Designing and Validating Cyber-Physical Energy Systems

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Online Training Series on the Digitalisation of Smart Energy Systems

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Outline of the Lecture

- Higher complexity in cyber-physical energy systems
- Engineering problems, needs, and research trends
- Methods for test preparation
- Advanced validation and testing methods
- Summary and conclusions

1. Higher Complexity in Cyber-Physical Energy Systems

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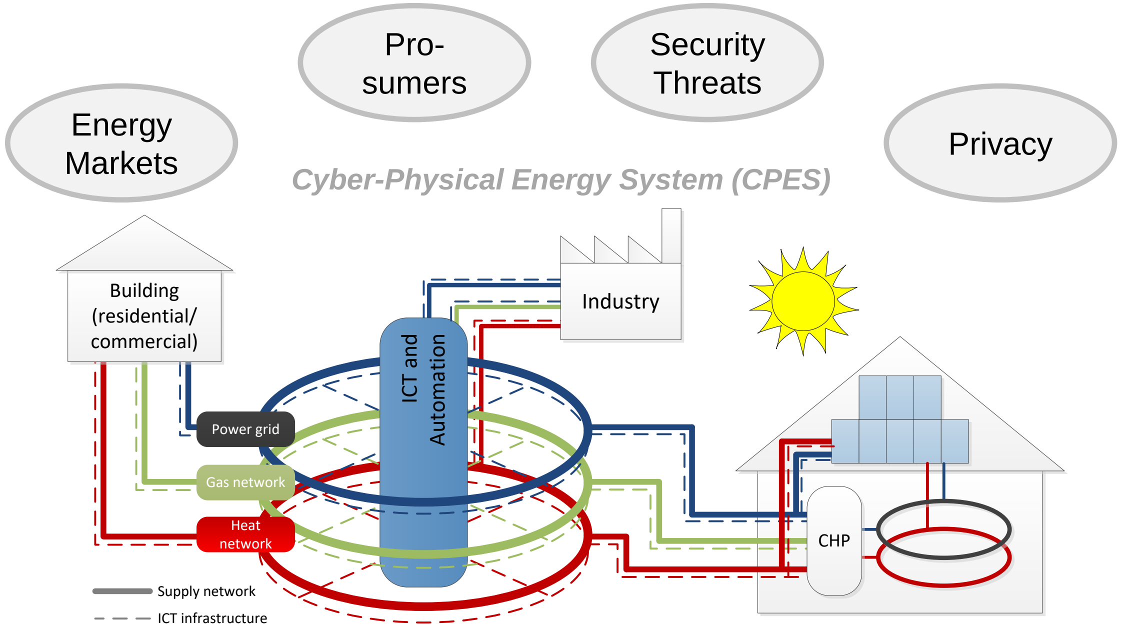
Higher Complexity in Cyber-Physical Energy Systems

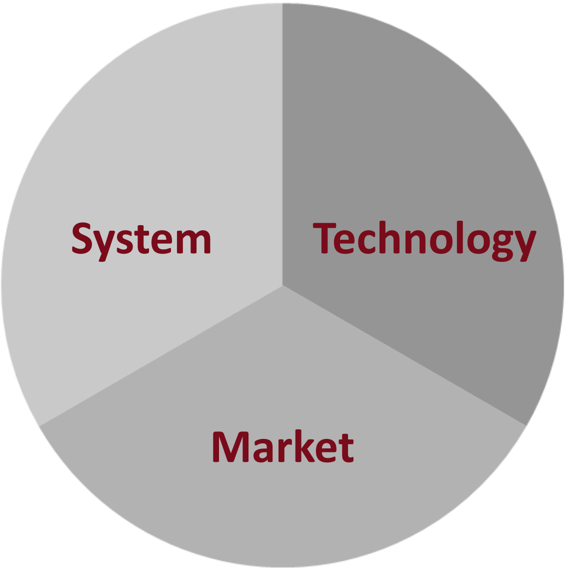
- Planning and operation of the energy infrastructure becomes more complex
  - Large-scale integration of renewable sources (PV, wind, etc.)
  - Controllable loads (batteries, electric vehicles, heat pumps, etc.)
- Trends and future directions
  - New energy solutions, such as energy communities, new market structures, etc.
  - Sector coupling energy (electricity, gas, heat), mobility, etc.
  - Digitalisation as the key enabler
- Cyber-physical energy systems
  - Physical systems and ICT systems can no longer be decoupled



Source: AIT

Higher Complexity in Cyber-Physical Energy Systems

- Driving forces for research in (electric) energy infrastructure



- 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.

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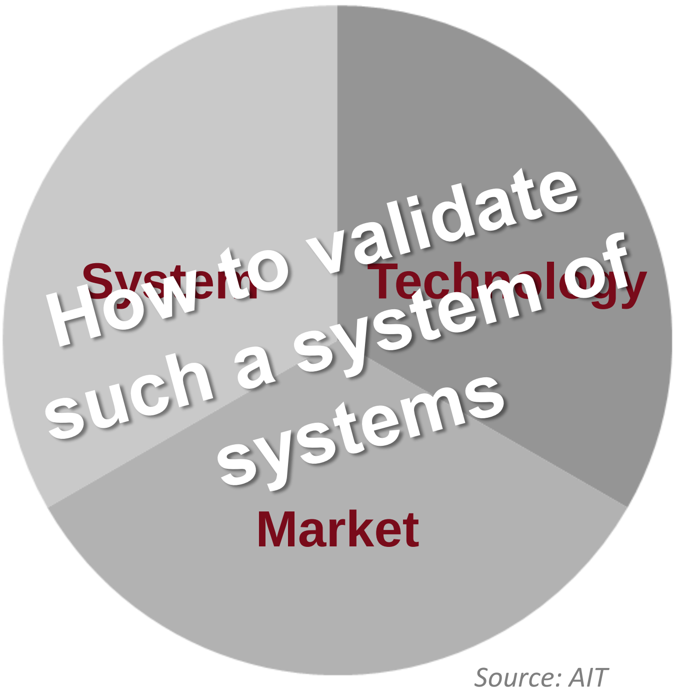
Higher Complexity in Cyber-Physical Energy Systems

- Key elements of future integrated smart grids and energy systems are
  - Advanced communication, automation, and control systems
  - Power electronics
  - Smart algorithms
  - Monitoring and data analytics
  - Interfaces/interaction with other energy systems
- Design and validation of power and energy systems characterized by
  - Lots of manual engineering steps
  - Partly missing integrated view on sub-domains (power, ICT, etc.)
  - Usage of less formalized approaches and tools (compared to other areas)



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2. Engineering Problems, Needs, and Research Trends

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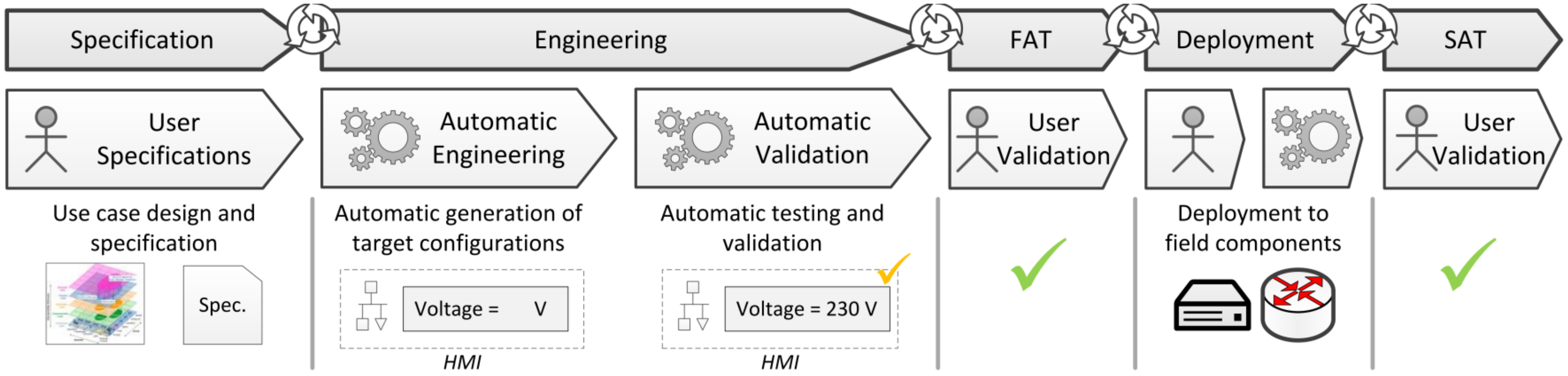
Engineering Problems and Needs

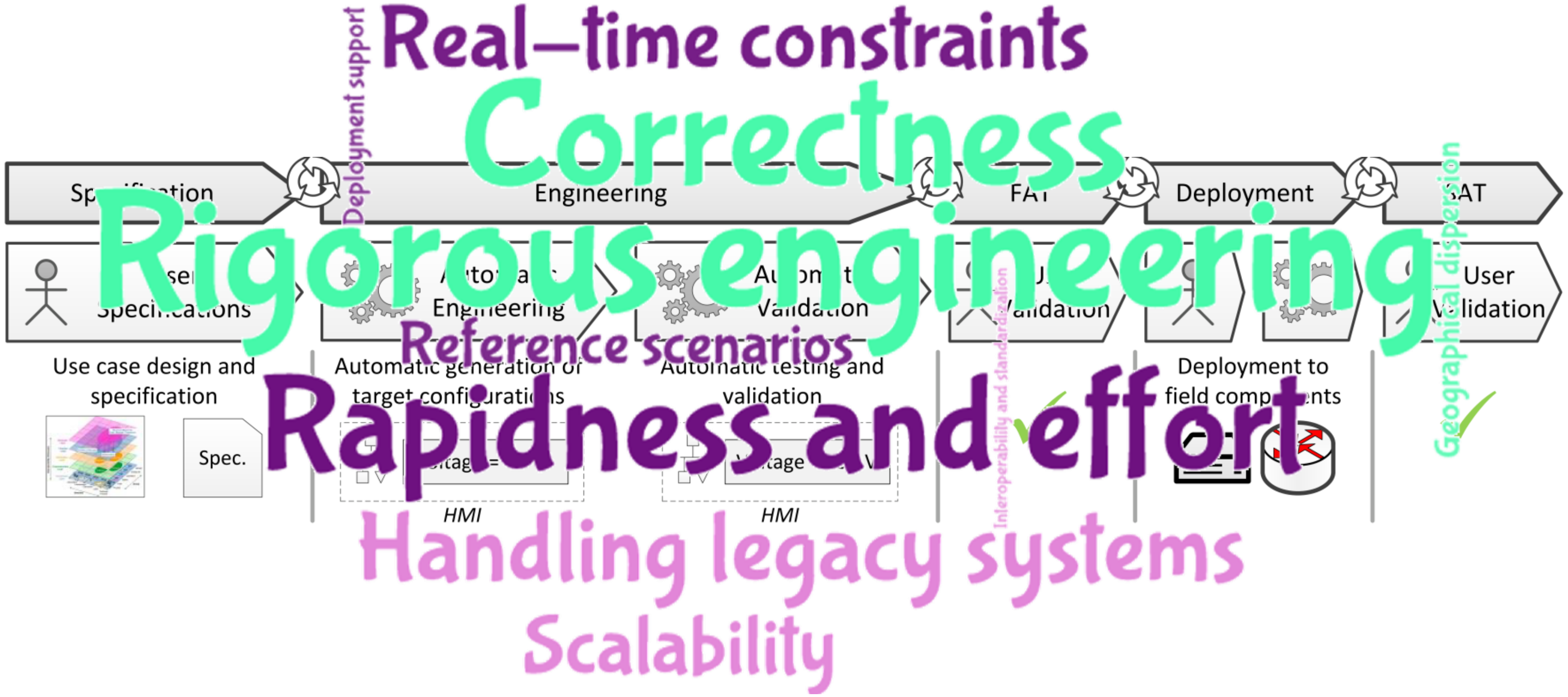
- Background and motivation
  - Reduction of manual steps necessary to handle complex CPES configs
  - Reduction of potential error sources due to manual steps and improvement of application/software quality required
  - Faster application development needed due to market behaviour and trends
- Providing support from design to implementation and installation



