Methods and Tools for Validating Cyber-Physical Energy Systems

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Motivation and Aims for the Tutorial

- Ongoing challenges and needs
  - Integration of renewables requires advanced ICT, automation, and control
  - The raising complexity of such Cyber-Physical Energy Systems (CPES) urge for integrated, multi-domain based validation methods and tools
  - Well-educated researchers and engineers in the domain of CPES
- Tutorial introduces and provides
  - Challenges in CPES development and validation
  - The integrated ERIGrid validation approach
  - A holistic validation procedure for CPES-based system-level testing
  - Enhanced simulation and lab-based testing methods
  - An overview of selected validation examples
  - Information about the free access to smart grid laboratories

About the Speaker

- 2001 MSc Industrial Engineering, VUT, Vienna
- 2003 PhD Mechanical Engineering, VUT, Vienna
  PROFACTOR Research, Steyr
- 2007 Senior Researcher at PROFACTOR Research
- 2010 AIT Austrian Institute of Technology
  Scientist Electric Energy Systems
- 2012 AIT Austrian Institute of Technology
  Senior Scientist Electric Energy Systems
- Involvement in several national and international research projects
- Evaluator for various international research programs
- Teaching at Vienna University of Technology (VUT) as a docent (Privatdoz.)
- Active in IEEE, CIGRE and IEC
- Core topic: Power Utility Automation in Smart Grids

Acknowledgements

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- Special thanks to all ERIGrid partners for their contributions to this tutorial
- This tutorial is sponsored and technically supported by the
  - IEEE IES TC on Smart Grids (TC-SG)
  - IEEE IES TC on Industrial Cyber-Physical Systems (TC-ICPS)
  - IEEE IES Standards TC

Outline of the Tutorial

- Background and motivation
- Status quo in validation and future needs
- The ERIGrid vision and approach
- Holistic validation procedure
- Simulation and lab-based testing methods
- Selected validation examples
- Discussion, feedback, and conclusions

Background and Motivation

INDIN 2018 Tutorial

Methods and Tools for Validating
Cyber-Physical Energy Systems

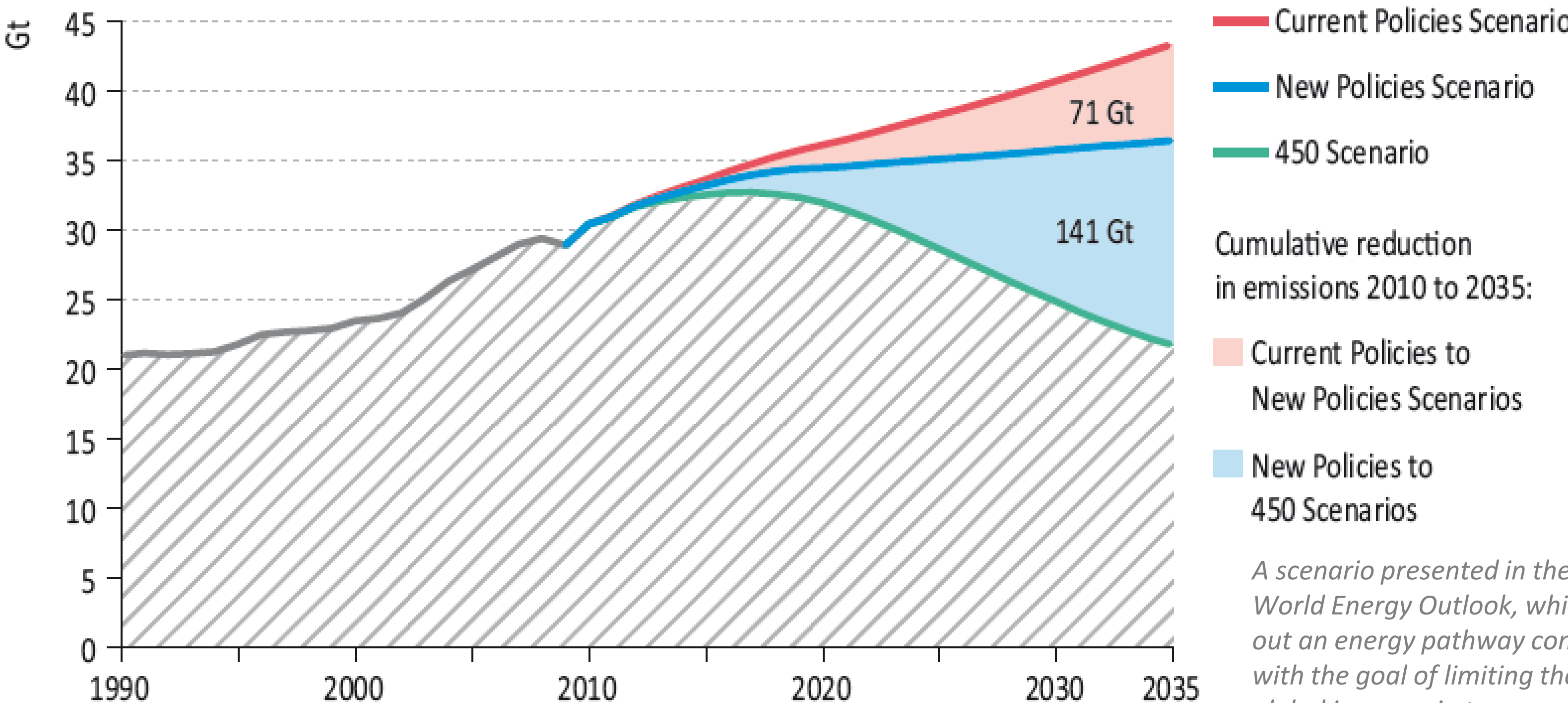
Societal Challenges

- Climate change
- Fossil fuels
  - Political instability of producing countries
  - Increase in demand and volatile prices
- Economic crisis
- Demographic and economic development in China, India & South East Asia
  - Increasing impact on quality of water, air, land resources
- European position in a fast changing world
  - Economic development – quo vadis?
  - Demographic development (ageing society etc.)
  - Welfare of the society

International Energy Agency (IEA)

- IEA Energy Technology Perspectives 2008
  - … "… a global energy technology revolution is needed …"
- IEA World Energy Outlook 2008
  - … "… The world's energy system is at a crossroads. Current global trends in energy supply and consumption are patently unsustainable environmentally, economically and socially …"
  - What is needed is nothing short of an energy revolution …"

World Energy-related CO_2 Emissions by Scenarios



Sources: OECD/ IEA, World Energy Outlook, 2011, P. 73

A scenario presented in the IEA World Energy Outlook, which sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2.

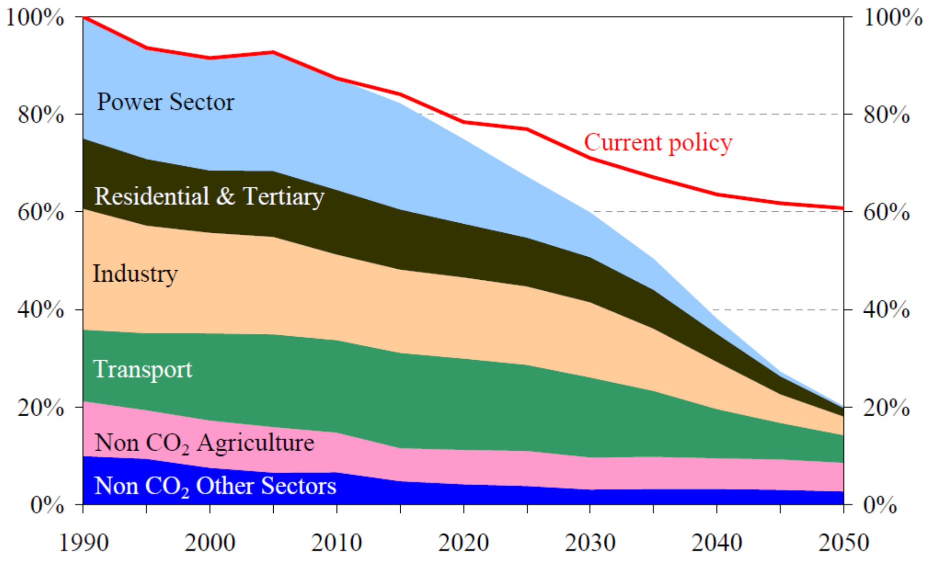
European Policy

- Changing Europe's energy system according to climate policy needs
  - Energy efficiency
  - Renewable integration
- Safe, secure, and affordable energy supply
- Europe`s leadership in energy technology and innovation
- Strengthening the role of cities
  - High living standards for citizens
  - Sustainable environment for next generations
  - High competitiveness of the cities
- Horizon 2020
  - Societal challenges, excellence in R&D, industrial leadership

Source: G. Öttinger, 10.11.2010

Europe 2020 Strategy and 2050 Roadmap

- Climate change and energy: The “20-20-20 targets” (in 2020)
  - Reduce Green-House-Gas (GHG) emissions by 20%
  - Increase share of renewables in EU energy consumption to 20%
  - Achieve an energy-efficiency target of 20%

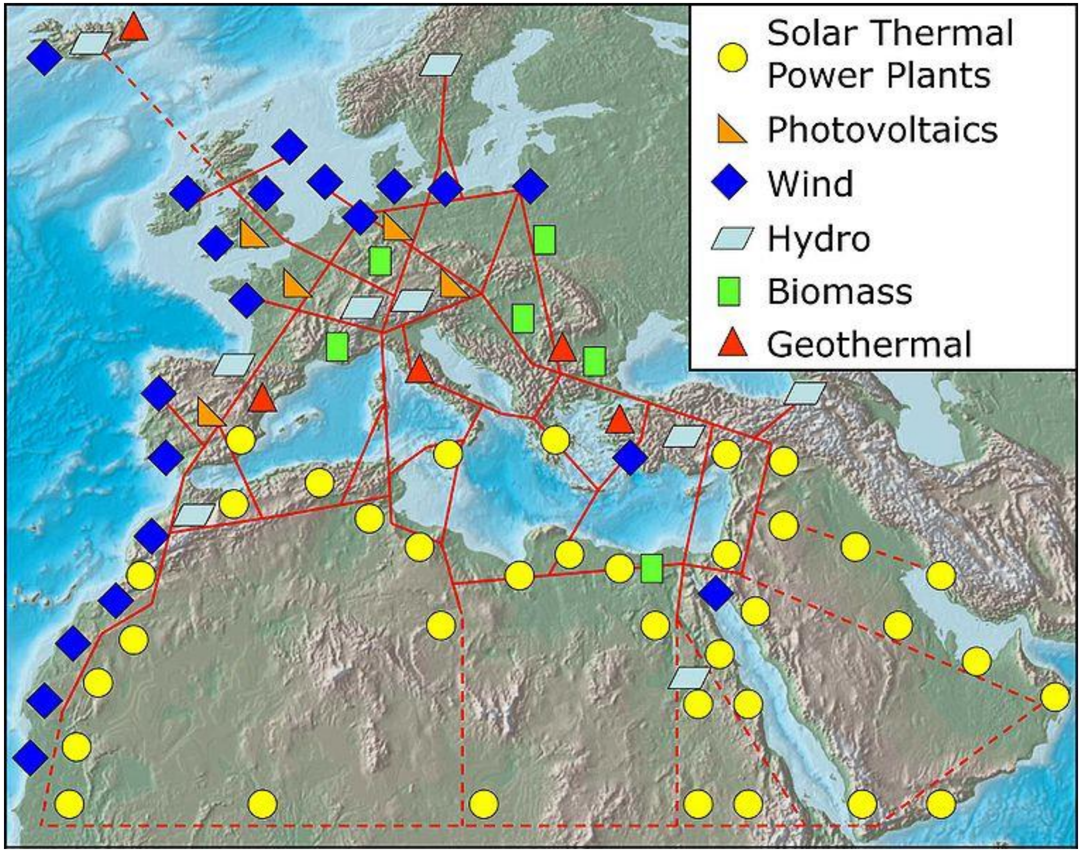


Source: EC, Low Carbon Economy Roadmap 2050

- Roadmap 2050: -80% GHG reduction
  - -80% GHG Reduction needs Radical Innovations!!!

Renewable Electricity Generation

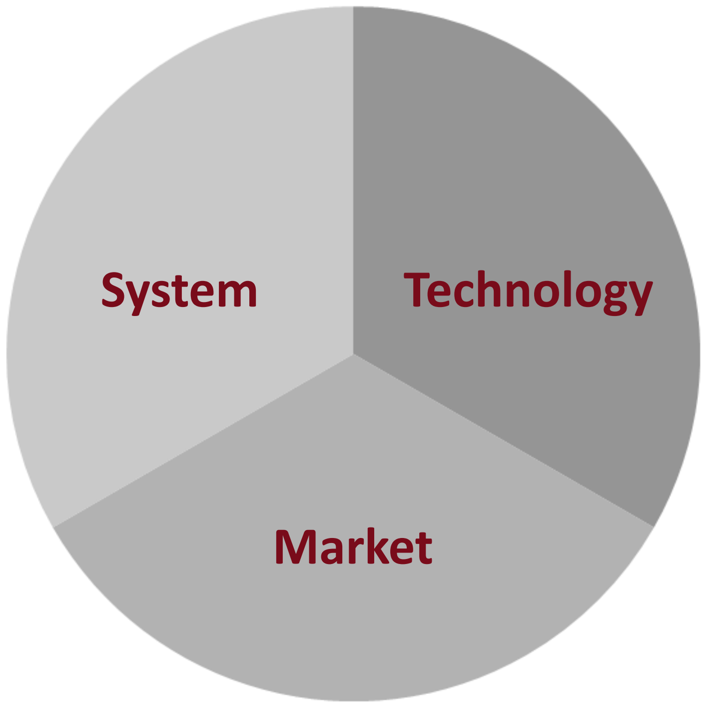
- Future developments in Europe



Driving Forces for Research in Electric Energy Infrastructure

Connecting European Smart Grid Infrastructures

- Urbanization
- Stochastic behavior of renewables
- Distributed generation
- Electrification of mobility
- Aging infrastructure

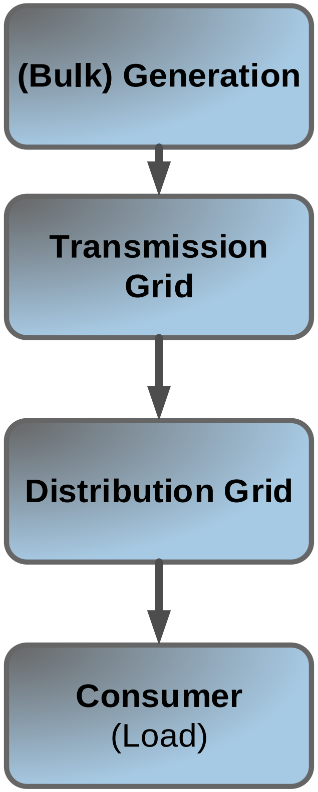


- Power electronics
- Communication and automation
- Electrical storages
- Generation (PV, wind power, etc.)
- Condition monitoring

- Liberalization and regulation of markets
- New business models for energy and mobility
- New industry players in energy business
- Market for primary energy, CO_2, nuclear waste, etc.

Power Distribution Grids in the Past

- Typical structure of the electricity system (~1900-2000)
  - Central generation infrastructure
  - Unidirectional power flow
  - Hierarchical structure

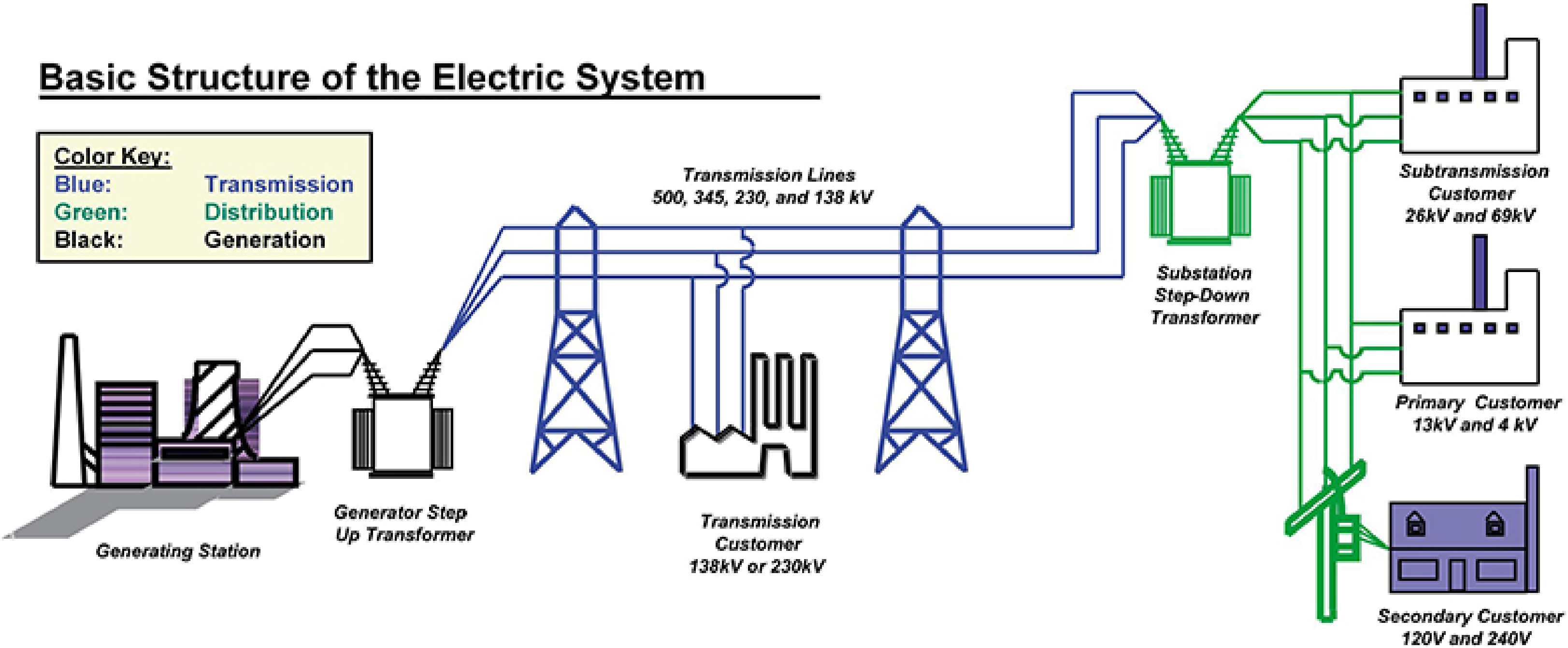


Transmission Grids (e.g., 380 kV, 220 kV, 110 kV)
Medium Voltage Distribution Grids (e.g., 10 kV, 20 kV, 30 kV)
Low Voltage Distribution Grids (e.g., 0,4 kV)

Source: H. Brunner (AIT)

Power Distribution Grids in the Past

- Typical structure of the electricity system (~1900-2000)

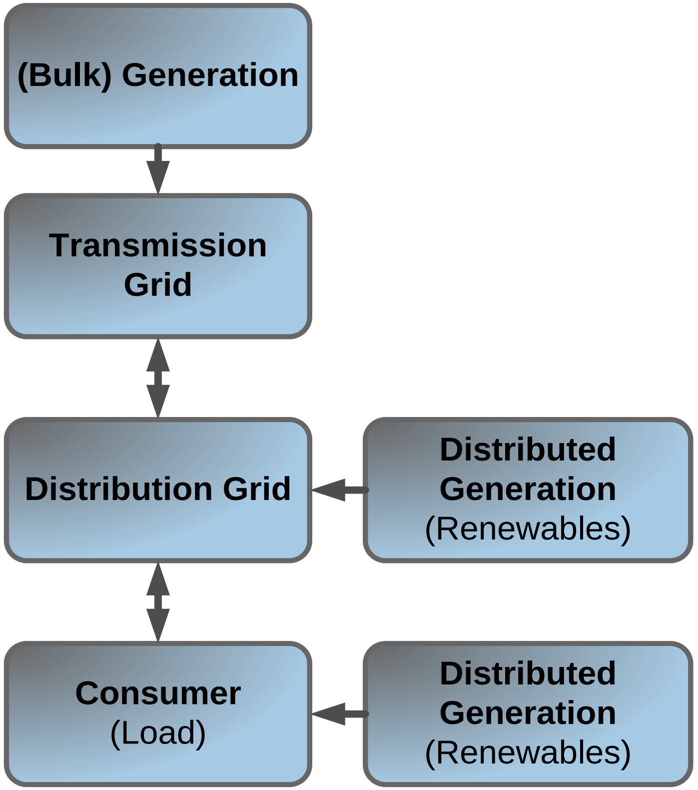


Bulk power generation - unidirectional power flow – passive system and users

Source: http://www.webpages.uidaho.edu/sustainability/chapters/ch06/ch06-p3a.asp

Integration of Renewable Generation

- "New" structure of the electricity system (from ~2000)
  - Central and distributed generation infrastructure
  - Fluctuating distributed generation (e.g., solar, wind)
  - Bidirectional power flow
  - Hierarchical structure



Source: H. Brunner (AIT)

Integration of Renewable Generation

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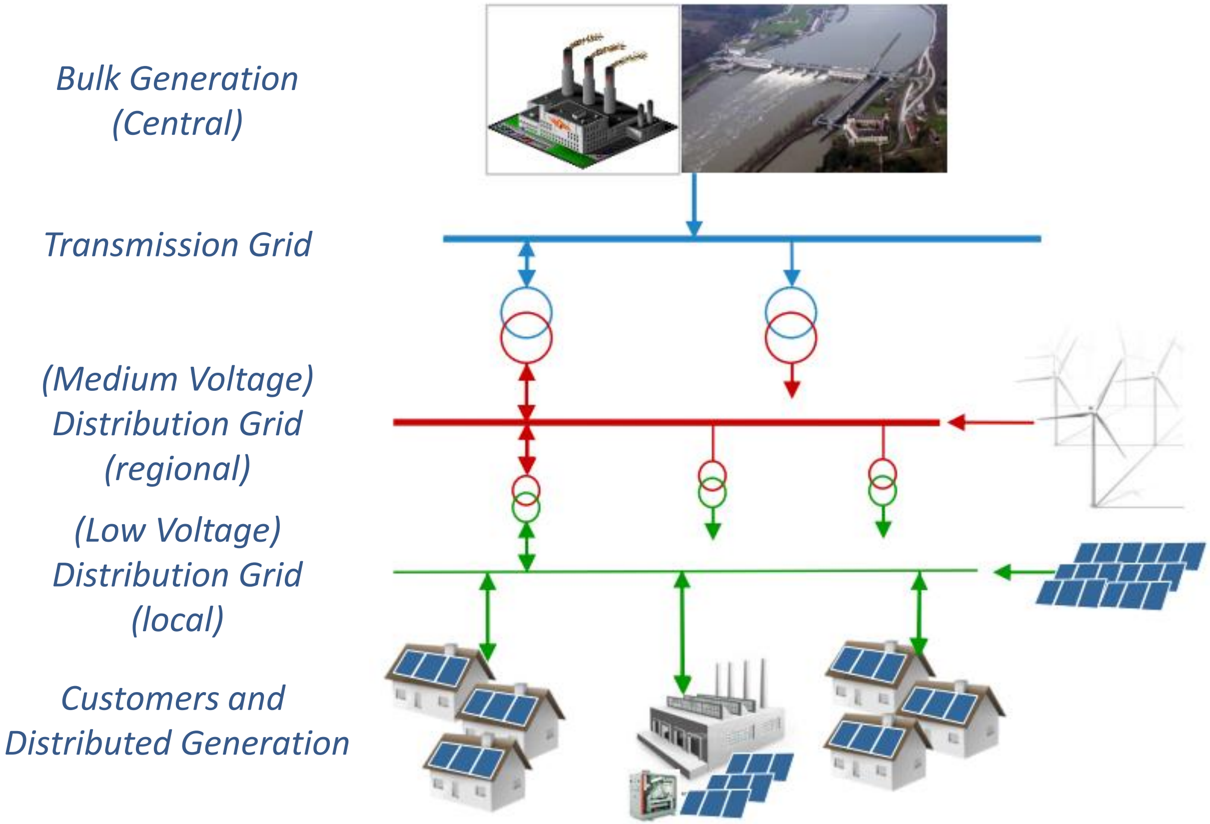
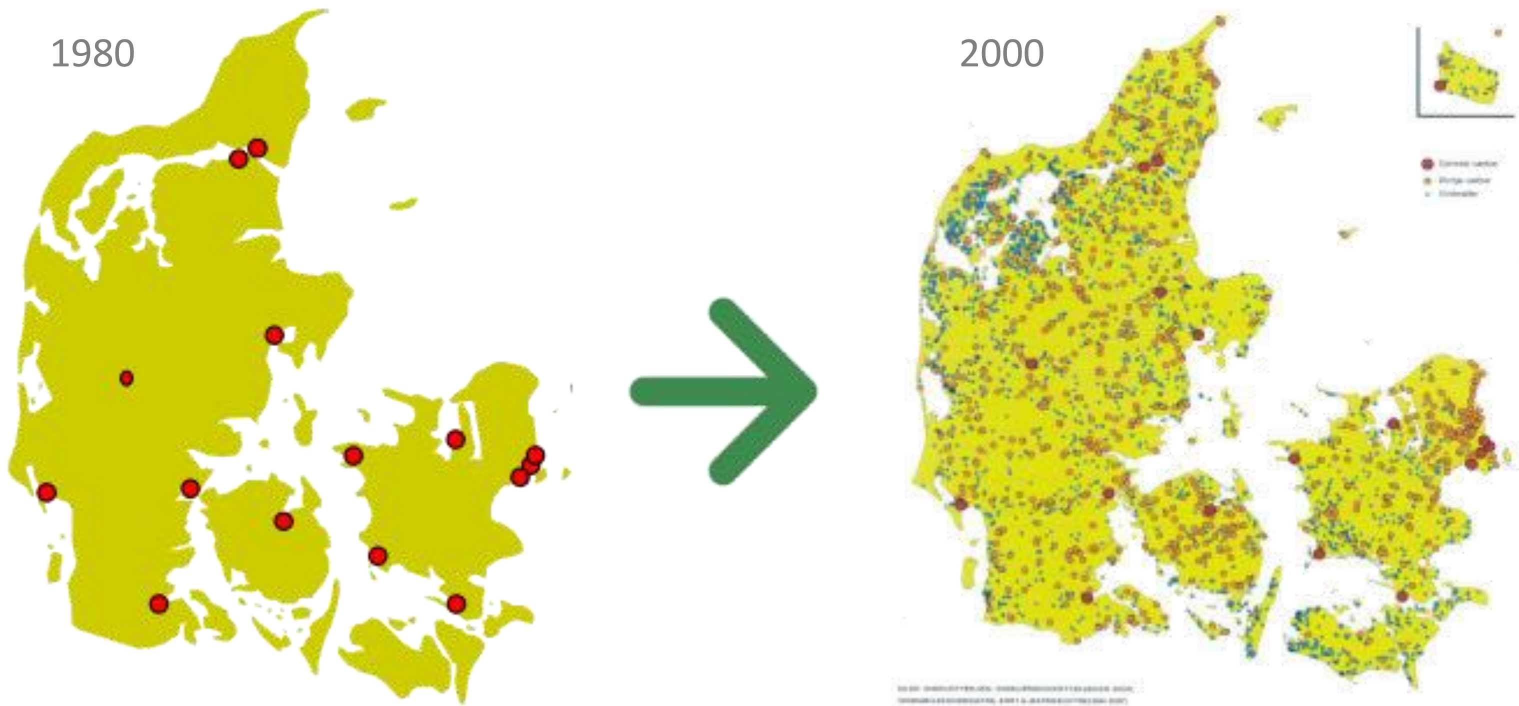


Source: Salzburg AG

Integration of Renewable Generators

- Example: Denmark



16 central power plants

Source: www.ens.dk

16 central power plants
+ 1000 CHPs
+ 6000 Wind turbines

Intelligent Electricity Networks "Smart Grids"

- Possible actions?
  - Best solution
    - Build a new power grid
    - Thicker lines, storages, etc.
    - However, that is beyond price
  - Smart solutions required
    - Advanced automation and control
    - Monitoring
    - etc.

