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

Prof. Dr. Veit Hagenmeyer
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
- 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 - ...)

Prof. Dr. Veit Hagenmeyer
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

- **Smart Energy System Simulation and Control Center (SEnSSiCC)**
  - Data Analysis
  - Smart Grid Lab and Real-Time Simulation
  - Microgrid with Grid-Control

**Plant network @ KIT**
- **Biomass residues**
- **Flash Pyrolysis**
- **HP-Gasifier**
- **HTHP Gas-Cleaning + Conditioning**
- **Synthesis**
- **Fuels/Chemicals**

**Bioliq® process (KIT)**
- Solar Power Storage Park
- Geothermal energy plant ‘MoNiKA’
- Wind Park (Partner)
- MW Electrolysis Facility (FZJ)
- Thermal Storage (DLR)

**Consumers**
- Buildings (e.g. Living Labs)
- Experimental Plants

**Energy Sources**
- Electrical Power Grid
- Gas grid
- **Solar Power**
- Storage Park
- **Geothermal energy plant ‘MoNiKA’**
- **Wind Park (Partner)**
- **MW Electrolysis Facility (FZJ)**
- **Thermal Storage (DLR)**

**Conversion Processes**
- Gas Turbine
- Electrical
- Electrochemical
- Chemical
- Thermal

**Storage/Conversion**

**Bioenergy Conversion Processes**
- **Biomass residues**
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**Smart Energy System Simulation and Control Center (SEnSSiCC)**
- Data Analysis
- Smart Grid Lab and Real-Time Simulation
- Microgrid with Grid-Control

Institute for Automation and Applied Informatics (IAI)
Existing Infrastructure

Bioliq Plant
- 2 MW fast pyrolysis
- 5 MW synthesis gas
- 150 kg/h dimethylether

1 MVA Photovoltaic Experimental Field

KIT as prosumer
- Campus North
  - 4500 employees
  - 21 MW peak load
  - 120 GWh/a

Energy Smart Home Laboratory
Infrastructure under Construction

Living Labs

Jet Fuel Synthesis

1,5 MWh Battery Storage

Thermal Energy Storage

Quelle: Younicos

Prof. Dr. Veit Hagenmeyer
Location at KIT

1 MW Photovoltaic Experimental Field
Location at KIT

1MW photovoltaics

1.5MWh Li-ion battery storage

3 Living Labs

800m² SEnSSiCC Labs

Plant network

bioliq® pilot plant

Source: EL2.0/PPQ-KIT
Energy Lab 2.0 – Components in Interaction

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bioliq® process (KIT)

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- Gas grid

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Smart Energy System Simulation and Control Center (SEnSSiCC)
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Institute for Automation and Applied Informatics (IAI)
Energy Lab 2.0
Schematic set-up
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)

- 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, Monitoring and Visualization Center

SCADA and basic concepts

Source: Pic courtesy of EL2.0/IAI/KIT
Data and Compute Platform

- Visualization
- Energy Management
- Outage Management
- Simulation of Power Grids

**Frontend Framework**

**Generic Microservice Backend (GMB)**

**Generic Data Services (GDS)**

- Data Relationship
- Schema
- Master Data
- Time Series Data
- Digital Assets

**Data Storage Technologies**

- Neo4j
- HBASE
- MySQL
- HDFS
- MongoDB
- OpenTSDB

**Big Data Analysis Tools**

- Apache Storm
- Elastic Search
- Apache Spark
- Apache NiFi

**Big Data Tools**

- Distributed Cluster Computing System (DCOS, MapR, Cloudera, …)
- Container Virtualization (Kubernetes, Docker, …)

**Energy Domain specific Services**

**Generic Operations**

(Data Analysis, Model, Optimization, Simulation)

**Process Operation Framework (Proof)**

**Cluster Management**

**Hardware and OS**

**Applications**

**Computing Cluster**

(Windows and Linux supported)
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
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
The German Grid

Installed PV-Generator density (peak)  Installed Wind-Generator density (peak)

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

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**

- **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
  - ...

Institute for Automation and Applied Informatics (IAI)
Smart Energy System Control Laboratory
Smart Energy System Simulation and Control Center

Main components:

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Main methodologies:

- Big Data, machine learning, artificial intelligence
- Advanced control and optimization methods
- 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

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 Facility 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

Advanced Control and Optimization Methods
Distributed nominal scheduling via convex optimization

Distributed battery scheduling

- 300 households, $N = 48$
- PV generation & battery
  - Convex QP ($\approx 40000$ variables)
  - Tackled via ADMM
  
  [Braun, Faulwasser et al. `16a, `17a]

→ Uncertainties? → Appino et al. `2017
→ Grid topology? Power flow restrictions?

- no storages
  $N-1$
  \[
  \sum_{k=0}^{N-1} \| \text{average-grid-load} - \text{average-demand} \|^2
  \]

- \[
  \sum_{k=0}^{N-1} \| \text{avg. rate of change of grid load} \|^2
  \]
Stochastic Optimal Power Flow

\[ D \in L^2(\mathbb{R}^{n_d}) \text{ with } \rho_D \]

\[ \rho_D(\xi) \]

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

s.t. \[ f(X, U, D) = 0, \]

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

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

Automatic Generation Control (AGC)

\[ U^*(D) \in L^2(\mathbb{R}^{n_u}) \]

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

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

- 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
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

Buffer overflows
- Format string vulnerabilities
- Dangling pointers
- SQL injections

Software attacks

Virus
- Worm
- Trojan
- Malicious Bot

Malware attacks

Against computer /IT layer

Against communication layer

Cyber attacks against SGs

Against control stations

Against equipment

Network attacks

Communications protocols attacks

Against Modbus
- Against DNP3
- Against IEC 61850
- Against ICCP

DDoS/DDoS attacks

MITM attacks
- Replay attacks

- 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

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

Smart Energy System Simulation and Control Center

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KIT Campus North – Buildings (IAI and neighbors)
KIT Campus North – Energy Lab and Bioliq (to be completed)
North of BW and South of Palatinate
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!
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