Source: AIT

FAT: Factory Acceptance Test
SAT: System Acceptance Test

Engineering Problems and Needs



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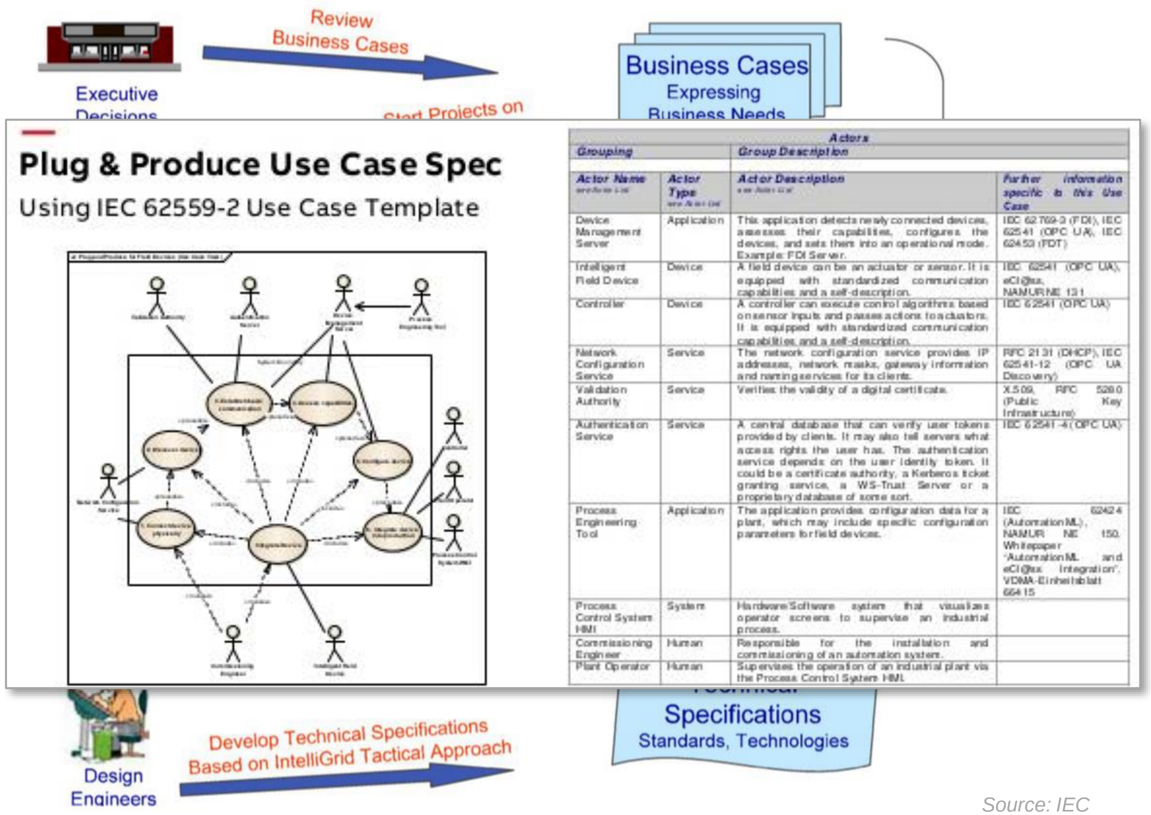
Status Quo in Research and Development

Specification

- IntelliGrid (IEC 62559) use case engineering approach
  - Structured process for specifying smart grid related applications
  - Identification of requirements and needs
  - Provision of use case templates



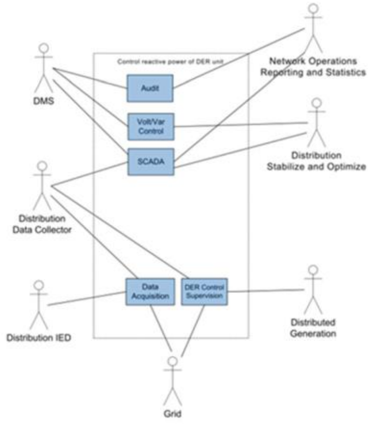
Actors			
Grouping		Group Description	
Actor Name	Actor Type	Actor Description	Further information specific to this Use Case
Device Management Server	Application	This application detects newly connected devices, assesses their capabilities, configures the devices, and sets them into an operational mode. Example: FDI Server.	IEC 62769-3 (FDI), IEC 62541 (OPC UA), IEC 62453 (FDT)
Intelligent Field Device	Device	A field device can be an actuator or sensor. It is equipped with standardized communication capabilities and a self-description.	IEC 62541 (OPC UA), eCl@ss, NAMUR NE 131
Controller	Device	A controller can execute control algorithms based on sensor inputs and passes actions to actuators. It is equipped with standardized communication capabilities and a self-description.	IEC 62541 (OPC UA)
Network Configuration Service	Service	The network configuration service provides IP addresses, network masks, gateway information and naming services for its clients.	RFC 2131 (DHCP), IEC 62541-12 (OPC UA Discovery)
Validation Authority	Service	Verifies the validity of a digital certificate.	X.509, RFC 5280 (Public Key Infrastructure)
Authentication Service	Service	A central database that can verify user tokens provided by clients. It may also tell servers what access rights the user has. The authentication service depends on the user identity token. It could be a certificate authority, a Kerberos ticket granting service, a WS-Trust Server or a proprietary database of some sort.	IEC 62541-4 (OPC UA)
Process Engineering Tool	Application	The application provides configuration data for a plant, which may include specific configuration parameters for field devices.	IEC 62424 (AutomationML), NAMUR NE 150, Whitepaper "AutomationML and eCl@ss Integration", VDMA-Einheitsblatt 66415
Process Control System HMI	System	Hardware/Software system that visualizes operator screens to supervise an industrial process.	
Commissioning Engineer	Human	Responsible for the installation and commissioning of an automation system.	
Plant Operator	Human	Supervises the operation of an industrial plant via the Process Control System HMI.	

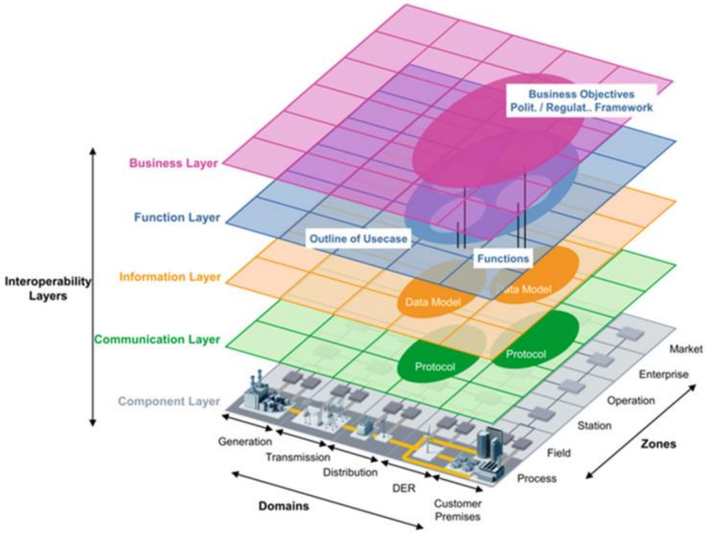
Source: IEC

Status Quo in Research and Development

Specification

- Smart Grid Architecture Model (SGAM)
  - Supports the specification of smart grid applications
  - Provides a structured process linking use cases into system architectures





Use Case Description → Business Layer Analysis → Function Layer Analysis → Component Layer Analysis → Information Layer Analysis → Communication Layer Analysis

Source: IEC

Status Quo in Research and Development

Engineering

- Power System Automation Language (PSAL) model-based engineering for smart grids
  - Model-Driven Engineering (MDE) of smart grid applications will reduce the amount of manual work needed to describe information in multiple models
  - Integrated MDE approach covering the whole engineering process to handle the multi-domain aspect of smart grids

Holistic approach

An approach that combines design, implementation, validation, and deployment is missing

Model-based

Model-based engineering concepts for smart grids are missing or only partly available

Multidisciplinarity

The multi-domain character of smart grids is not covered by existing approaches

→ *Domain-specific approach Power System Automation Language (PSAL)*

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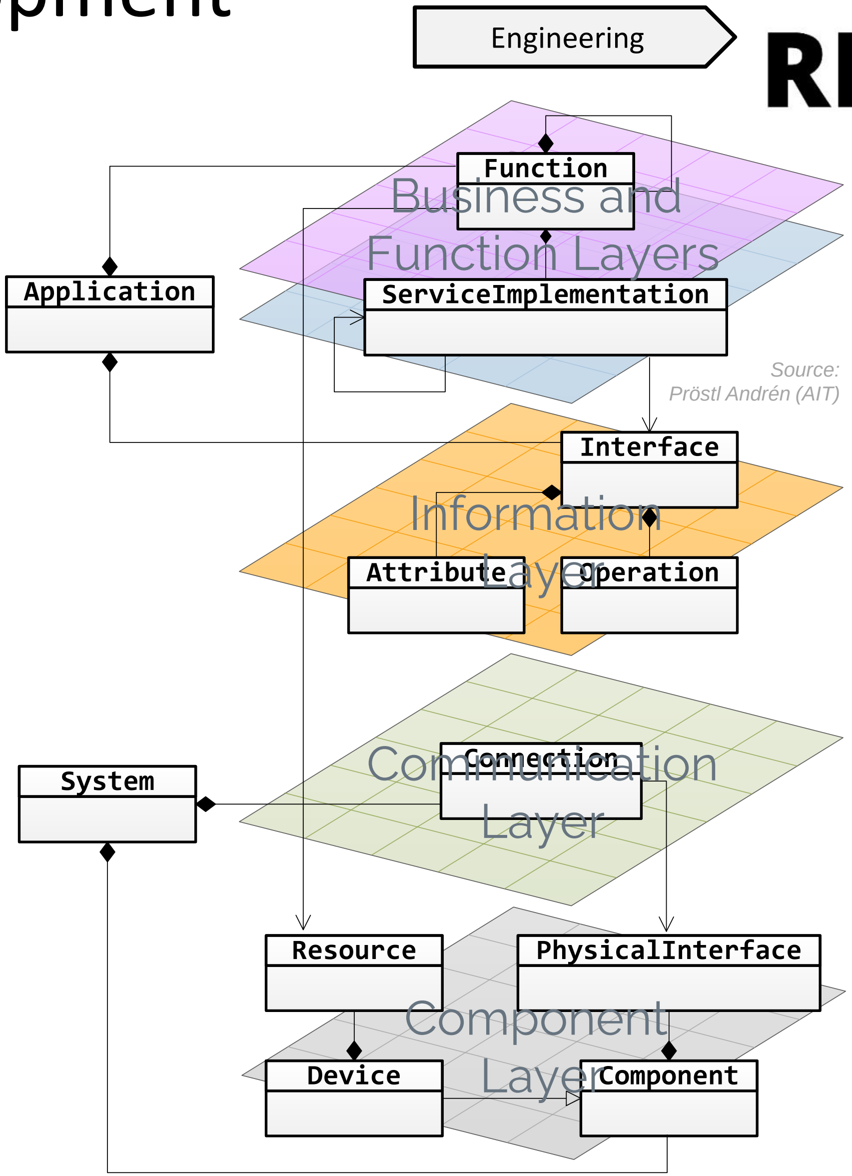
Status Quo in Research and Development

