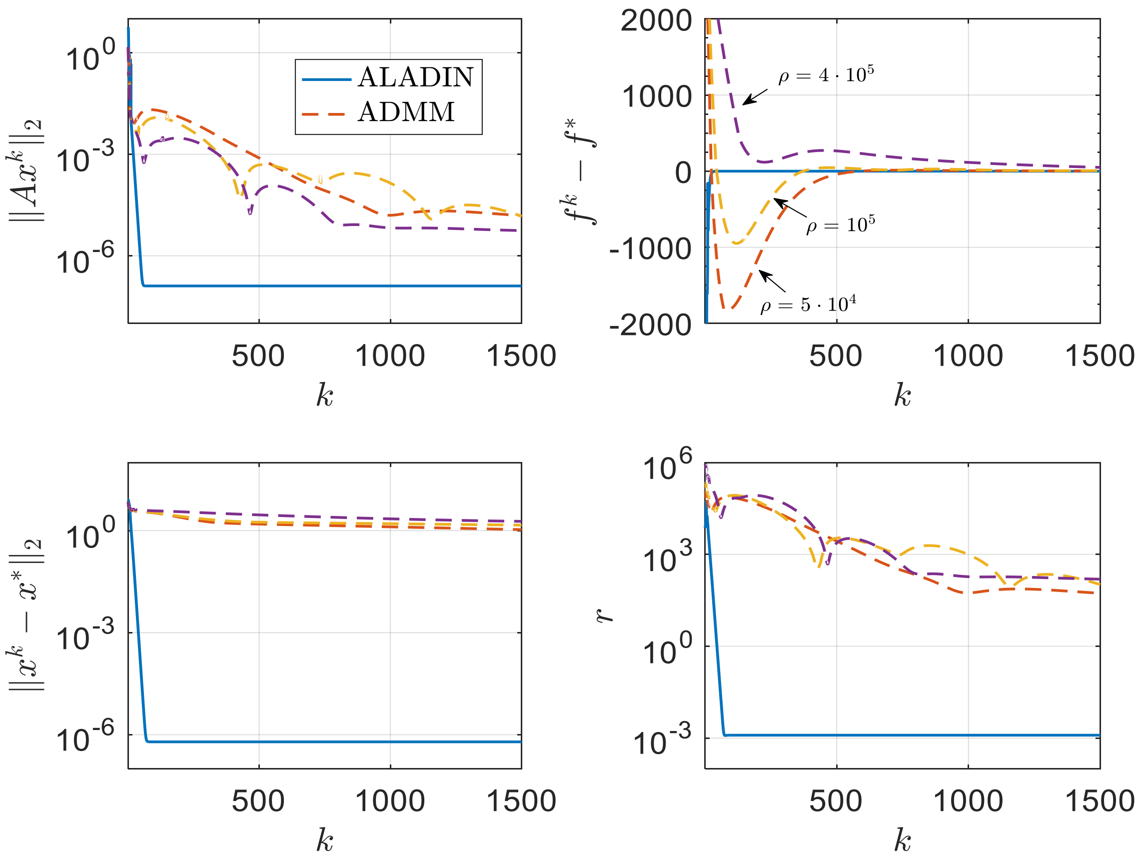
TSOs in Germany

Toy example



https://de.wikipedia.org/wiki/Tennet_Holding#/media/File:Regelzonen_deutscher_%C3%9Cbertragungsnetzbetreiber_neu.png

Results – considering line constraints



→ Tailored non-convex algorithms outperform standard methods.

