Grid Integration Advanced Simulation Tools and System Testing

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Agenda

- Intro to Center for Electric Power and Energy, The Technical University of Denmark
- Challenges in Smart Grids and Integrated Energy Systems
- Requirements for tools
- Examples
- Conclusion

History of DTU – a short introduction

Established | **Present Campus** | **Mergers & Autonomy**

1829 – **1857**

Den Polytekniske Læreanstalt

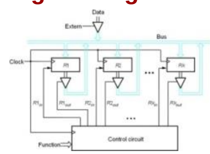
HC Ørsted

Chemistry

Mech. Eng.

1903

Electrical Engineering



Civil Engineering

1970

IT

1974

New campus inaugurated

1994

Merger with DIA

1995

Renamed DTU

2001

DTU-Act & autonomy

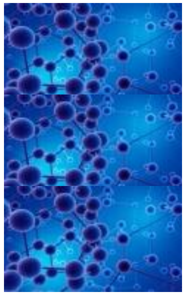
2007

Merger with:

- Risø National Laboratory
- Danish National Space Center
- Danish Institute for Fisheries Research
- The Danish Institute for Food and Veterinary Research
- Danish Transport Research Institute

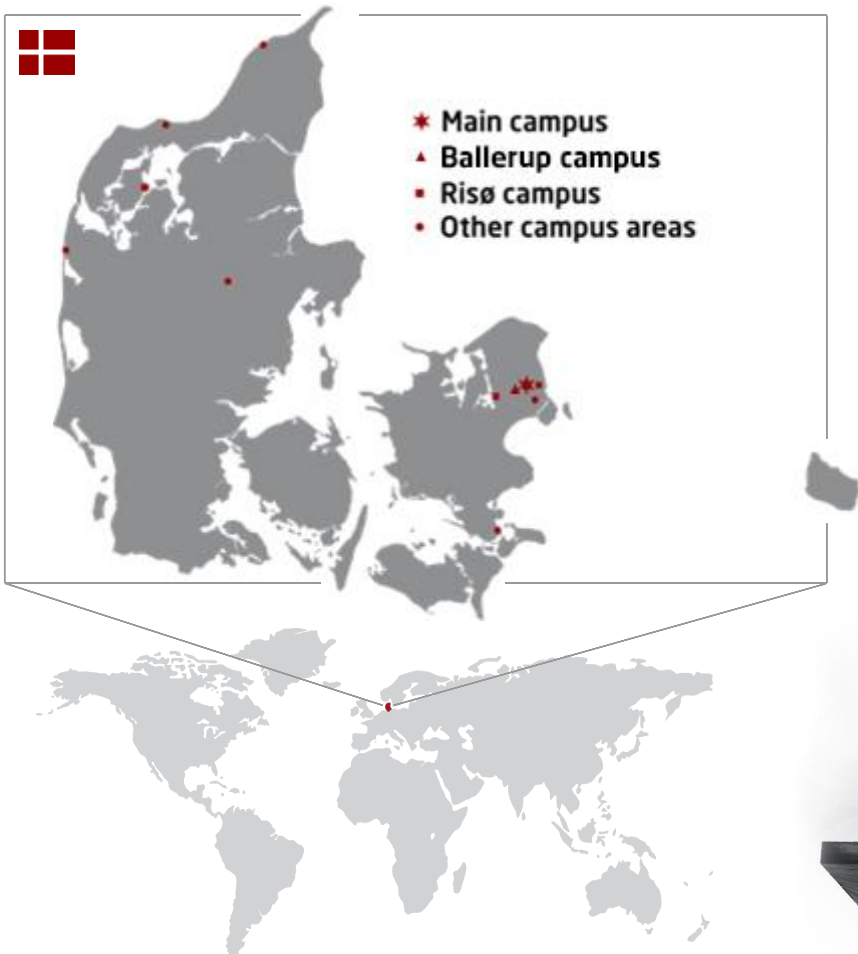
2008

Life-science & Bioengineering



Technical University of Denmark

(founded 1829; first rector H.C. Ørsted)



Key figures

Total students	~10.000
including PhD	1.150
and Int. MSc	1.000
Research publications	4.000

Ranking

Leiden Ranking 2013:
no. 1 in Scandinavia
no. 7 in Europe

Center for Electric Power and Energy (CEE)

Department of Electrical Engineering

- Development of a reliable, cost efficient and sustainable energy system based on renewable energy

- Competence areas
  - Power component engineering
  - Power system engineering
  - Distributed energy resources and control
  - Energy system operation and management
  - Electricity markets and energy analytics

- Approx. 100 staff incl. 30 PhD-students

- Located at Lyngby Campus and Risø Campus

- Bachelor and master programs
  - Electrical Engineering / Electric Energy Technology / Wind Energy / Sustainable Energy

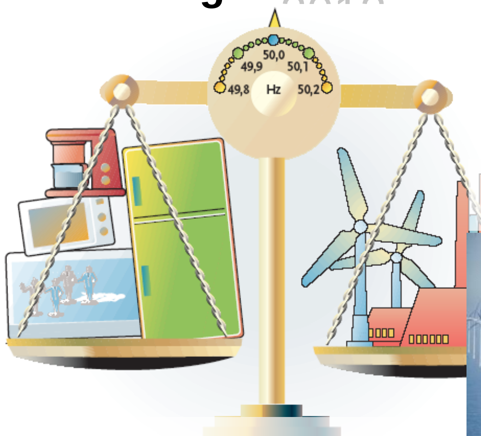
- Strategic partnerships

WinPV

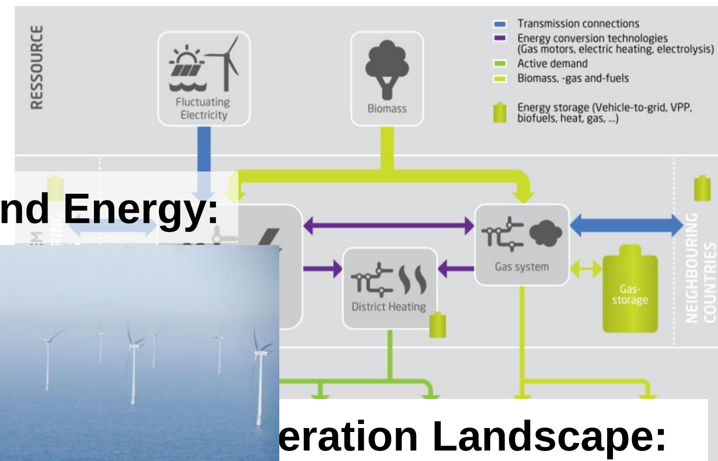
Research Challenge addressed by CEE

Development of a reliable, cost-efficient and sustainable energy system based on renewable energy

Balancing the Power System:



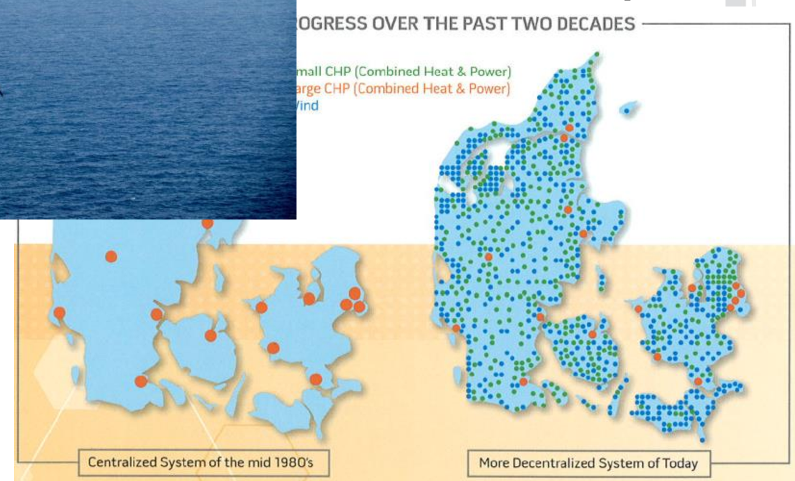
Coherent Optimal Energy System:



Cost Effective Wind Energy:

Stability and Relia

eration Landscape:



PowerLabDK

TECHNOLOGY DEVELOPMENT | TESTING | TRAINING | DEMONSTRATION

World-class experimental facilities

World-class experimental platform for technology development, testing, demonstration, research and training.

PowerLabDK combines experimental facilities in several locations

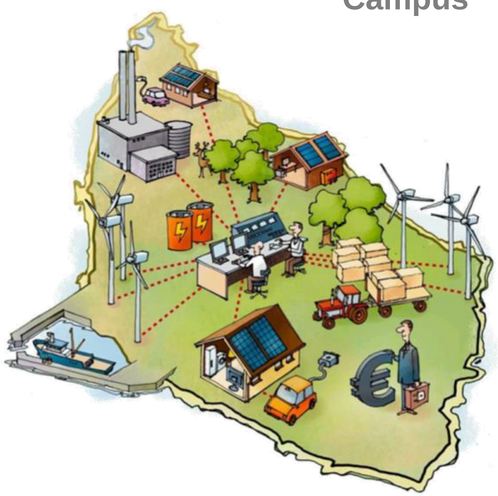
Flexible multi-purpose laboratories

Lyngby & Ballerup Campus

Large-scale test system

Risø Campus

Full-scale energy system with real users



The Island Bornholm
28,000 Customers
33% Wind Power
50% Renewable Energy
Islanding capability

Stakeholders

danishenergyassociation, IBM, SIEMENS, ENERGINET/DK, VATTENFALL, DONG energy, nkt cables, ABB