- PSAL model-based engineering for smart grids
  - Based on SGAM

```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
    requests Field.Controls fieldControls
  }
  module Field {
    interface Controls {
      attribute float32 activePowerSetpoint
}}}
```

```
system DistributionSystem {
  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```

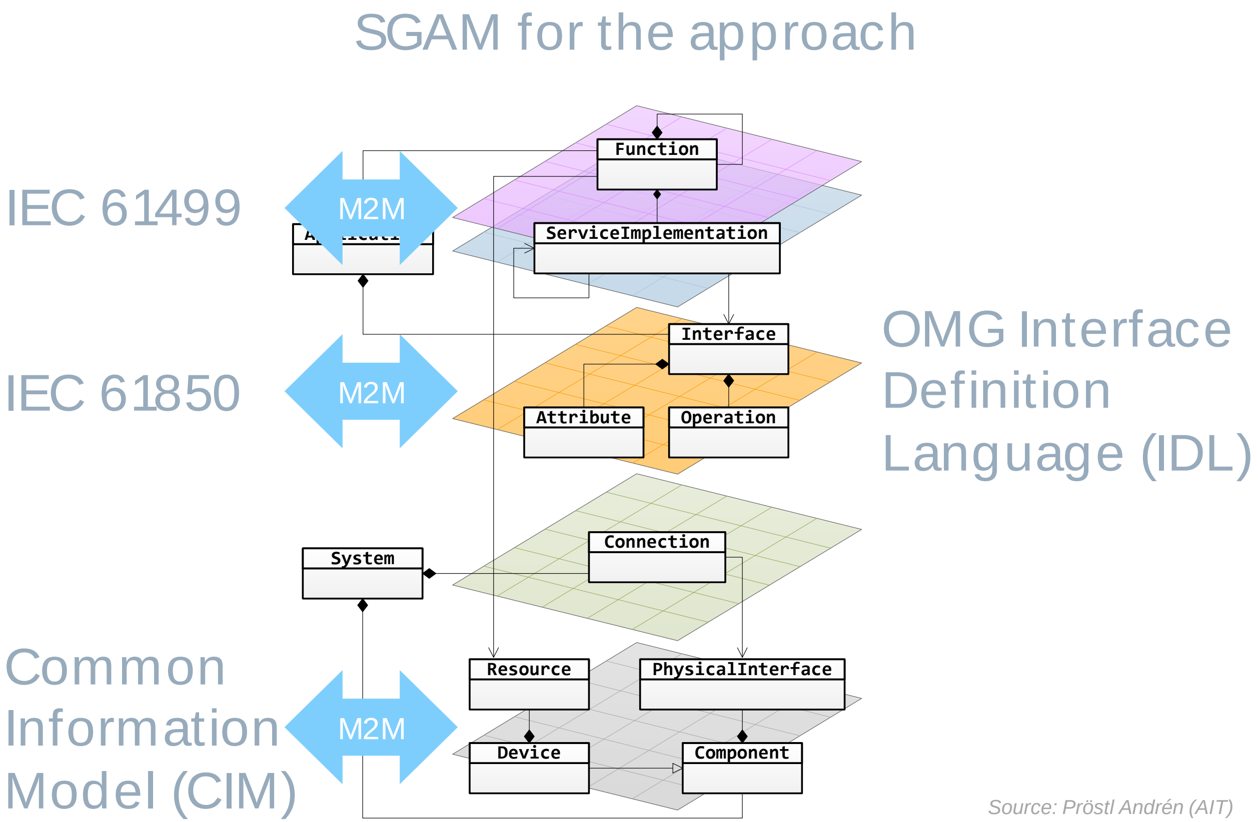


Source: Pröstl Andrén (AIT)

Status Quo in Research and Development

Engineering

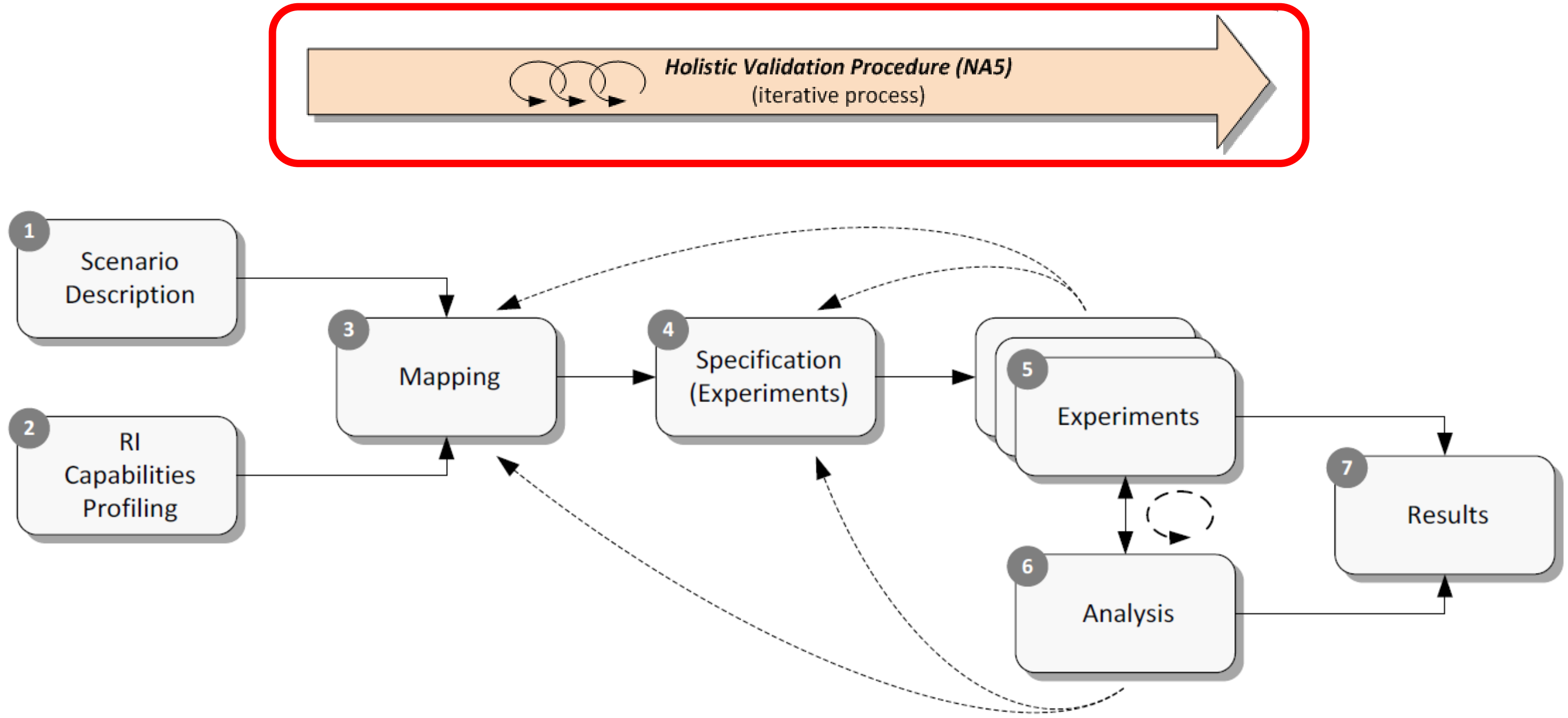
- PSAL model-based engineering for smart grids
  - Basis for PSAL



Source: Pröstl Andrén (AIT)

System-level Validation and Testing

- ERIGrid holistic testing approach for smart grid systems



*"**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"*

4. Methods for Test Preparation

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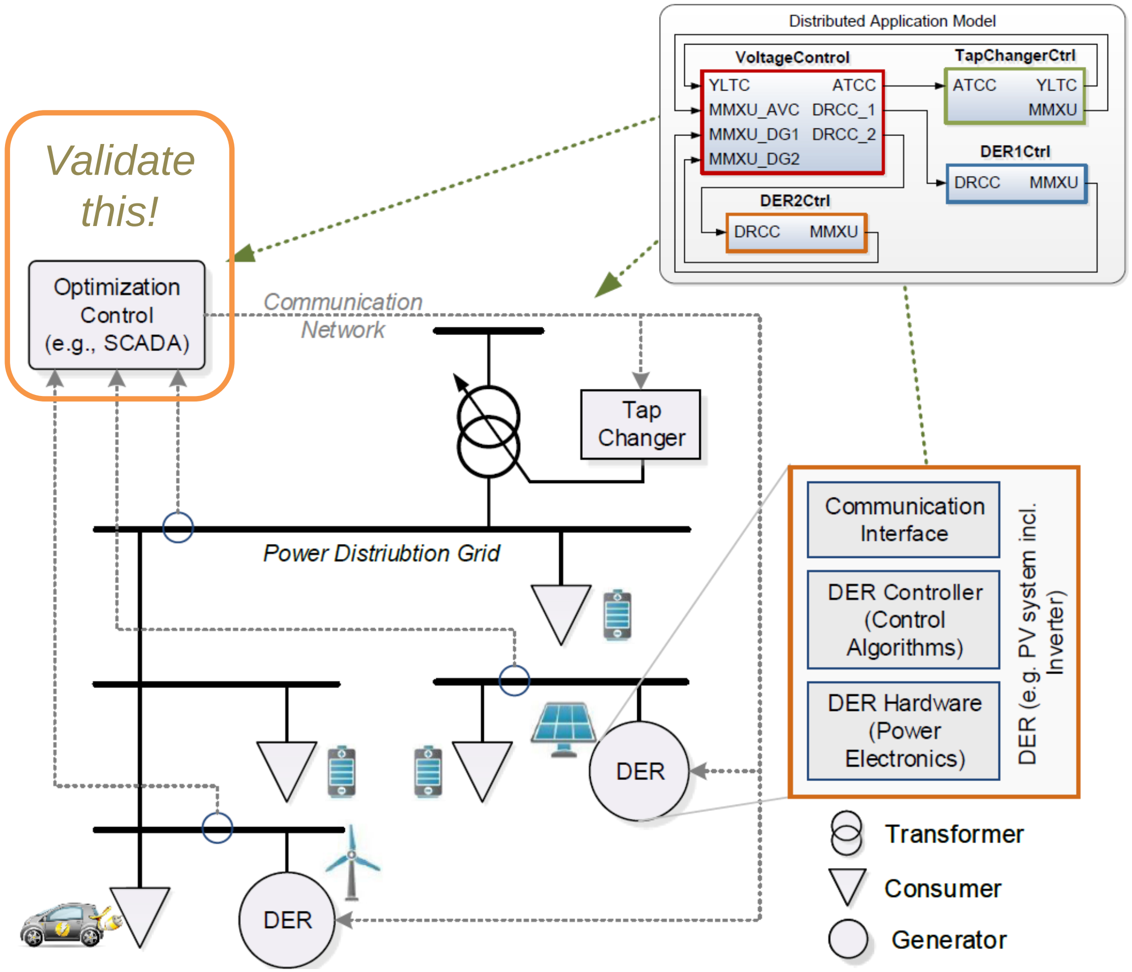
System-level Validation and Testing

Challenges

- Testing of smart grids and energy systems components and concepts
- Many domains involved (holism)
- Setups and workflows differ across Research Infrastructures (RI)/labs
  - Experiments are often hardly reproducible
  - Often limited by RI capabilities



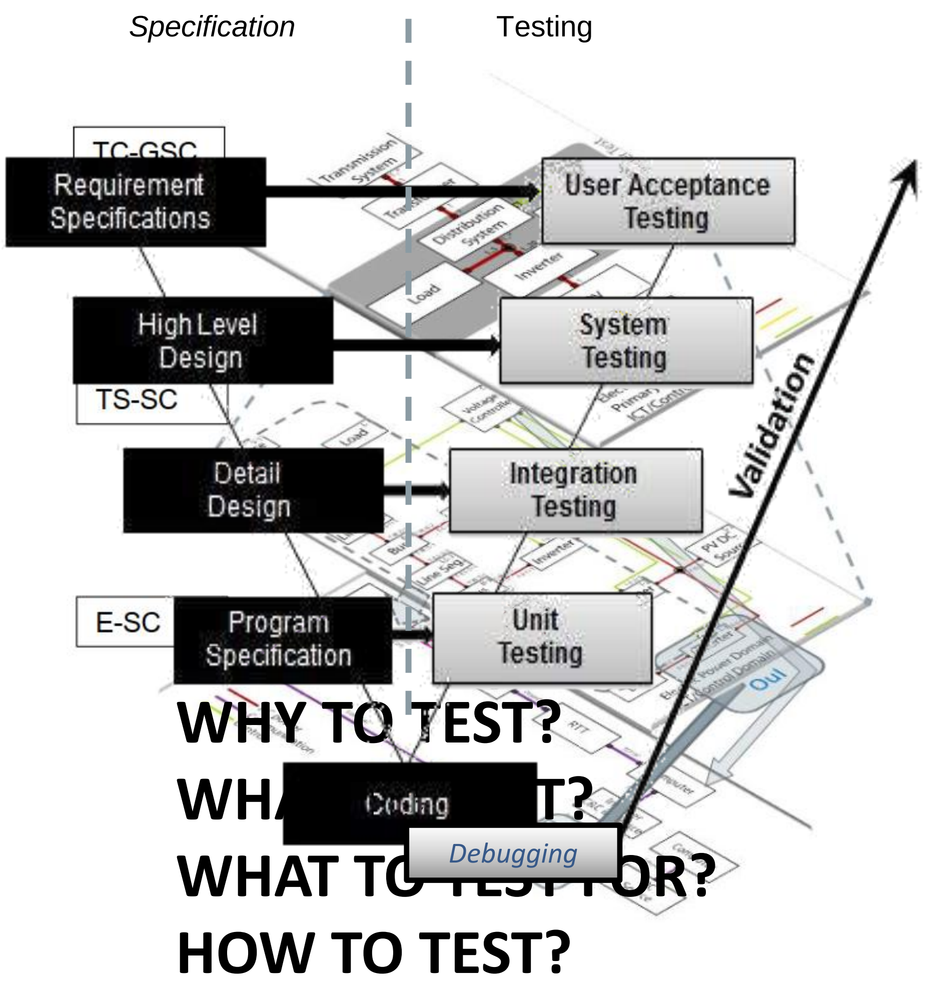