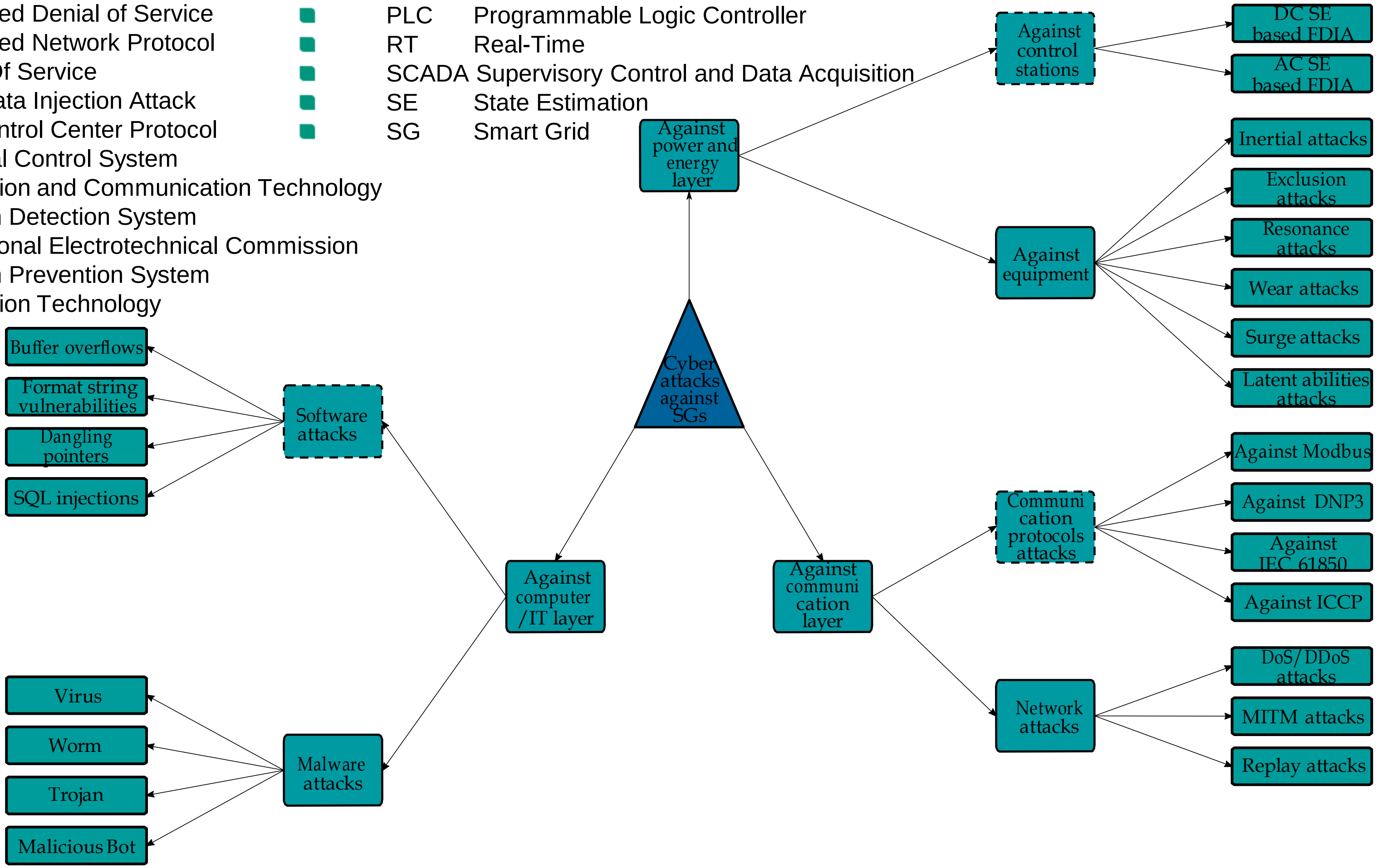
Reliable, safe and secure software structures

- The connection with the internet draws new problems to the automation of energy systems.
- The standard methods of IT security will not satisfy these problems.
- Secure software architectures have to be defined.
- Communication structures have to be monitored and data deeply and semantically inspected.
- Models of the control structure have to be used to obtain plausibility of calculated control values (behavioral analysis).
- A secure infrastructure with identities of all communicating components and a secure transport layer will secure the energy systems of the future behaving as required by the user.