Supported by

GREEN LABS DK, EUDP, VÆKSTFORUM SJÆLLAND, Vækstforum Hovedstaden

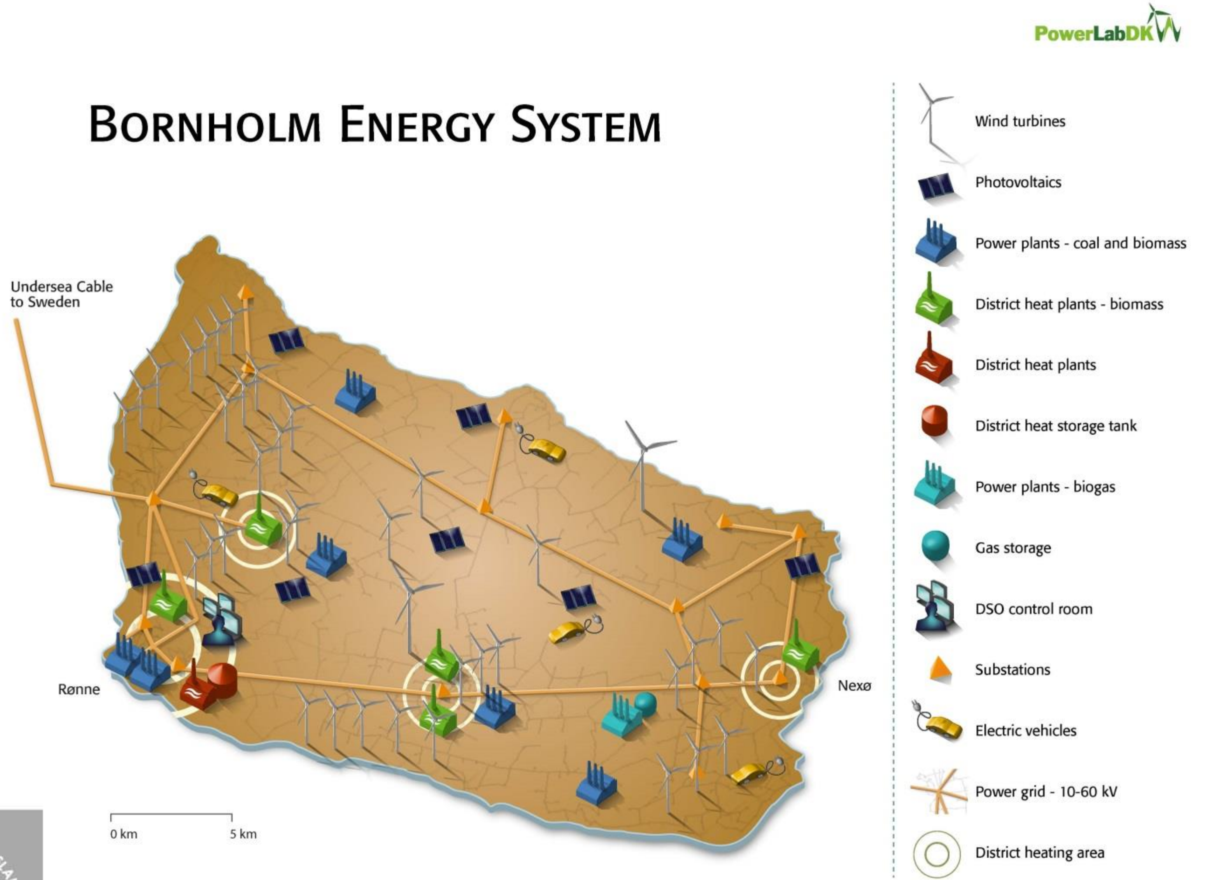
Investment

18 mill. Euro

TECHNOLOGY DEVELOPMENT | TESTING | TRAINING | DEMONSTRATION

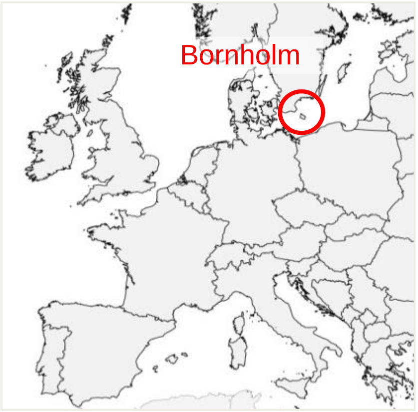
Bornholm

Living-Lab with 40,000 Inhabitants and 50% Renewable Energy Penetration and 33% Wind Power



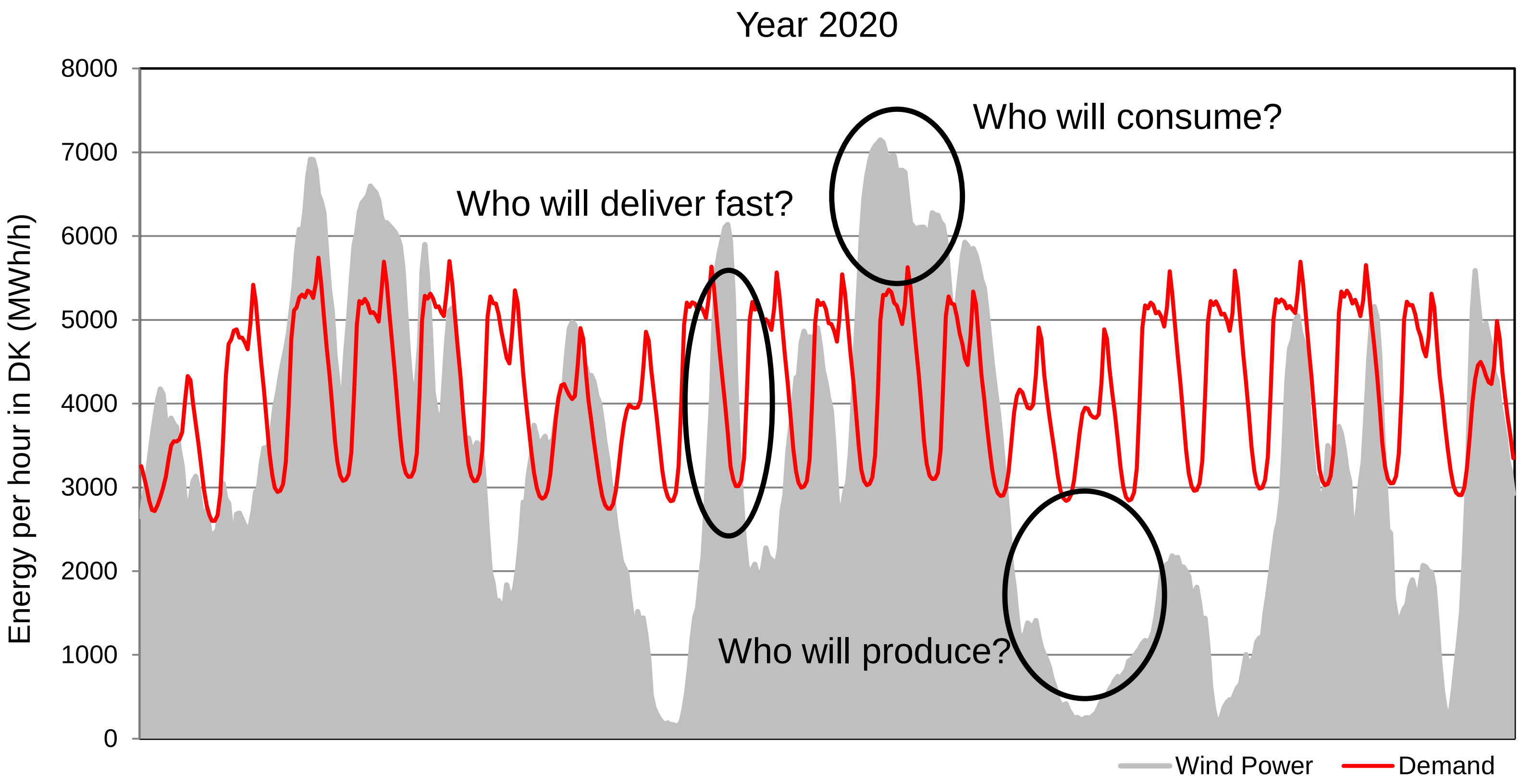
Resources:
- *Wind power*
- *Solar power*
- *Biomass*
- *Biogas*
- *District heating*
- *Combined heat and power*
- *eMobility*
- *Active demand*