System-level Validation and Testing

Aims

- Formalize the 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

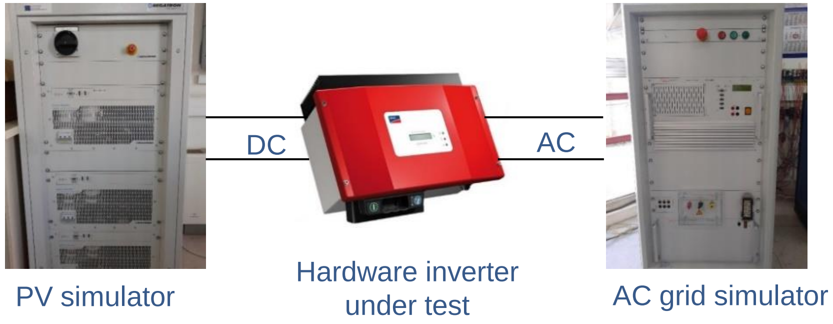


System-level Validation and Testing

Component Test vs. *Holistic System Test*

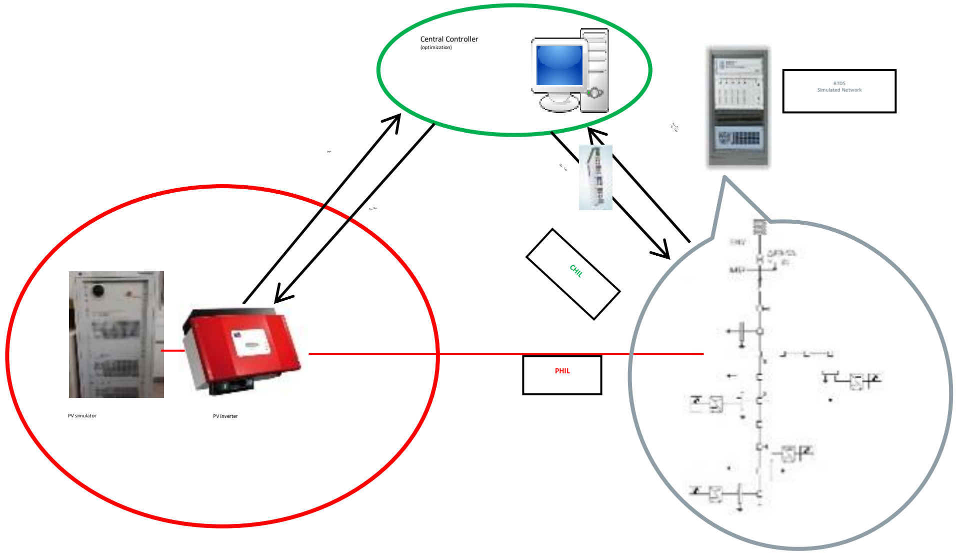
Component Test

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



Holistic System Test

- Combining several tests (testing process)
- Using simulations
- Testing a system rather than just components



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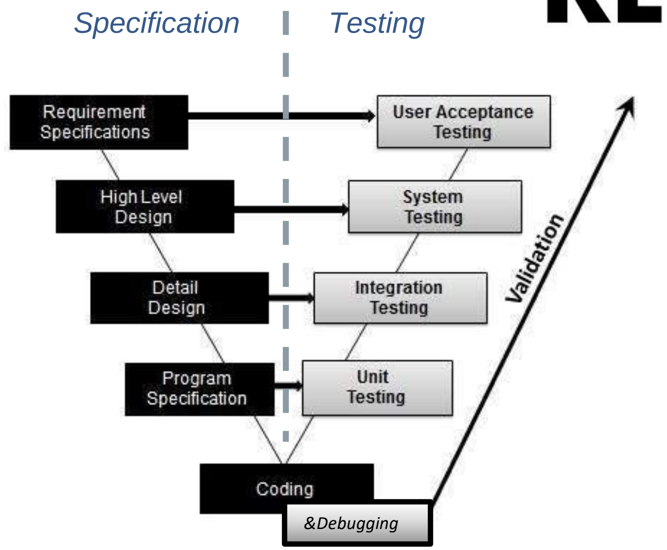
System-level Validation and Testing

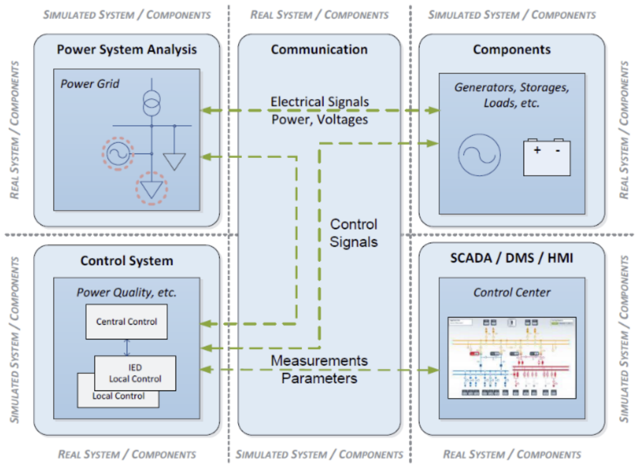
I. System validation
Alignment of Specifications & Testing

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

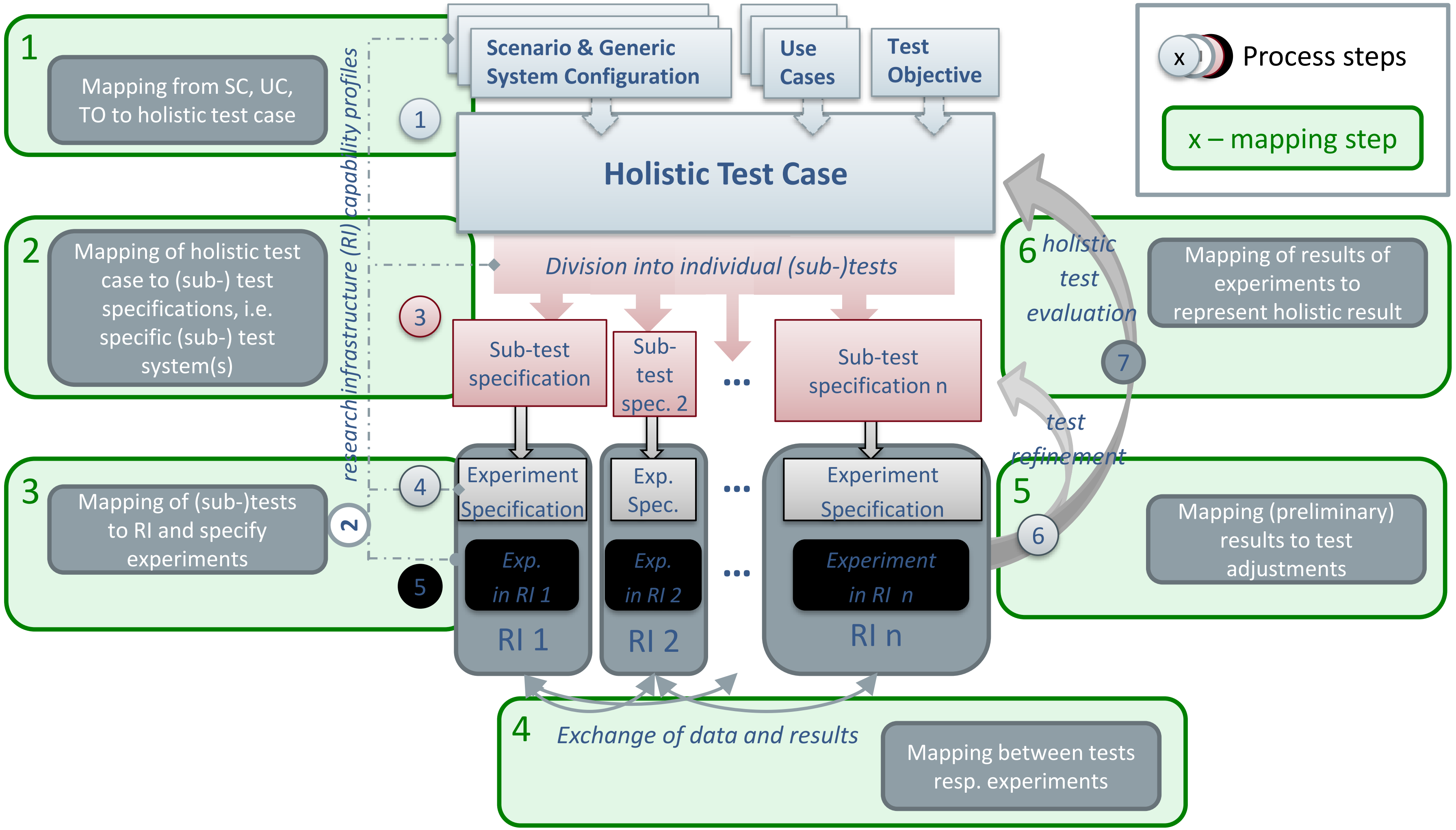
III. Tests that combine multiple domains
e.g., power, comm., and automation

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



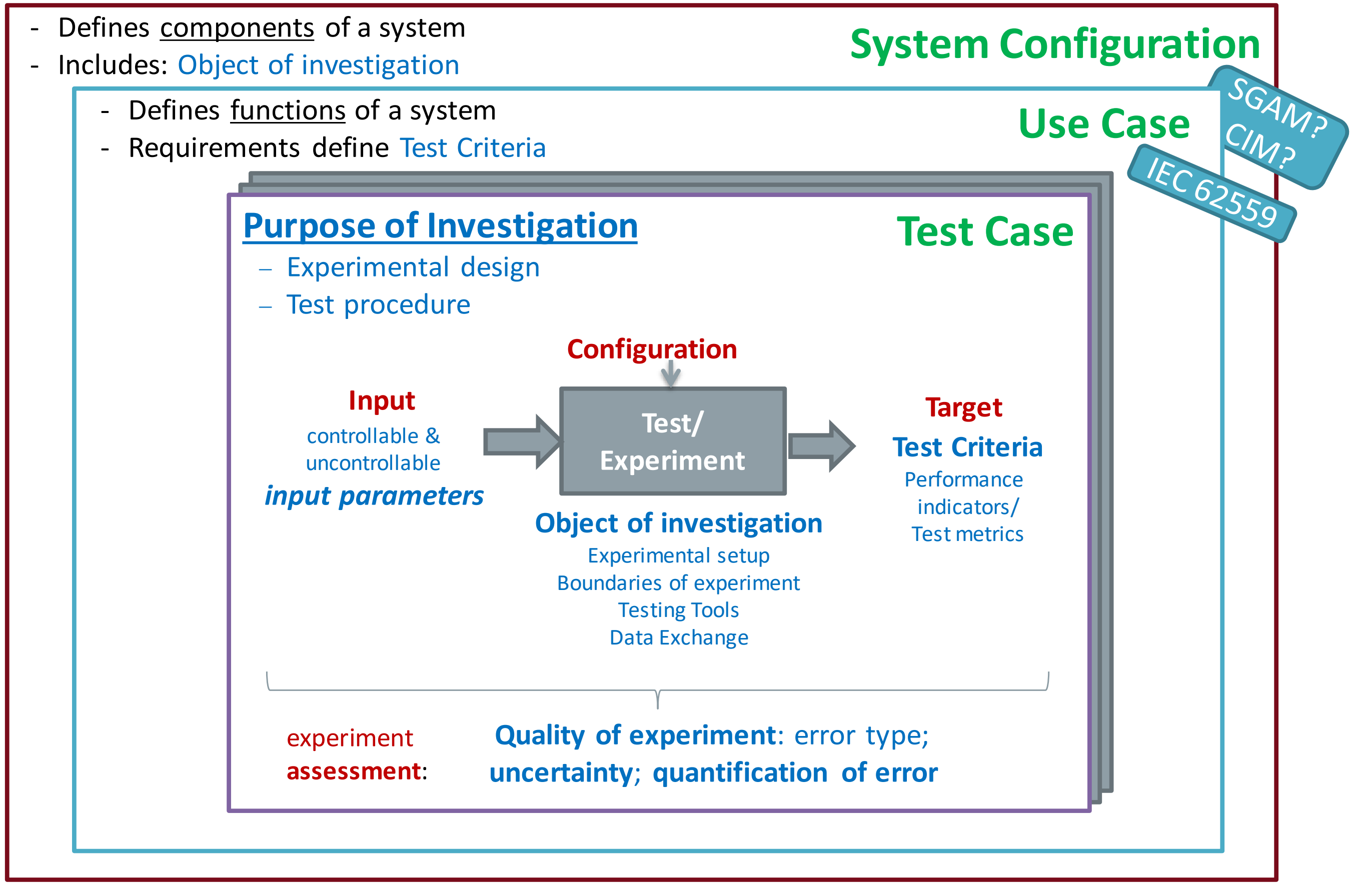


System-level Validation and Testing



System-level Validation and Testing

- Holistic Test Description (HTD)



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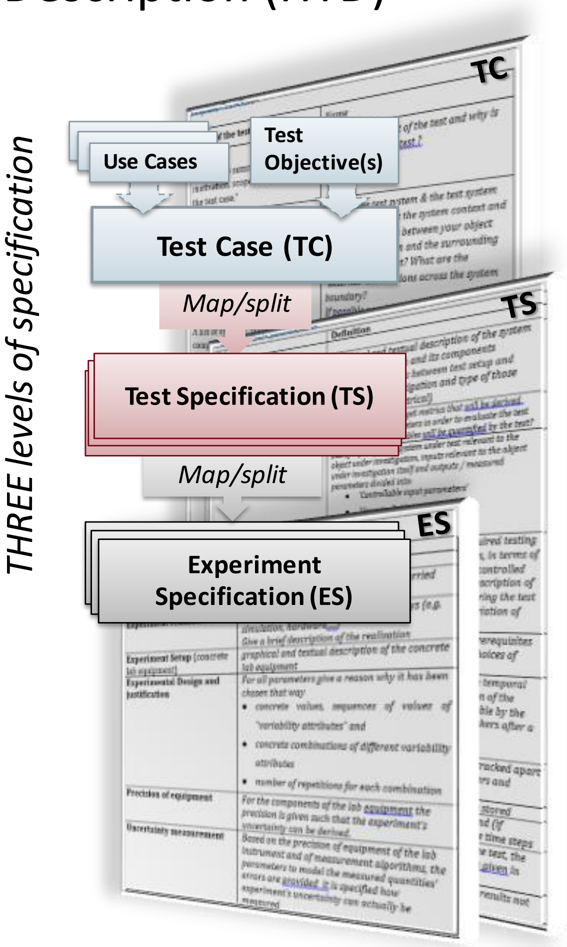

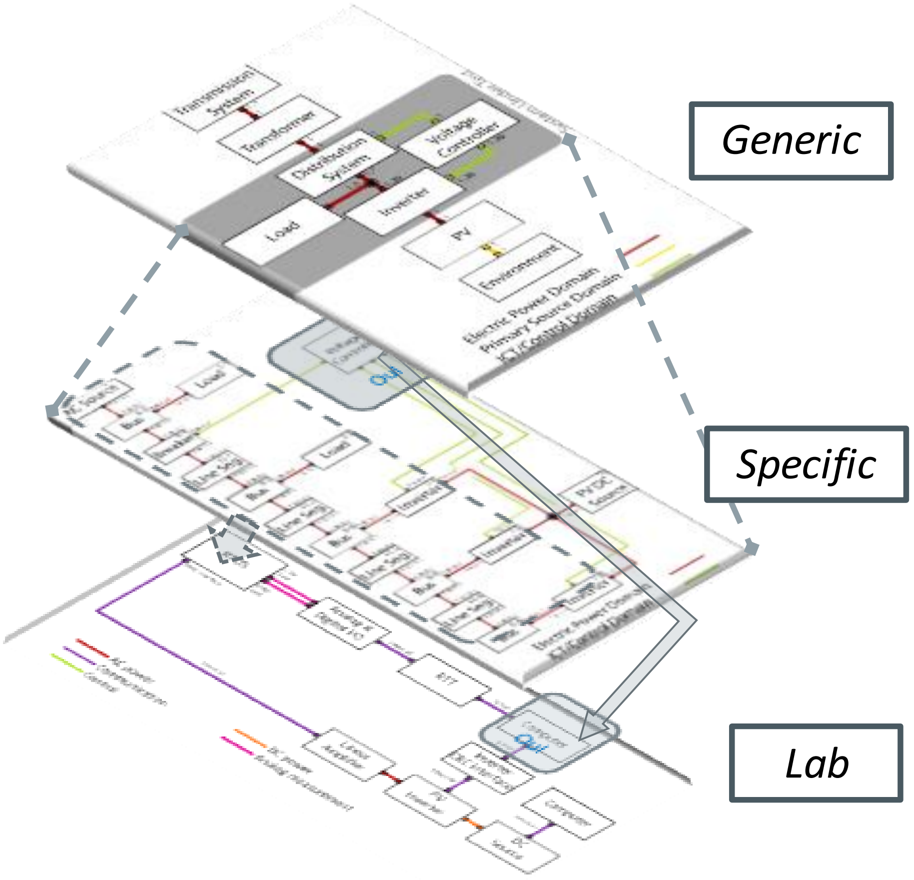