Example: First complete classification of cyber attacks in Smart Grids

Abbreviations:

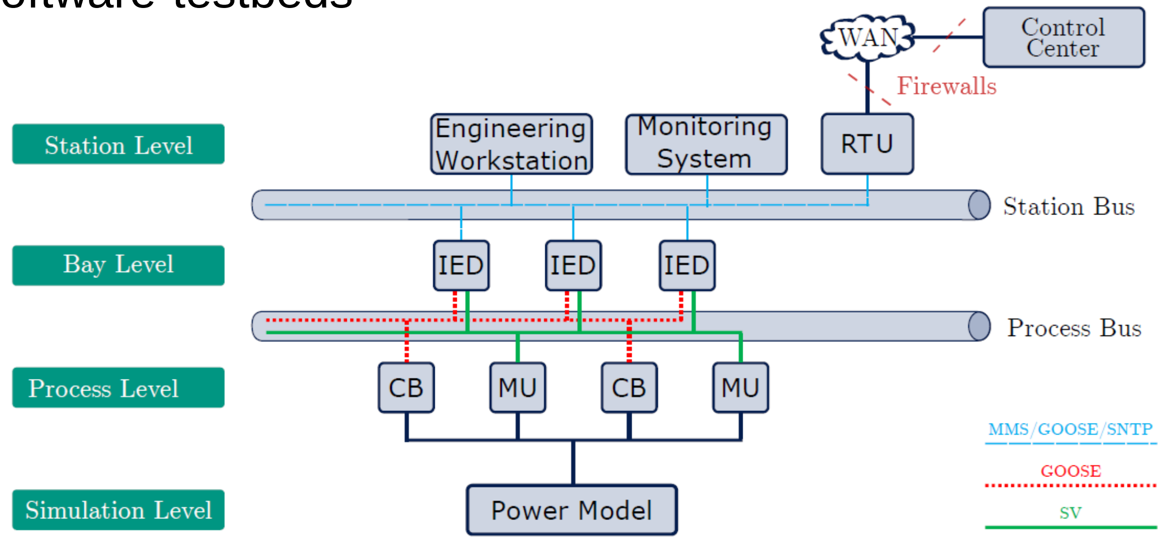
- AMI Advanced Metering Infrastructure
- BDD Bad Data Detection
- DDOS Distributed Denial of Service
- DNP Distributed Network Protocol
- DOS Denial Of Service
- FDIA False Data Injection Attack
- ICCP Inter-Control Center Protocol
- ICS Industrial Control System
- ICT Information and Communication Technology
- IDS Intrusion Detection System
- IEC International Electrotechnical Commission
- IPS Intrusion Prevention System
- IT Information Technology
- MITM Man-In-The-Middle
- PCS Process Control System
- PLC Programmable Logic Controller
- RT Real-Time
- SCADA Supervisory Control and Data Acquisition
- SE State Estimation
- SG Smart Grid



[1] *G. Elbez, H. B. Keller, and V. Hagenmeyer, "A New Classification of Attacks against the Cyber-Physical Security of Smart Grids," in ARES 2018: International Conference on Availability, Reliability and Security, Hamburg, Germany, August 27-30 2018.*

Example: Safety of IT-Communication in / between Substations

- Communication safety in/between substations following IEC 61850 not well addressed
  - Establishment of software-testbeds[2]



→ Implementation and simulation of attack scenarios

→ Test attacks on Multicast-Protocols

[2] G. Elbez, H. B. Keller, and V. Hagenmeyer, "A Cost-efficient Software Testbed for Cyber-Physical Security in IEC 61850-based Substations," in SCG 2018: IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids, Aalborg, Denmark, October 29-31 2018.