Features:
- *Nord Pool market*
- *Islanding capability*

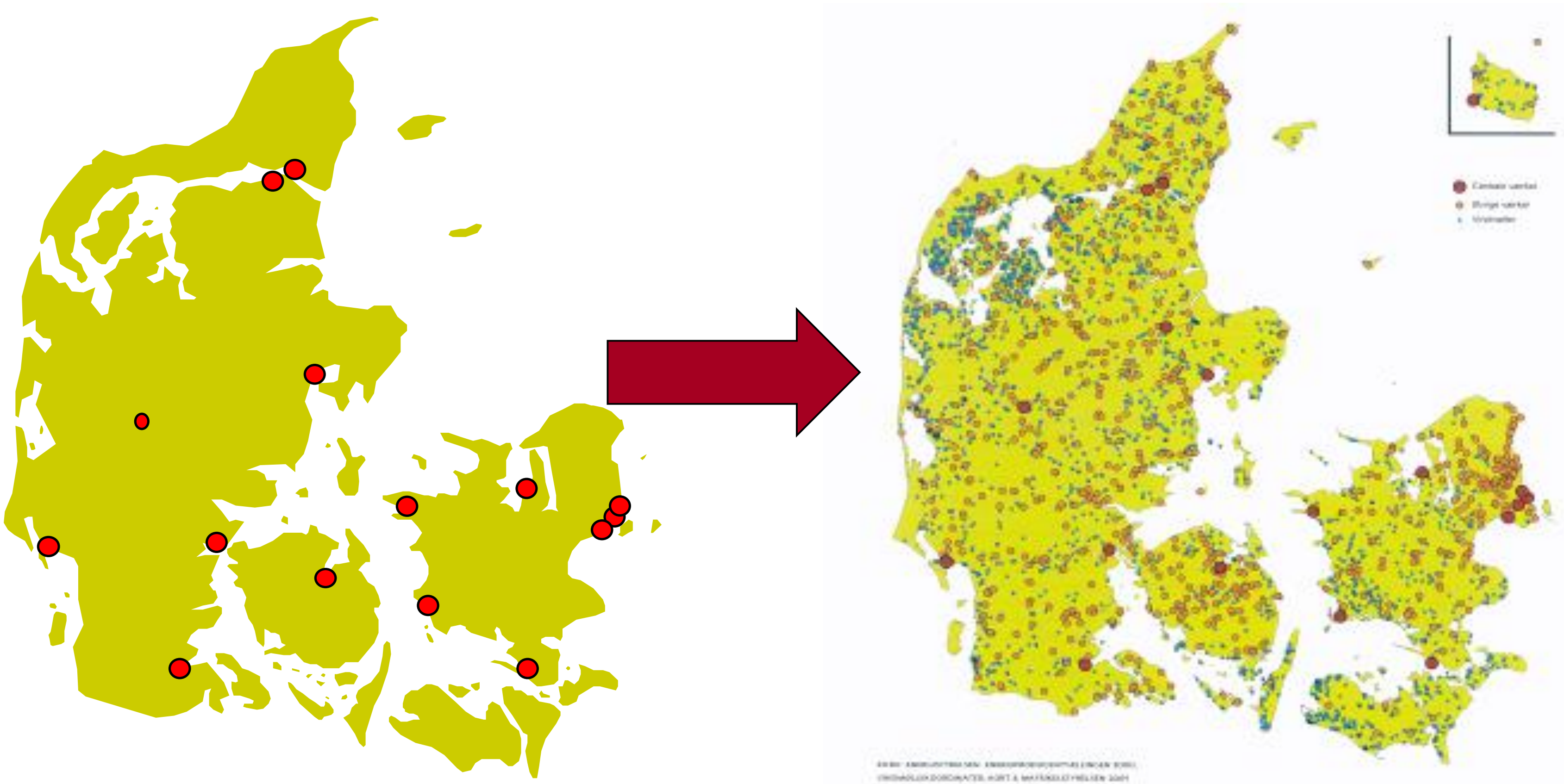


BRIGHT GREEN ISLAND BORNHOLM

The Challenges
Energy and Power Balancing

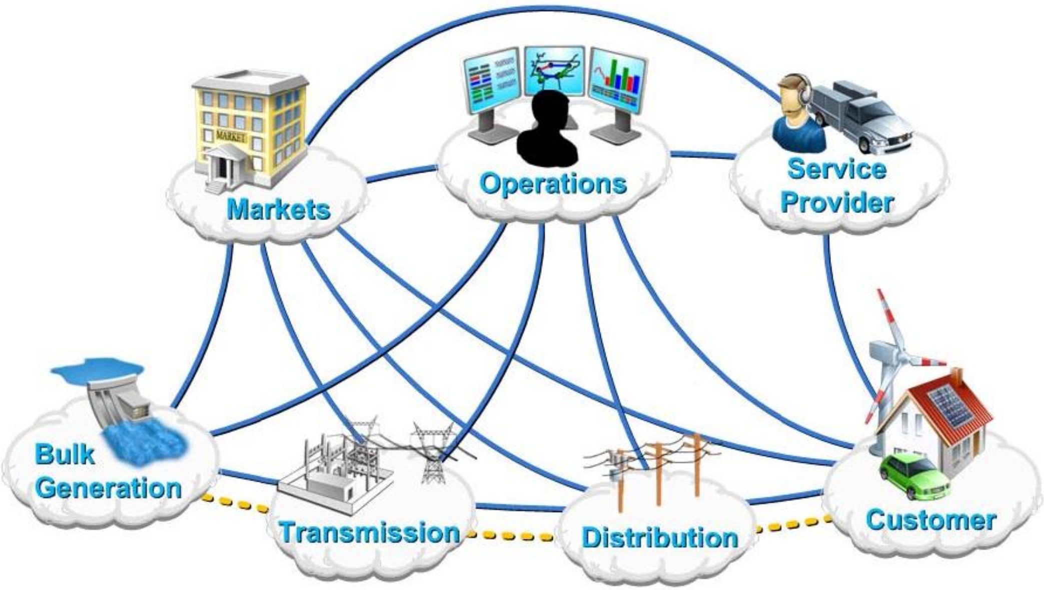


The DK Power Generation Landscape



Smart Grid

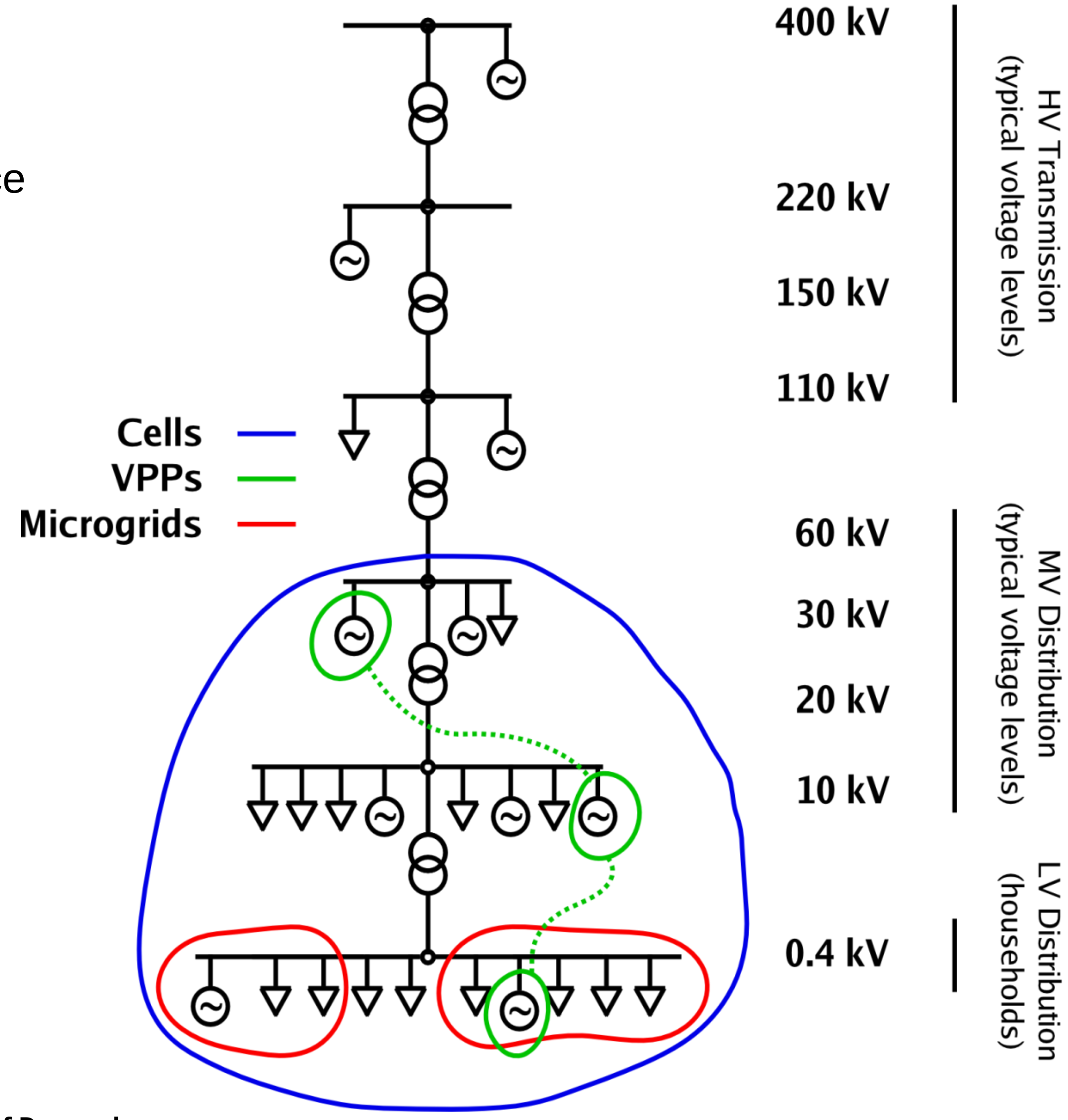
- Unbundled system
  - Transmission System Operators TSOs
  - Distribution System Operators DSOs
  - Balance Responsible Parties BRPs
  - Aggregators AGGR
  - End Consumers



Source: NIST

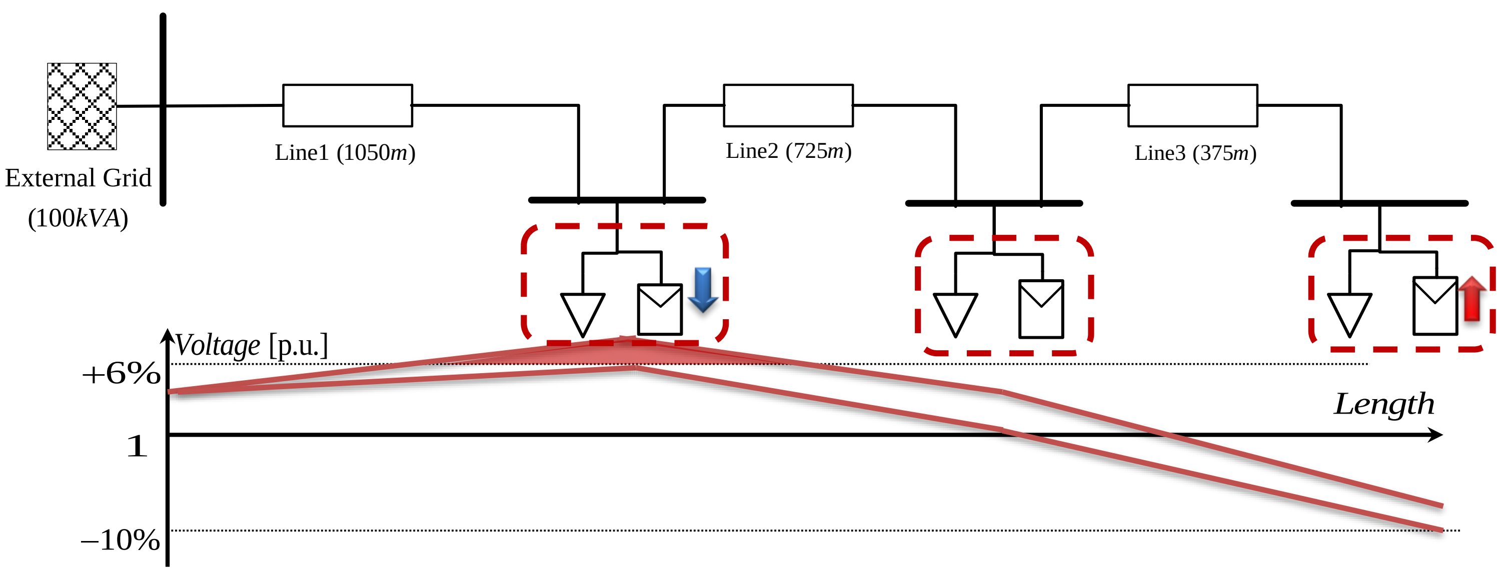
Aggregation concepts

- Several existing concepts for resource aggregation in power system control
- Microgrids
- Cells
- Virtual Power Plants (VPPs)

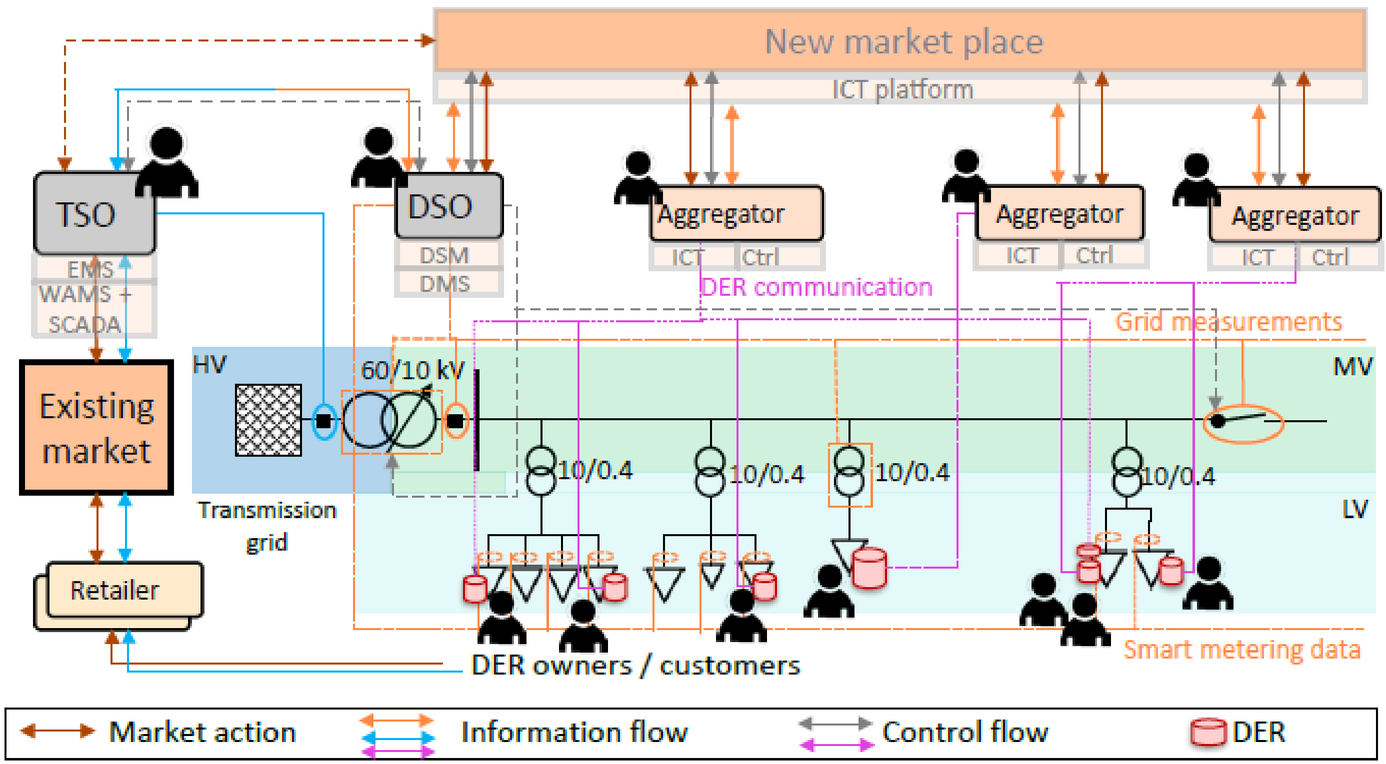


DER integration in distribution grids

- Background: An increasing fraction of PV in the grid changes the operating condition in the network. PV inverters and controllable loads in resident houses can be applied to improve the integration → Mitigate the fluctuations of voltage in LV network (EN50160: +/- 10% in 10 minutes average rms)
- Problem formulation: How to regulate active power and reactive power of available components to smooth the voltage profile along the feeder, by minimizing the overall cost of services and power loss.