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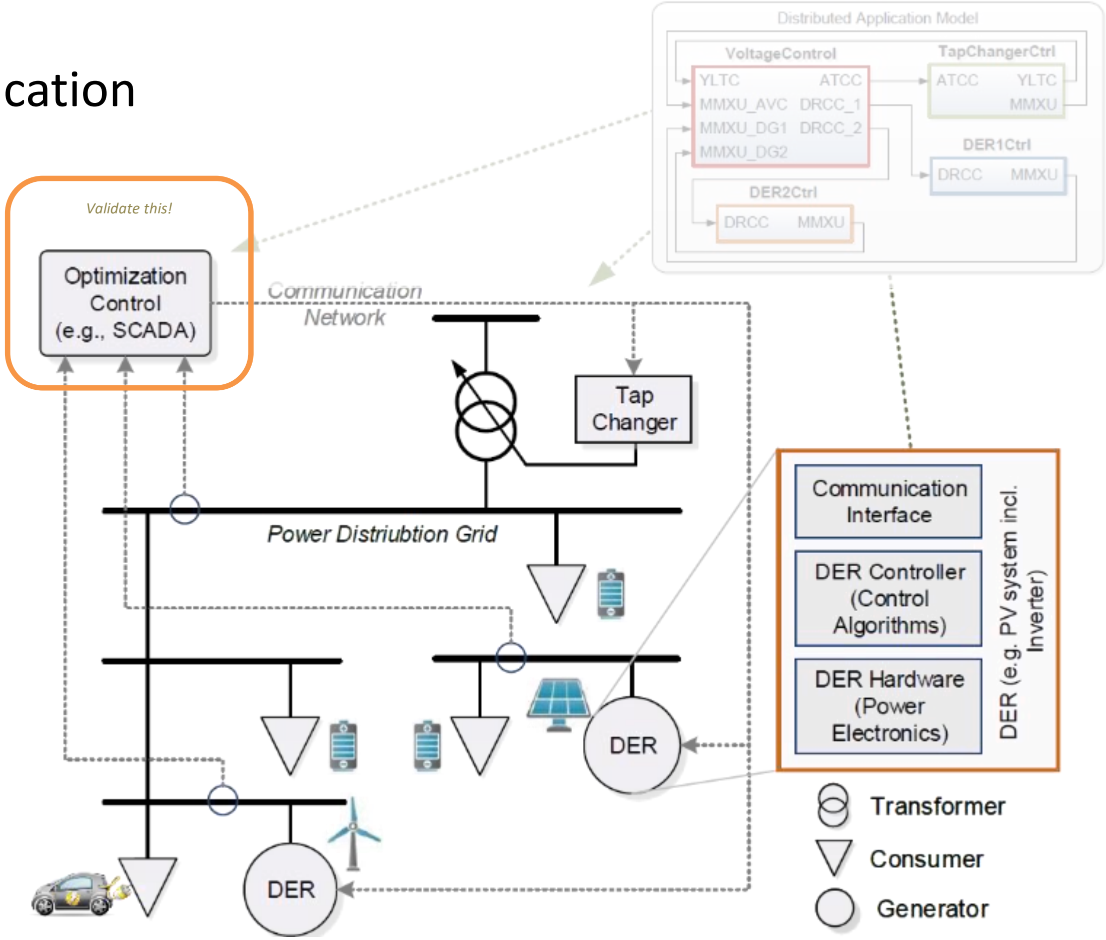
System-level Validation and Testing

Holistic testing

- Key questions to be answered for test specification

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



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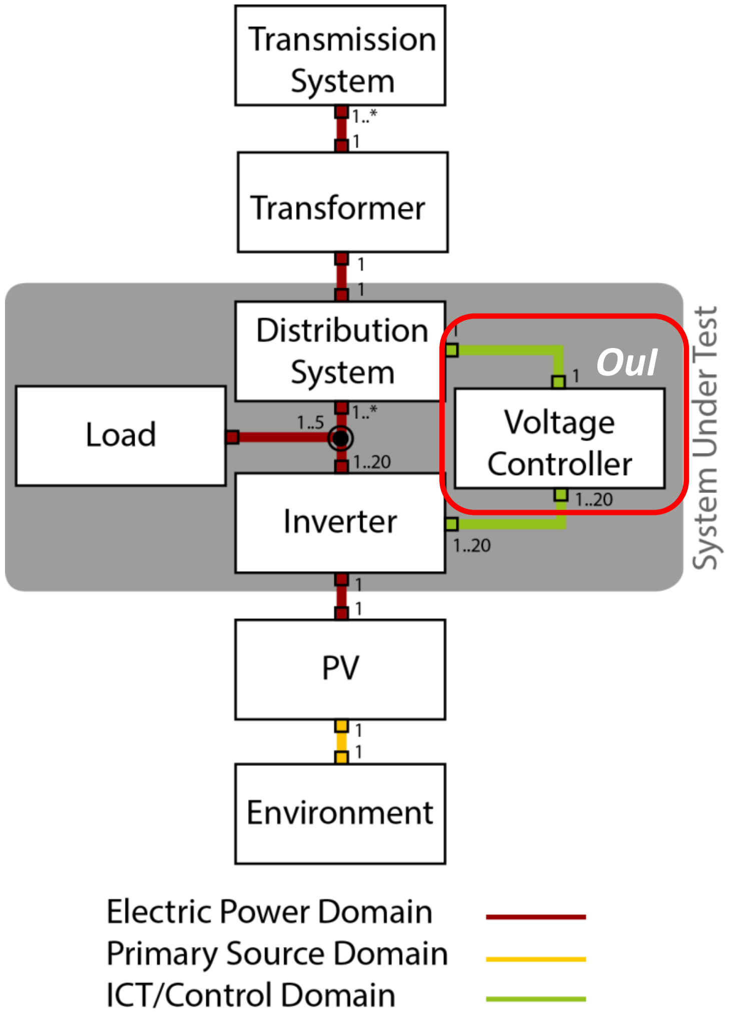
System-level Validation and Testing

Holistic testing

- *System under Test (SuT)*
  Is a system configuration that includes all relevant properties, interactions and behaviours (closed loop I/O, 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



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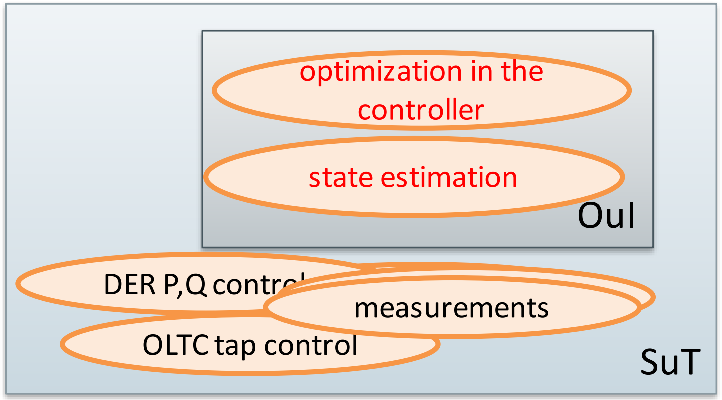
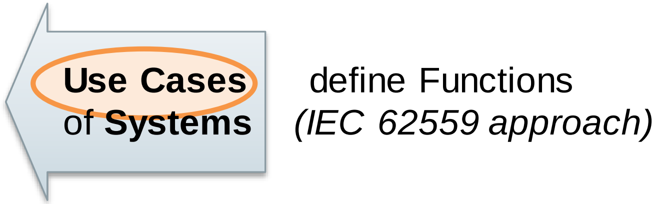
System-level Validation and Testing

Test system functions

- *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 (operationalized) by the object under investigation
  Remark: the FuI are a subset of the FuT





System-level Validation and Testing

Holistic testing

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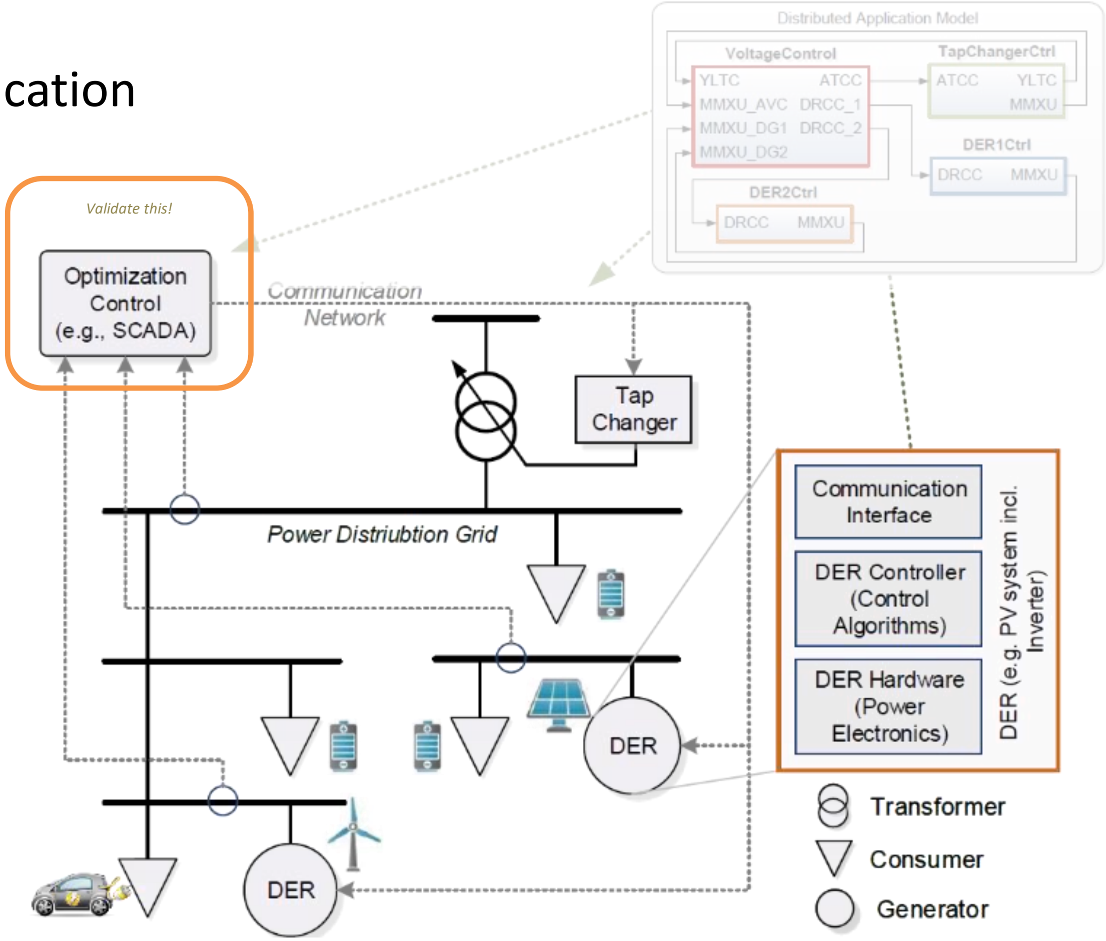

System-level Validation and Testing

Purpose of Investigation (PoI)

- Validation
- Verification

- Characterization