Smart Energy System Simulation and Control Center

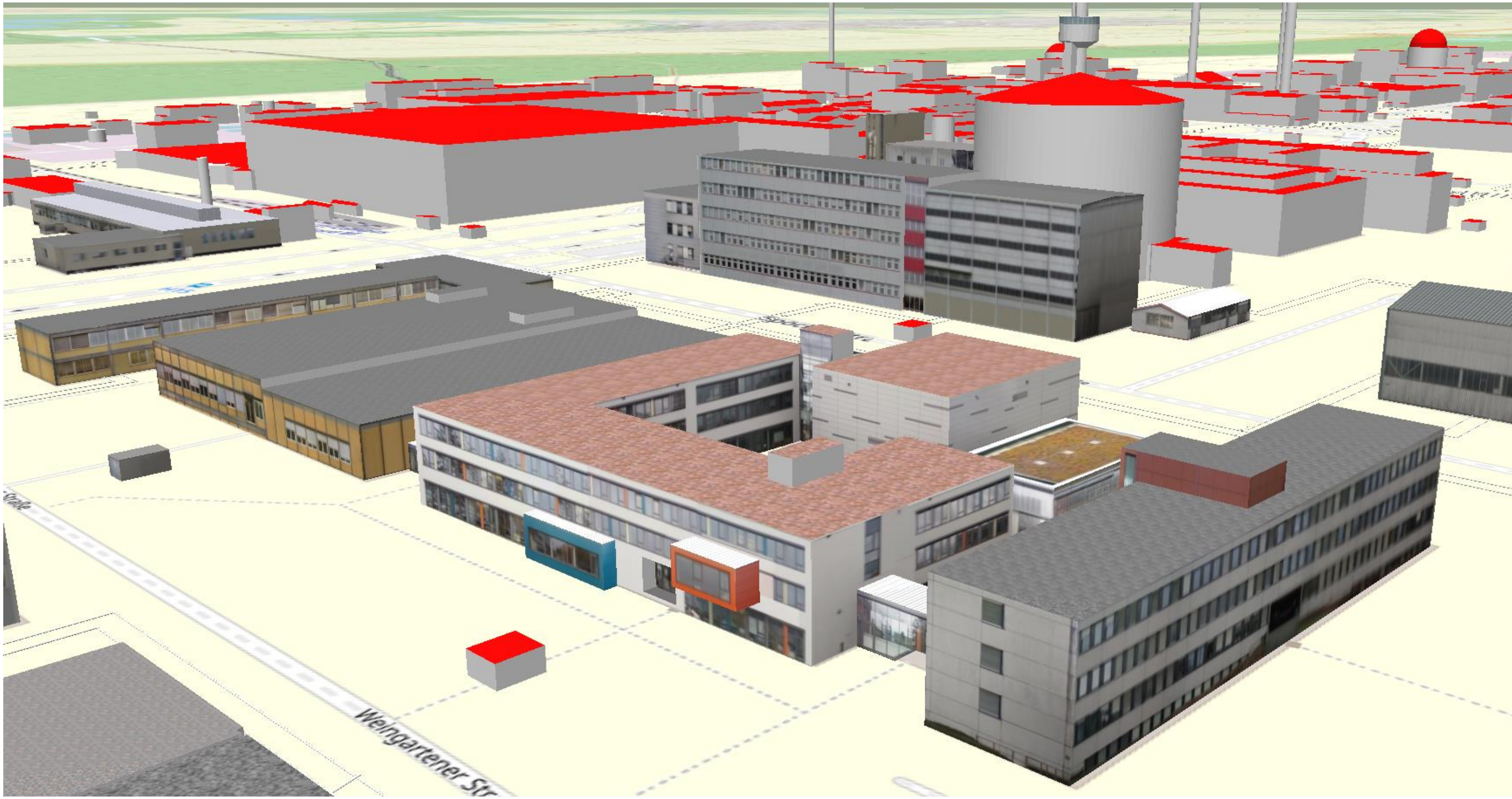
Main components:

- Control, monitoring and visualisation center
- Energy grids simulation and analysis laboratory
- Smart energy system control laboratory