Intelligent Electricity Networks “Smart Grids”

- Vision

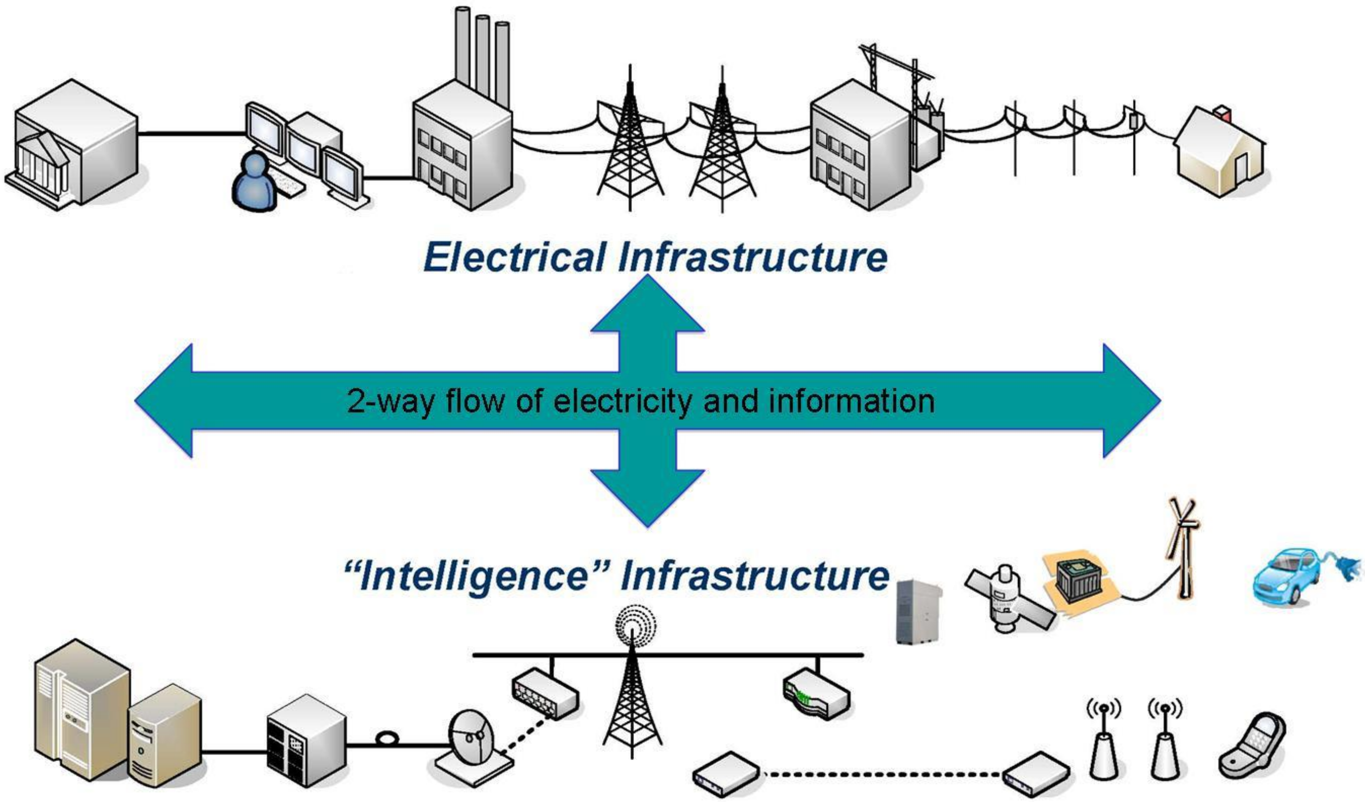
Source: European Technology Platform Smart Grids

Intelligent Electricity Networks "Smart Grids"

- Smart Grids at different levels
  - Transmission system (Trans-European demand/supply matching)
    - Super Grids (offshore wind farms in northern Europe – hydro storages in the Alps – large scale solar/PV systems in southern Europe/Africa)
  - Medium Voltage (MV) / Low Voltage (LV) distribution system
    - Smart Grids (active distribution grids, integration of distributed generators and storage systems)
  - Local energy system (e.g,. for buildings or small areas; low voltage systems)
    - Micro Grids (islanding, grid-connected)

Intelligent Electricity Networks
"Smart Grids"

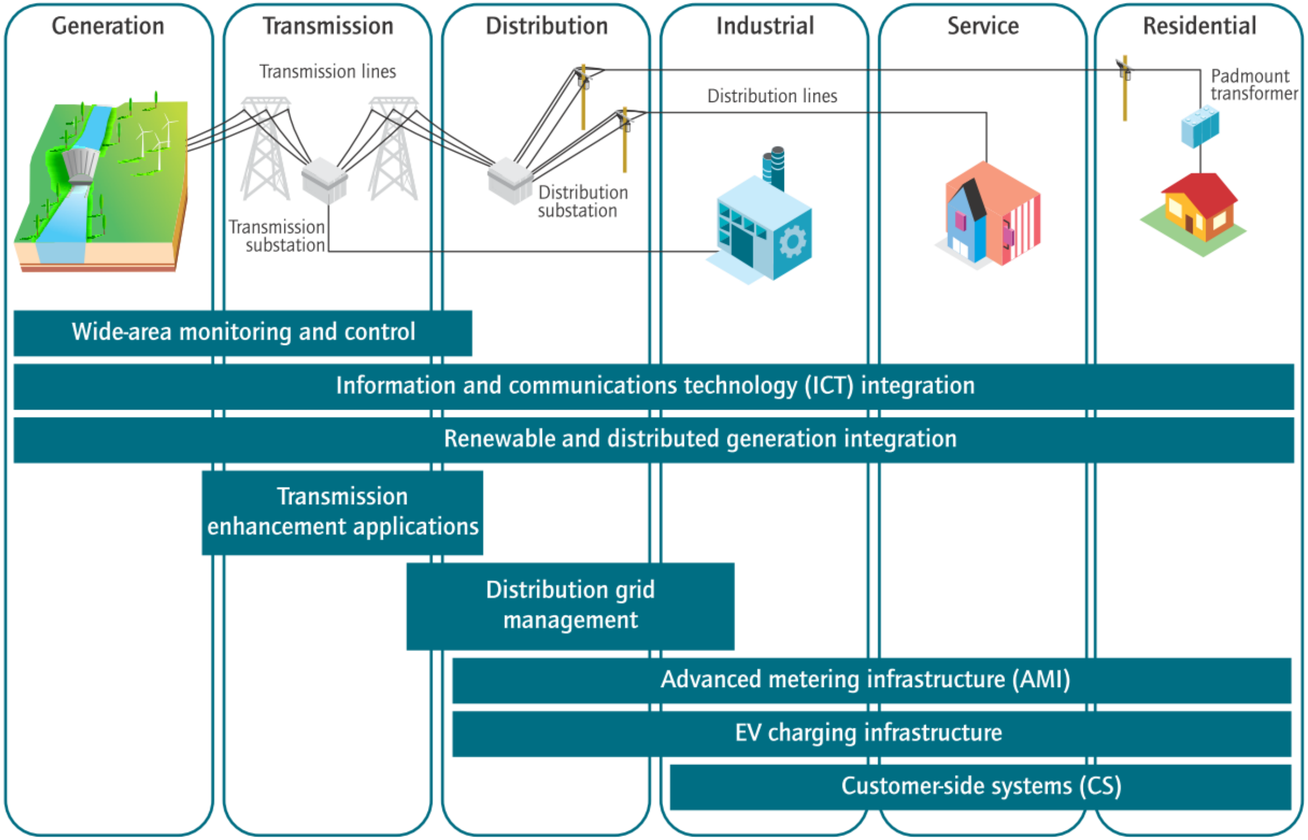
- Integration of (critical) infrastructure systems: electrical + ICT/automation



Source : NIST

Intelligent Electricity Networks
"Smart Grids"

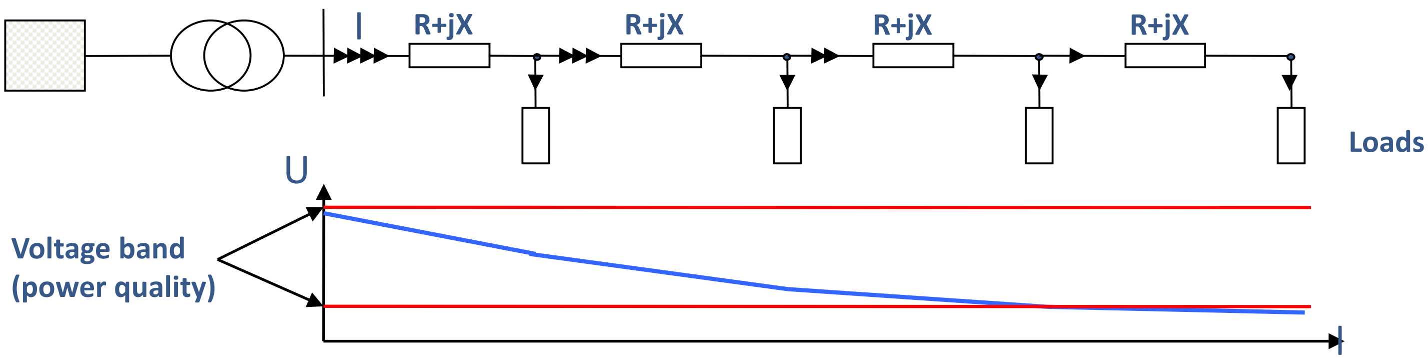
- Technology areas



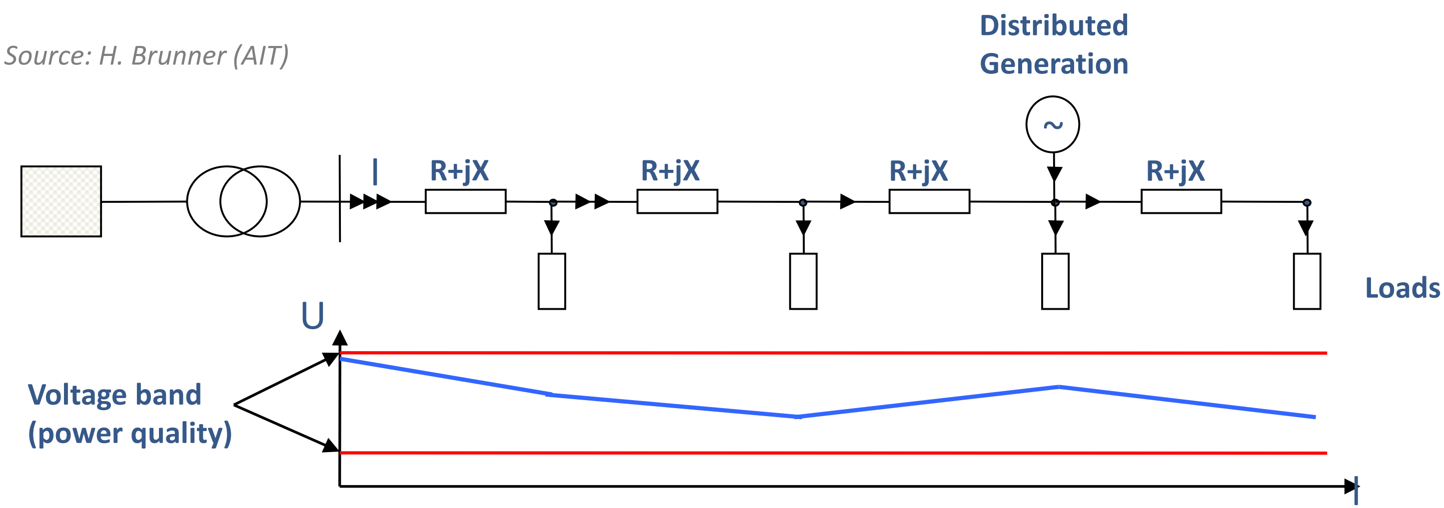
Source: IEA

Example Voltage Control

- Voltage drop along (distribution) lines and distributed generation



Source: H. Brunner (AIT)



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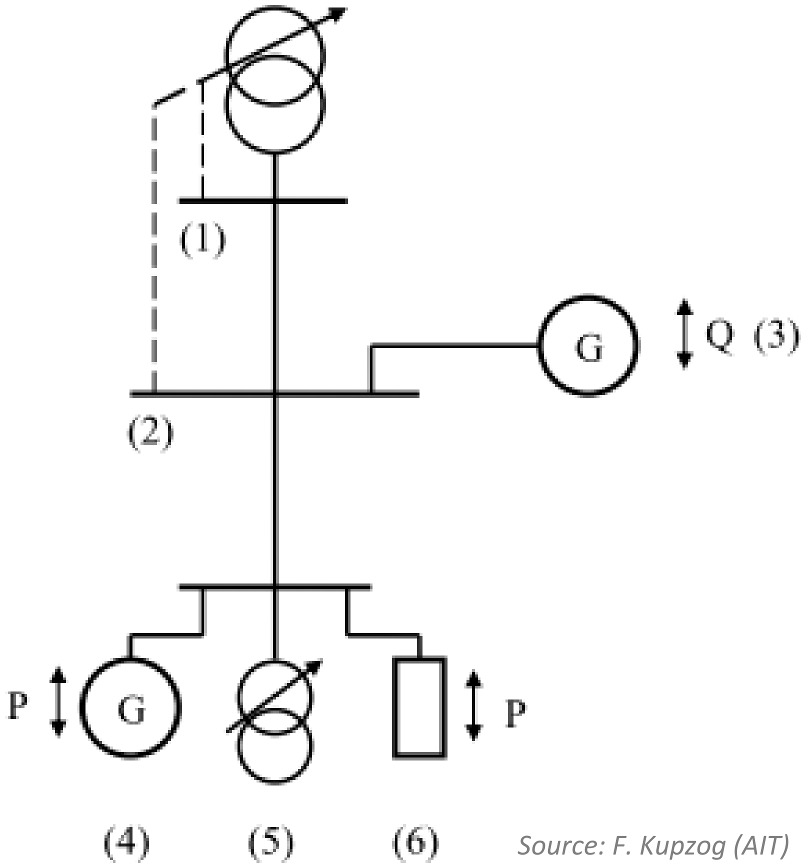
Example Voltage Control

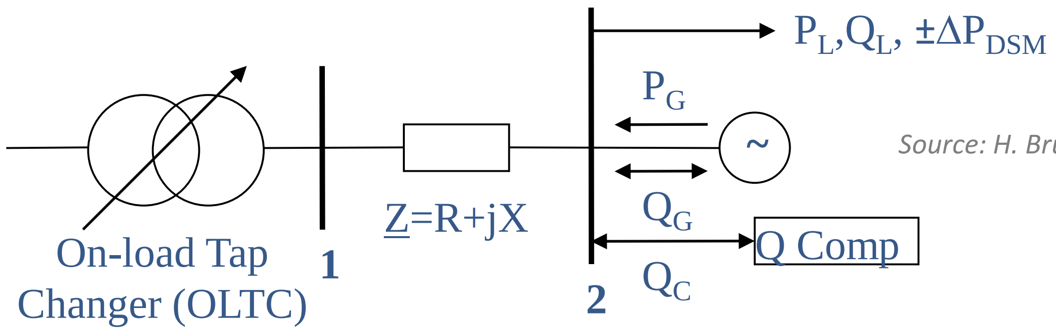
- What can be influenced?
  - On-load Tap Changer (OLTC) (1,2)
  - Generators (3, 4)
  - Adjustable transformers (low voltage) (5)
  - Demand Side Management (DSM) (6)



Source: F. Kupzog (AIT)

Example Voltage Control

- Voltage band management through changes in generation and consumption



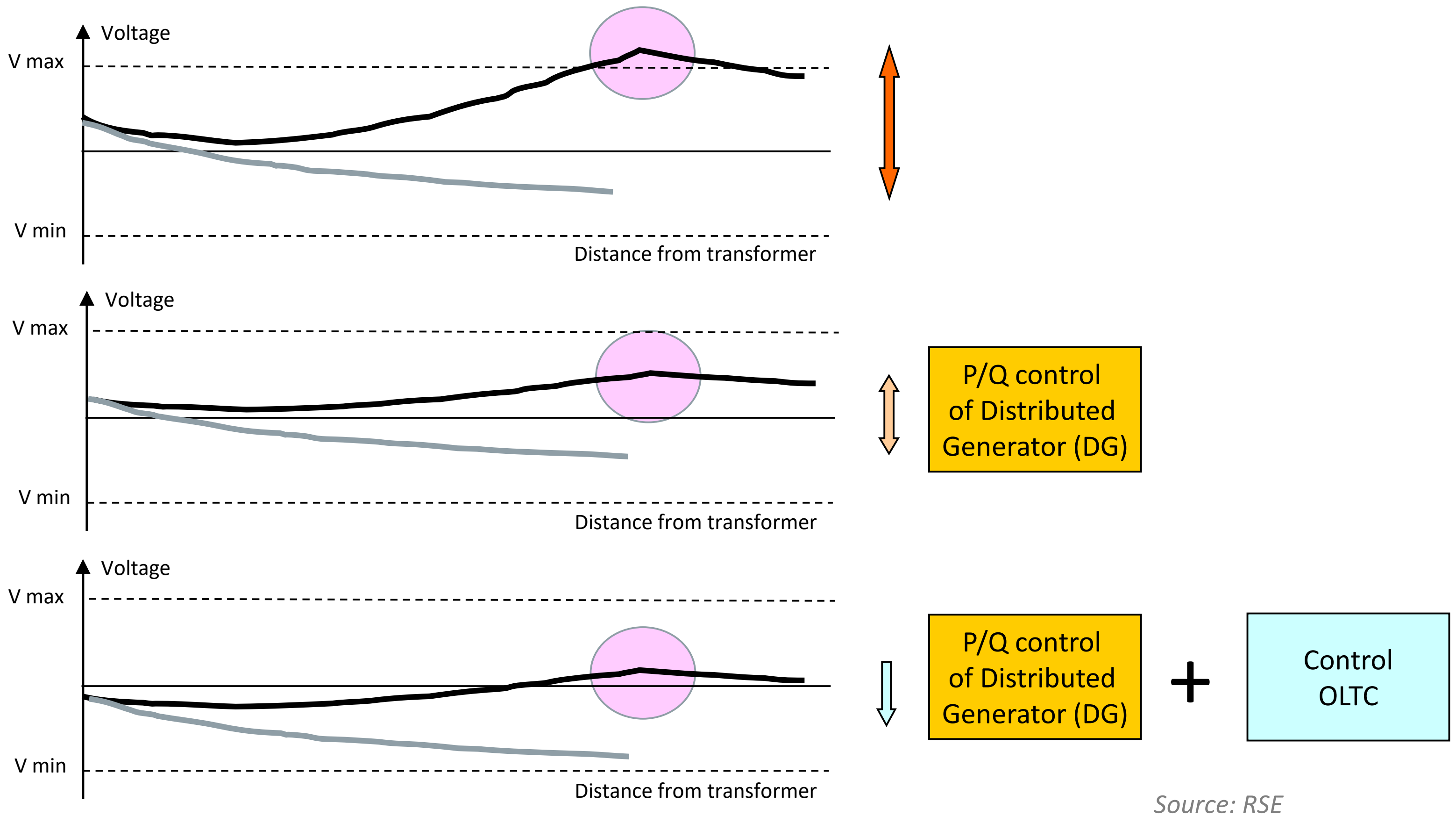
Source: H. Brunner (AIT)

$$U_2 \approx U_1 + \underbrace{(R\cdot(P_G - P_L \pm \Delta P_{DSM})}_{\text{Active Power}} + \underbrace{X\cdot(\pm Q_G - Q_L \pm Q_K))}_{\text{Reactive Power}} / U_2$$

Voltage Level	R/X ratio	Voltage Level influenced by
Transmission Grid (>110kV)	$R_{Line} << X_{Line}$	Reactive Power
MV Distribution Grid (5 - 60 kV)	$R_{Line} < X_{Line}$	Active and Reactive Power
LV Distribution Grid (0,4 kV)	$R_{Line} > X_{Line}$	Active Power

Example Voltage Control

- Voltage control possibilities



Source: RSE

Status Quo in Validation and Future Needs

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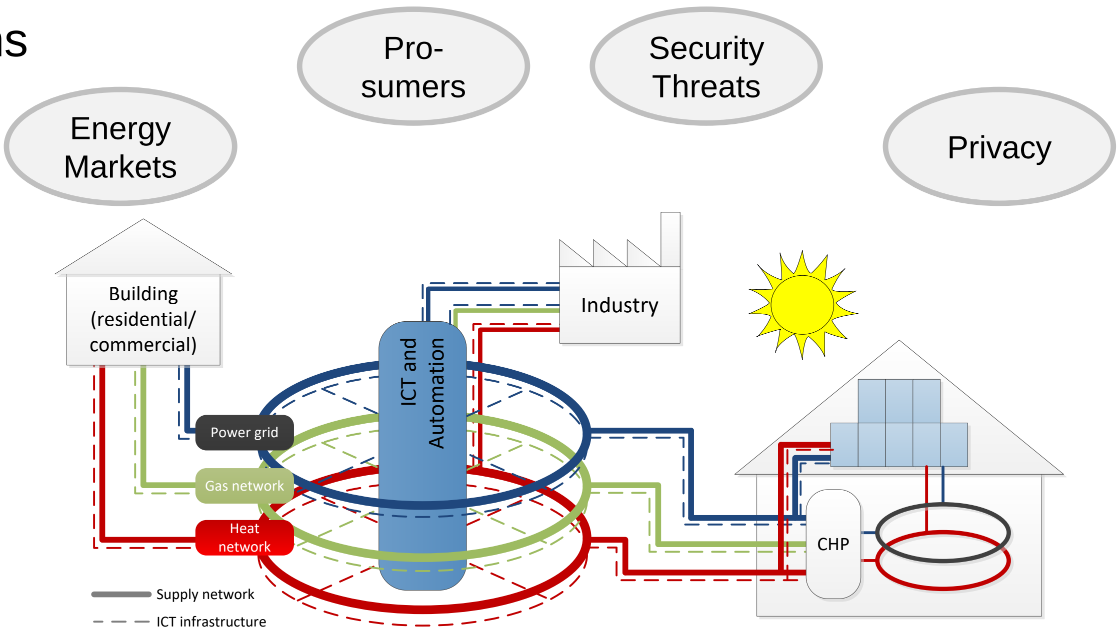
Methods and Tools for Validating
Cyber-Physical Energy Systems

Cyber-Physical Energy System

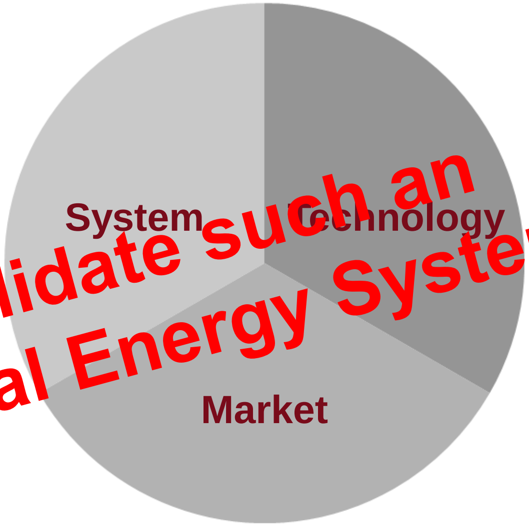
- Planning and operation of the energy infrastructure becomes more complex
  - Large-scale integration of renewable sources (PV, wind, etc.)
  - Controllable loads (batteries, electric vehicles, heat pumps, etc.)
- Trends and future directions
  - Digitalisation of power grids
  - Deeper involvement of consumers and market interaction
  - Linking electricity, gas, and heat grids for higher flexibility and resilience



→ Integrated Cyber-Physical Energy System (CPES) or Smart Grid

Cyber-Physical Energy System

- Key elements of future integrated smart grids for mastering the increasing requirements and system complexity are
  - Power electronics
  - Advanced communication, automation^, and control systems
  - Smart algorithms
  - Monitoring and data analytics



How to design and validate such an Integrated Cyber-Physical Energy System?