Market Based Power System Control with Flexibility



Simulation and testing challenges

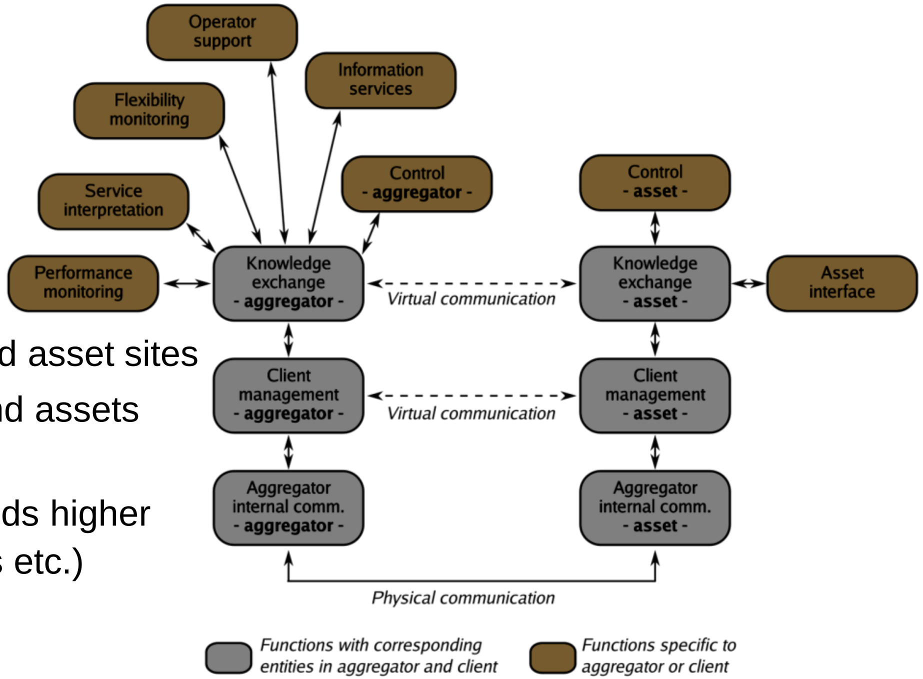
- The changes in the power system and frame conditions require new tools and methods for analysis and deployment
- It is desirable to have a tool chain that eases the effort from conception of ideas through initial investigation, proof of concept implementation to deployment
- For the tools some of the main challenges are
  - Simulation of distributed control systems
  - Simulation of multi-energy systems
  - Transition between simulation and lab/field
  - Joint system descriptions

Distributed control systems

- The term "smart grid" covers a wide range of technologies; the common element is an increased degree of automation.
- Regardless of the application area, automation in the year 2016 is almost synonymous with distributed, networked information systems, from smart sensors and sensor networks to substation logic and demand response gateways.
- A property of smart grid / smart energy applications is that the controlled physical systems are all linked through an energy network (e.g. an electrical distribution grid) and influence each other.
- In many cases, this circular interdependency does not permit the sequential simulation of energy network and automation system.

Distributed control systems

- **Use case 1:**
  Aggregation of fast services (e.g. regulating power)
- Aggregator has complex interactions with numerous other actors/services:
- Trading platforms
- Forecasting services
- Human operators
- Realtime system data
- System operators
- Communication between aggregator site and asset sites
- Communication between asset site entity and assets
- Control time constants are within
  seconds to minutes, but communication needs higher resolution (data availability / race conditions etc.)

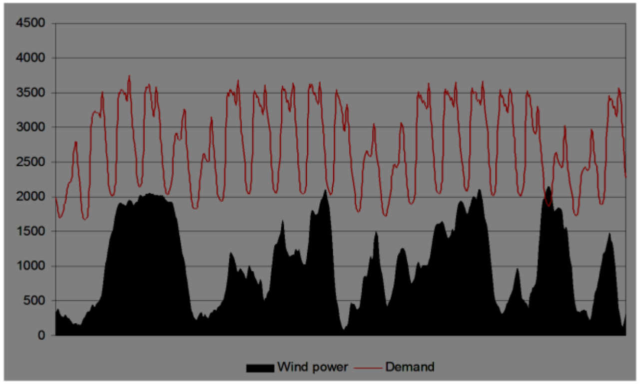


Distributed control systems

- **Use case 2:**
  Peer-to-peer control systems
- Various future applications at the research stage: e.g. Blockchain trading, grid-embedded SCADA functions, cell-based grid control (e.g. ELECTRA project)..., but performance measurement/comparison is difficult.
- In order to implement open peer-to-peer systems, i.e. systems without a fixed participant list, asynchronous network algorithms are required for performing many "housekeeping" tasks. (e.g. voting, spanning tree creation, mutual exclusion)
- The performance (e.g. convergence, robustness) of such algorithms depends on the correct representation of artefacts such as communication latencies ***within*** the (distributed) controller.
- Distributed software systems can be validated with existing communication simulators; however, in distributed ***control*** software systems, cosimulation is needed.
- Relevant communication time precision is 100µs-1ms -> event-based simulation.

Multi-energy systems

- Definition of multi-energy systems: energy systems with multiple energy carriers (and therefore multiple energy distribution infrastructures) in which energy can be exchanged between carriers. Example: Electricity, district heating/cooling, natural gas.
- Combination of district heating and electricity currently in focus in Europe, and especially in Denmark:
- 42% wind penetration (2015), expected to rise to 75% by ~2030
- 65% of DK households connected to district heating (95% in Copenhagen)
- Significant potential for system relief, e.g. dumping excess wind power into the heat network
- Simulation is challenging because the energy exchange between systems usually happens inside many complex components with embedded control.



DK West, January 2008

Multi-energy systems

- **Use case 1:**
  Heat peak shaving by network integrated electrical booster heaters
- Installation of small electrical booster heaters in the outer branches of the heat network allows the district heating network to be sized for a lower capacity by using electrical energy for peak shaving.
- Currently not coordinated with the operation of the electrical distribution system
- Heater control must respect constraints in the electrical system
- Relevant time scales: Control seconds to minutes, electrical system seconds to minutes, heat system minutes to hours (depending on how heat propagation is modelled).

Multi-energy systems

- **Use case 2:**
  Aggregation of decentralized heat injectors
- Current district heating systems correspond to electrical distribution grids before independent power producers
- Decentralized injection of waste heat (e.g. supermarket coolers) or excess renewable heat (e.g. rooftop solar thermal) is interesting for different reasons (efficiency, sufficiency, cross-network support)
- Heat-generating units are under a demand response scheme
- Trade-off between the needs of two networks in different energy domains
- Relevant time scales: Control seconds to minutes, electrical system seconds to minutes, heat system minutes to hours (heat propagation time).

Transition between simulation and lab/field

- The natural progression of research on a new control algorithm (for example an aggregator) would be from simulation to lab test to field test. In a research enviroment, full specifications do not usually exist up front, and development iterations are needed.
- How to represent control logic in a simulation in a way that porting between simulation, lab and field does not require a rewrite (validation issue, but also a large effort). Currently discussed in ELECTRA.
- Transitioning from lab to field can be done relatively straightforward by defining a common execution platform ("field-deployable lab"). This applies to realtime simulations as well, at least to some degree.
- The biggest challenge is the transition from a non-realtime system to a realtime system: It is difficult to write software that works equivalently in both contexts.
- Function blocks (IEC 61499) are one existing approach, but have difficulties representing complex software

Joint system descriptions

- Existing domain-specific tools all have their own system description languages and input formats -> configuration management nightmare
- Possible solution: Joint configuration file with compilers/translators for individual tools. However, no useable joint description language for power grids, other energy networks, ICT infrastructure and ideally control logic exists.
- Ongoing attempt in the H2020 ERIGrid project to develop a system configuration description language for use with simulations and research implementations. The current approach uses the generic network model (and parts of the vocabulary) of CIM, but aims at a lower modelling depth.

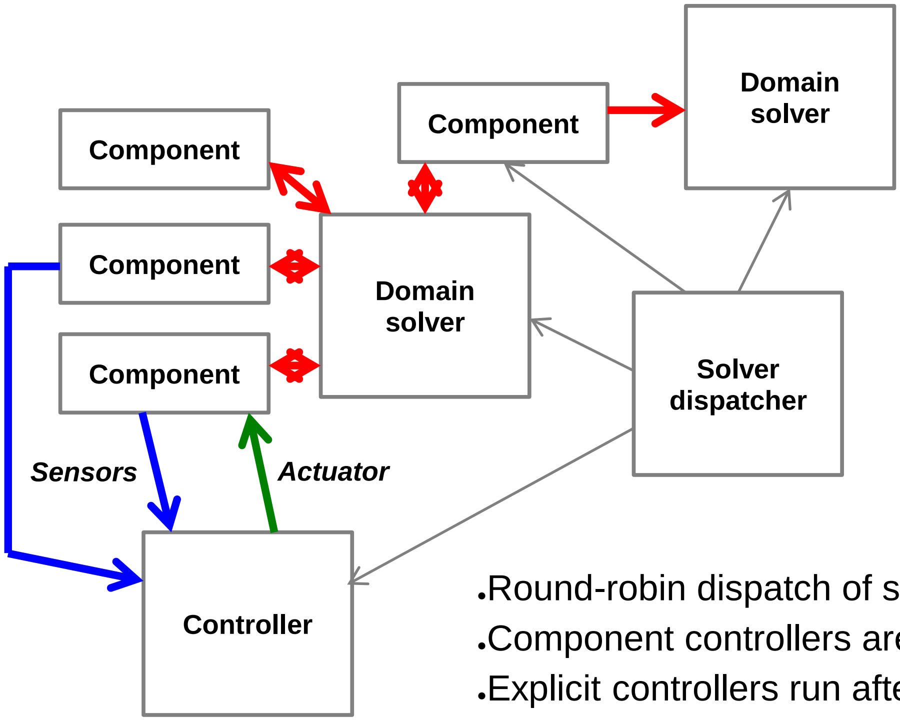
IPSYS: Main objectives

- Tool for technical performance analysis of isolated and interconnected energy systems.
- Tool for research on distributed control of power systems
- In many cases, the interaction between multiple energy (storage) domains has to be modelled: Electricity, heat, cooling, drinking water, hydro runoff, gas-based storage etc.
- Control is key - detailed modelling of the impact of different control strategies is very important.
- IPSYS is meant to supplement other models for planning, dynamic stability analysis etc.
- Input of environmental parameters in various formats (time series, parametrisation of stochastic behaviour etc.).
- New types of energy resources, energy domains and controllers must be easy to add to the model.

IPSYS: Main features

- Timestep simulation, quasi-static model
- Explicit interaction between different balancing domains. Currently: Electrical, mechanical, thermal, hydraulic, gas flow
- Explicit modelling of the electrical network (load flow, active and reactive power sharing)
- Explicit modelling of distributed control hierarchies (sensors, actuators, supervisory controllers)
- Explicit modelling of energy storage
- Very flexible system configuration
- Highly modular architecture
- High performance (originally C++, ported to Java)
- Input from external time series or internal time series generators
- Built-in optimisation module

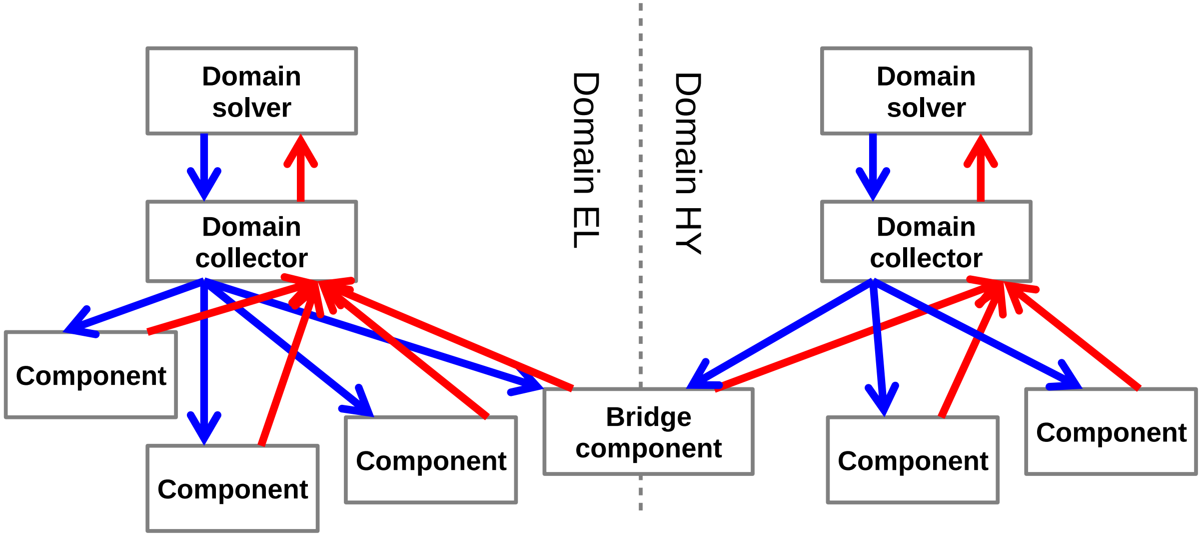
The IPSYS model: Domains, components and nodes