Modelling / 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*)

System-level Validation and Testing

- *Test objective → PoI → Test Criteria*
- *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

Quality attributes (thresholds)

"1.2: convergence within 2s" (*validation*)
"3.* estimation quality characterized with confidence 95%" …

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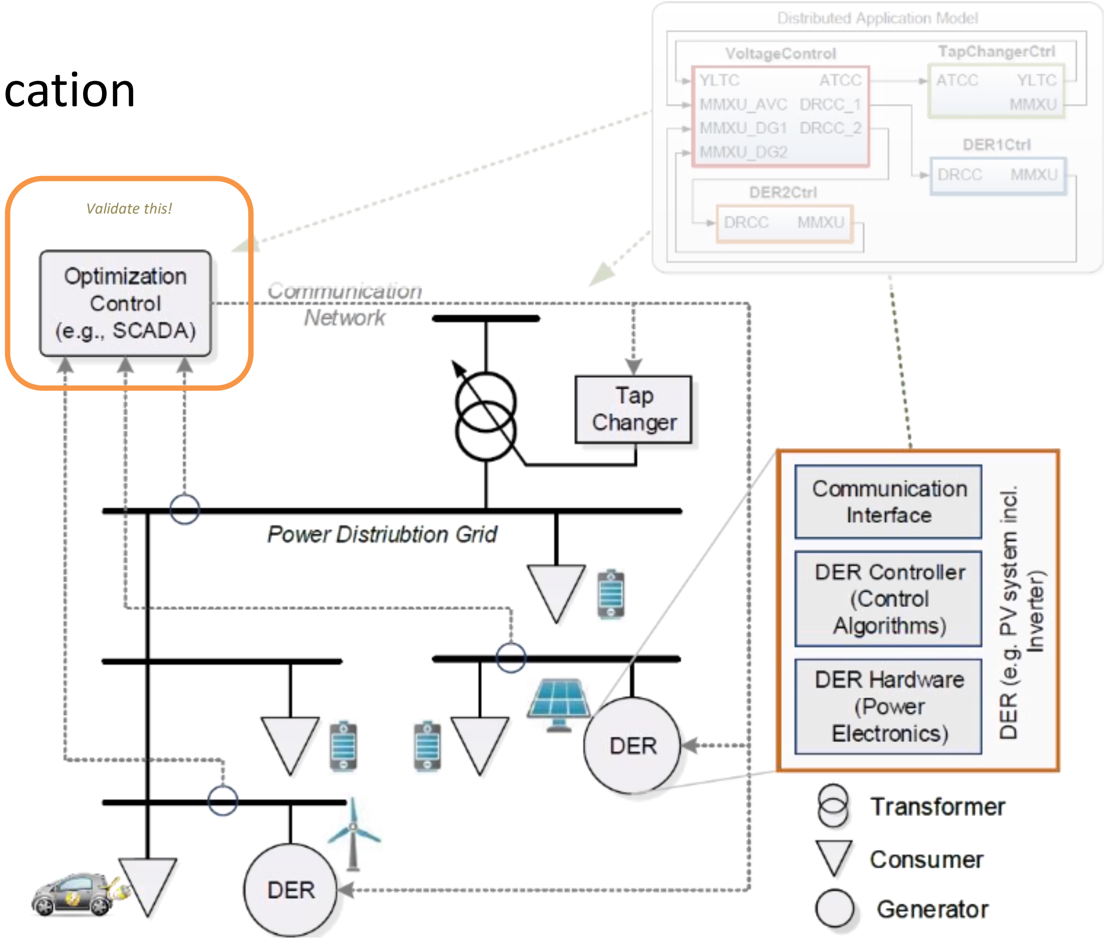
System-level Validation and Testing

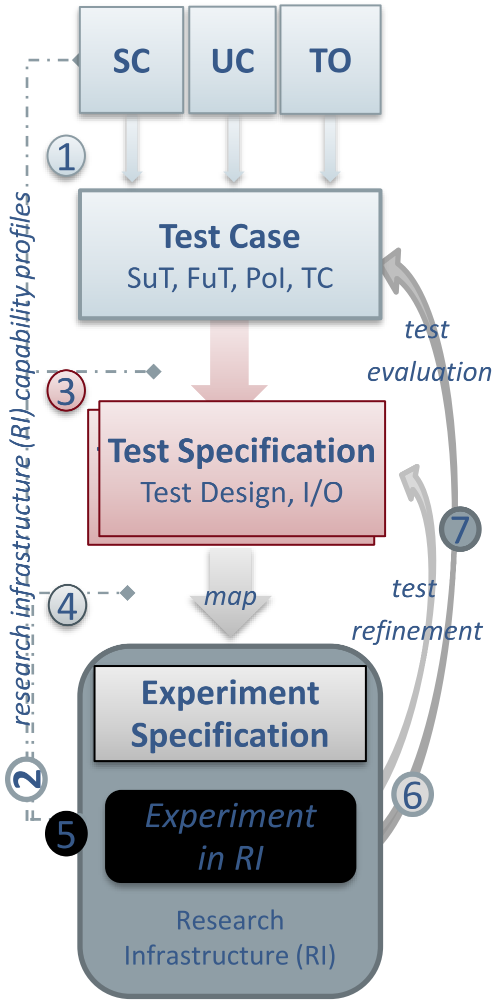
Holistic testing

- Key questions to be answered for test specification

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



System-level Validation and Testing

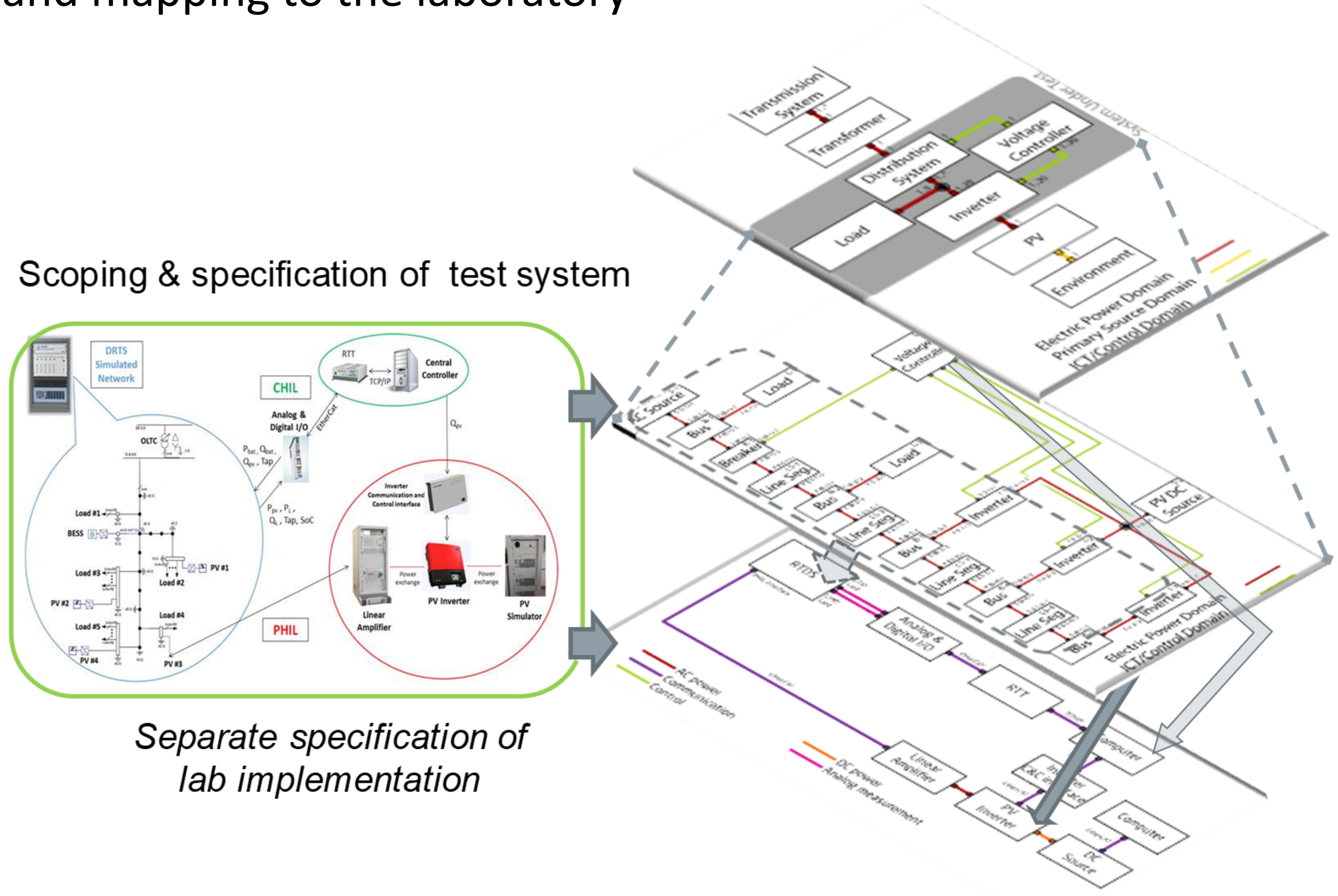


- Given
  - Purpose of Investigation (PoI) and Test Criteria
  - System and Domain categories and relations
- To specify
  - Precise system (specific system configuration)
  - Which variables to manipulate and which to measure?
  - How to quantify the test metrics (based on test data)?
    - Sampling 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)

System-level Validation and Testing

Detailing test setup and mapping to the laboratory

Scoping & specification of test system

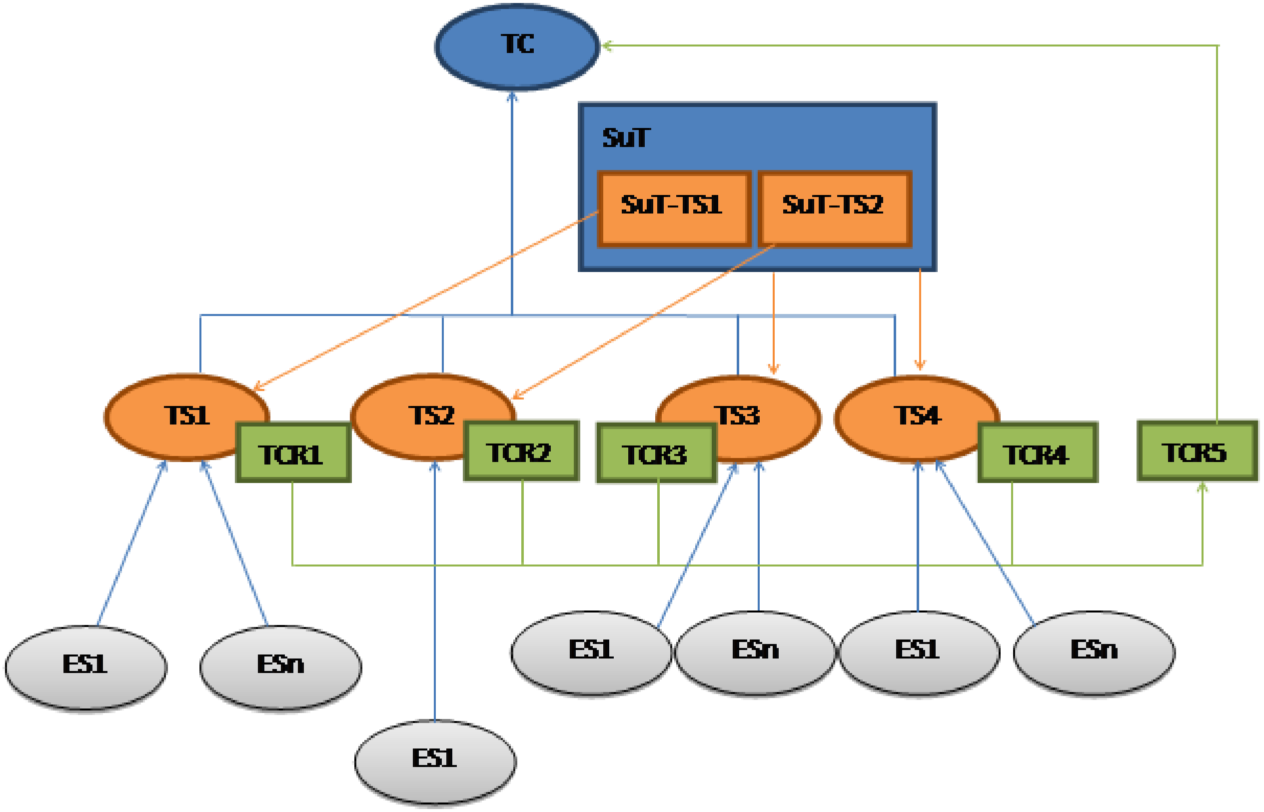


Separate specification of lab implementation