Status Quo in Design and Validation

- In the past individual domains of power and communication systems have been often designed and validated separately
- Available methods and approaches are

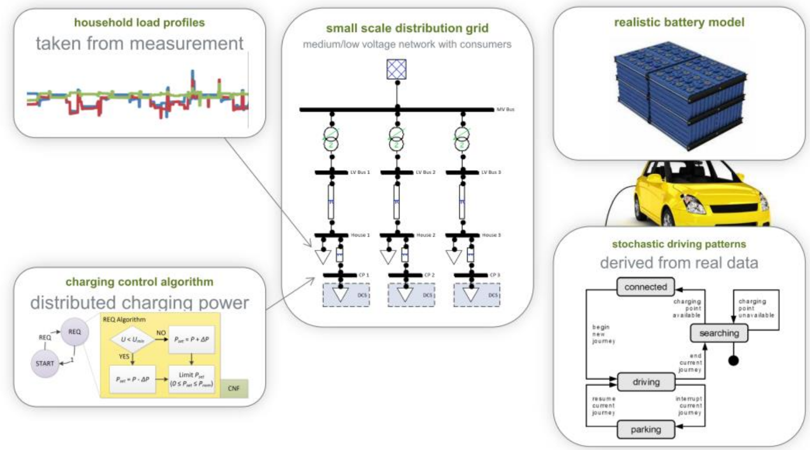
	Req. & Basic Design Phase	*Detailed Design Phase*	*Implementation & Prototyping*	*Deployment / Roll Out*
Software Simulation	+	++	O	-
Lab Experiments and Tests	-	-	++	+
Hardware-in-the-Loop (HIL)	-	-	++	++
Demonstrations / field tests / pilots	-	-	-	++

Legend:
- … less suitable, o … suitable with limitations, + … suitable, ++ … best choice

Status Quo in Design and Validation

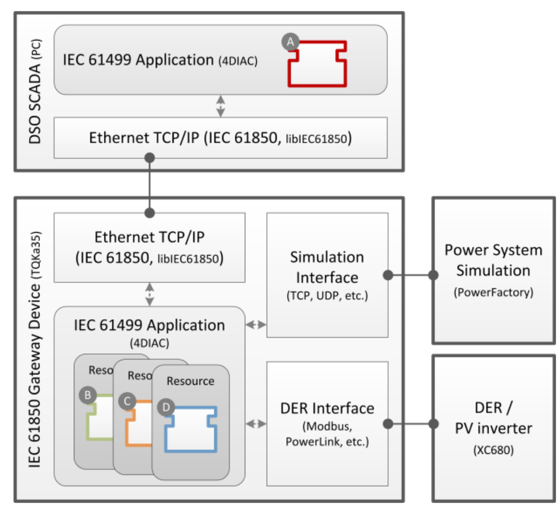
- Promising validation approaches
  - Co-simulation: coupling of domain-specific simulators

    (example: dynamic charging of electric vehicles)



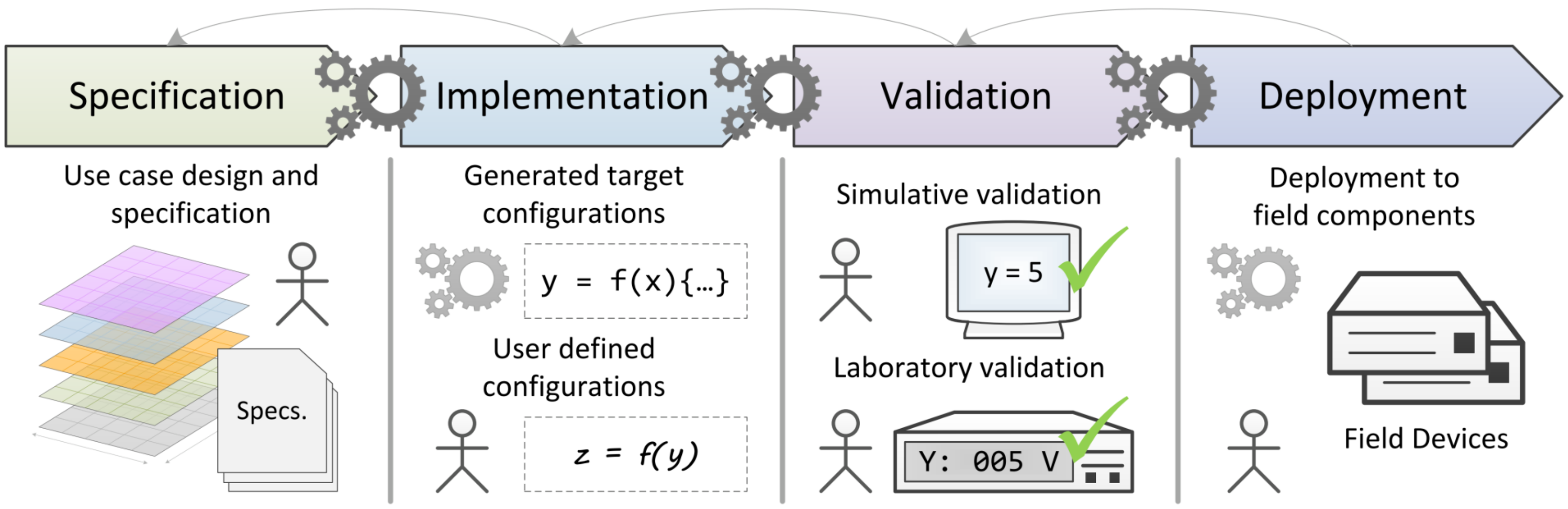
  - Hardware-in-the-Loop (HIL) experiments
    - Controller-HIL (CHIL)

      (example: remote control of inverter-based DER)
    - Power-HIL (PHIL)



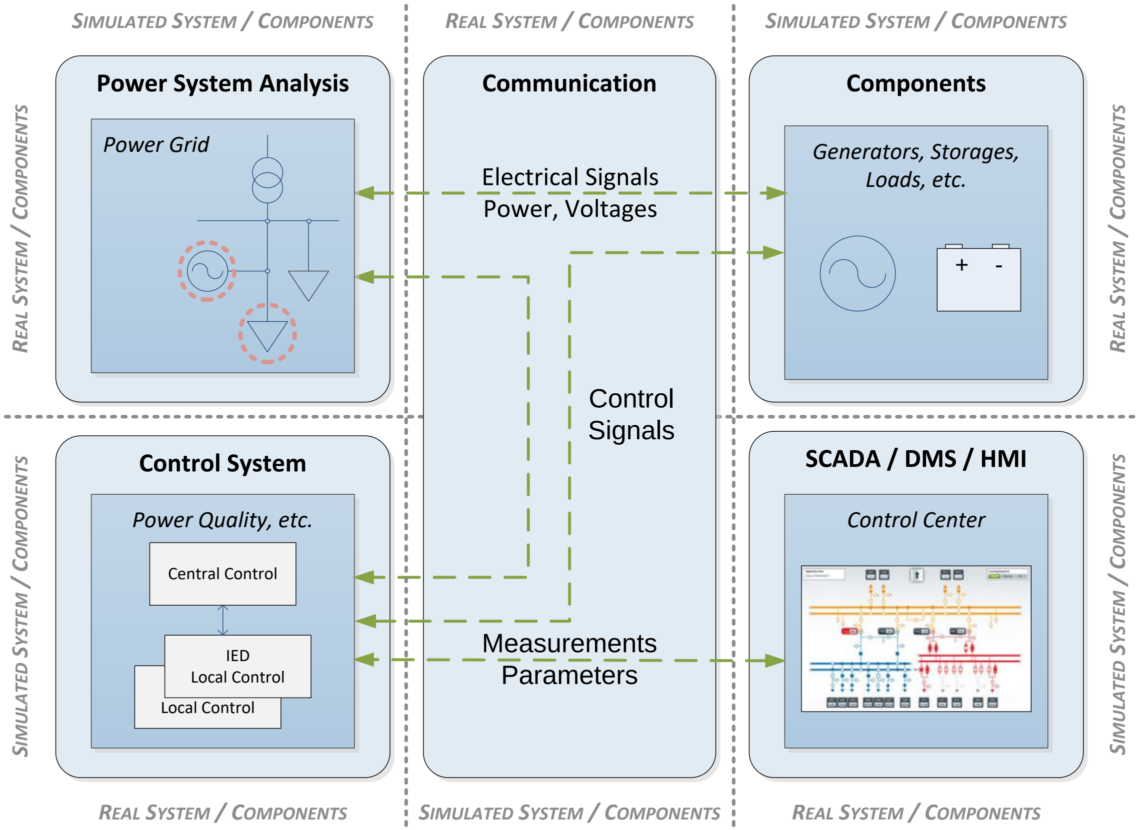
Future Needs and Developments

- Vision: *“Providing support from design to implementation & installation”*
  - Integrated system design
  - Validation and testing
  - Installation and roll out



Future Needs and Developments

- A cyber-physical (multi-domain) approach for analysing and validating smart grids on the system level is missing today
  - Existing methods focusing mainly on component level issues
  - System integration topics including analysis and evaluation are not addressed in a holistic manner



Future Needs and Developments

- A holistic validation framework and the corresponding research infrastructure with proper methods and tools needs to be developed
- Harmonized and standardized evaluation procedures need to be developed
- Well-educated professionals, engineers and researchers understanding integrated smart grid configurations in a cyber-physical manner need to be trained on a broad scale

The ERIGrid Vision and Approach

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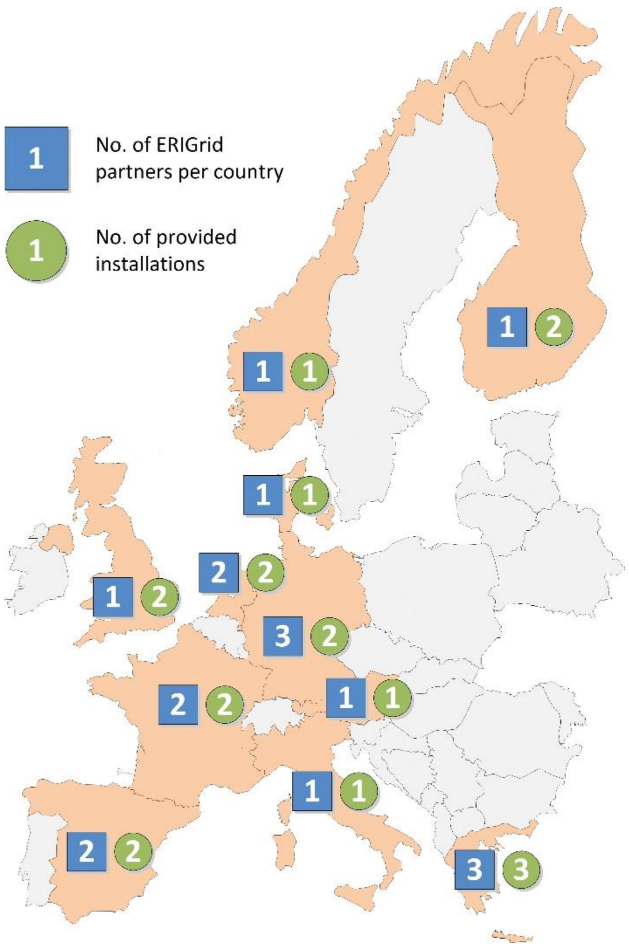
Methods and Tools for Validating
Cyber-Physical Energy Systems

Project Facts

- H2020 call “INFRAIA-1-2014/2015”
  - Integrating and opening existing national and regional research infrastructures of European interest
- Funding instrument
  - Research and Innovation Actions (RIA) Integrating Activity (IA)
- 18 Partners from 11 European Countries + 3 Third Parties involved
- Involvement of 19 first class Smart Grid labs
- 10 Mio Euro Funding from the EC
- ~1000 Person Month

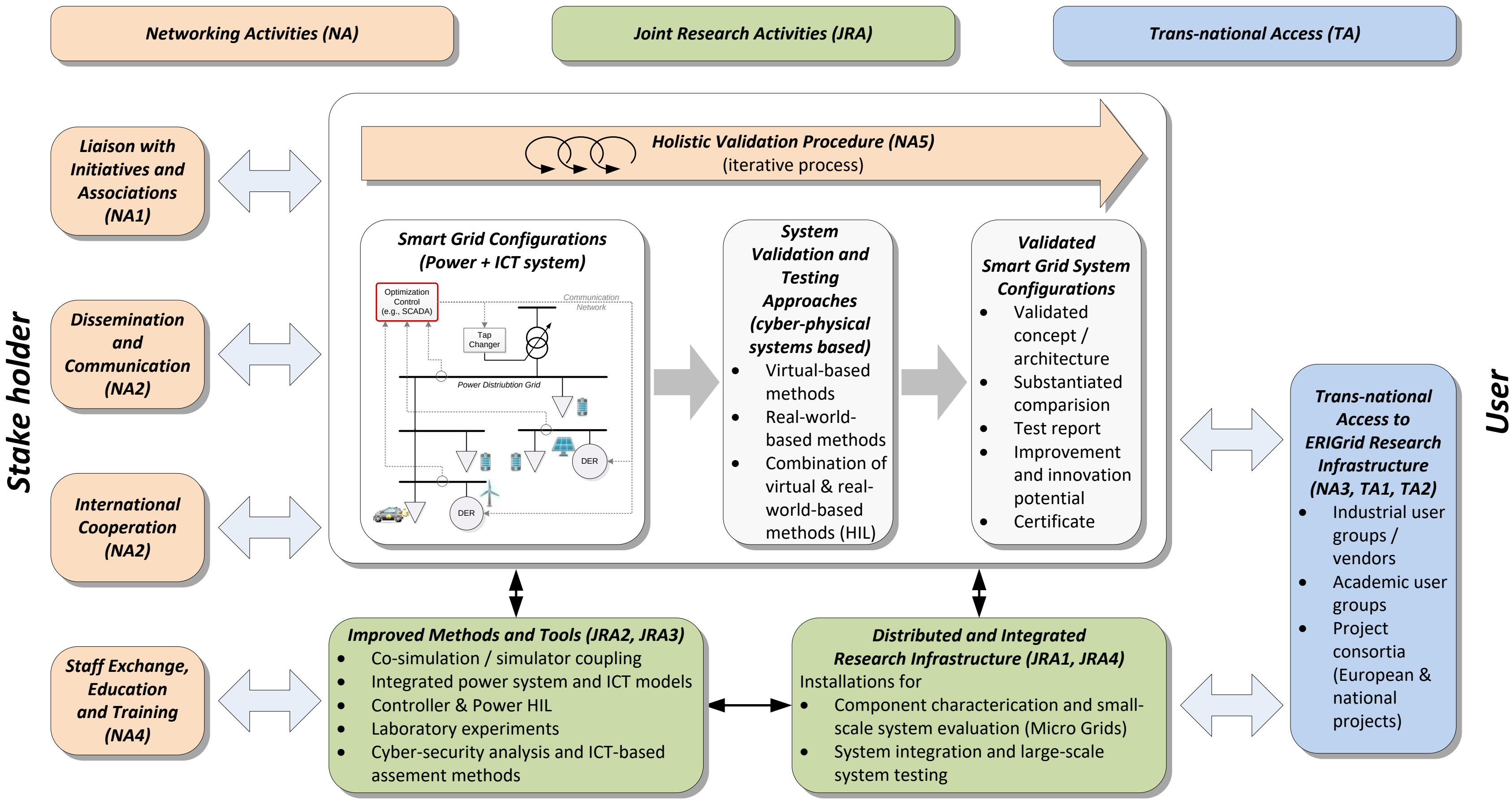


Main Goals

- Supporting the technology development as well as the roll out of Smart Grid approaches, solutions and concepts in Europe with a holistic, cyber-physical systems approach
- Integrating the major European research centres with a considerable, outstanding Smart Grid research infrastructure to jointly develop common methods, concepts, and procedures
- Integrating and enhancing the necessary research services for analysing, validating and testing Smart Grid configuration
- System level support and education for industrial and academic researchers in Smart Grid research and technology development is provided to foster future innovation
- Strengthening the technical leadership of the European Research Area in the energy domain

Overview ERIGrid Approach

- Leading research infrastructure in Europe for the domain of Smart Grids



The ERIGrid
Trans-national Access opportunity

- Free of charge access to best European smart grid research infrastructures
  - **Scientists** from research, academia and industry are invited to apply for the Trans-national Access (TA)
  - Successful applicants will be provided with **free of charge** access to ERIGrid research facilities (incl. lab installations)

SmartEST Laboratory at AIT

Smart metering communication platform at TECNALIA

  - The **expenses**, including travel and accommodation will be **reimbursed** under ERIGrid conditions
  - Calls open **every 6 month**

Provided Smart Grids Research Infrastructures

- Various testing and research possibilities are provided such as
  - DER/power system components characterization and evaluation
  - Smart Grid ICT/automation validation
  - Co-simulation of power and ICT systems
  - Real-time simulation and Power/Controller Hardware-in-the-Loop (HIL)

How to Apply?

- User Groups have to fill out the application template from the website (https://erigrid.eu/transnational-access/) and send it to erigrid-ta@list.ait.ac.at
- Targeted topics includes smart grid concepts and configurations like
  - Fluctuating renewable energy, distributed energy resources
  - Active prosumers (incl. EVs)
  - Demand side management
  - Power system components
  - ICT, cyber-security, electricity markets, regulation, etc.

Support for filling out an application can be asked to the targeted RIs.

TA calls are launched every 6 months.

Evaluation criteria can be found on the project website.

Next call will open on 15.08.2018 and closes on 15.11.2018

Holistic Validation Procedure

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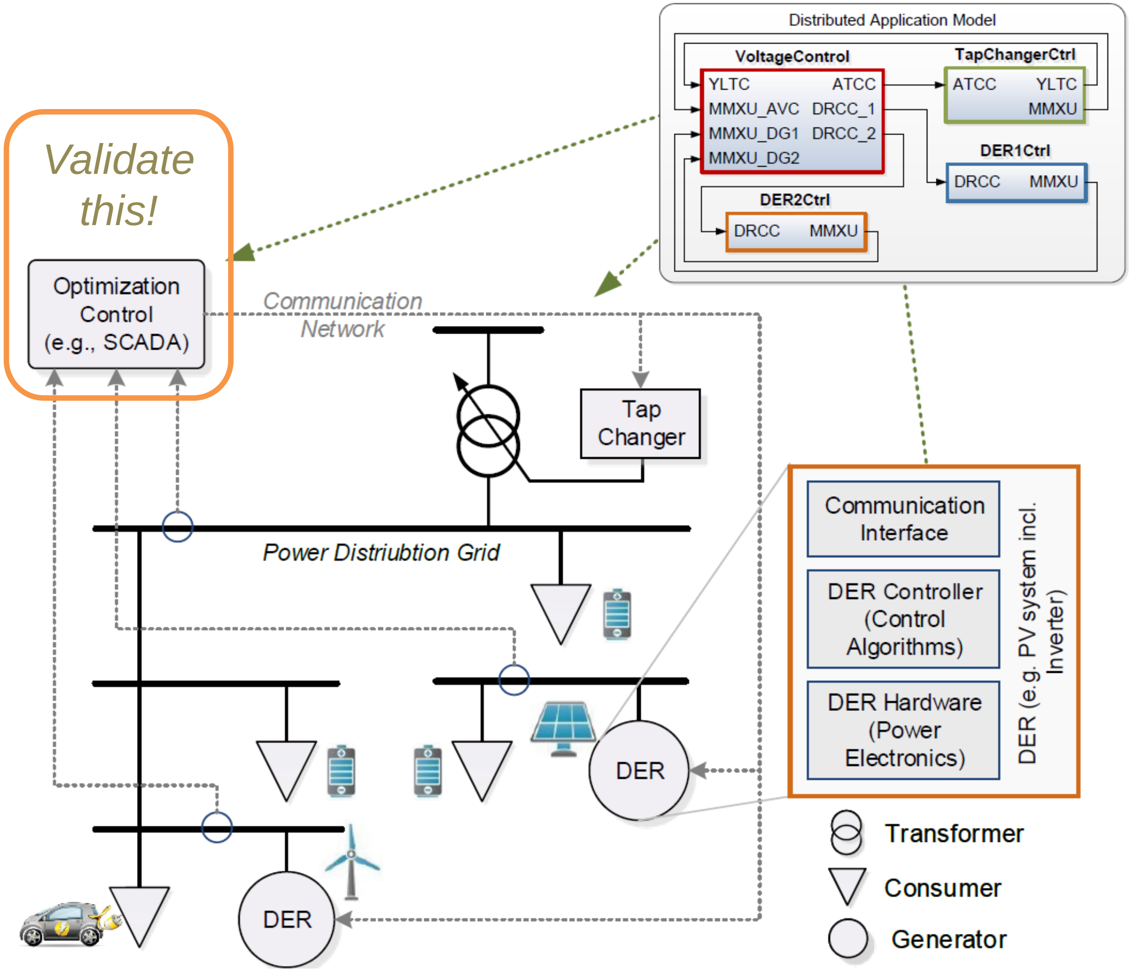
Cyber-Physical Energy Systems

Challenges

- Testing/validation of novel CPES components and concepts
- Many domain involved (holism)
- Setups/workflows **differ** across Research Infrastructures (RI)
  - Experiments are often **hardly reproducible**
  - Often limited by RI capabilities



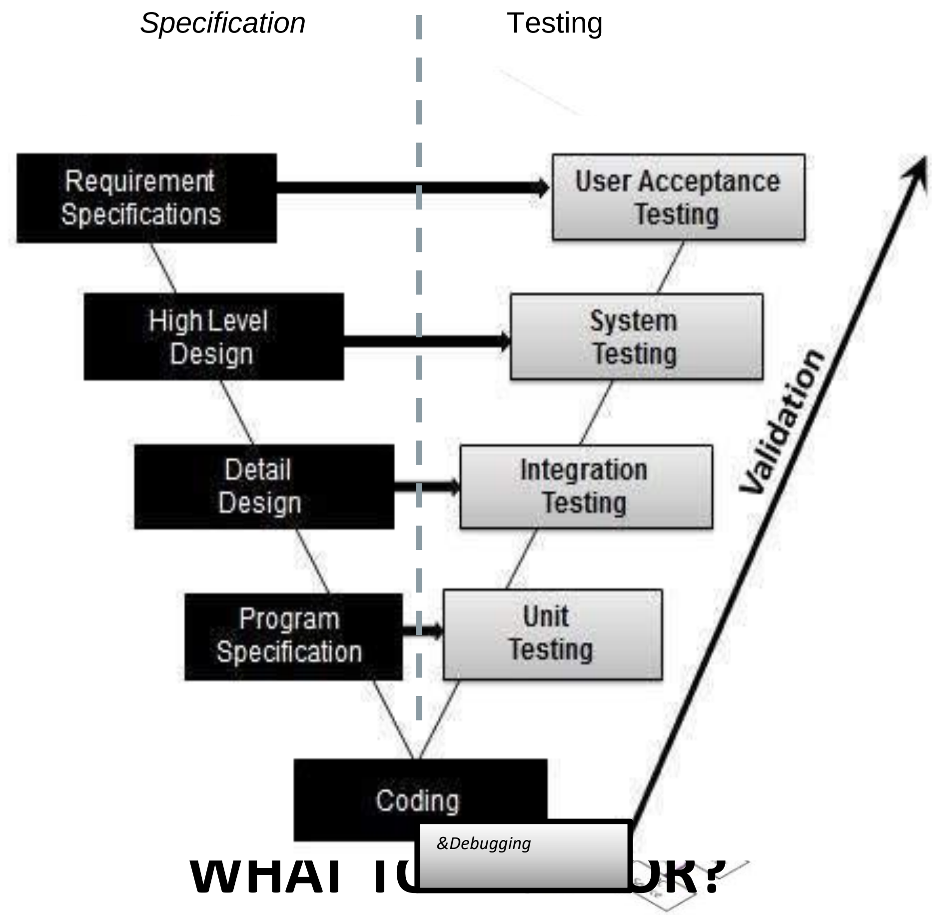
Aims and Objectives

Aims

- Formalize testing process
  - Testing → documented and reproducible
  - Basis for knowledge exchange

Objectives

- **Formal process covering all stages of test planning**
  - Overview of resources
  - Consider state-of-the-art
  - Operationalize, refine



HOW TO TEST?