- Each domain has a separate solver
- Components which are in more than one domain ("bridge components") transfer data after domain equilibrium

- Round-robin dispatch of solvers until global equilibrium achieved
- Component controllers are implicit
- Explicit controllers run after each solving round

The IPSYS model: Domains and solvers



- Solvers are split in two parts: One part handling the flow of data to and from the individual system components, and one part doing the math
- Data may have to get pulled and pushed several times per solving step in order to represent nonlinearities in the components (e.g. implicit controllers)

Type library

– **Component types**
- Wind turbine
- PV system
- Diesel genset
- f/P Dump load
- Battery (different models)
- Transformer
- Transmission line
- Stochastic el. consumption
- Desalination
- Grid tie
- DSM household
- Refrigerated warehouse
- Electric vehicle
- Gas compressor
- Gas storage
- Heat consumer
- Heat storage

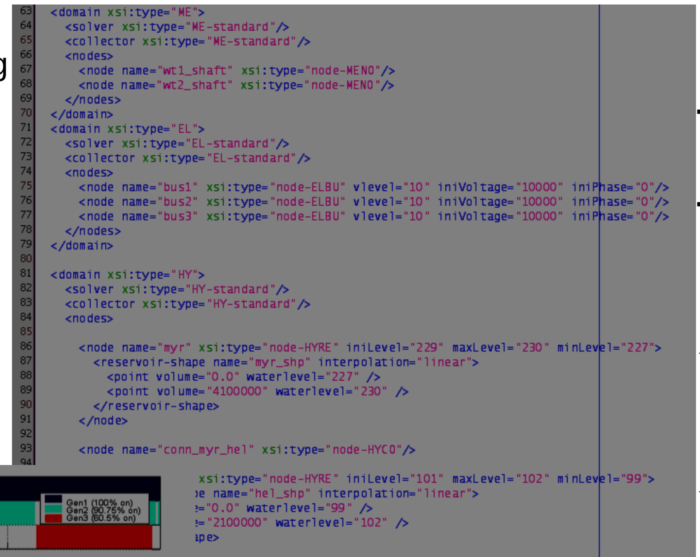
– **Component types (cont'd)**
- Hydro turbine
- Hydro reservoir
- Fuel cell
- Electrolyser
- CHP plant

– **Domain types**
- Electrical (3-ph AC power system)
- Mechanical
- Hydraulic (reservoirs and flow)
- Freshwater
- Heat
- Gas (Hydrogen storage)