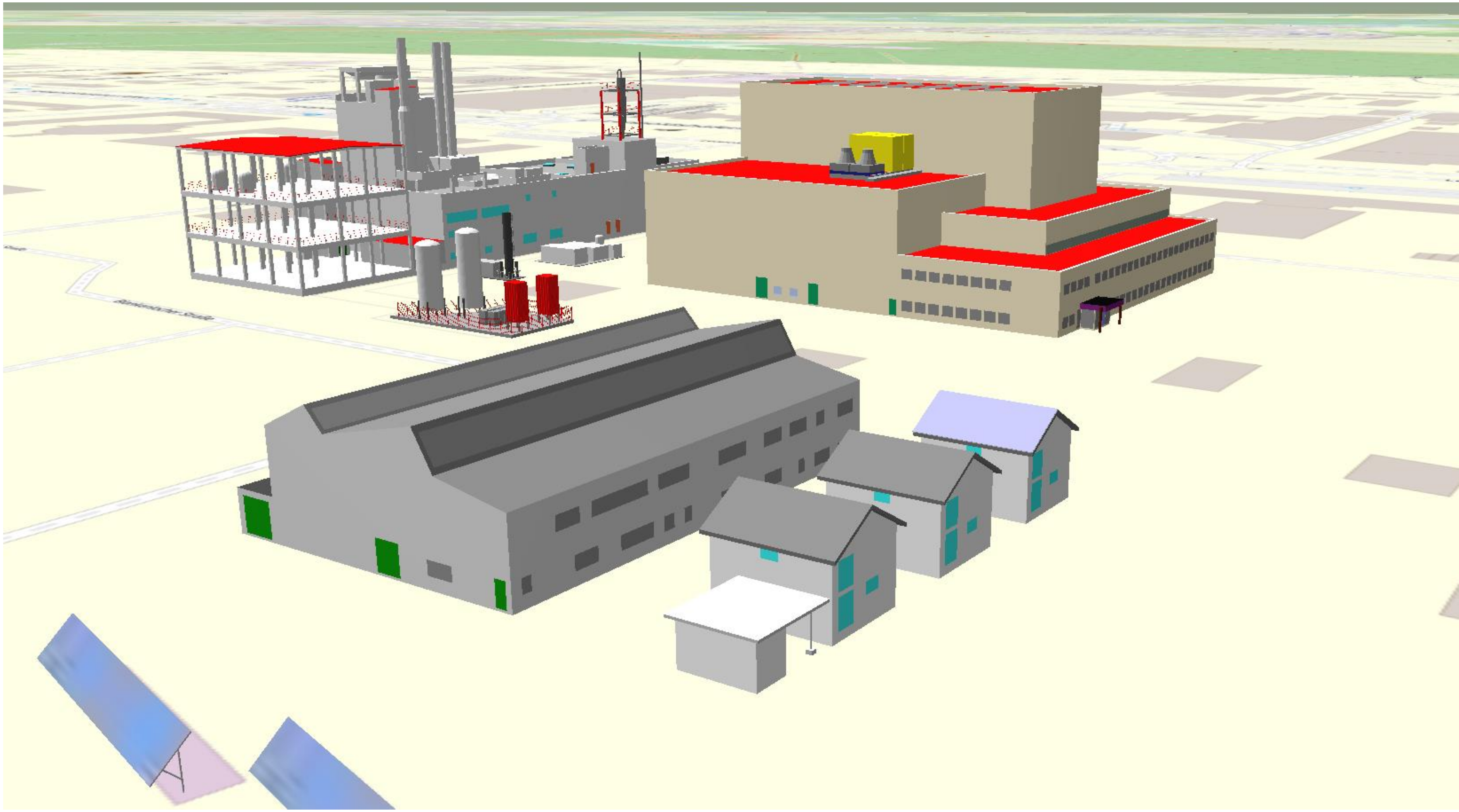
Main methodologies:

- Big Data, machine learning, artificial intelligence
- Advanced control and optimization methods
- Reliable, safe and secure software systems

KIT Campus North –Buildings (IAI and neighbors)