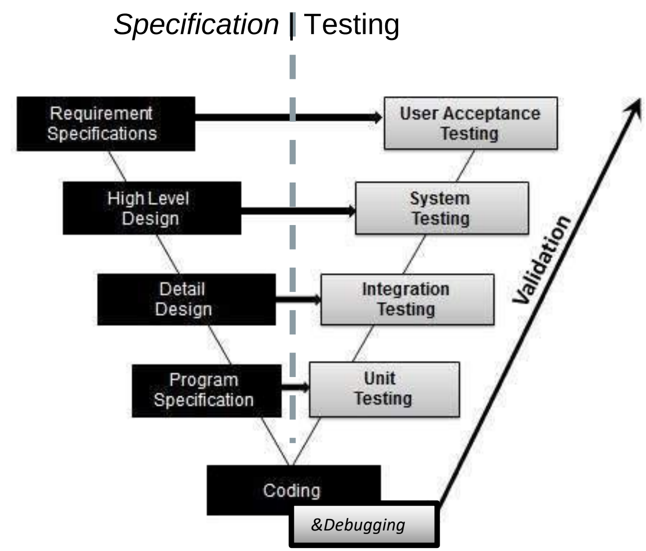
“Holistic” System Validation

I. **System validation**
alignment of Specifications & Testing

II. **Integrated hardware & software testing**
Validate “systems” not components

III. Tests that **combine multiple domains**
e.g., power, comm., and automation

IV. **Systematically design tests & integrate results** from various experiments for a holistic assessment
i.e., combine simulation, co-simulation, HIL, PHIL, CHIL, different labs, etc.



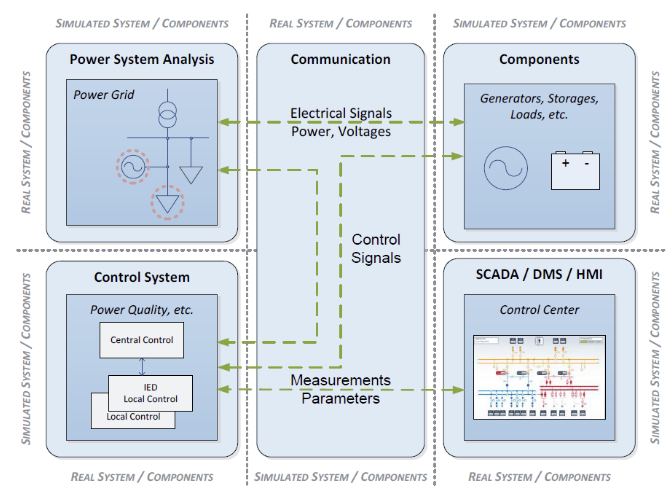
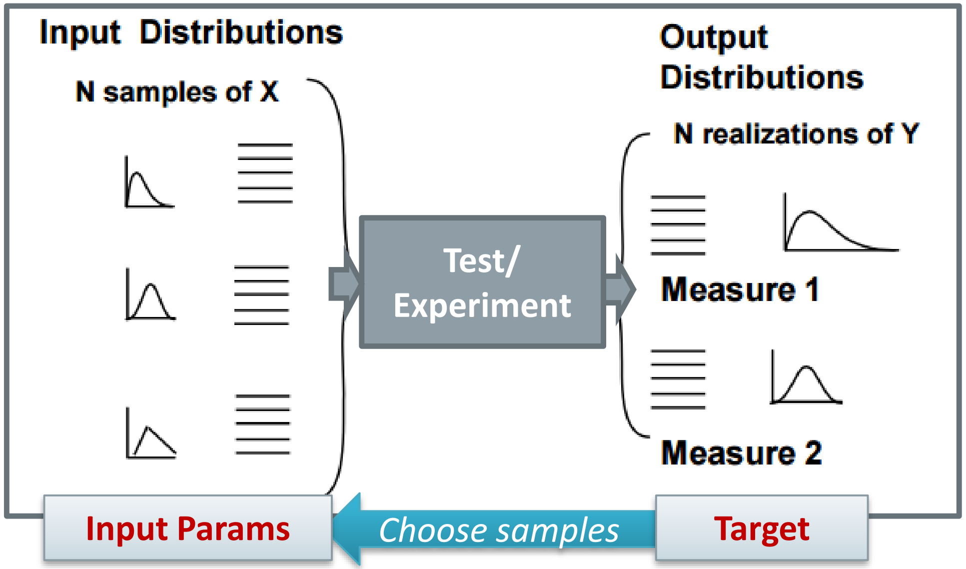


Figure 1.3: Improved methods and tools for Smart Grid validation and testing – possibility to combine virtual (simulated) and real components

‘Design of Experiments’ (DoE)

- Efficient test design due to sampling-oriented approach



- Target measures / metrics
  e.g., “average control error”
- Design sampling space on a ‘need-to-know’ basis
  e.g., 3 levels of package loss rate, 20 levels of disturbance

Component Test vs. Holistic Test

Component Test

- Example: inverter MPPT test, anti-islanding
- No interactions with the system
- Usually open loop test (predefined voltage, frequency; setpoints are applied to the hardware under test)

PV simulator

Hardware inverter under test

AC gid simulator

Holistic/System Test

- Combining several tests (testing process)
- Using simulations

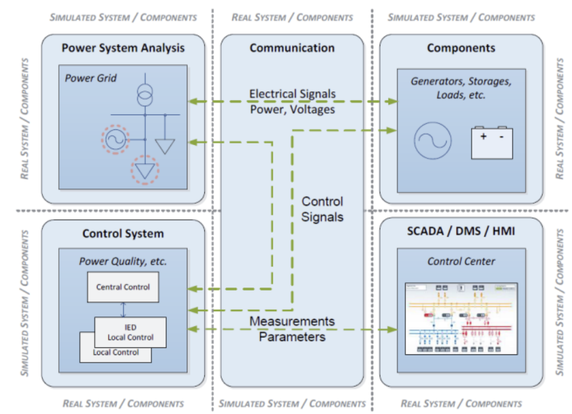
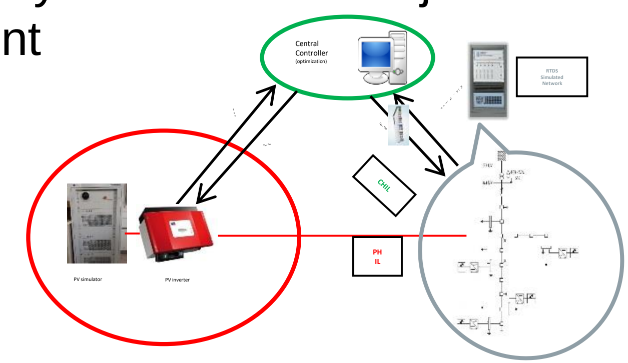


Figure 1.3: Improved methods and tools for Smart Grid validation and testing – possibility to combine virtual (simulated) and real components

- Testing a system rather than just component



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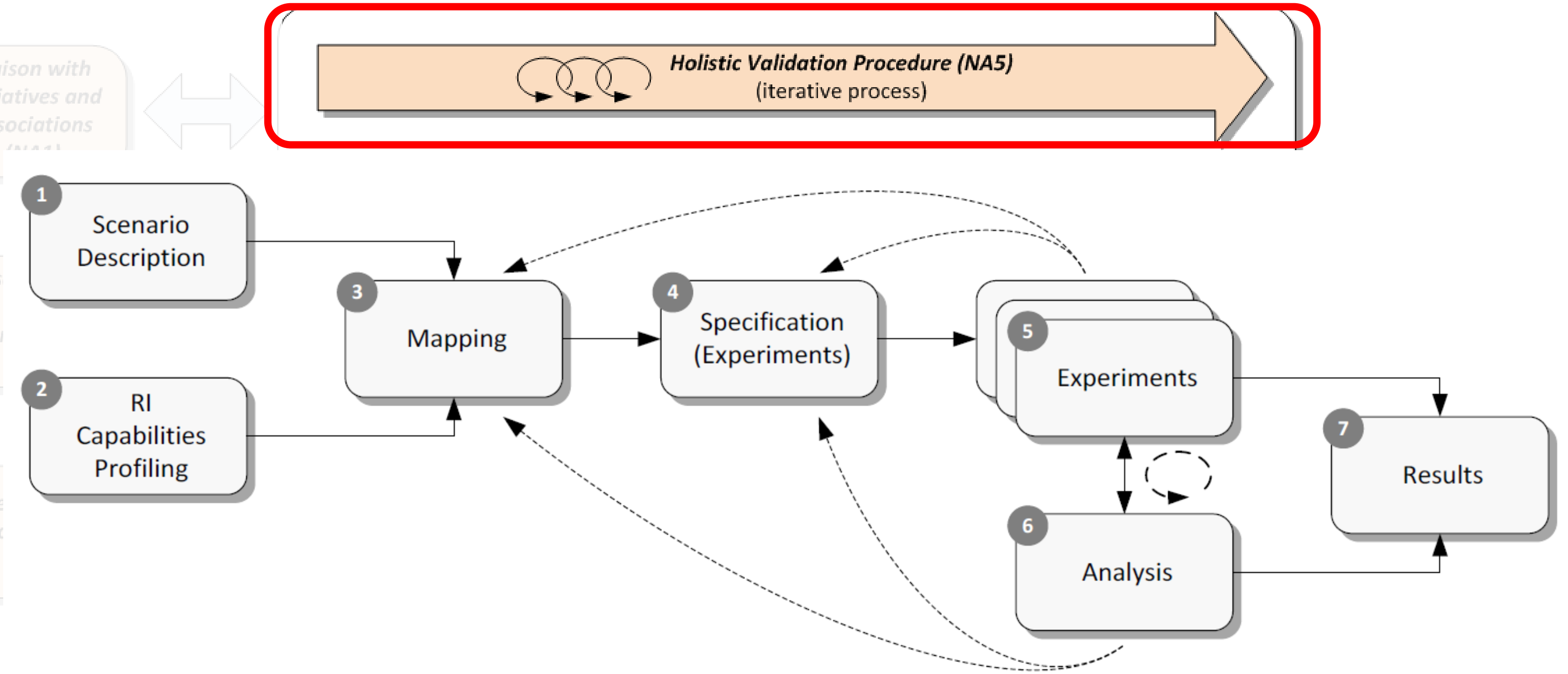
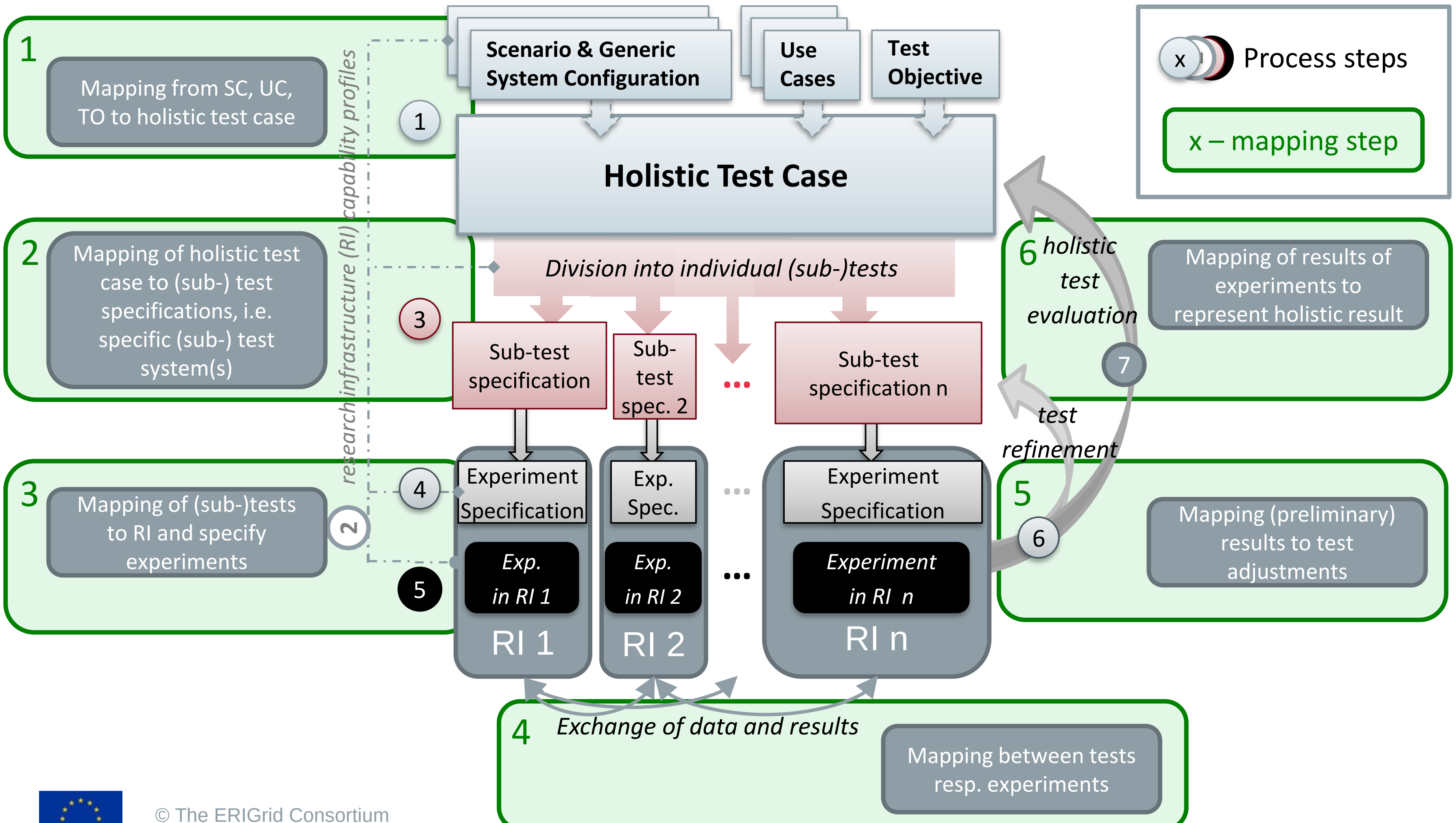
System Validation – A Holistic Procedure



"**Holistic testing** *is the* *process* *and* *methodology* *for the evaluation of a concrete function, system or component (object under investigation) within its relevant operational context (system under test), corresponding to the purpose of investigation"*

Holistic Testing Procedure
Different Mapping Steps



A Generic Experiment / Validation

System Configuration

- Defines components of a system
- Includes: Object of investigation

Use Case

- Defines functions of a system
- Requirements define Test Criteria

SGAM? CIM?

IEC 62559

Test Case

Purpose of Investigation

- Experimental design
- Test procedure

Configuration

Input

controllable &
uncontrollable
input parameters

Test/ Experiment

Object of investigation

Experimental setup
Boundaries of experiment
Testing Tools
Data Exchange

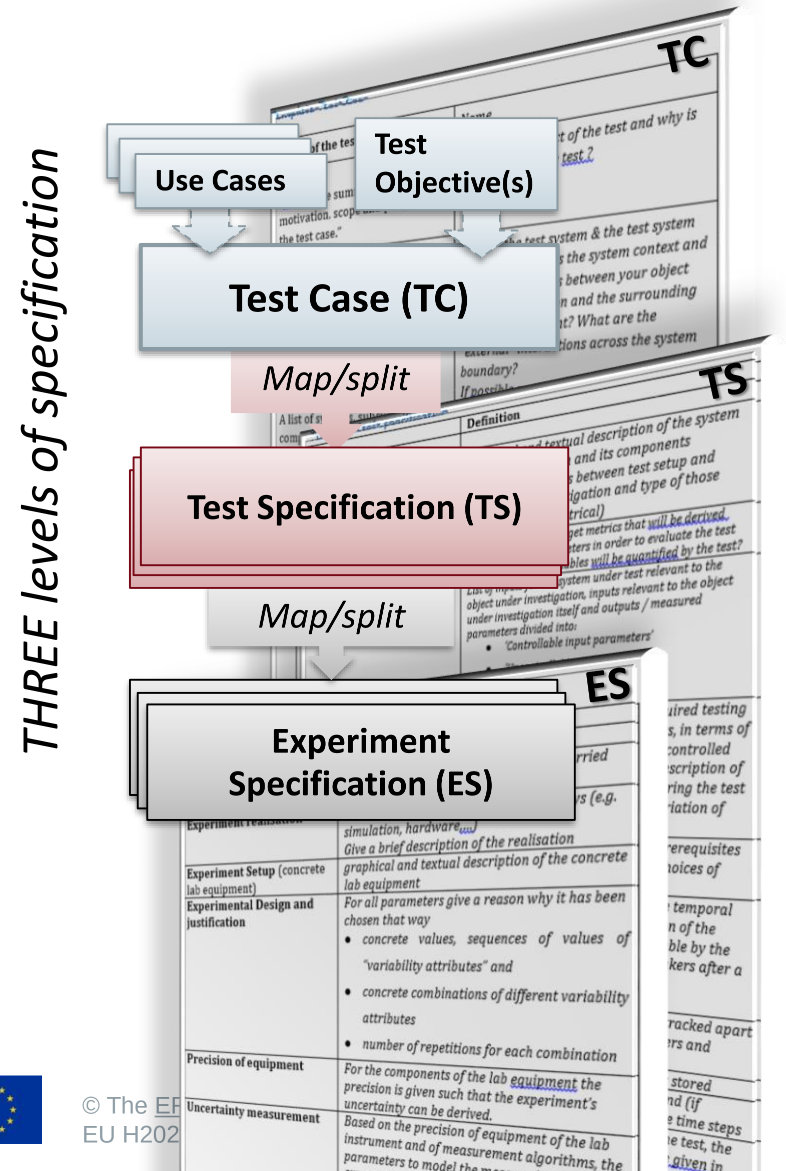
Target

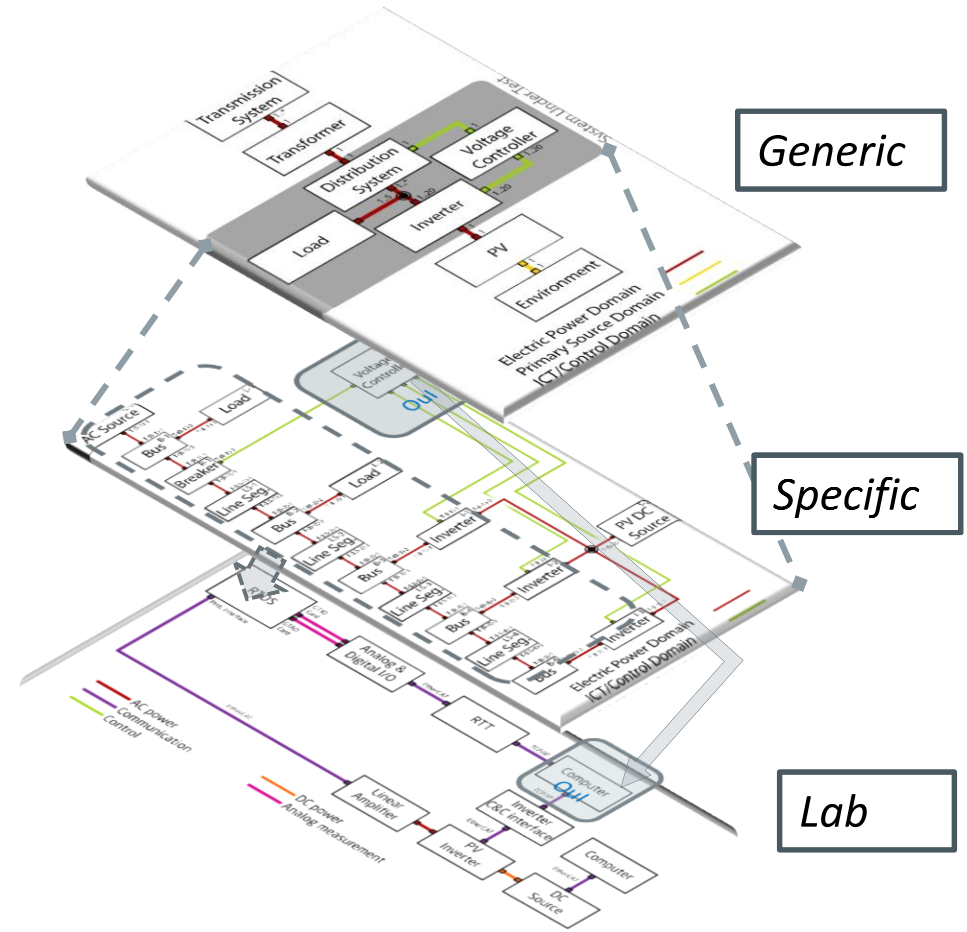
Test Criteria

Performance
indicators/
Test metrics

experiment **assessment**: **Quality of experiment**: error type; **uncertainty; quantification of error**

Holistic Test *Description*

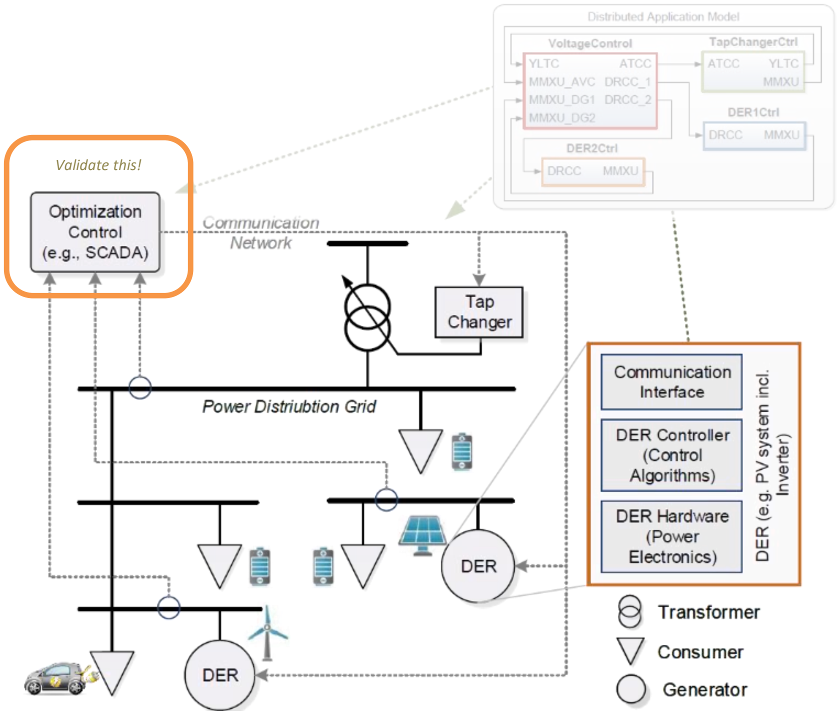




Holistic Testing

- Key questions to be answered for **test specification**

Why to test?
What to test?
What to Test *For*?
How to test?