– **Timeseries generators**
- Wind
- Solar
- Load

Input, output and optimization

- Output: Time series and separate event log
- Each component offers a set of output channels, which can be individually added to the output
- External post-processing and visualisation (Matlab, Java)



```
<domain xsi:type="ME">
  <solver xsi:type="ME-standard"/>
  <collector xsi:type="ME-standard"/>
  <nodes>
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    <node name="wt2_shaft" xsi:type="node-MENO"/>
  </nodes>
</domain>
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  <solver xsi:type="EL-standard"/>
  <collector xsi:type="EL-standard"/>
  <nodes>
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    <node name="bus2" xsi:type="node-ELBU" vlevel="10" iniVoltage="10000" iniPhase="0"/>
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  </nodes>
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    </node>

    <node name="conn_myr_hel" xsi:type="node-HYCO"/>

 xsi:type="node-HYRE" iniLevel="101" maxLevel="102" minLevel="99">
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ape>
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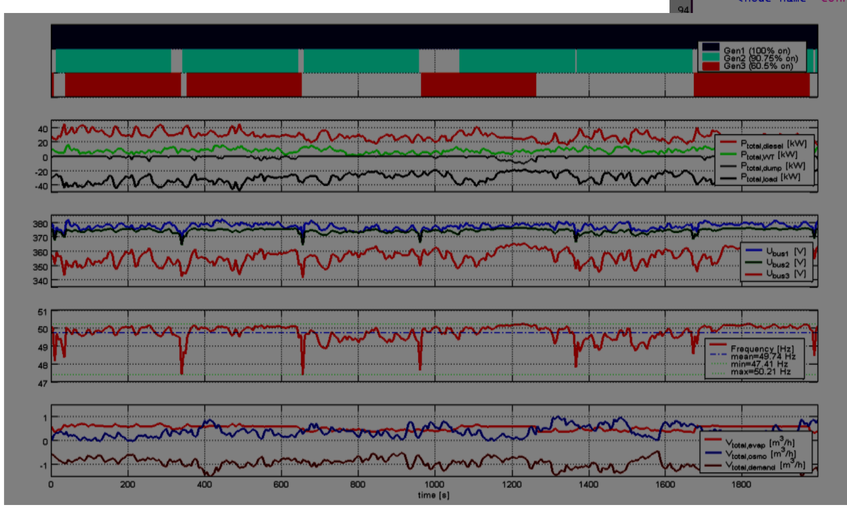
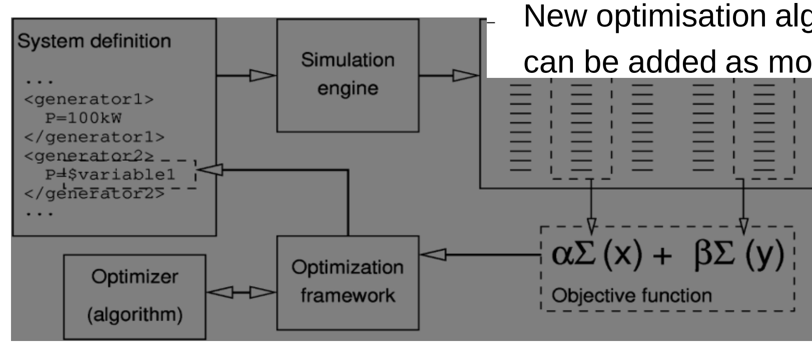


- IPSYS is only a simulation engine, separate pre- and postprocessing.
- Energy system definition as structured XML - No GUI
- Timeseries input in various formats (we tend to use raw binary)
  - Any simulation parameter can be used as an optimisation variable
  - Any combination of output timeseries can be used to build the objective function
  - New optimisation algorithms can be added as modules



Case study: Faroe Islands

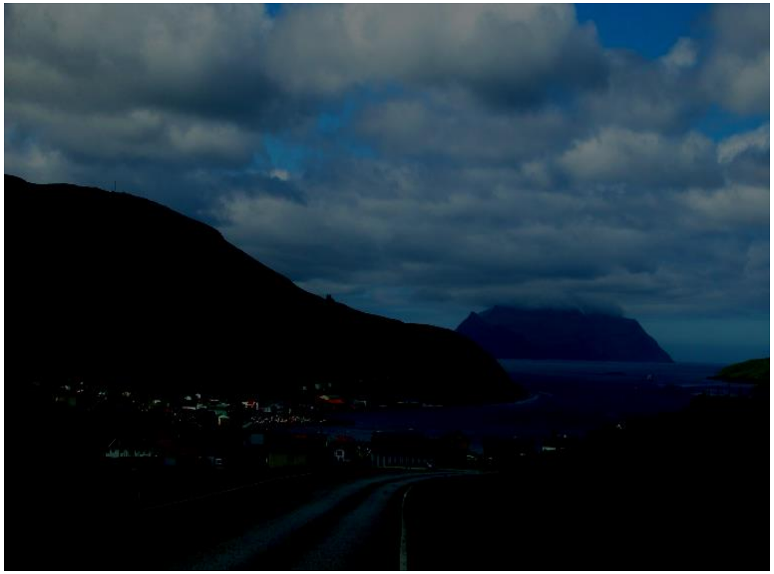
- Island power system with 50.000 customers, 60kV backbone
- 60% Diesel, 35% Hydro, 5% Wind
- 5 hydro reservoirs (one cascade), 7 turbines

- **Objective**: How much wind power can be tolerated in the present system?

Case study: Faeroe Islands

- **Modelling issues**:
- No direct measurement of reservoir inflow
- Reservoir levels and production available

- **Control issues**:
- Use of water: Turbine dispatch when inflow is increasing
- Start/stop strategy for diesels / minimum runtime
- Dynamic load sharing / droop shifting

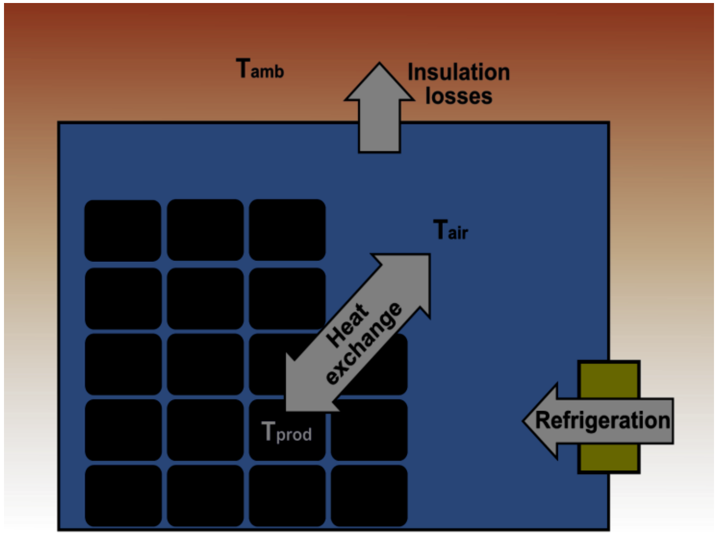


Case study: Nightwind

- **Objective**: Using refrigerated warehouses for large-scale demand response

- **Modelling issues**:
- Thermal model of coldstore and stored product.
- Heat losses due to product throughput

- **Control issues**:
- Integration of GA-based control strategy provided by a third party



Advantages/disadvantages

- IPSYS is a pragmatic model; does not aim at being usable for 100% of missions. Complexity in scale, not necessarily depth.
- Modularity enables a very intuitive approach to inter-domain coupling: All coupling is done by dedicated logic in the bridge components, the solvers don't know about each other.
- Cross-platform, open source (BSD 3-clause), headless -> runs embedded, easy handling, deployment, extension, integration
- Single configuration

✗ Not easily representable as system of ODE without either giving up modularity and flexibility -> FMI ME probably no-go