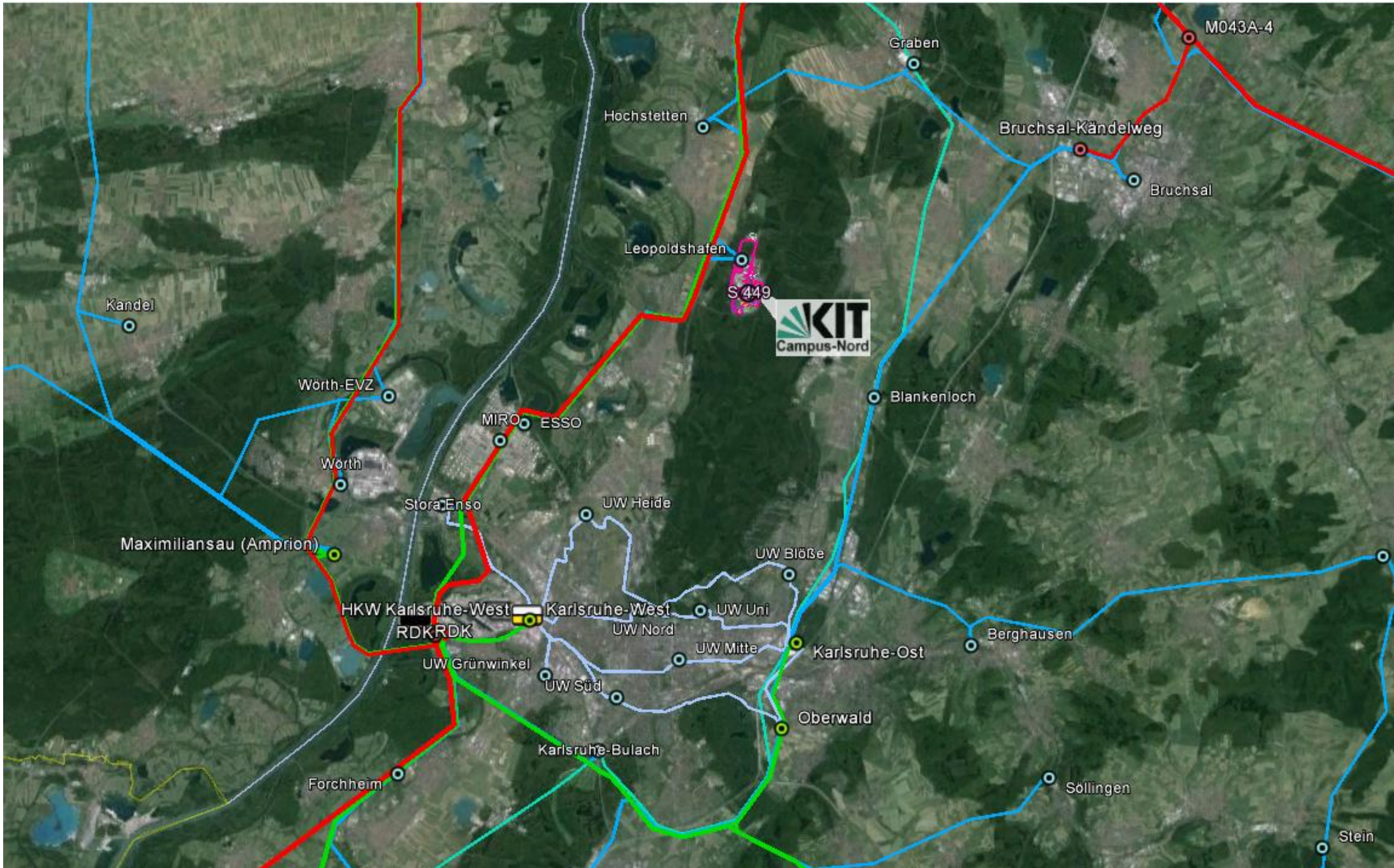


KIT Campus North – Energy Lab and Bioliq (to be completed)