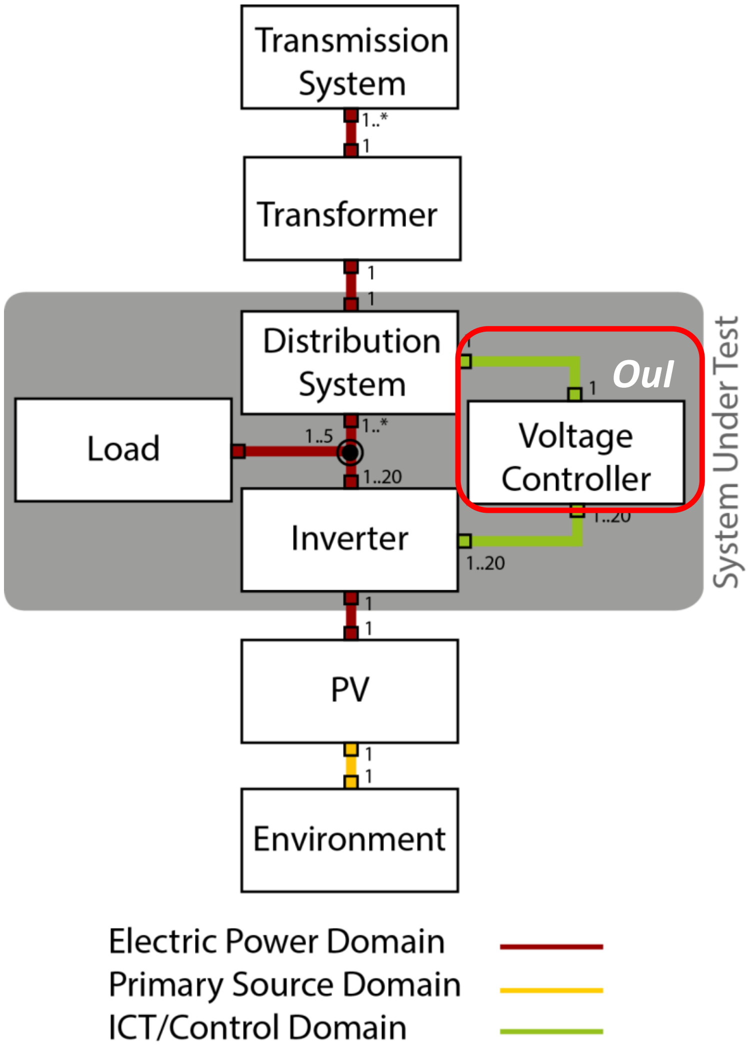
Test **System & Domain**

System under Test (SuT):
Is a <u>system configuration</u> that includes all relevant properties, interactions and behaviors (closed loop I/O and electrical coupling), that are required for evaluating an OuI as specified by the test criteria

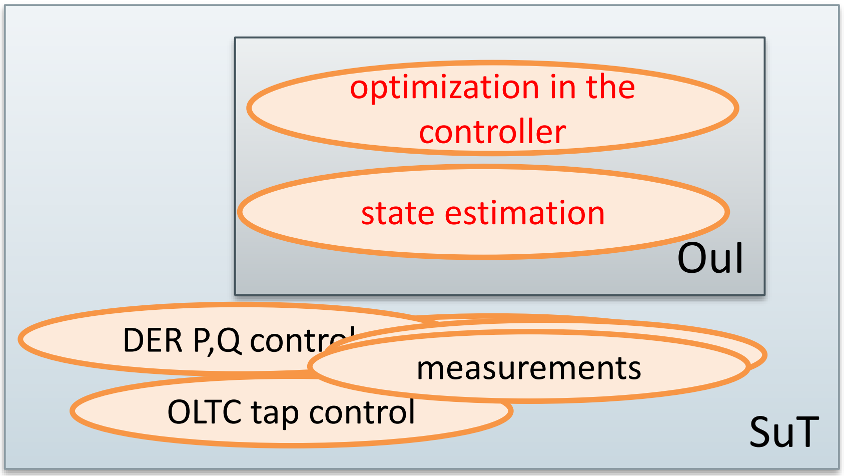
Object under Investigation (OuI):
The component(s) (1..n) that are subject to the test objective(s)

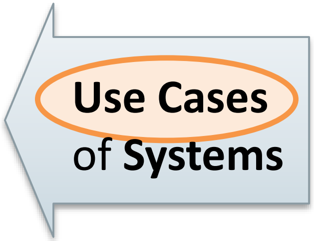
Remark: OuI is a subset of the SuT

Domain under Investigation (DuI)*:*
Identifies the domains of test parameters and connectivity relevant to the test objectives



Test System **Functions**





define Functions *(IEC 62559 approach)*

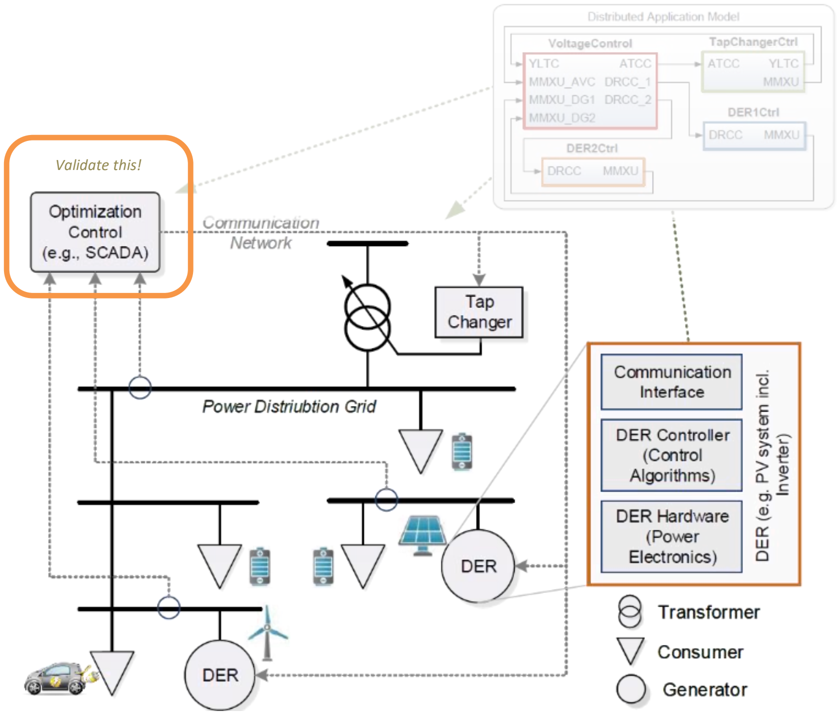
Functions under Test (FuT):
The functions relevant to the operation of the system under test, as referenced by use cases

Function(s) under Investigation (FuI):
The referenced specification of a function realized (operation-alized) by the object under investigation
Remark: the FuI are a subset of the FuT

Holistic Testing

- Key questions to be answered for **test specification**

  Why to test?
  What to test?
  What to Test *For*?
  How to test?



Purpose of Investigation (PoI)

- **Verification**

- **Validation**
- **Characterization**

Modeling / Understanding

Scoring / Performance

Test objectives/PoI:
Characterization and validation of the DMS controller

1. Convergence of the optimization (*validation*)
2. Performance of the optimization under realistic conditions (*characterization*)
3. Accuracy of the state estimation (*characterization*)

Designing Test Criteria

Detailing Sequence

- **Test objective → PoI → Test Crit.**
- **Test criteria:**
  How to break down the PoIs?
  - *Target Metrics* (TM, criteria): List of metrics to quantify each PoI
  - *Variability attributes:* Controllable or uncontrollable parameters to “disturb” SuT
  - *Quality attributes* (thresholds): Test result level or quality of the TM required to pass or conclude the testing

Target metrics:

1. 1.1 convergence (when/how often?),
   1.2 how fast?
   1.3 solution quality
2. 2.1 voltage deviation
   2.2 number of tap changes,
   2.3 network losses
3. Voltage, P, Q estimation errors

Variability attributes: load patterns (realistic, annual variation; applies to criteria 1-3); communication attributes (packet loss, delays)

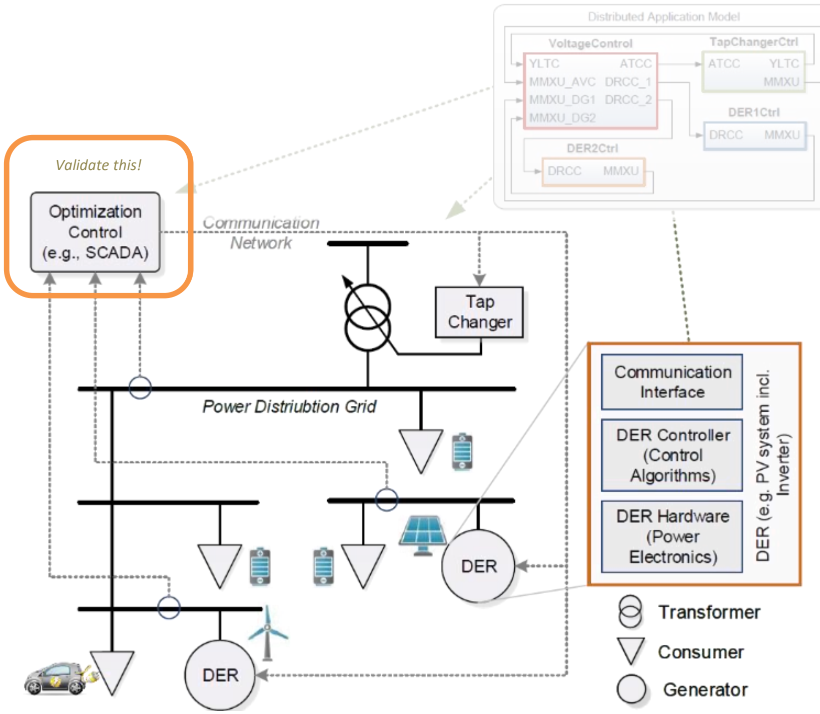
Quality attributes (thresholds):

“1.2: convergence within 2 sec” (*validation*)
“3.* estimation quality characterized with confidence 95%” …

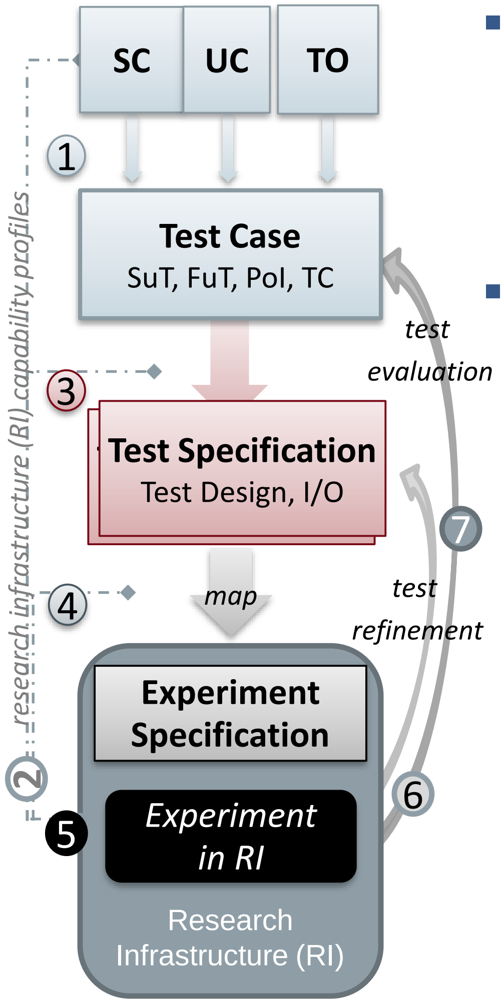
Holistic Testing

- Key questions to be answered for **test specification**

  Why to test?
  What to test?
  What to Test *For*?
  How to test?



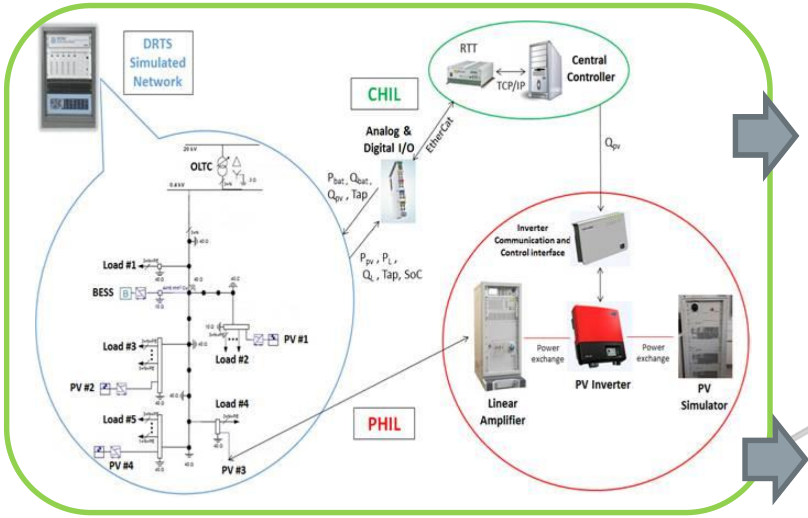
Test Specification and Design

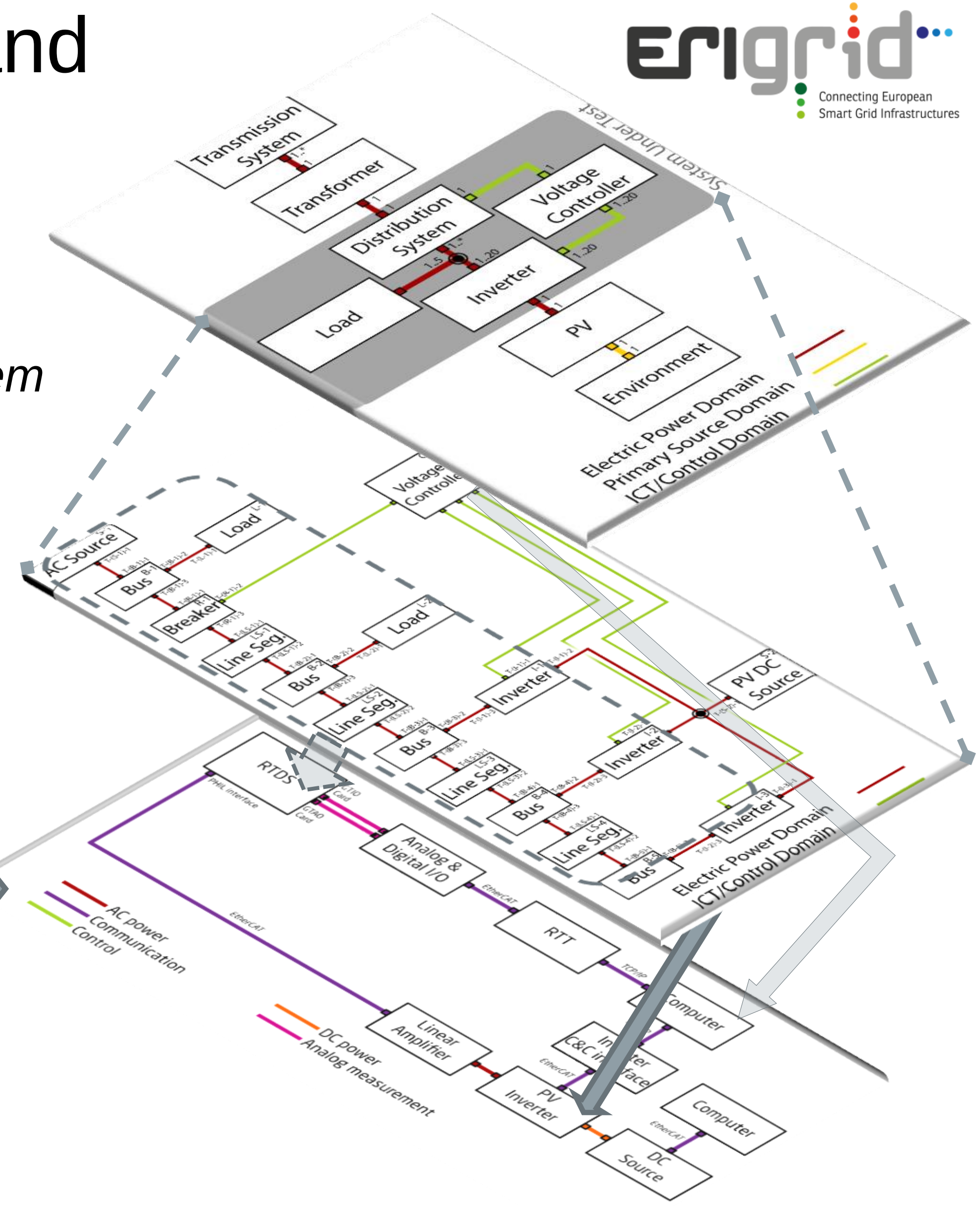


- **Given**
  - ✓ Purpose of Investigation (PoI) and Test Criteria
  - ✓ System and Domain categories and relations
- **To Specify**
  - ❑ Precise system (specific system configuration)
  - ❑ Which variables to manipulate and which to measure?
  - ❑ How to quantify the test metrics (based on test data)?
    - ❑ Sampling of the input spaces (design of experiments methodology)
    - ❑ Combination and interpretation of the outputs
  - ❑ The test design / procedure
  - ❑ Mapping to actual lab setup (experiment setup)

Detailing Test Setup and Mapping to the Lab

Scoping & specification of test system





Separate specification

of lab implementation

Holistic Test Case Example

TEST CASE:

- **Narrative**: For a DMS controller in development stage (simple implementation) the performance of the DMS algorithm and controller should be evaluated under realistic conditions. This test, could be seen as the last step before installing the DMS in the field.
- **SuT**: DMS, DER, OLTC, transformer, distribution lines, telecom network
  - OuIs: DMS_controller
  - DuI: **Electric power** and **ICT**
- **FuT**: DER P,Q control, measurements, OLTC tap control, comm. via ICT
  - FuI: optimization in the controller, state estimation
- **Test objectives/PoI**: *Characterization and validation* of the DMS controller
  1. Convergence of the optimization (*validation*)
  2. Performance of the optimization under realistic conditions (*characterization*)
  3. Accuracy of the state estimation (*characterization*)
- **Test criteria** – *how to formulate these objectives?*

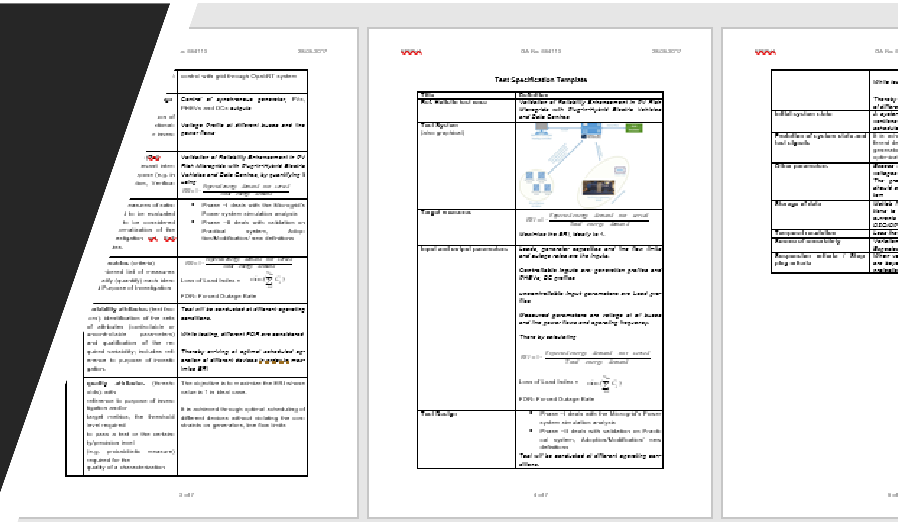
Target criteria - Variability attributes: - Quality attributes

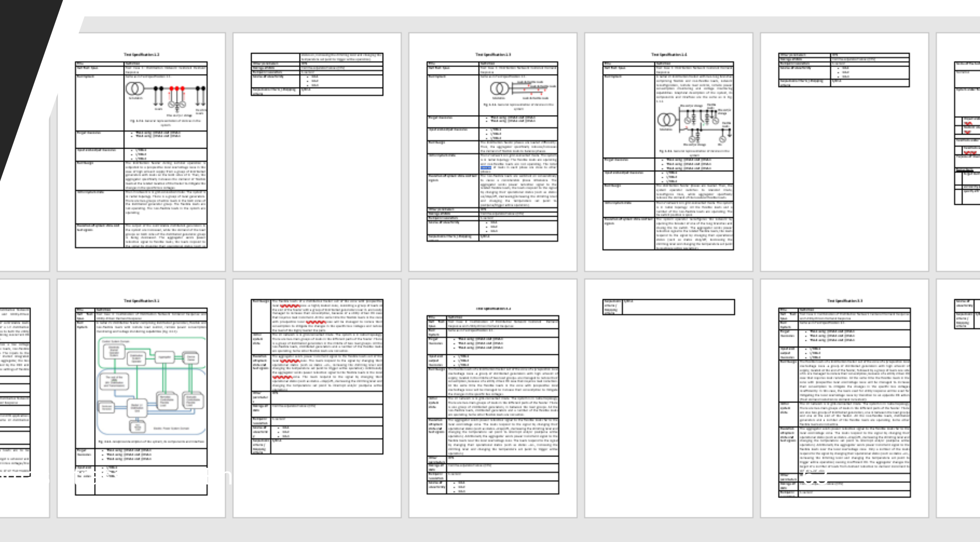
Potential Test setups:

- Pure simulation (e.g., co-simulation)
- Combination of virtual & physical interfaces and simulated components (PHIL and CHIL)
- Full hardware setup

ERIGrid Transnational Access: *Preparation & Documentation*

- External Lab users apply description procedure
- E.g. DiNODR – distribution network oriented application of demand response – *currently ongoing in SYSLAB*
- "The preparation work **helped us a lot**. Except minor changes in the plan and configurations due to a number of device, communication and control unavailabilities, we are **following our test and experiment specifications**. The template is also useful for our user team to **exchange ideas in an organized and effective** way. "
  - Alparslan Zehir (DiNODR)





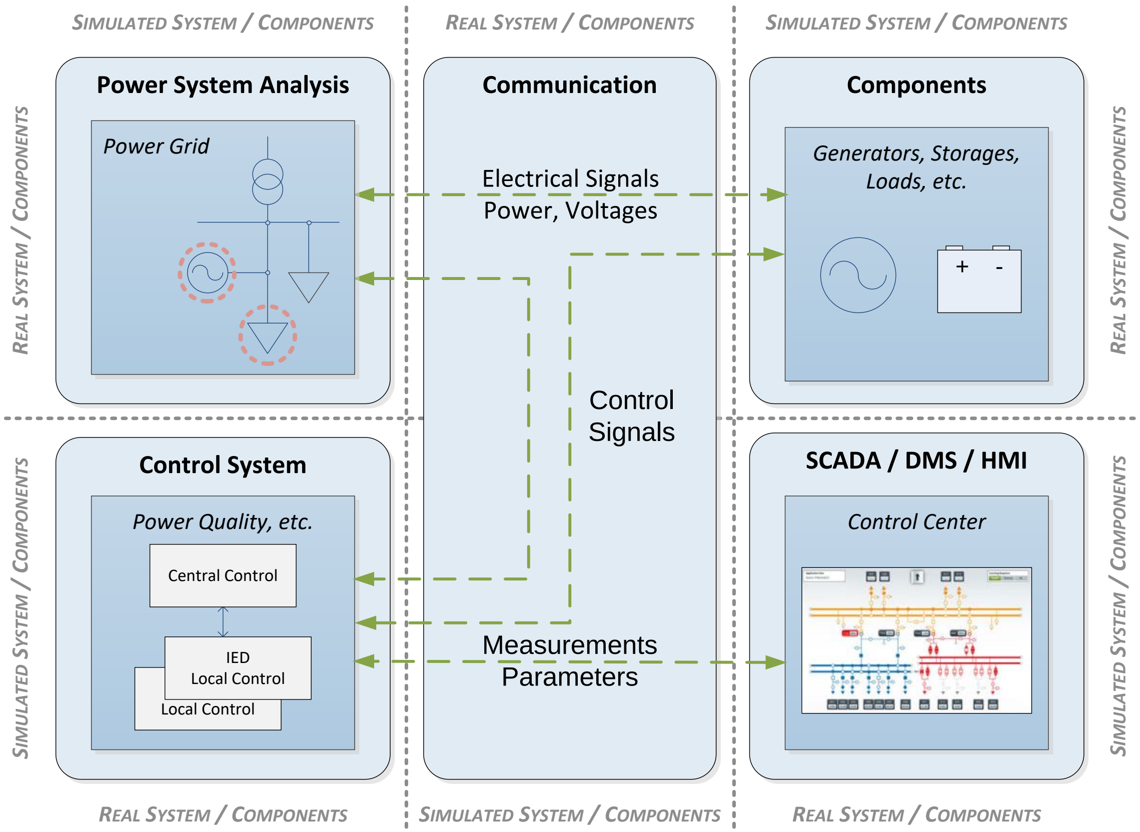
Simulation and Lab-based Testing Methods

INDIN 2018 Tutorial

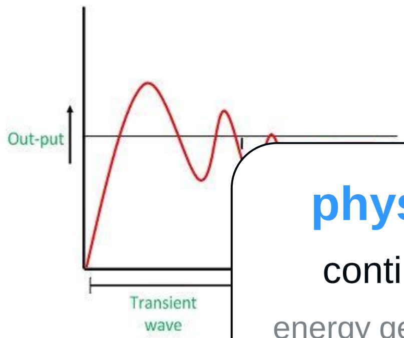
Methods and Tools for Validating
Cyber-Physical Energy Systems

Improved Testing Methods and Tools

- Simulation-based approaches



Simulation Challenges



physical world

continuous models

energy generation, transport, distribution, consumption, etc.

roles/behavior

game theory models

agents acting on behalf of a customer, market players, etc.

Cyber-Physical Energy System

information technology

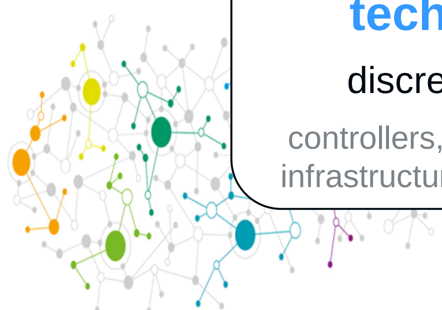
discrete models

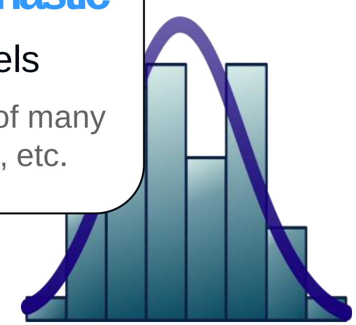
controllers, communication infrastructure, software, etc.

aggregate / stochastic

statistical models

weather, macro-view of many individual elements, etc.