System-level Validation and Testing

Additional structure and documentation → *Qualification Strategy*

- How many tests/experiments are derived from the test case?
- Which PoI & Test Criteria are associated with which test?
- Are different SuT associated with different tests?
- Which tests/experiments need input from each other? Or can be done in parallel?
- Information gained from comparison between tests



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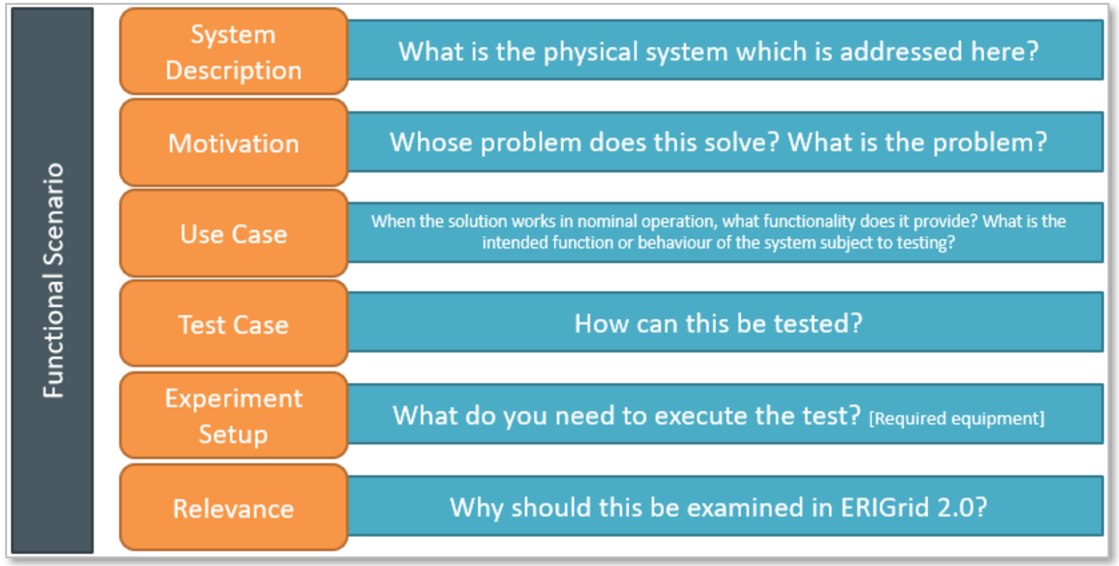
Test Case Profiles Concept

Collected functional scenarios and test cases

- Identification of relevant scenarios (6) and test cases (25)
- Provision of functional scenarios with broad domain view
- Further details at
  - D-NA4.1 Functional Scenarios (D5.1)
  - D-NA4.2 Common Reference Test Case Profiles (D5.2), and
  - https://github.com/ERIGrid2/test-cases



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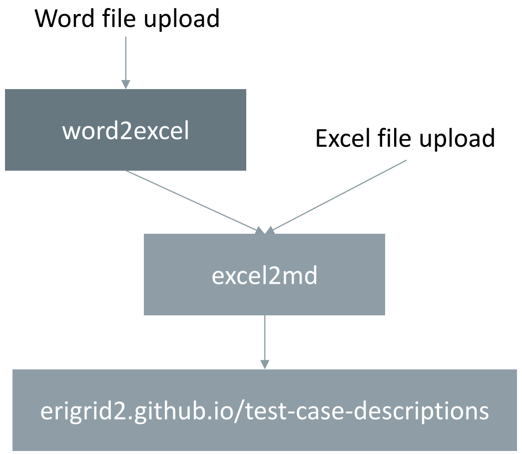
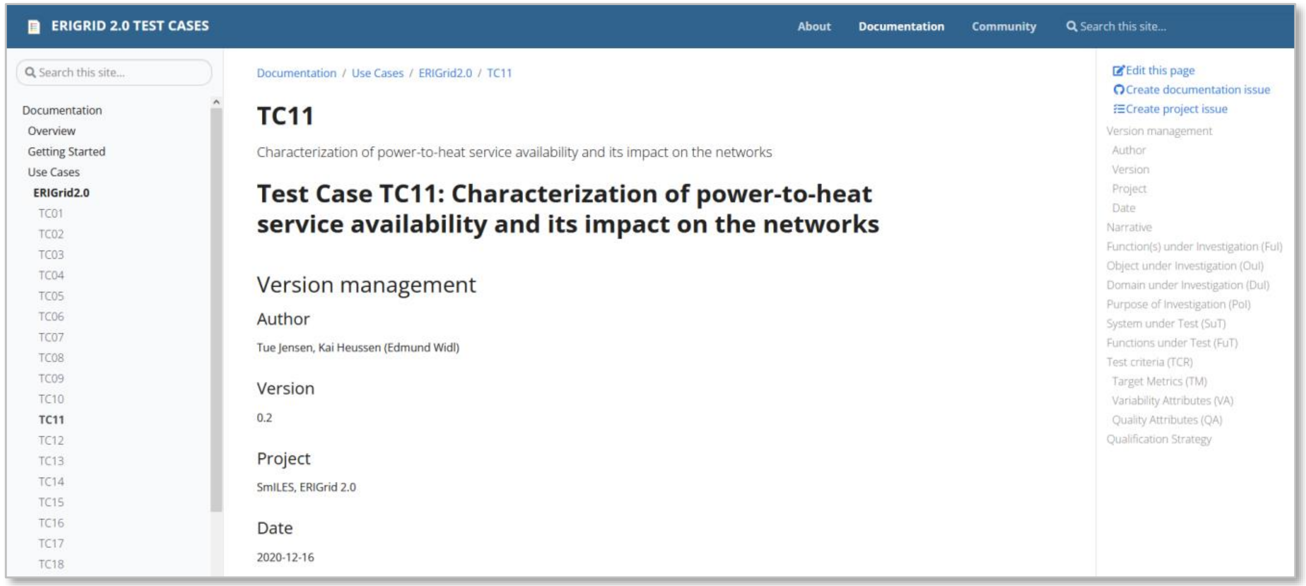
Test Case Profiles Concept

Collected functional scenarios and test cases

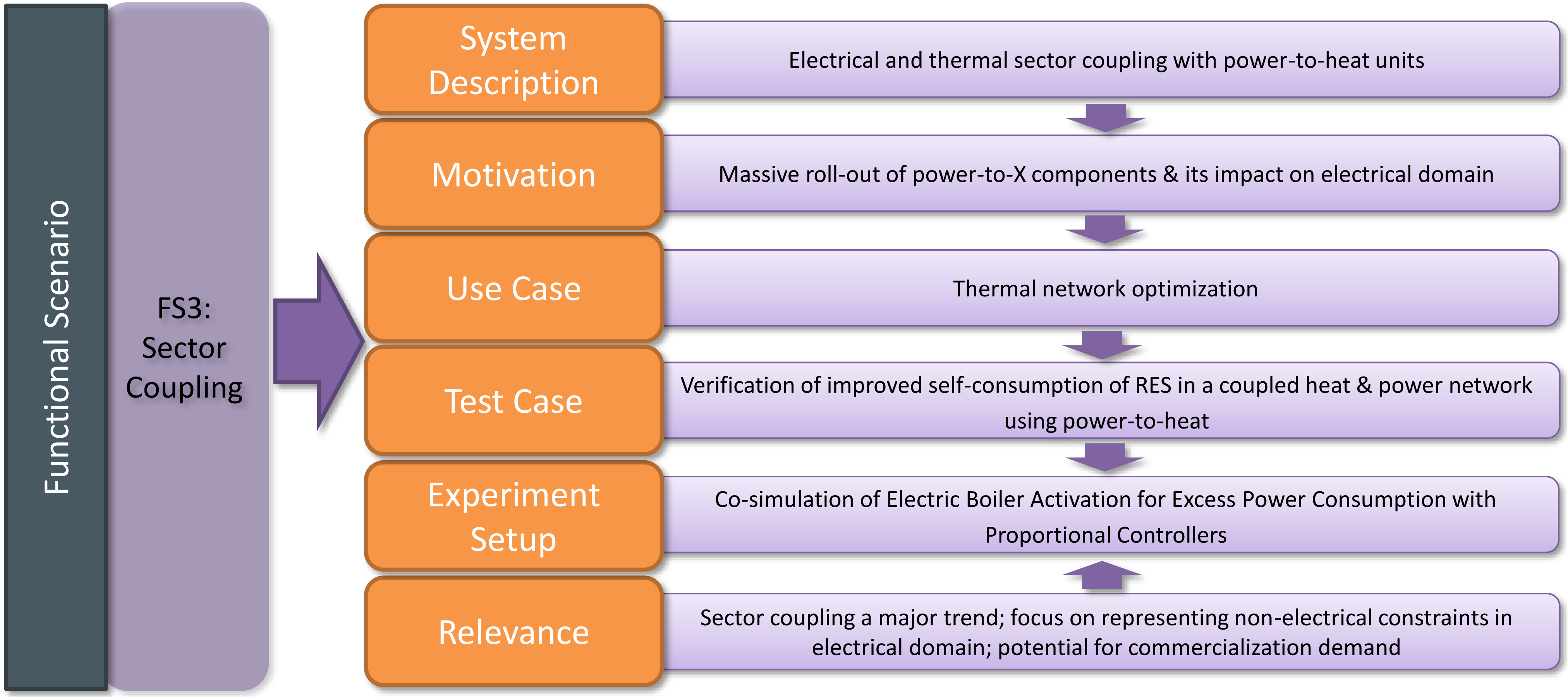
- Harmonise the development of holistic test case procedures
- Provision of tools for test reporting