✗ -> not trivial to exploit parallelism (low hanging fruits: parallel domain solving, multithreaded matrix libraries inside solvers)

✗ Controller model with explicit sensors/actuator "wiring" is not useful for larger (smart grid) scenarios

Time scales

	Power system	Communication network
Time scale	Transient -> quasistatic -> static	Discrete (packets) -> continuous (queueing)
Size scale	One node per country -> one node per building	WAN -> substation LAN
"Complexity scale"	Explicit controllers -> implicit controllers with/without harmonics unbalanced/balanced	Link layer -> transport layer -> application layer

=> different component models for each case.

What if the scales don't match?

Towards deployment

- Lab testing
- Living lab

The SOSPO project

Secure Operation of Sustainable Power Systems

Future power system

C37.118

OPC

Control center

SW-platform constructed in PowerLabDK

- Streams PMU snapshots from the RTDS and can make real time changes to running simulation
- Functions as a ”SW-in-the-loop”
- Well suited of implementation of new methods that use wide area data for monitoring or control

The future power system simulated with RTDS

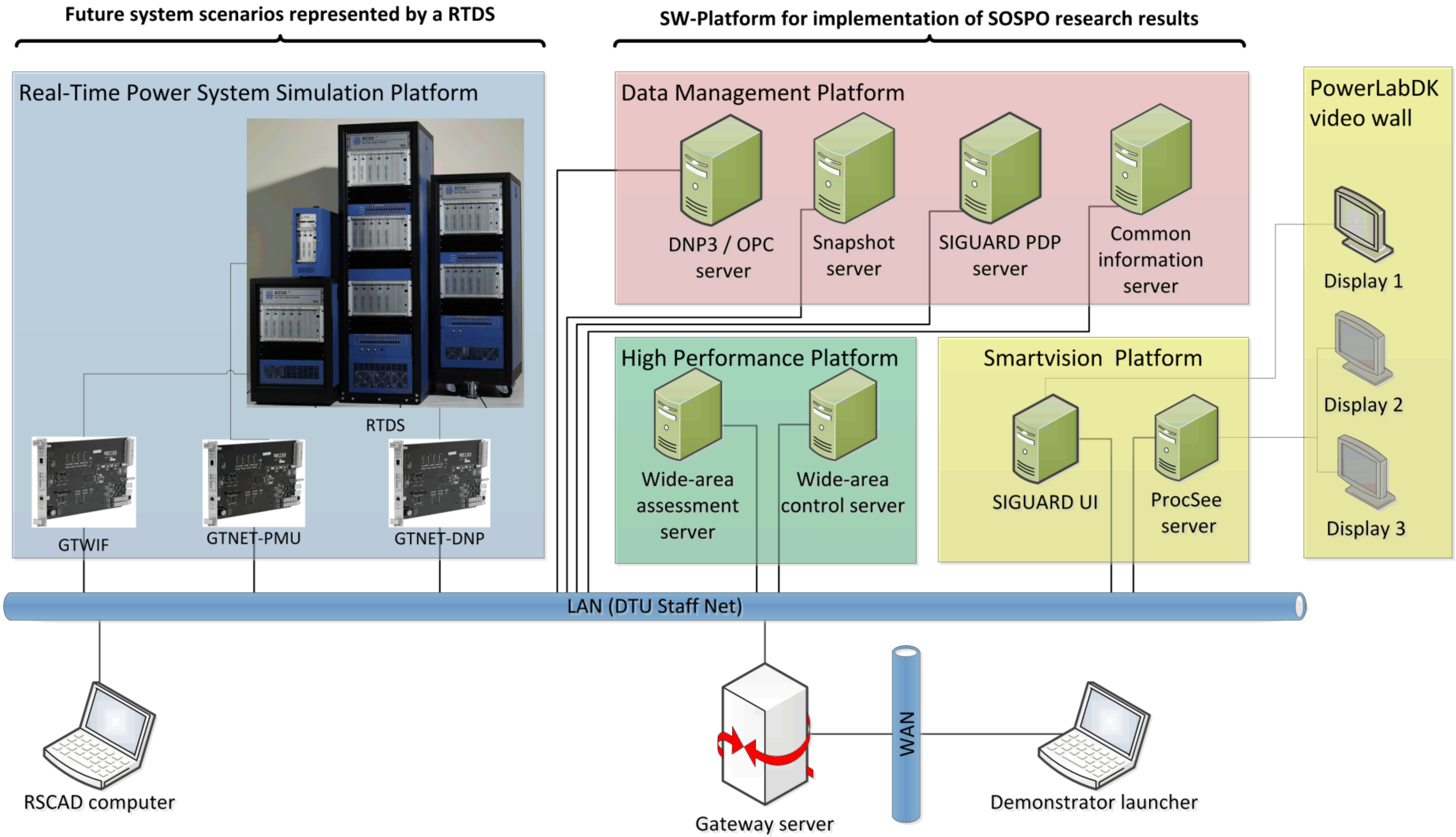
SOSPO R&D results implemented in a SW-demonstrator

Examples of innovative R&D achievements

- New method giving early warning for blackouts -> world record fast stability assessment (Assessment time 2.5 ms in system with 7917 nodes, 1325 gens; Tested on 2003 SW-DK blackout -> ≈ warning 80 s before blackout)
- Methods for early blackout prevention, for real-time assessment of transient voltage dip (dynamic security assessment) and for fast determination of N-1 steady-state security
- Software experimental framework in PowerLabDK; Three patents applications.

SOSPO SW-Platform

An advanced modular development platform



PowerLabDK

SYSLAB and PowerFlexHouse

Intelligent distributed energy system in practice

www.powerlab.dk

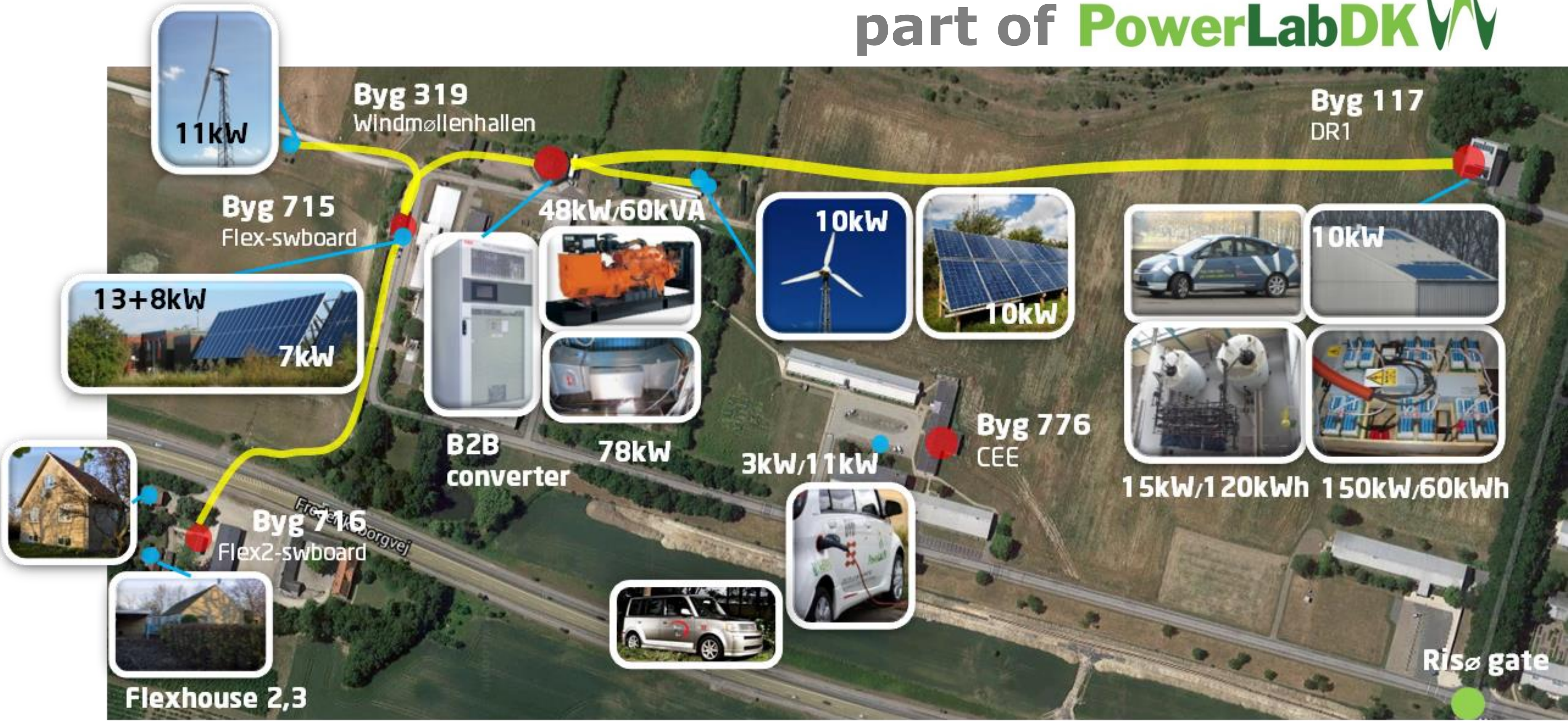
DTU Technical University of Denmark

INGENIØRHØJSKOLEN KØBENHAVN - University College

ØSTKRAFT energi til gode oplevelser

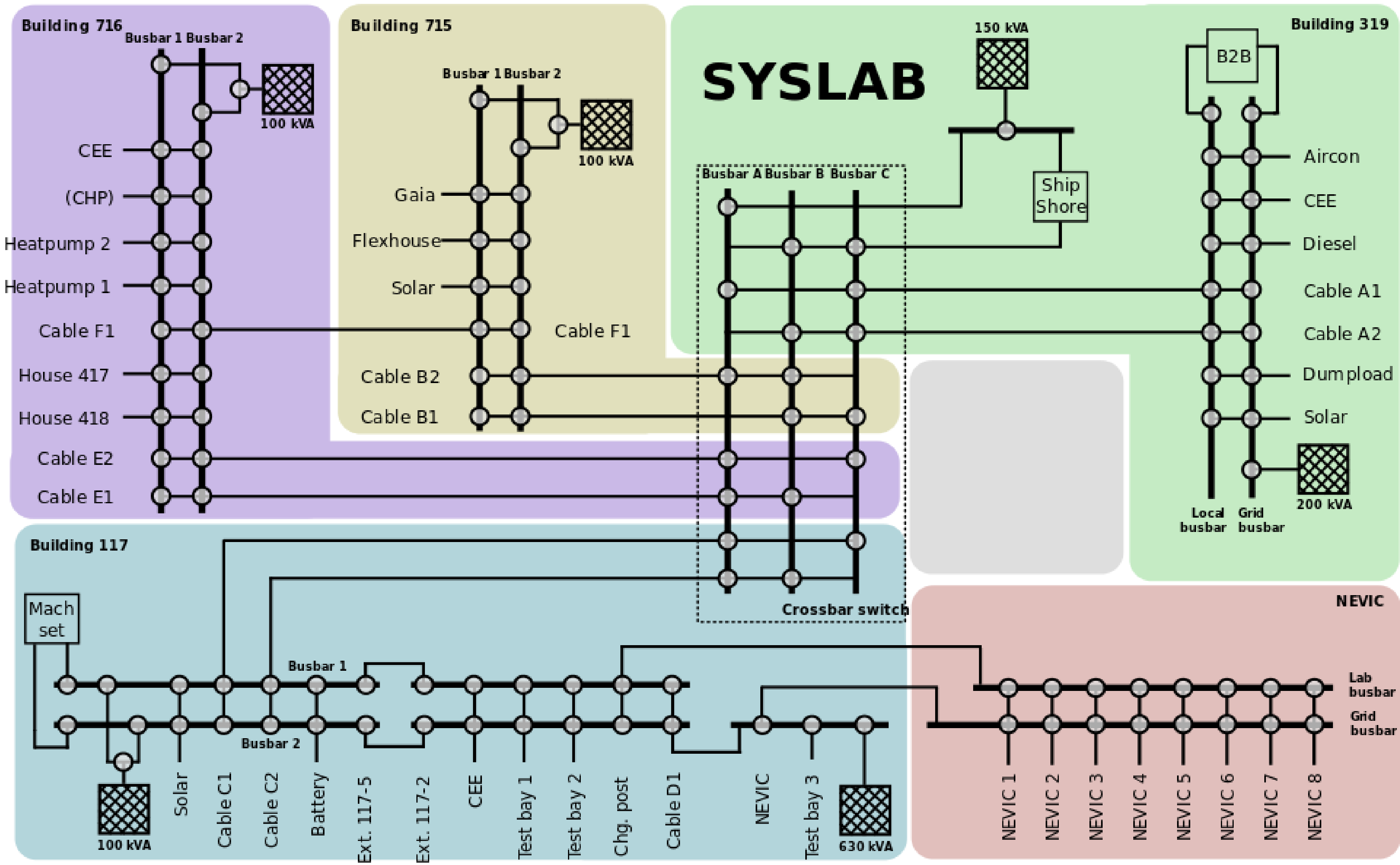
SYSLAB – Distributed Energy System Laboratory

part of PowerLabDK



- 3 additional load simulators (mobile and stationary)
- Capacitor bank
- Hydrogen-based CHP (to be installed)

SYSLAB Grid topology (2013)



SYSLAB / Hardware platform

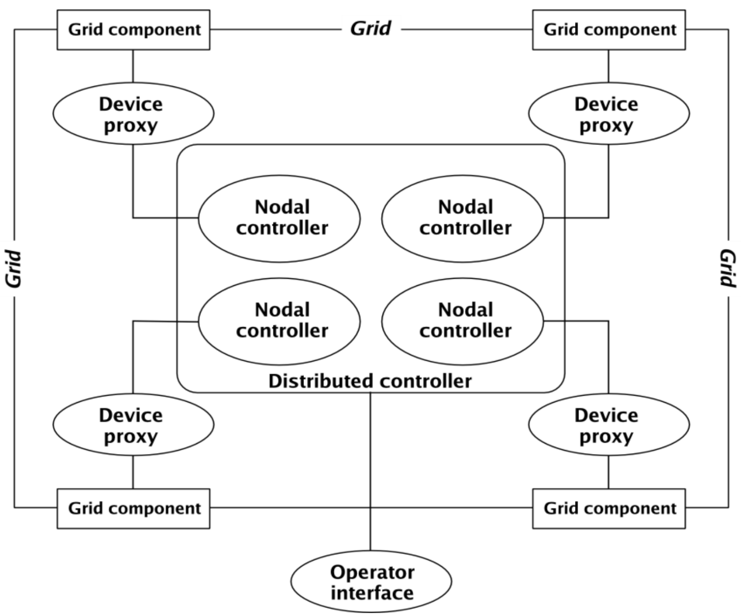
•Every unit is supervised locally by its own controller "node". Nodes contain a computer, measuring and network equipment, data storage, backup power and field buses "in a box".

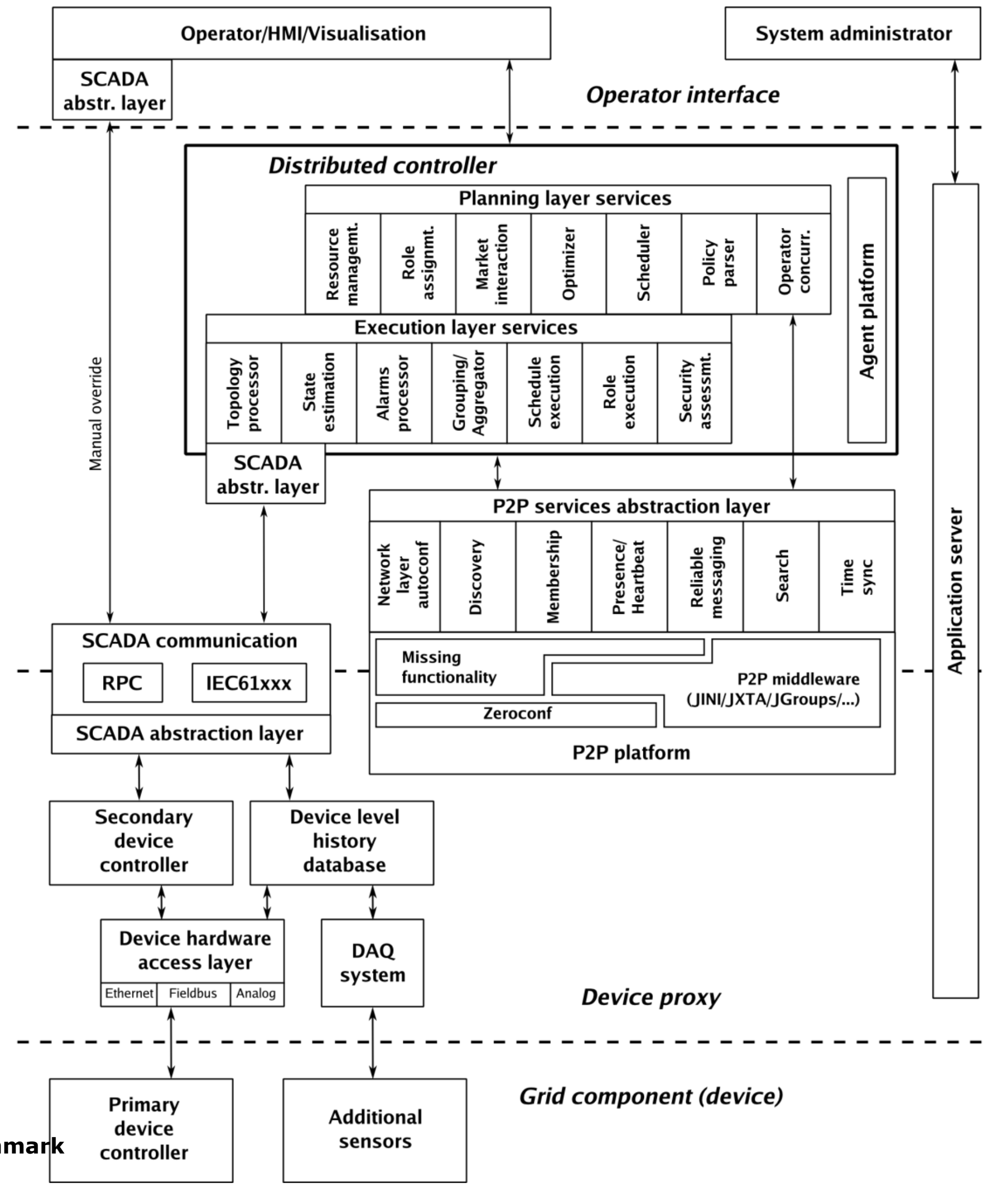
•Each node can communicate with all other nodes.

•The design does not enforce a central controller. The whole system can be run from anywhere.

•21 SYSLAB nodes +20 helper machines, total ~1000 source files

Execution platform

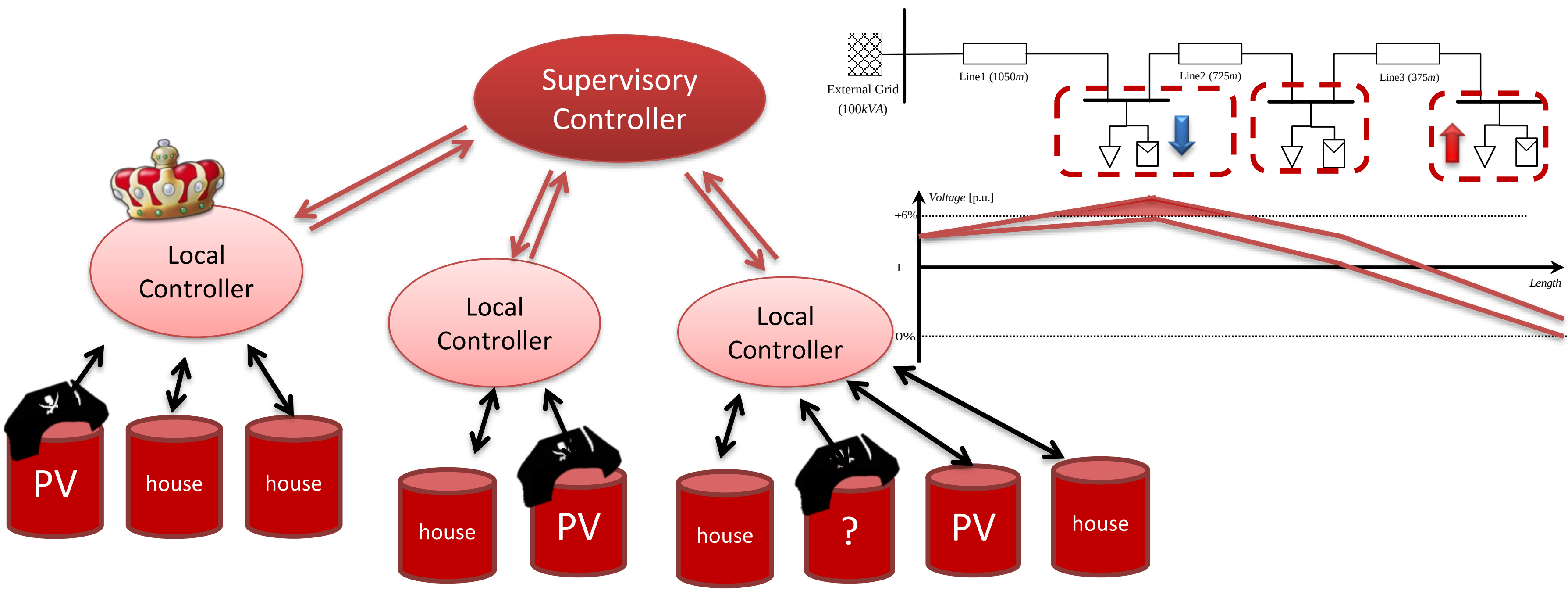




- Interactions between entities defined in software, not hardware
- easier transition between the current system (static hierarchy) and future paradigms, as research progresses