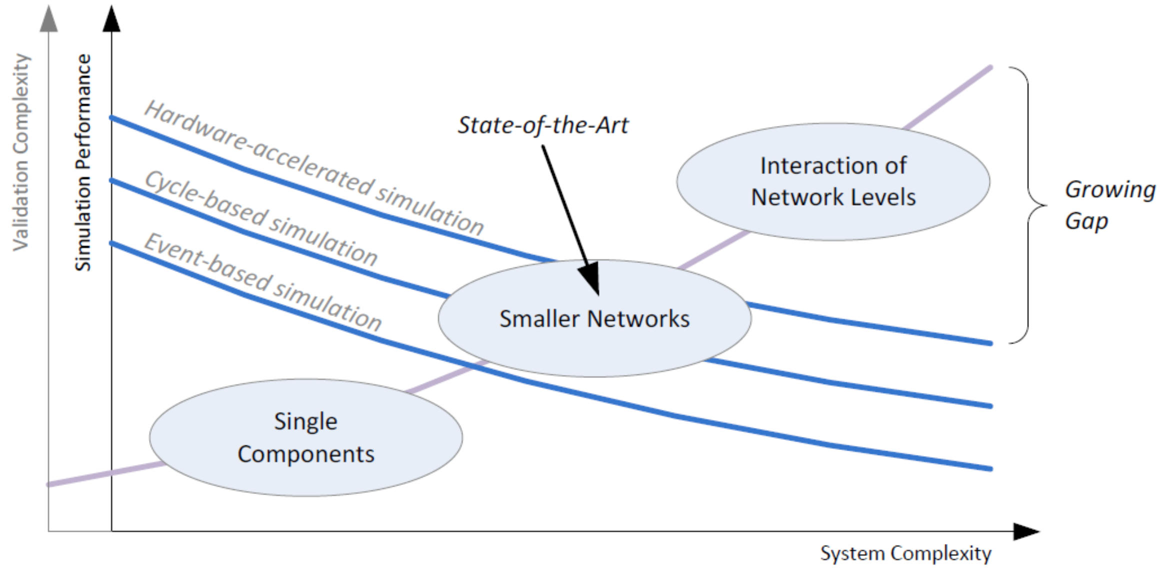


Aims and Objectives

- Develop advanced co-simulation based methods
- Simulation-based validation of smart grid scenarios
- Utilisation of standardised interfacing methods such as the Functional Mock-up Interface (FMI)
- Application and adaptation of existing scenario development and execution tools like mosaik
- Application of optimisation techniques, design of experiments, ICT assessment methods beyond state-of-the-art
- Develop tool-specific FMI wrappers
- Develop FMI-based smart grid model library
- Assess and large-scale system phenomena by an integrated simulation environment

Co-Simulation

- Smart grid system comprises of complex infrastructure, involving interaction among various domains
- This continuous interaction among the various components, devices and domains leads to huge amounts of data being exchanged
- Co-simulation helps in coupling among these domains to create a realistic representation of any smart grid infrastructure and its behaviour



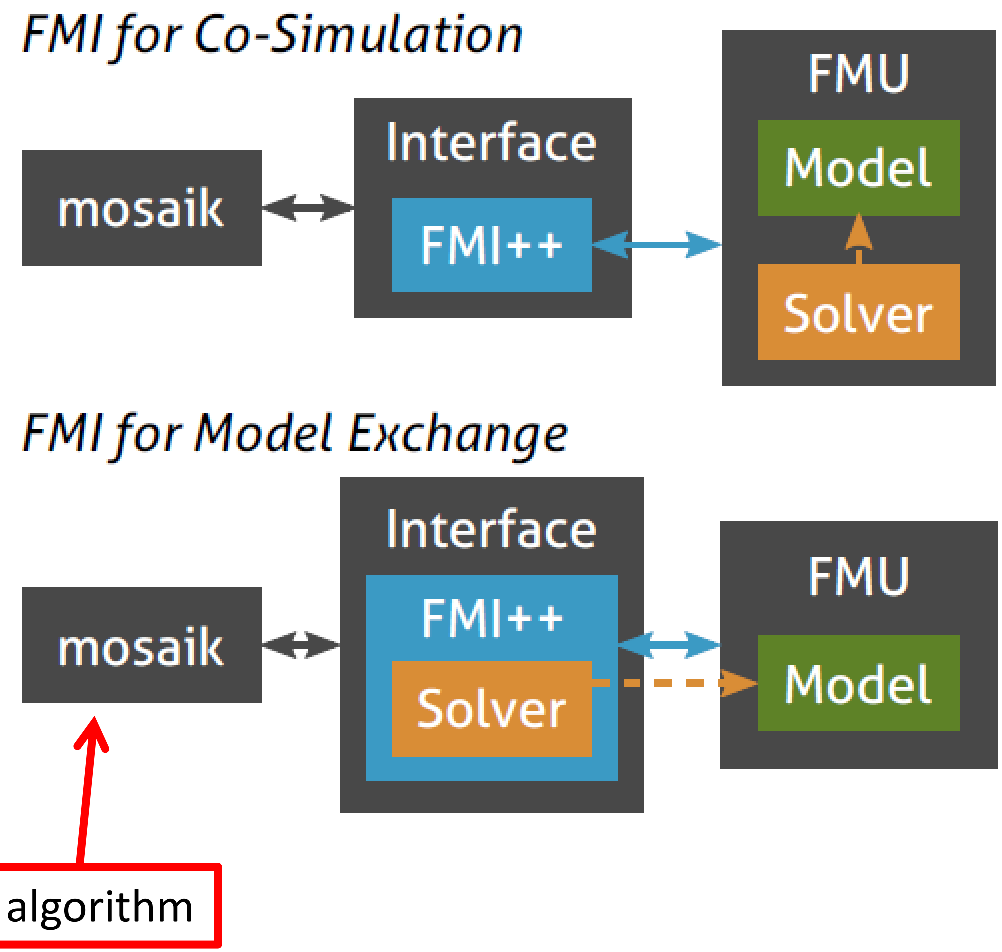
The Tools
Functional Mock-up Interface (FMI)

FMI is a tool independent standard to support

- Co-simulation of dynamic models
- Model exchange

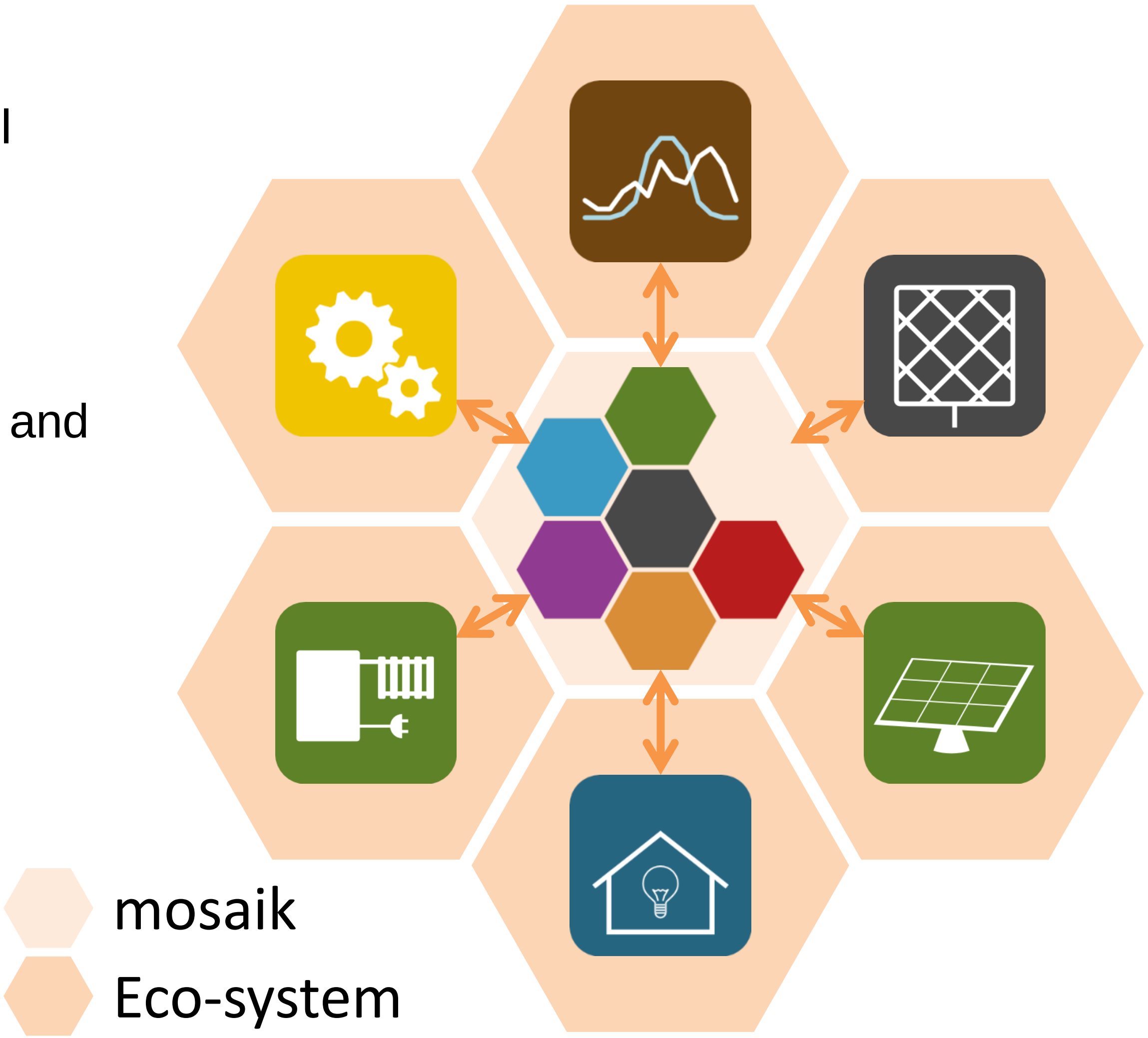
Specifies the functionality that a model or simulator should offer when connected externally

Stems from automotive industry, currently supports over 100 tools

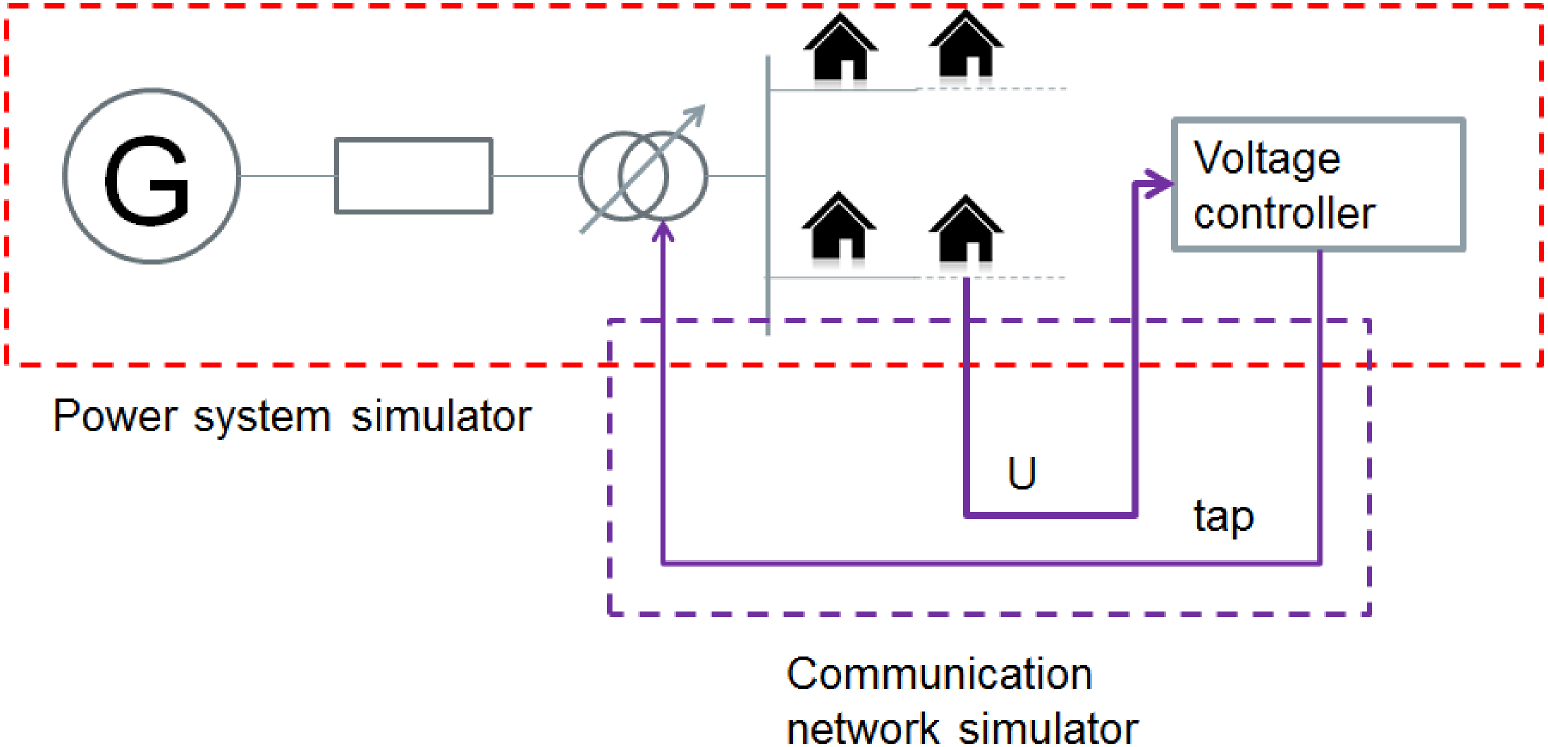


The Tools
mosaik

- Orchestrates the overall simulation study
- Testbed for multi-agent systems
- Adapted for continuous and discrete simulations
- Flexible scenario description
- High modularity

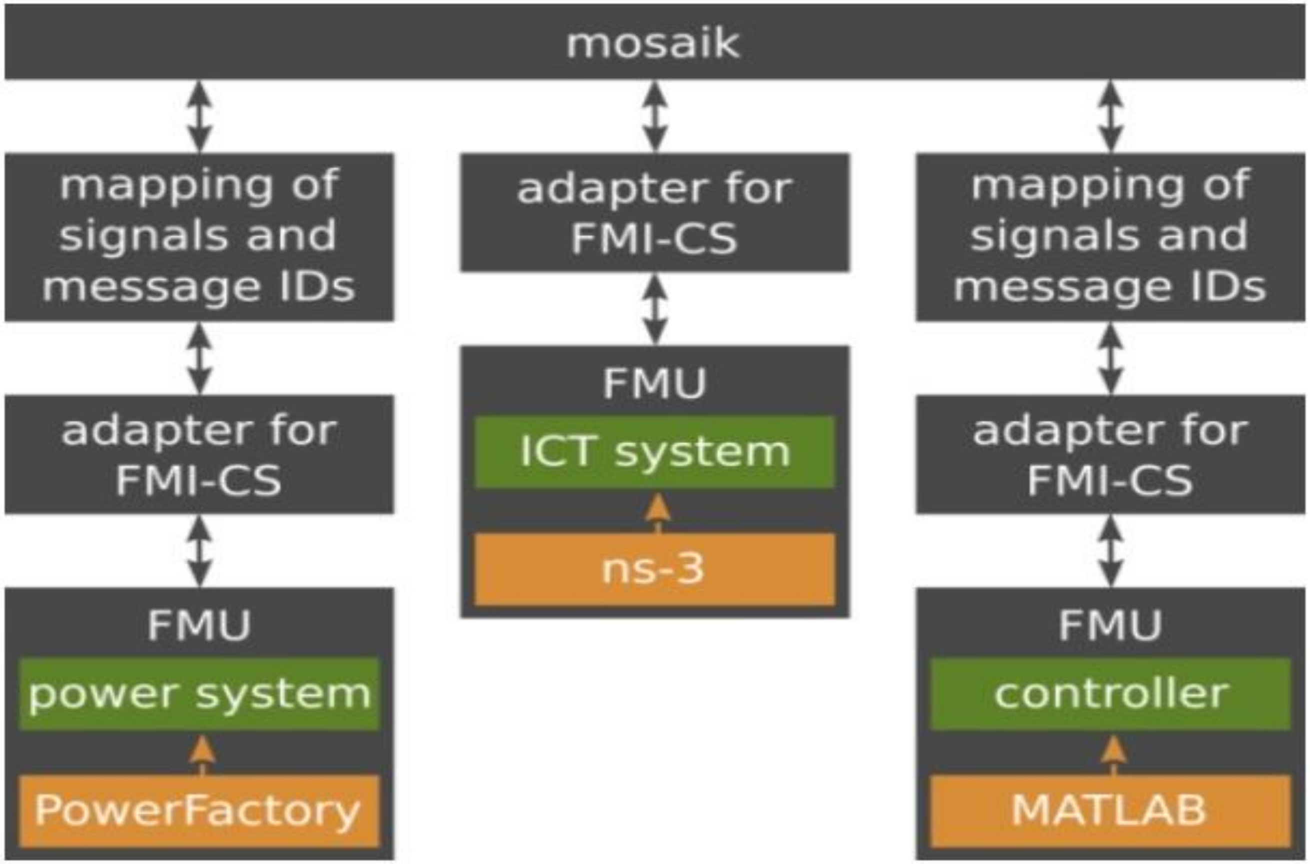


Validation Example
Coord. Voltage Controller (CVC)



General Setup of CVC system

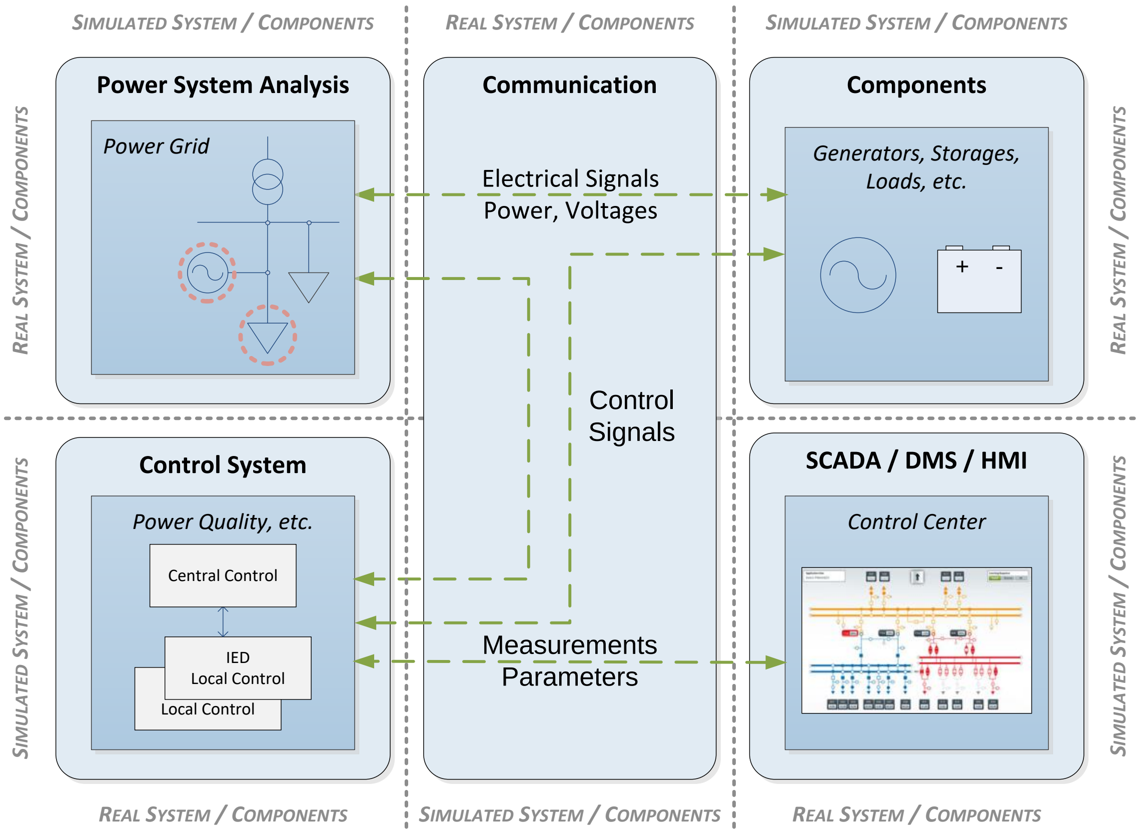
Validation Example
Coord. Voltage Controller (CVC)



Experimental setup of CVC system

Improved Testing Methods and Tools

- Lab-based approaches



Laboratory Integration Obstacles

- Power grids are mature infrastructures and have been extensively standardised
  - No standards for smart grid labs or what there primary purpose should be
  - Consequently, the use of ICT/automation systems (architectures, interfaces, etc.) is subject to large variations between facilities
- Smart grid labs are complex infrastructures with unique properties
  - Experimental nature of the installations
  - Changing user groups
  - Evolving configurations
- Finding a common ground when talking about lab integration can be a challenge

SmartEST Laboratory at AIT

Smart metering communication platform at TECNALIA

Issues Addressed in ERIGrid

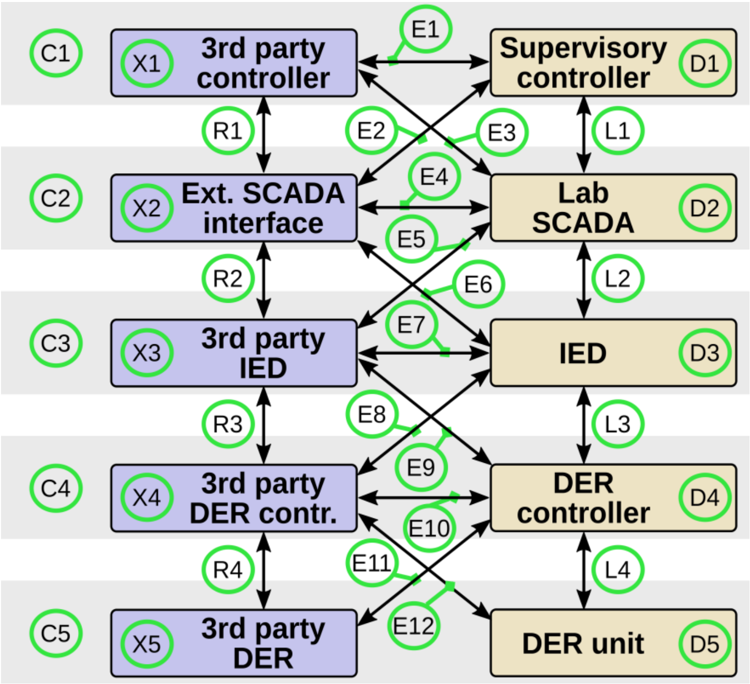
- Generic reference model for control hierarchies, interfaces and data flow in smart grid laboratories
- Documentation of complex DER behaviour
- Documentation of controller deployment procedures
- Uniform naming of signals and objects

Need for a Generic Reference Model

- Status quo
  - Availability of communication interfaces between the different parts of a lab determines to which degree the lab presents itself to the user as a collection of hardware components or as an integrated system
  - The automation and control aspects are often missing from descriptions of lab capabilities which tend to focus on the performance of the power equ.
- A one-size-fits-all model is complicated because
  - A wide range of automation levels/concepts is found among partner labs
  - Ad-hoc automation for individual experiments is not uncommon
  - Automation may involve communication between lab components and/or between the lab and third party equipment (under test)
  - The automation may be considered as infrastructure, as part of the system under investigation, or a combination of both

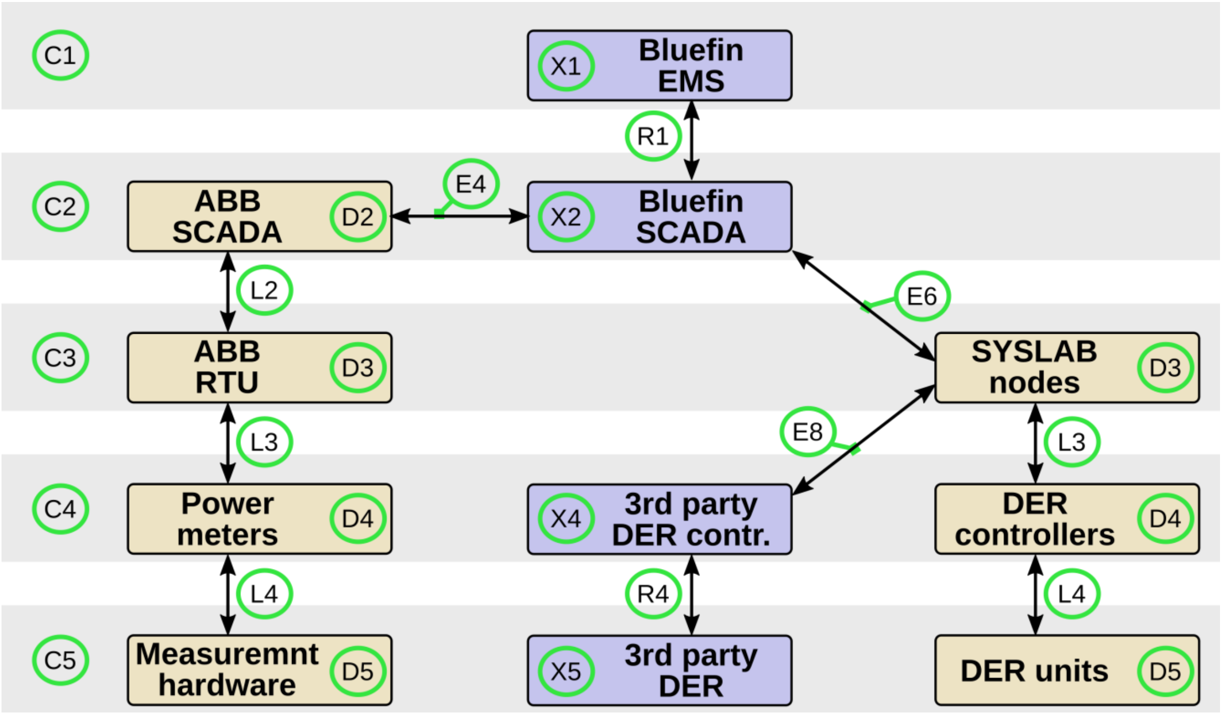
Generic Reference Model Description

- The model abstracts away from individual devices, controllers, protocols etc. as well as time, in order to focus on classes of controllers and interfaces
- Definition of five hierarchy levels at which control functionality may be deployed (both internal to the lab & external)
- Definitions of 20 communication interface locations
- Use cases for 12 interfaces between lab installations and external systems
- Partner examples of concrete experiment configurations