KIT Campus North

Karlsruhe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MIRO
ESSO
Blankenloch
Wörth
Stora Enso
UW Heide
Maximiliansau (Amprion)
UW Blöße
HKW Karlsruhe-West
Karlsruhe-West
UW Uni
RDKRDK
UW Nord
UW Mitte
Berghausen
Karlsruhe-Ost
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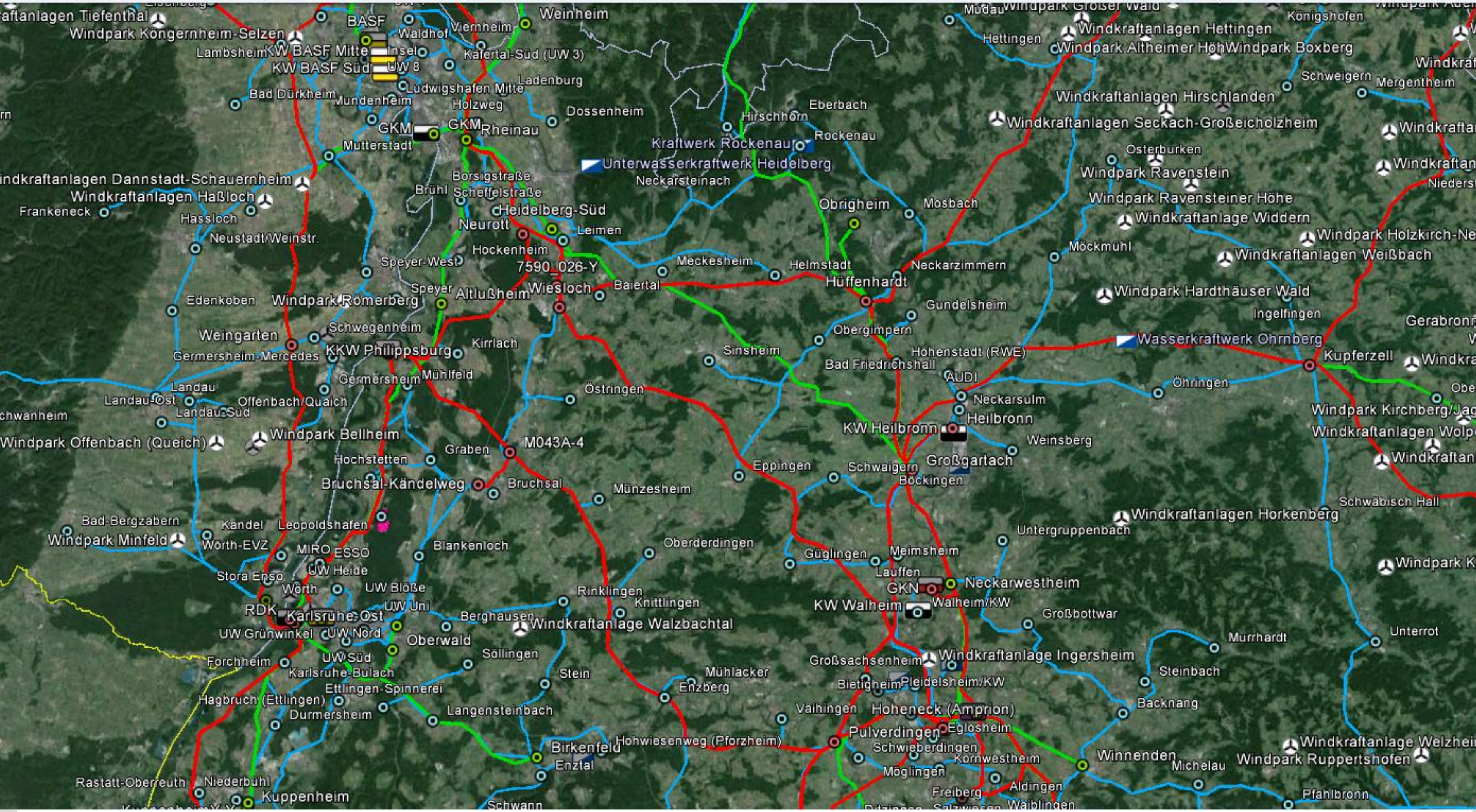
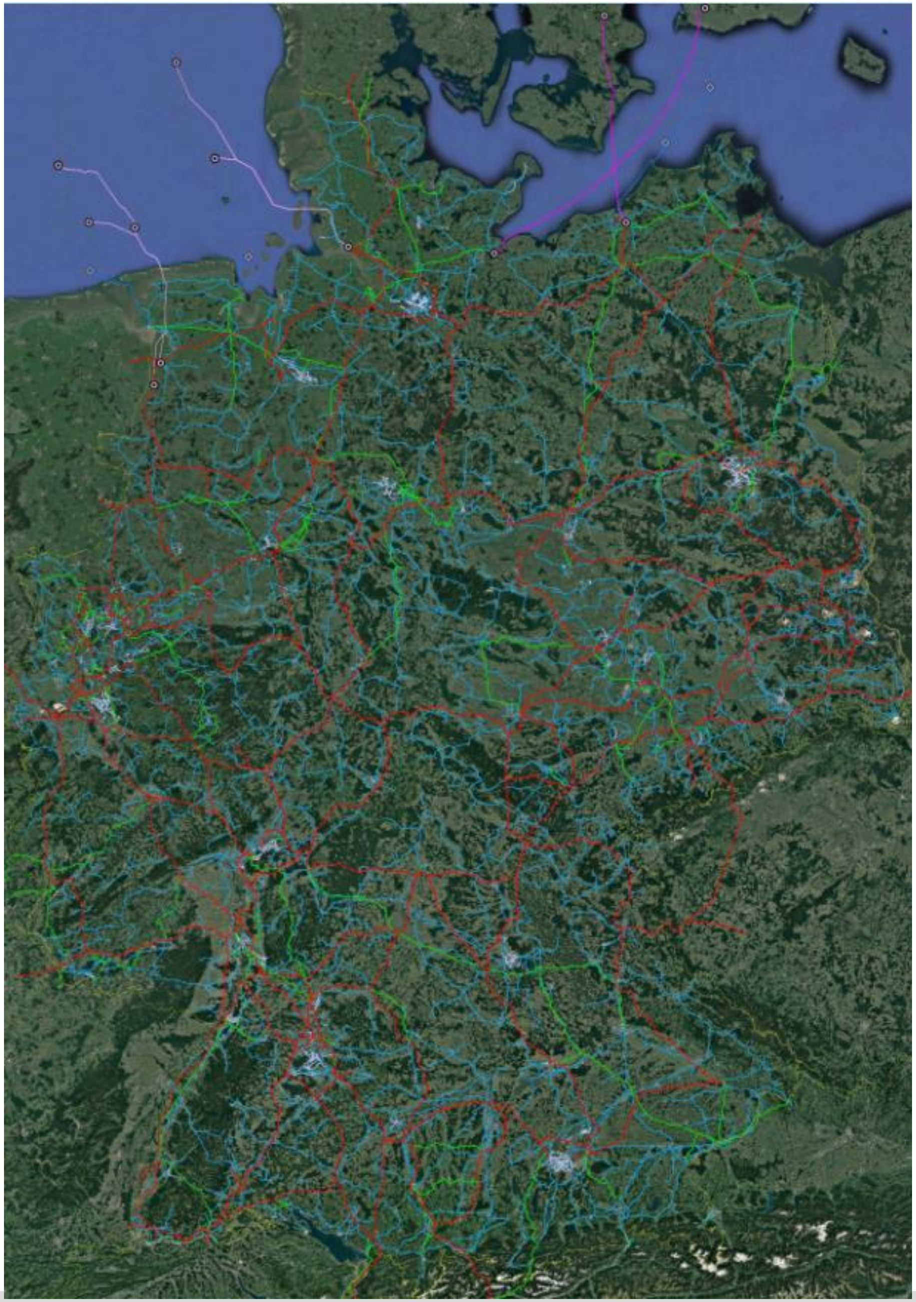
Oberwald
Karlsruhe-Bulach
Forchheim
Söllingen
Stein

North of BW and South of Palatinate



Germany



Europe

Summary & Outlook

- Energy Lab 2.0 represents a unique energy research environment
- ITC plays an important role for balancing the different energy flows
- Smart Energy System Simulation and Control Center (SEnSSiCC)
  - 3 Main Components
    - Control, monitoring and visualisation center
    - Energy grids simulation and analysis laboratory
    - Smart energy system control laboratory
  - 3 Main Methodologies
    - Big Data, machine learning, artificial intelligence
    - Advanced Control and optimization methods
    - Reliable, safe and secure software structures
- This year the buildings will be completed, the gradual commissioning will take place and first experiments will be possible
- All cooperations very welcome!

Karlsruhe Institute of Technology

Energy Informatics in Energy Lab 2.0 – A Research Platform for the Energy Transition

Prof. Dr. Veit Hagenmeyer

Institute for Automation and Applied Informatics (IAI)