Voltage Controller for distribution feeder

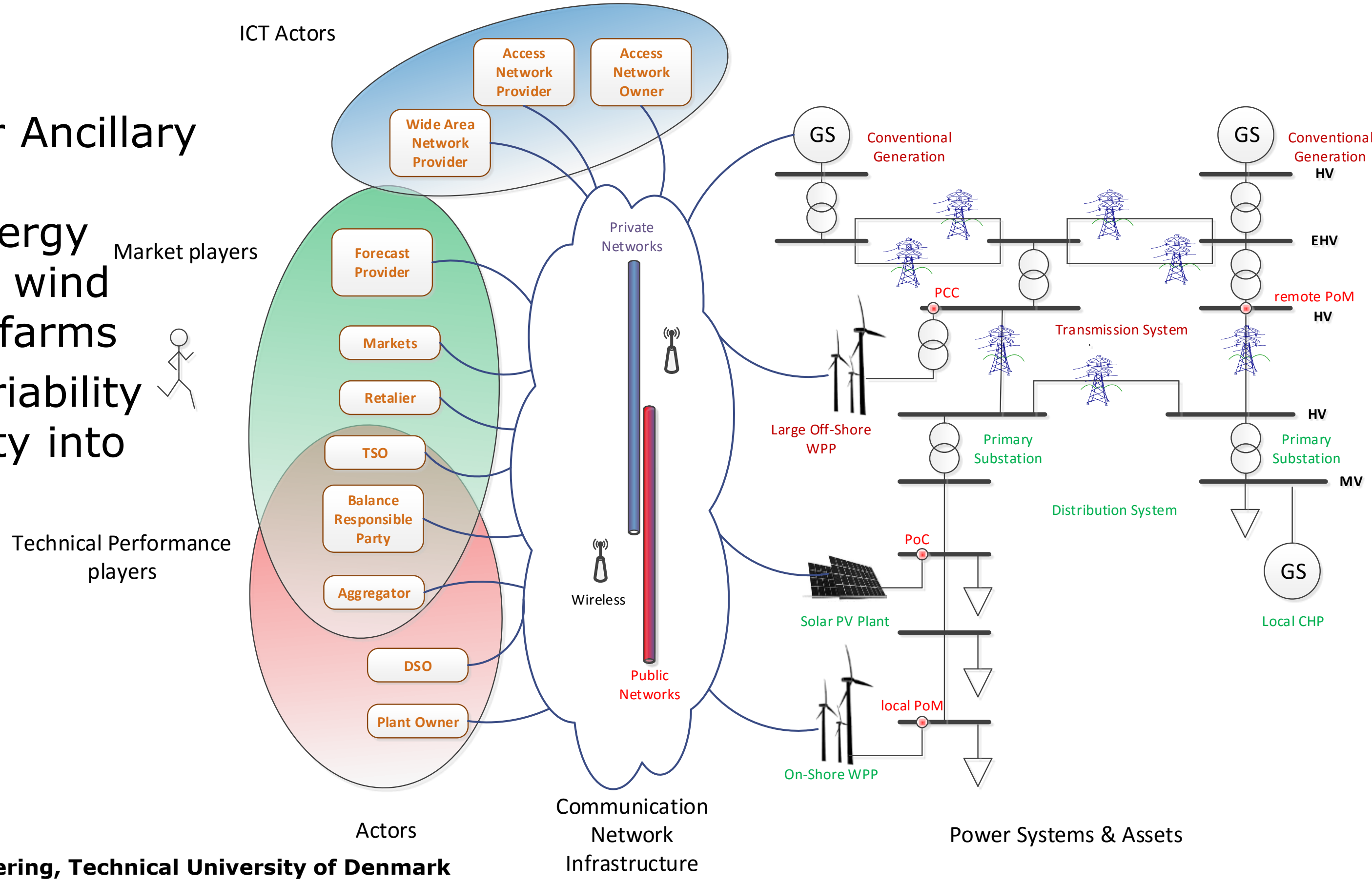
- Challenge: implement control infrastructure AND control algorithm
- Simulation setup: Matlab that includes power flow and controller with explicit information exchange between components
- Experiment setup: Fixed topology of a radial feeder (SYSLAB), contracted services with PVs and residential loads (10 heaters per house) of certain cost.
- Aggregation: flexible active power and reactive power
- Goal: voltage within the limit band & efficient power delivery



RePlan (1/2)

- Project funded by Danish TSO Energinet.dk
- Partners: DTU (Wind, Elektro), Aalborg University, Vestas

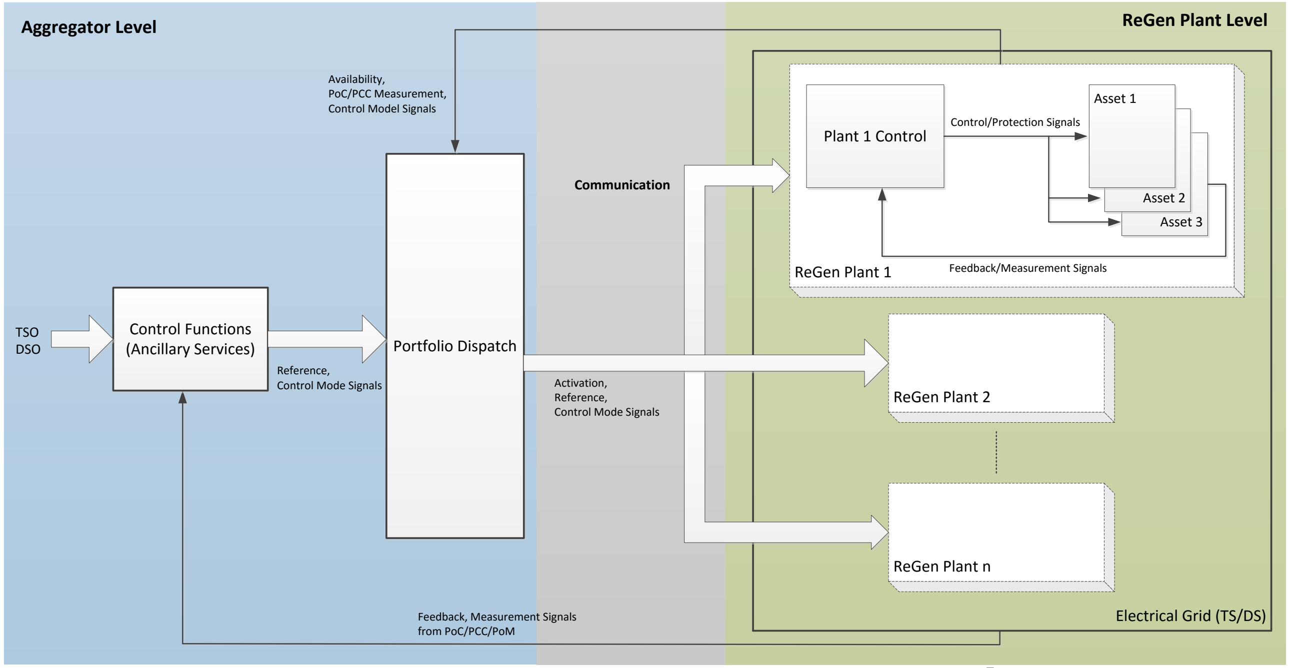
- How to deliver Ancillary services from Renewable Energy Plants, mainly wind farms and PV farms
- Taking the variability and uncertainty into account



RePlan (2/2)

- Resource allocation based on service, RePlant availability and present operating conditions
- Optimal dispatch of portfolio
- Takes distributed nature of problem explicitly into account (spatial correlation, communication etc)

- Wind based System incl. controllers implemented in Opal-RT
- PV based system implemented in Matlab incl. optimal dispatch algorithm and will be transferred to lab

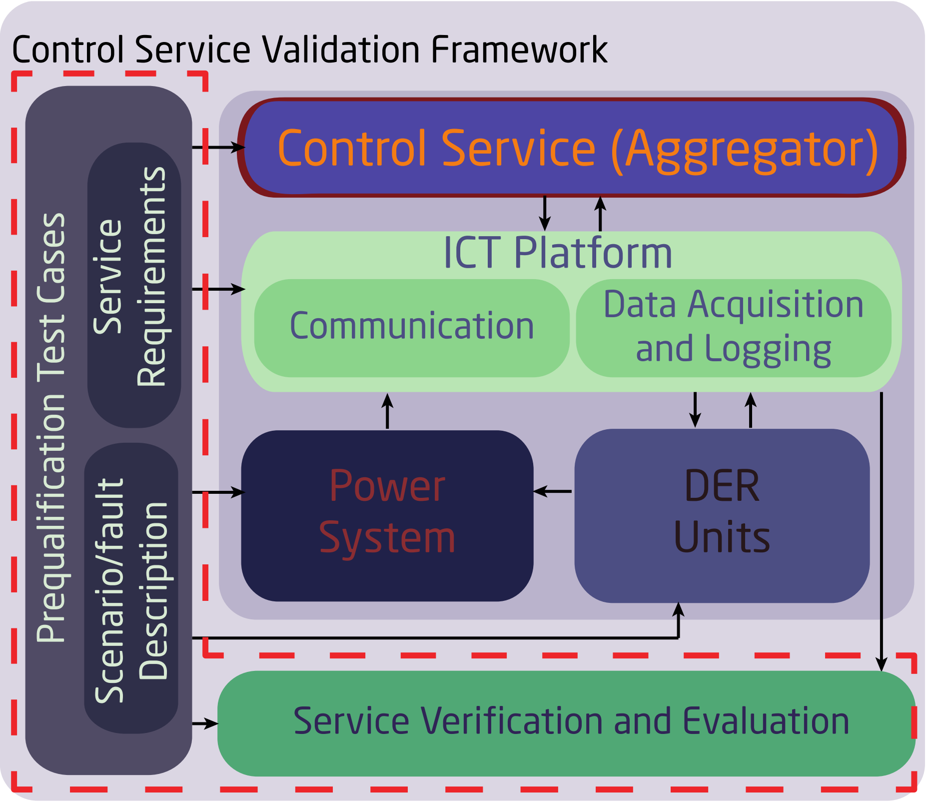


WinPV

DTU

Validation of control services

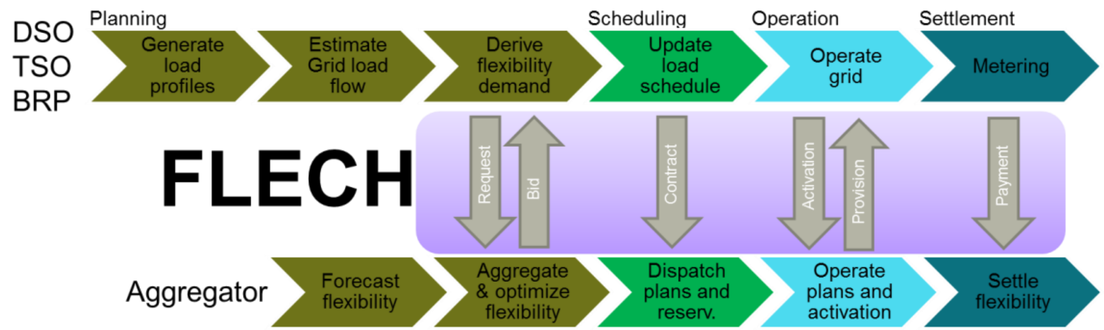
- **Main question:**
- How do we ensure the reliability of services provided by Control Services (e.g. Demand Response)?
- Can formalized methods for validation be applied?
  - Implementation in Matlab
  - Initial Proof of Concept implementation in SYSLAB
  - Aiming at simulation based test environment
- Collabotation with Energinet.dk, Aggregators and DSOs

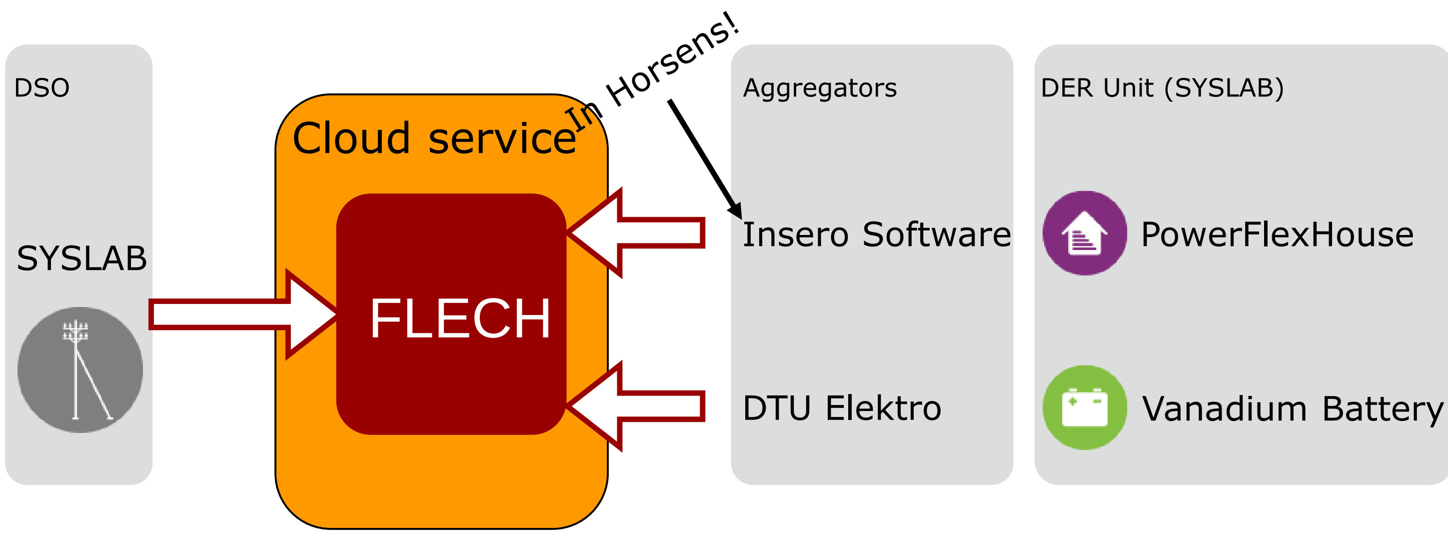


- Published paper: "Performance Assessment of Aggregation Control Services for Demand Response" @ IEEE PES ISGT 2014
- Technical report : "FLECH PowerMax Service Requirement Specification".

FLECH Demo Setup

- Moving from simulation in Matlab to lab test
- Multi-location test
- Collaboration between ICT developer (IBM), Aggregator (Insero) and University (DTU)





Conclusion

- The new and changed situation with Smart Grids require new tools
  - Many new active components participate in control
  - Unbundled power sector means new responsibilities and functionalities
  - New control concepts are made possible by new sensors and ICT systems
  - Integration of different parts of the energy system links sub-systems
- The new tools require additional insights into the physical systems as well as modelling techniques
- The simulation tools are part of a development chain from concept to product
- Lab facilities, living labs and field tests are needed as part of the development chain and they should be integrated with simulation tools
- Collaboration with all players are necessary including TSOs, DSOs, /BRPsAggregators, components suppliers and system integrators
- Universities can play a crucial role in the development and testing

Questions

Thank you

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