Generic Reference Model
Example DTU SYSLAB & Electric lab

- Performance evaluation of a third-party smart grid automation system
- Augmentation of a low automation host lab (DTU Electric lab) with components and control infrastructure from a highly automated lab (DTU SYSLAB)



Complex DER Component Behaviour

- Lab equipment (esp. DER units) often exhibits complex and undocumented behaviour when operated during experiments
  - Documentation often focuses on the operation under standard conditions
  - Examples include deratings, internal limits, safety circuits, alternate operating modes, functions added as part of laboratory integration etc.
- The productive use of a particular component often relies on unofficial knowledge associated with experienced lab staff – sometimes a single person
- ERIGrid conducted a survey of examples across partner labs, the results can be seen as a first step towards a more systematic documentation

Controller Deployment Procedures

- Deploying controllers – software or hardware, from the unit level to the system level – is important for many types of smart grid testing
- It is very difficult for an outside user or research partner to gain an overview of the exact capabilities of a laboratory with respect to controller deployment. This complicates the selection of a suitable facility for an experiment.
  - Uniqueness of the individual laboratories
  - Many possible interaction patterns
  - Policies and safety/stability concerns (an interface exists, but it should not be used)
- Survey of controller hosting capabilities across partner labs
  - Physical capabilities
  - Interfaces
  - Procedures

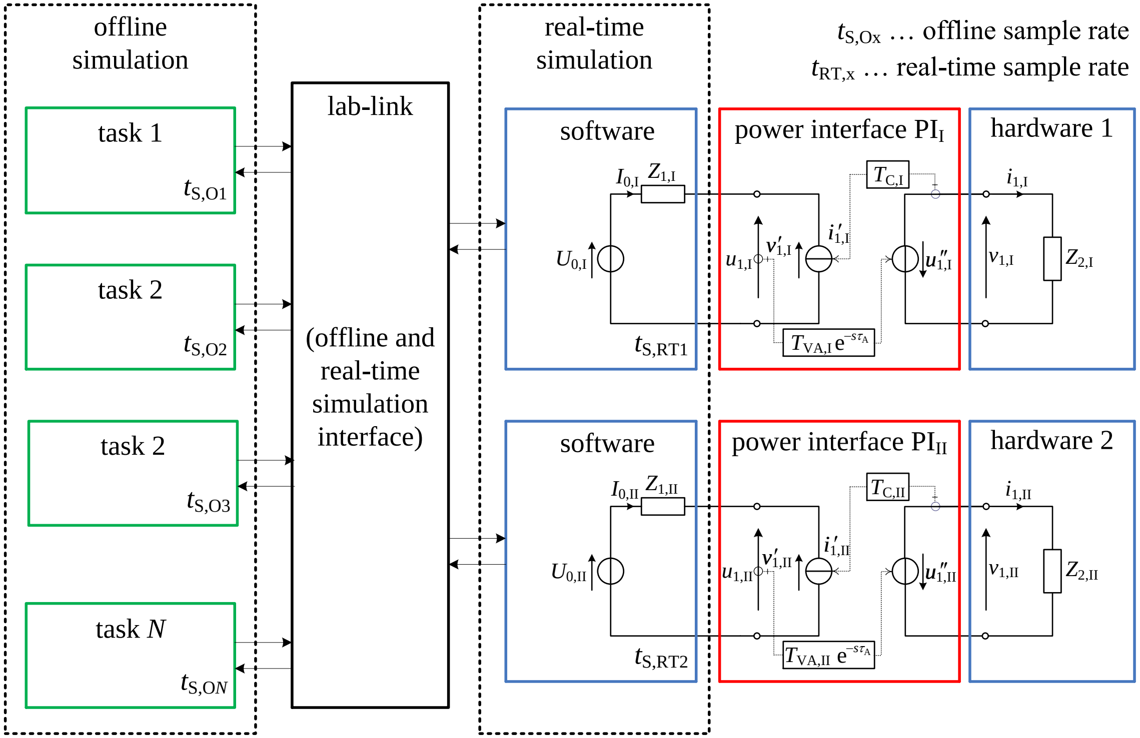
Signal and Object Naming

- The partner labs have been developed from very different architectural viewpoints, resulting in different ways of modelling information
- Establishing a harmonized object and signal naming convention is necessary for machine-to-machine communication between labs
- Existing standards lack flexibility
  - Lab-specific description of primary hierarchy (physical, electrical, automation based, information based, etc.)
  - Additional domains (control, communication, etc.)
  - Unambiguous description of components which belong to multiple hierarchies and/or multiple domains

- ERIGrid has developed naming conventions suitable for the detailed description of static (objects) and dynamic (signals) data in smart grid laboratories.

Coupling Co-Simulation and Real-Time Hardware-in-the-Loop (HIL)

- Cyber-physical (multi-domain) approach for analysing and validating smart grids on system level
- Improved validation and testing methods with focus on co-simulation & HIL



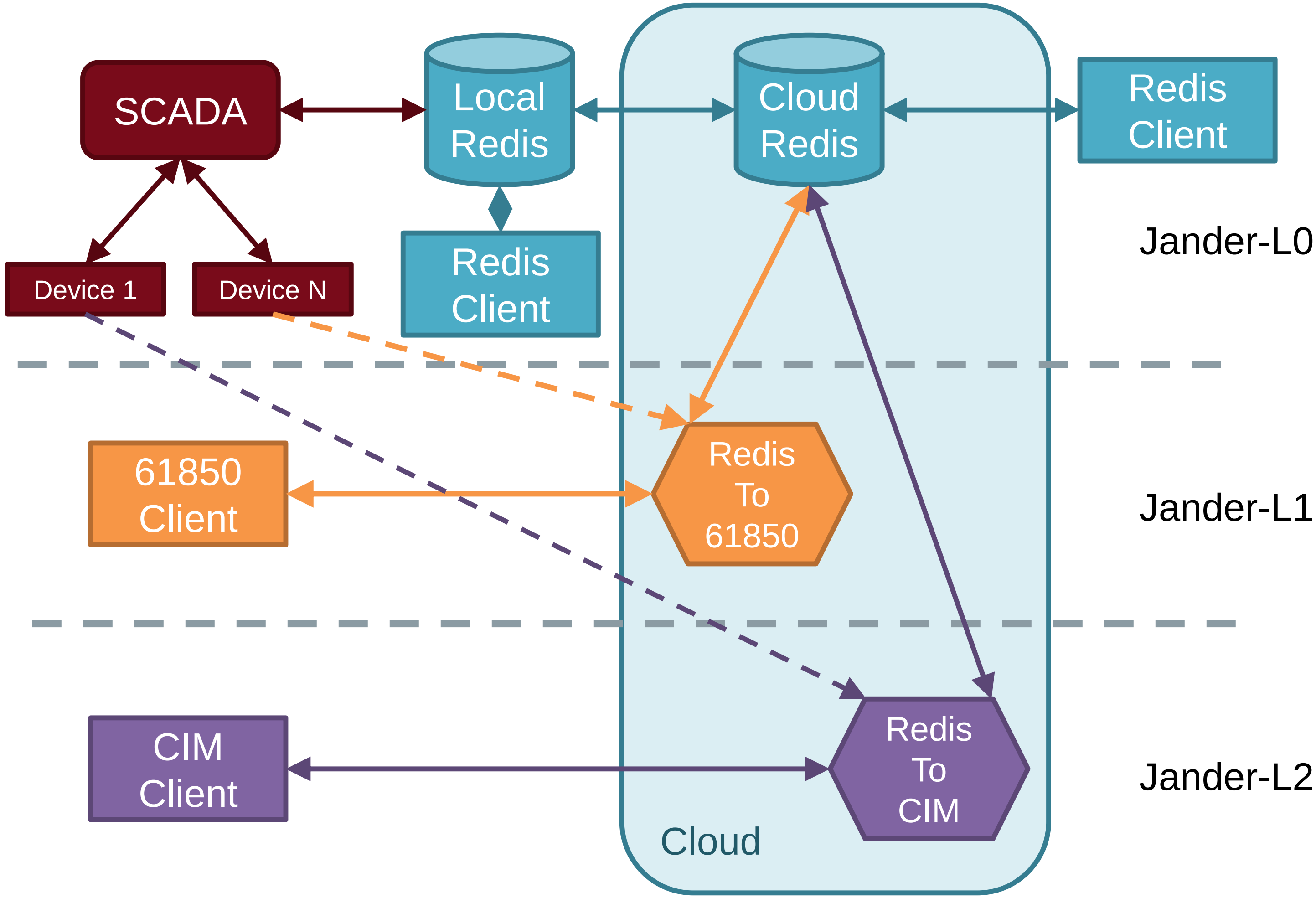
EU H2020 Programme GA No. 654113

Connecting Smart Grid Labs
Real-Time Data Exchange via JaNDER

- Joint Test Facility for Smart Energy Networks with DER (JaNDER)
  - Result from FP7 DERri
  - Proof-of-concept of real-time data exchange between lab facilities
- Several shortcomings of DERri JaNDER version (addressed in ERIGrid)
  - Installation effort (e.g., requirement for firewall changes)
  - Lack of official multi-lab test cases in DERri
  - No context information beyond raw real-time data
- Virtual Research Infrastructure (VRI)
  - Integration of all ERIGrid participating labs
  - Virtually integrated pan-European smart grid research infrastructure

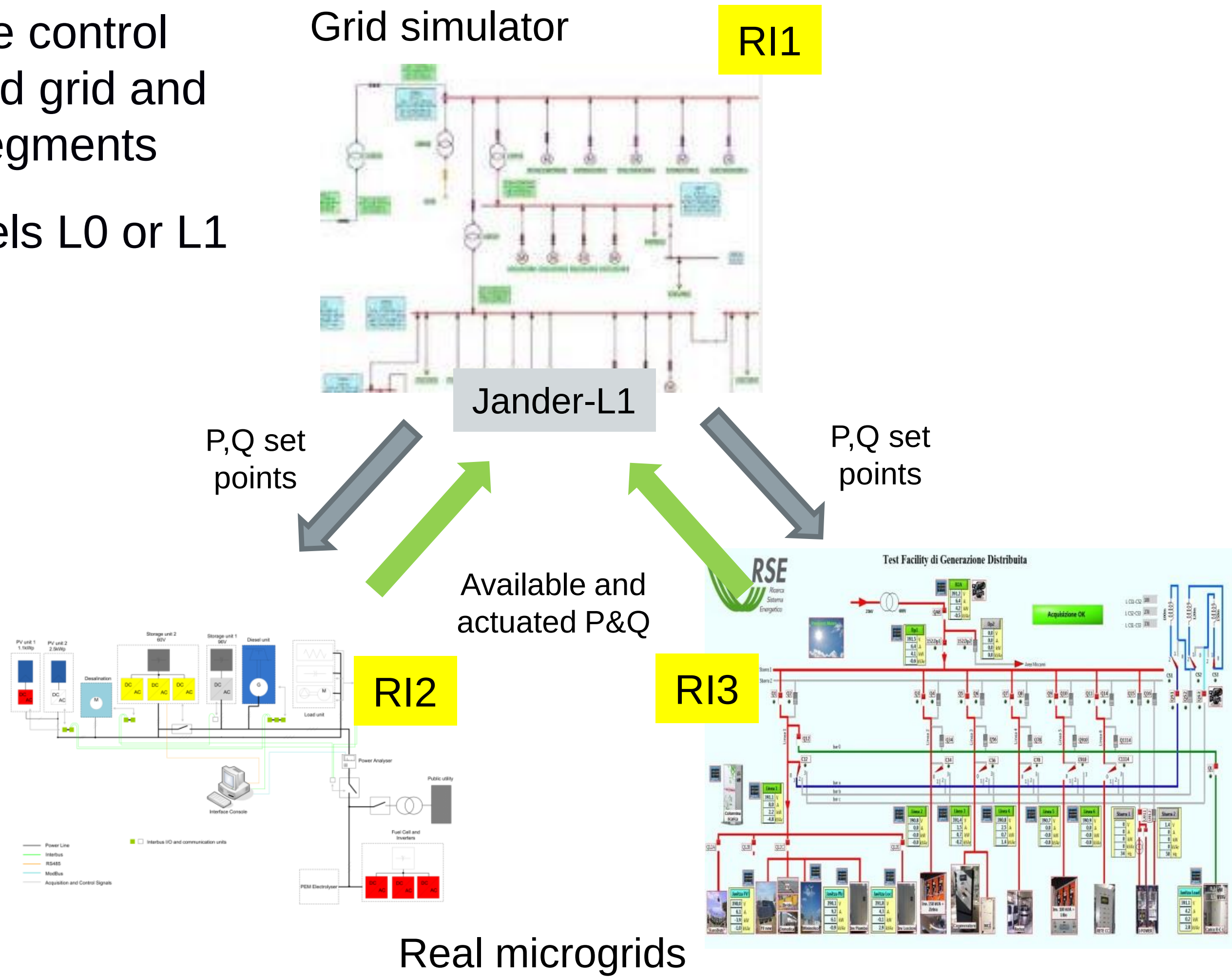
EU H2020 Programme GA No. 654113

Connecting Smart Grid Labs
JaNDER Architecture



Connecting Smart Grid Labs JaNDER Example

- Coordinated voltage control between a simulated grid and two physical grid segments
- Using JaNDER levels L0 or L1



Selected Validation Examples

INDIN 2018 Tutorial

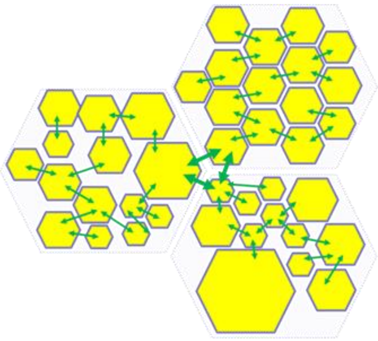
Methods and Tools for Validating
Cyber-Physical Energy Systems

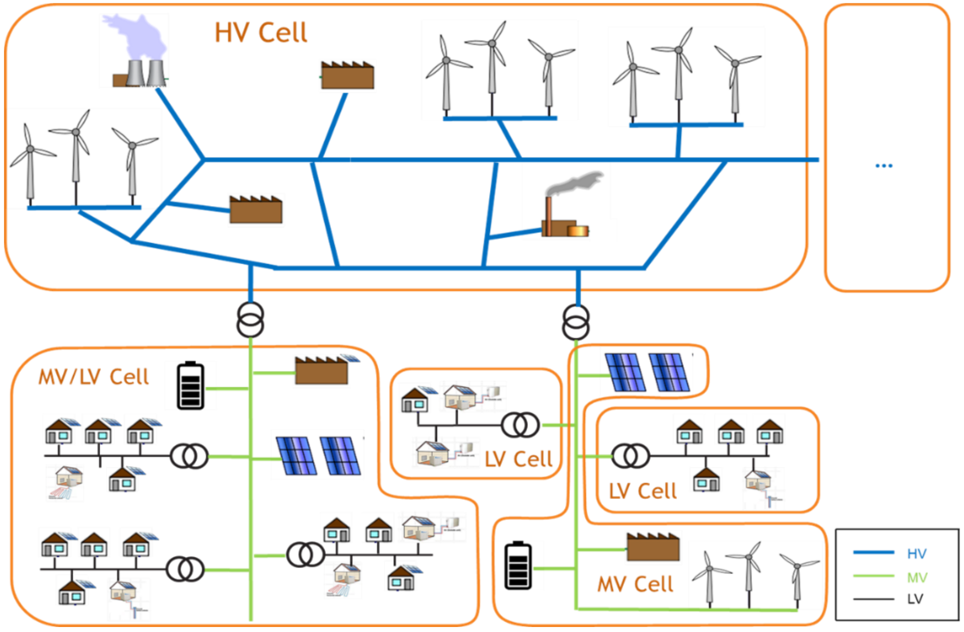
Selected Validation Examples

- Power system control testing
- Cyber-physical attacks investigation

Power System Control Testing

- Cell-based power systems control
  - ELECTRA IRP Web-of-Cells (WoC) approach
- Controller analysis and investigation
  - Focus on voltage control of a cell
- Validation goal
  - Testing of the WoC control implementation





EU H2020 Programme GA No. 654113

Power System Control Testing

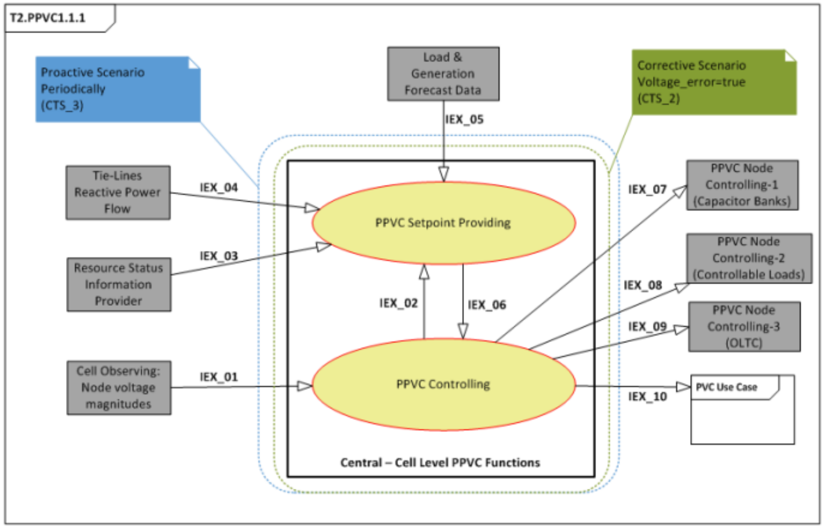
- Holistic Test Description: Test Case

Name of the test case	**Power quality and voltage control (PVC+PPVC)**
Narrative “a storyline summarizing motivation, scope and purpose of the test case.”	Can PPVC replace the present secondary (local) and tertiary voltage control (global) schemes existing in power grids by a decentralized control located at a cell level? How would PPVC interact with PVC and balancing control? How would PPVC respond to different network conditions?
System under Test (*SuT*): *(power system & ICT boundaries): SRPS + CTL*	Power distribution network (several voltage levels), On-Load-Tap Changing Transformers (OLTC), inverter-based Distributed Energy Resources (DER) (PV, wind turbine, energy storage systems), synchronous and induction machines, (controllable) loads
Objects under Investigation (*OuI*) "the component(s) (1..n) that are to be characterized or validated”	PVC+PPVC controlling
Domain under Investigation (*DuI*): “Identifies the relevant domains or sub-domains of test parameters and connectivity.”	• Power system • Control/ICT

EU H2020 Programme GA No. 654113

Power System Control Testing

- Holistic Test Description: Test Case

Functions under Test (*FuT*) List all functions required in operation of test system	 **Figure 0** Overview PPVC functions **In-focus Functions:** PPVC controlling, PPVC Set-point providing **Emulated functions:** Reserves information provider, load and generator forecastor, tie-line powerflow setpoint provider **Observer/Actuation Function:** DER-AVR device, DER-Controllable Q device **Actuation Function:** Capacitor banks, OLTC **Observer function:** Voltage pilot nodes

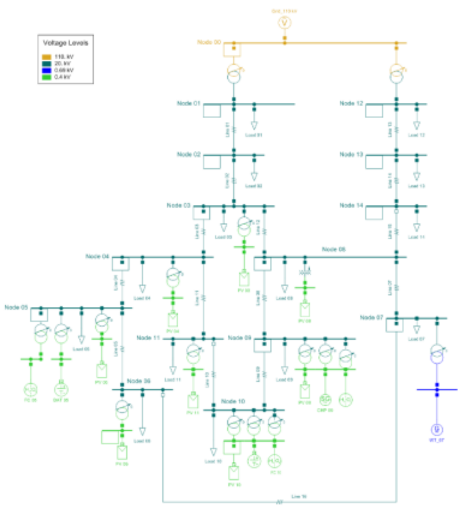
Power System Control Testing

- Holistic Test Description: Test Case

	Function(s) under Investigation (*FuI*) "the referenced specification of a function realized (operationalized) by the object under investigation"	• PPVC Set-point providing • PPVC Controlling
Purpose of Investigation *(PoI)* "a formulation of the relevant interpretations of the test purpose (e.g. in terms of Characterization, Verification, or Validation)"		3.4 Simulation-based proof-of-concept analysis of the PVC+PPVC use case, incl. sensitivity analysis, clustering concept for the identification of potential ELECTRA cells, scalability analysis, comparison with a business as usual case. 3.5 Hardware-in-the-Loop based proof-of-concept analysis of the PVC+PPVC use case incl. a selected number of DER units (PV system, Energy Storage Systems, etc.), sensitivity analysis.
Test criteria: "the measures of satisfaction that a need to be evaluated for a given test to be considered successful." A formalization of the purpose of investigation wrt. SuT and FuT attributes.		• Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes
	target metrics (criteria) A numbered list of measures to (quantify) each identified criterion	• Minimum power losses in the cell, Reactive power flows in the tie-lines within safety limits • Safe and robust voltage for all nodes
	variability attributes (test factors):	• Topology change resulting in change in number of tie-lines • Loss of a line • Loss of a generator
	quality attributes (thresholds):	• Power quality standard EN50160 • All node voltages within the specified limit (+ or -10%)

Power System Control Testing

- Holistic Test Description: Test Specification

ID / Title	Simulation-based proof-of-concept analysis of the PVC+PPVC use case, incl. sensitivity analysis, clustering concept for the identification of potential ELECTRA cells, scalability analysis, comparison with a business as usual case
Ref. Test case	Test Case 3
Responsible Entity	AIT
Experiment Type	Clustering, simulation
Test System (also graphical)	Usage of CIGRE MV distribution network (original and modified version) as depicted in the following figure.  **Figure 1** The modified CIGRE medium voltage network

Power System Control Testing

- Holistic Test Description: Test Specification

Table 1 Modifications to the CIGRE MV test network

	Node 3	Node 4	Node 5	Node6	Node 7	Node 8	Node 9	Node 10	Node 11
Source Type	PV;	PV	PV; FC; BAT	PV	WT	PV	PV; FC; CHP	PV; FC BAT;	PV
Source rating [kVA]	22;	22;	33; 1000 ; 1000	30;	1500	33;	30; 500 ; 500	40; 14 ; 210	10;
Tfmr rating [kVA]	500	500	500; 800; 500	800	2500	500	500; 500; 500	500; 500; 500	500

Table 2 Modifications to line length

Line lengths	Line 01	Line 02	Line 03	Line 04	Line 05	Line 07	Line 08	Line 09	Line 10	Line 11	Line 12	Line 13	Line 14	Line 15	Line 16

Research Infrastructure	---
Input parameters	• Generation profiles • Load profiles • Grid topology • Tie-line exchanges • DER controllers parameters
Output parameters	• Power losses • Node voltages
Target measures	• Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes
Test Design	Comparison of different cell-configurations and different OPF implementations
Initial system state	*Description of conditions that are prerequisites to actually run the test and initial choices of parameters.*
Evolution of system state and test signals	*Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds); incl. variability attributes*

Power System Control Testing

- Holistic Test Description: Experiment Specification

Title	Simulation of PVC+PPVC with CIGRE MV test grid
Ref. Test Spec.	Test Case 3, Test Specification 3.4
Research Infrastructure	PowerFactory, Python API, Python Scripts
Experiment Realisation	Simulation
Experiment Setup (concrete lab equipment)	**A) Sensitivity Analysis of the CIGRE MV test network**
Experimental Design and Justification	**1. Calculation of normalized electrical distance** a. Calculate the Jacobian matrix and use it to obtain the *∂Q/∂u* matrix. $\begin{bmatrix}\Delta P \\ \Delta Q\end{bmatrix} = \begin{bmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial u} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial u}\end{bmatrix}\begin{bmatrix}\Delta \delta \\ \Delta u\end{bmatrix}, \quad J_4 = \frac{\partial Q}{\partial u}$ b. Calculate the sensitivity matrix *B* by calculating the inverse of *J4*. $B = J_4^{-1} = \frac{\partial u}{\partial Q} \text{ where } b_{ij} = \frac{\partial u_i}{\partial Q_j}$ c. Calculate the attenuation matrix α by dividing the non-diagonal elements by the diagonal elements using the following equation. $\alpha_{ij} = b_{ij} / b_{jj}$ d. Calculate the electrical and obtain the normalized distance matrix $D_{ij} = -\log(\alpha_{ij} \,.\, \alpha_{ji})$ $D_{ij}^{norm} = D_{ij}/\max(D_i)$

Power System Control Testing

- Holistic Test Description: Experiment Specification

B) Hierarchical clustering

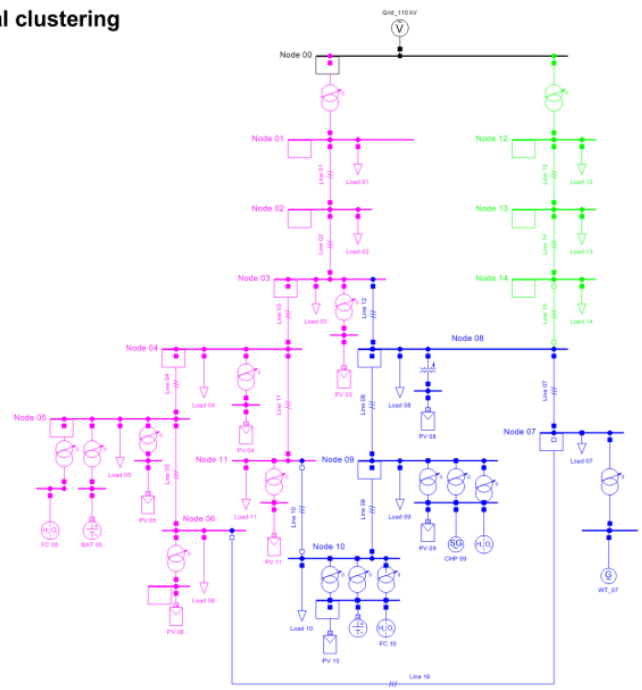


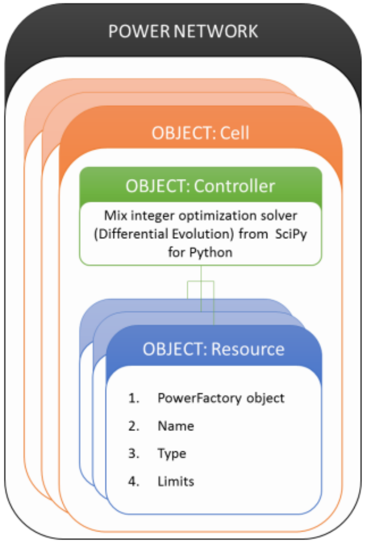
Figure 8 The modified CIGRE medium voltage network

C) Simulation setup overview

Once the clusters have been identified and the cells have been created next step is to create an autonomous independent coordinating controller for each of the zones. In the final step, the simulation results for the cell based optimal power flow (CBOPF) are to be compared to three other scenarios

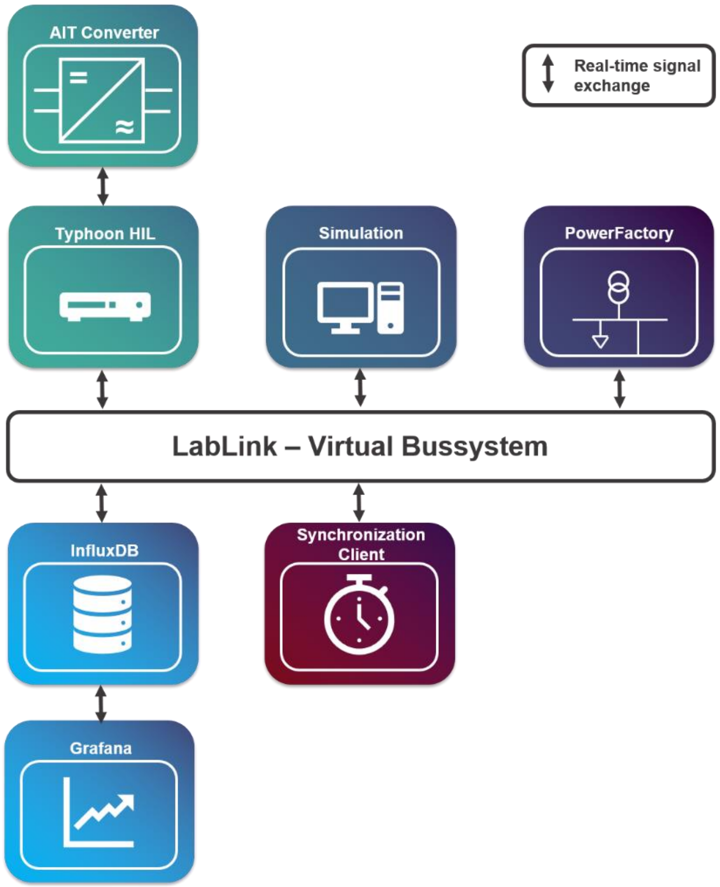
Power System Control Testing

- Holistic Test Description: Experiment Specification

	namely QDS with no control, QDS with local var control and the centralized OPF. The sensitivity of voltage regulation capability and the objective function to the number of cells formed is important to understand. Figure 9 given a graphical overview of the overall simulation process. An instance of PowerFactory has been created using the Python API provided by DIgSILENT. Within the network, multiple cell objects have been created (one for each cell). Each cell object can have multiple resource objects. These objects correspond to controllable VAR devices connected within the cell boundary. These resources can have both continuous (e.g. PV inverters) or discrete (e.g. Transformers) operation. Within the resource object, operational limits for each resource should also be defined. Finally, a coordination controller object within the cell object is responsible for calculating the new optimal set points for the resources connected with the network. The coordinating controller uses a differential evolution solver provided by SciPy. Each cell controller runs autonomously and independently.  **Figure 9** Python code overview

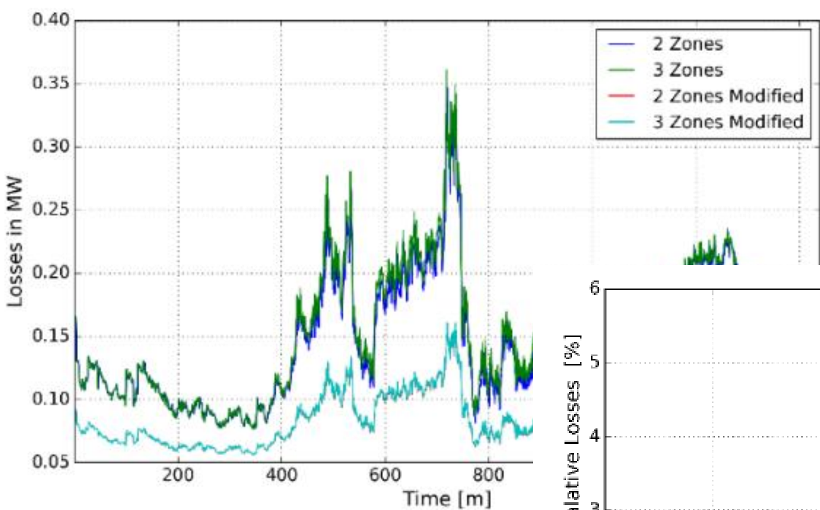
Power System Control Testing

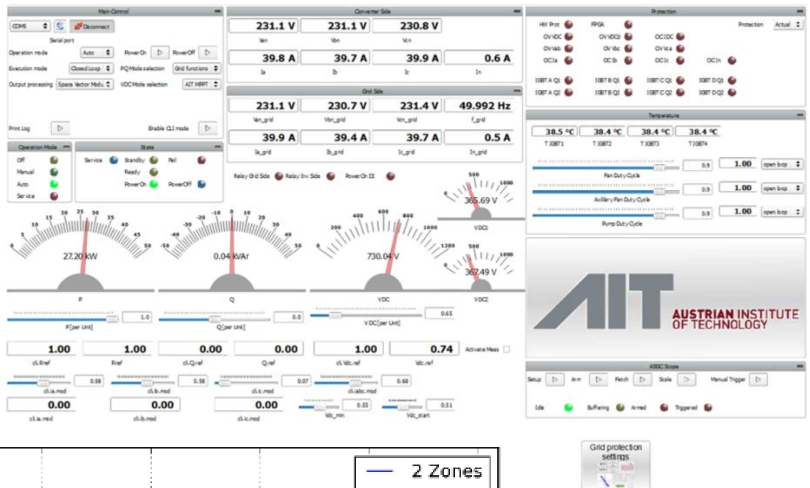
- Realized test with
  - PowerFactory Client
  - Simulation Client
  - Typhoon HIL Client
  - InfluxDB Client
  - Synchronization Client

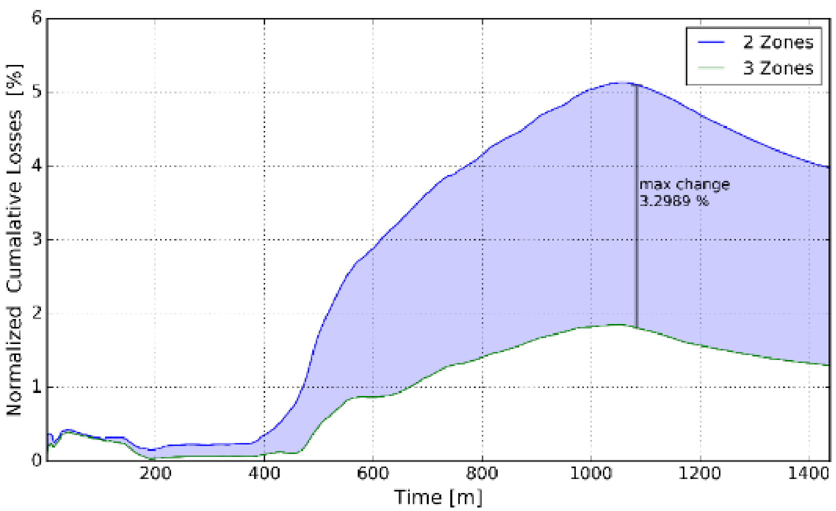


Power System Control Testing

- Achieved results

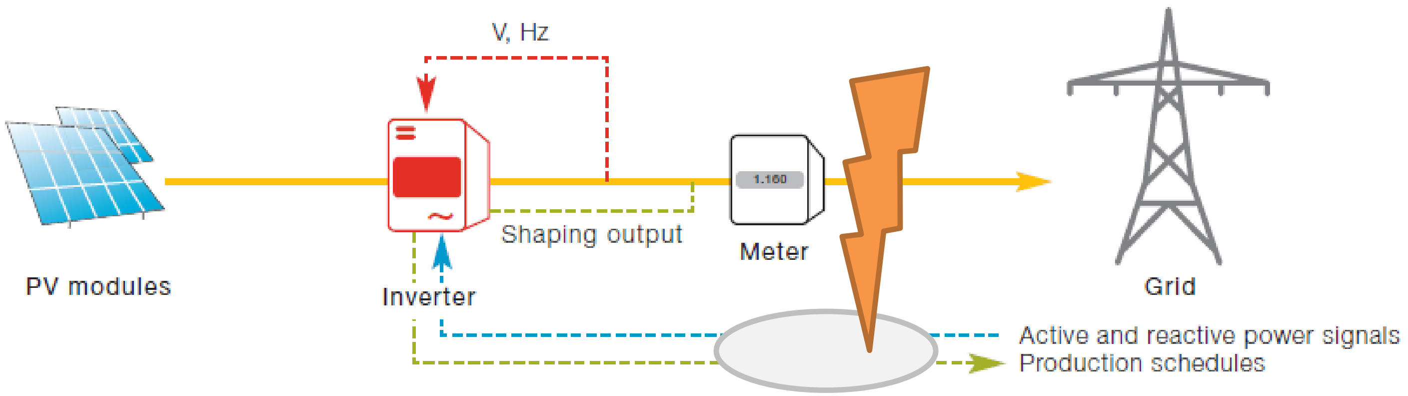






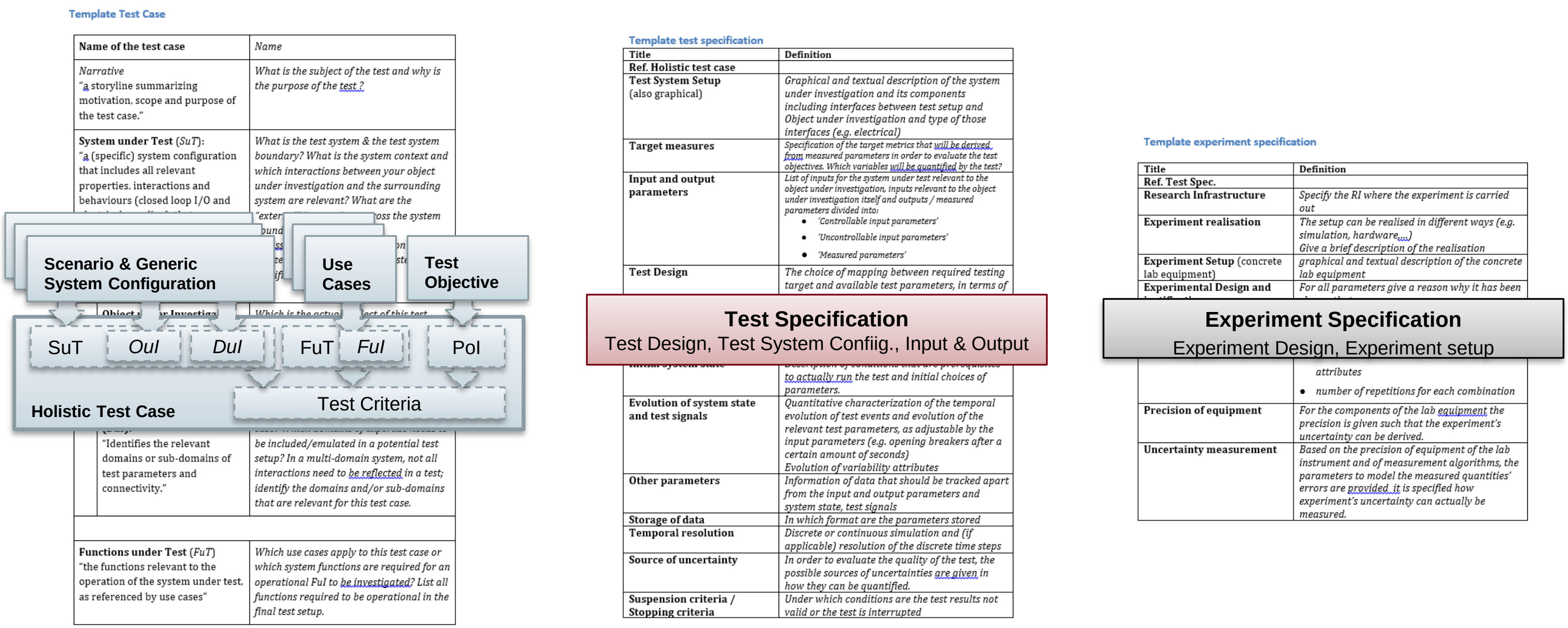
Cyber-Physical Attacks Investigation

- Energy application
  - IEC 61850 remote controlled inverter-based DER
- Cyber-physical attacks investigation
  - Man-in-the-Middle attack scenario
- Validation goal
  - Analysing the influence of the attack on the energy infrastructure



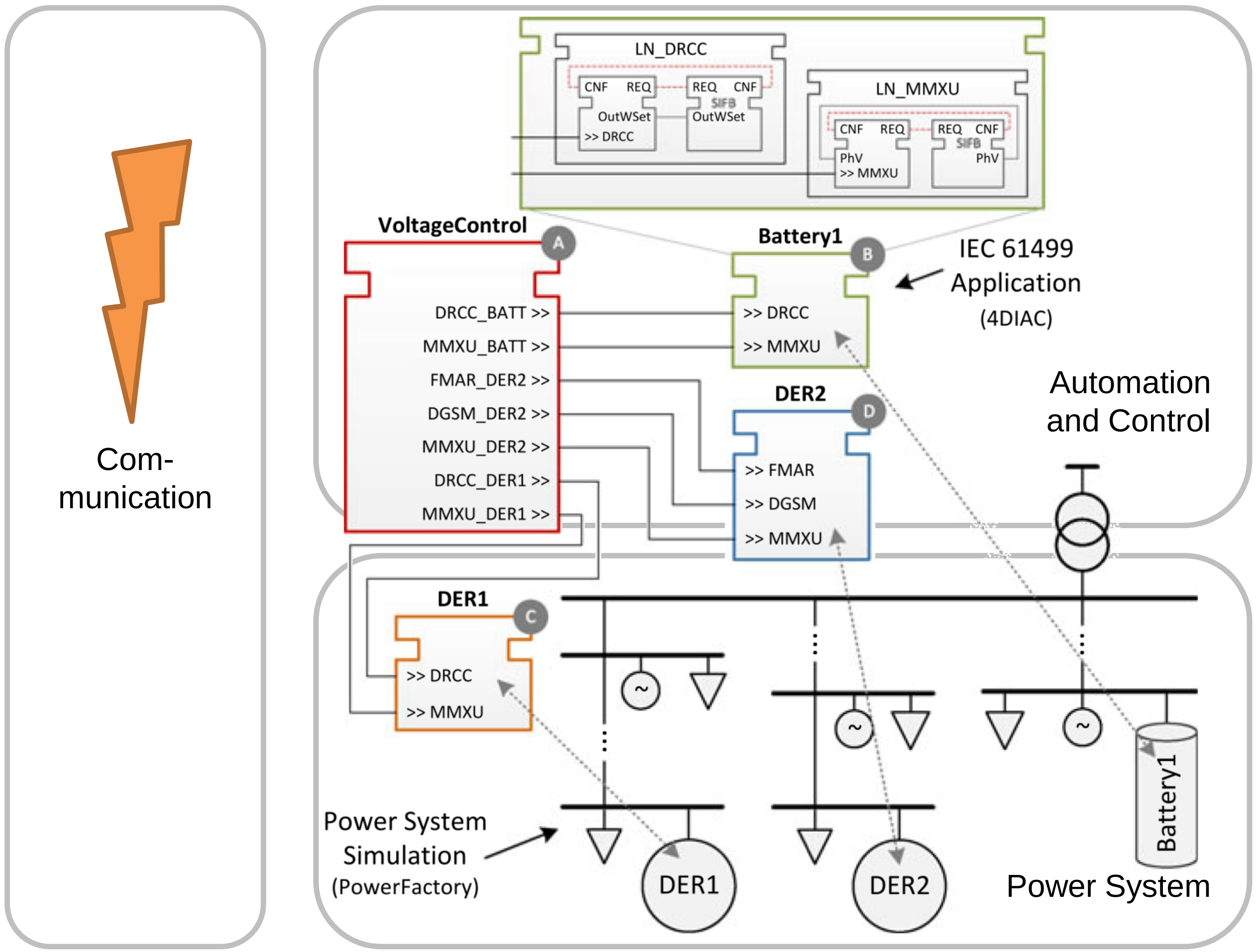
Cyber-Physical Attacks Investigation

- Formal test case description



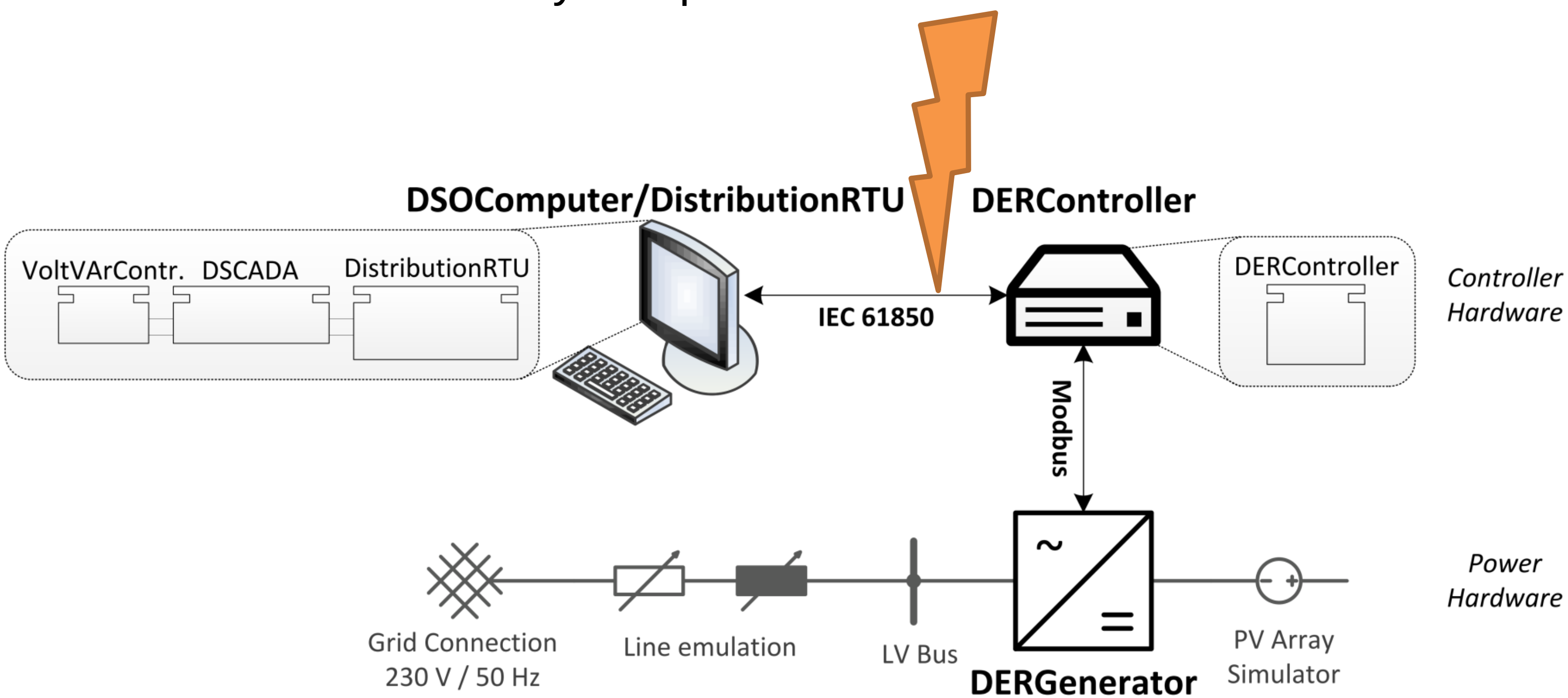
Cyber-Physical Attacks Investigation

- Simulation-based analysis
  - Coupling of different domains (power, ICT, control & automation)



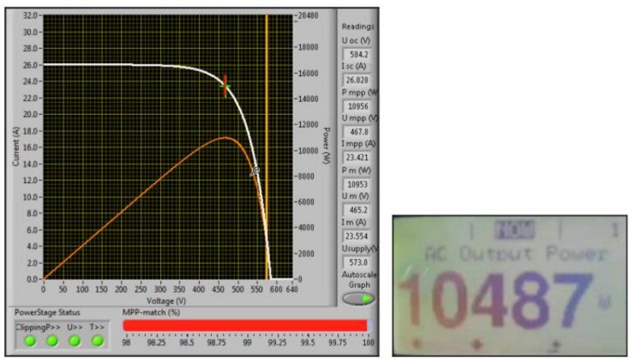
Cyber-Physical Attacks Investigation

- Lab-based analysis
  - AIT SmartEST laboratory setup

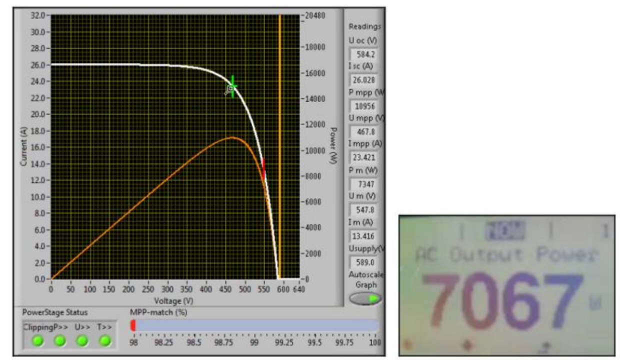


Cyber-Physical Attacks Investigation

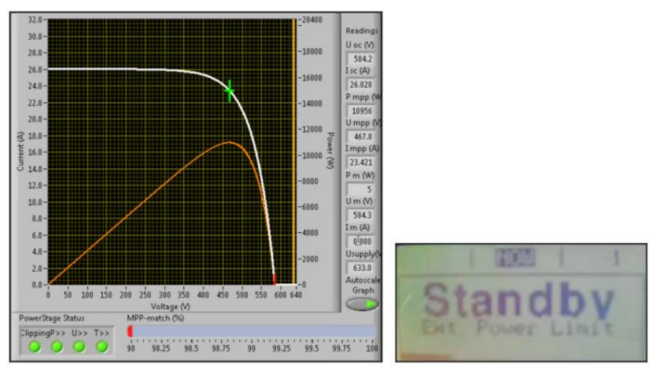
- Lab-based analysis
  - Attack (manipulation) of inverter set-points (active power)



(a) 100% of power limitation by the operator



(b) 60% of power limitation by the operator



(c) 10% of power limitation by the attacker

Discussion, Feedback and Conclusions

INDIN 2018 Tutorial

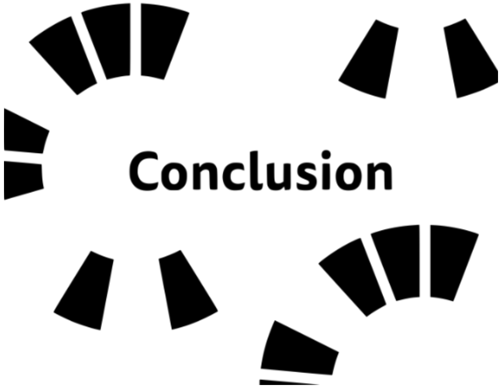
Methods and Tools for Validating
Cyber-Physical Energy Systems

Discussion and Feedback

- Questions?
- Open issues?
- etc.

Conclusions

- A large-scale roll out of smart grid solutions, technologies, and products can be expected in the near future
- New technologies, suitable concepts, methods and approaches are necessary to support system analysis, evaluation and testing issues of integrated approaches
- Advanced research infrastructures are still necessary
- Flexible integration of simulation-based methods, hardware-in-the-loop approaches, and lab-based testing looks promising for overcoming shortcomings



Future Activities and Research

- Improvement and integration of design and validation tools from different domains (power system + ICT + markets + consumer behaviour)
- Development of system level validation procedures and benchmark criteria
- Improvement of research infrastructures supporting system level validation
- Education, training and standardization is also a key factor

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