- Further details at https://erigrid2.github.io/test-case-descriptions/





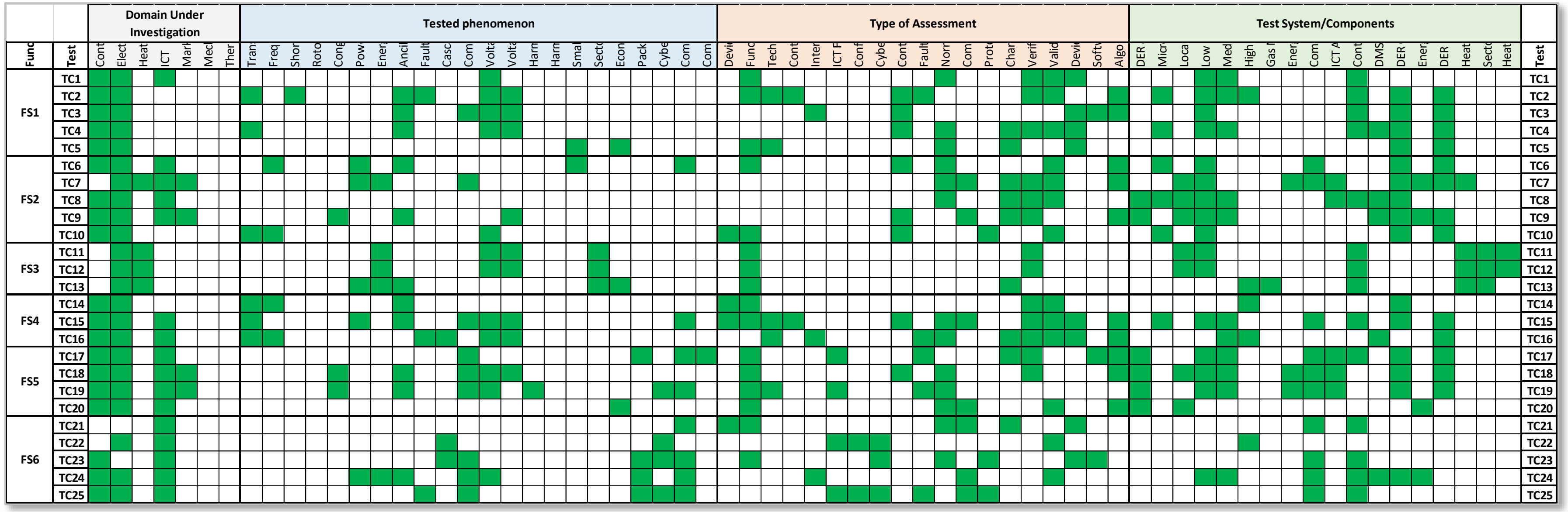
Test Case Profiles Concept

- Example of a Functional Scenario (i.e., FS3 Sector Coupling from ERIGrid 2.0)



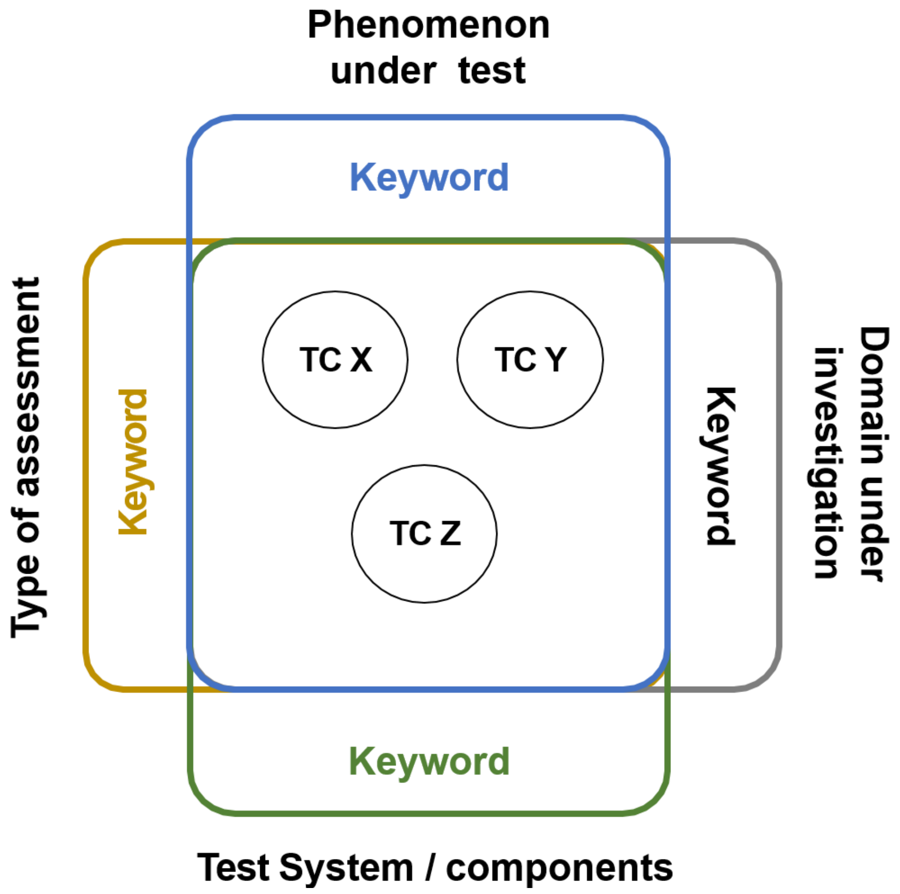
Test Case Profiles Concept

- Outcomes and experiences from ERIGrid 2.0
  - 25 TCs based on 6 FS defined
  - HTD used to formulate TCs
  - Each TC got keywords assigned
  - Keywords help to
    - Define characteristics of techn. areas
    - Select TCs



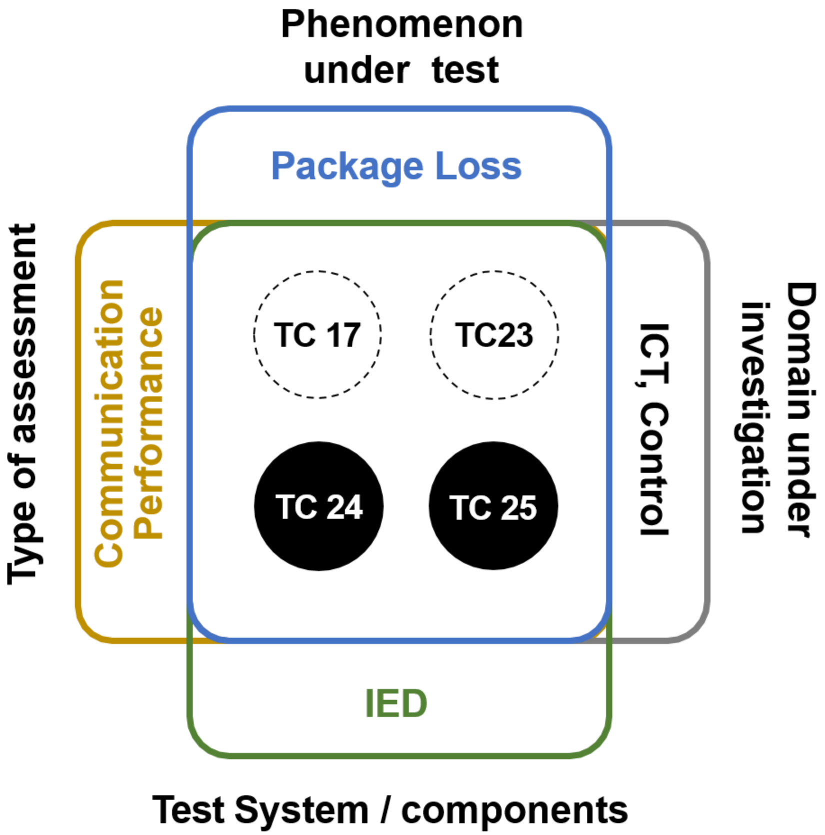
Test Case Profiles Concept

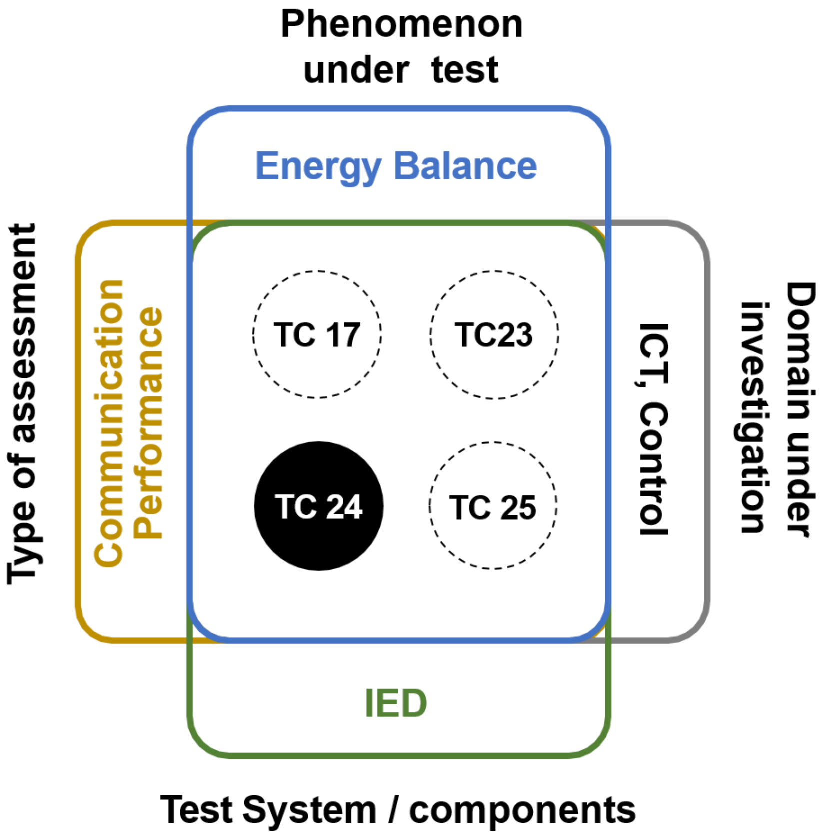
- Outcomes and experiences from ERIGrid 2.0
  - Keywords focus on 4 dimensions
    1. Domain under investigation
    2. Phenomenon under test
    3. Type of assessment
    4. Test system
  - Derivation of Test Case Profiles (TPCs)
    - Collection of TCs that share similarities
    - Similarities in context of application and testing facility properties



Test Case Profiles Concept

- Different possibilities based on user's back-ground and interests
  - Beginner Entering to new Domain
  - Suitable Bench-mark identification
  - Project's case studies presentation
  - Aligning infra-structure capabilities with roadmaps

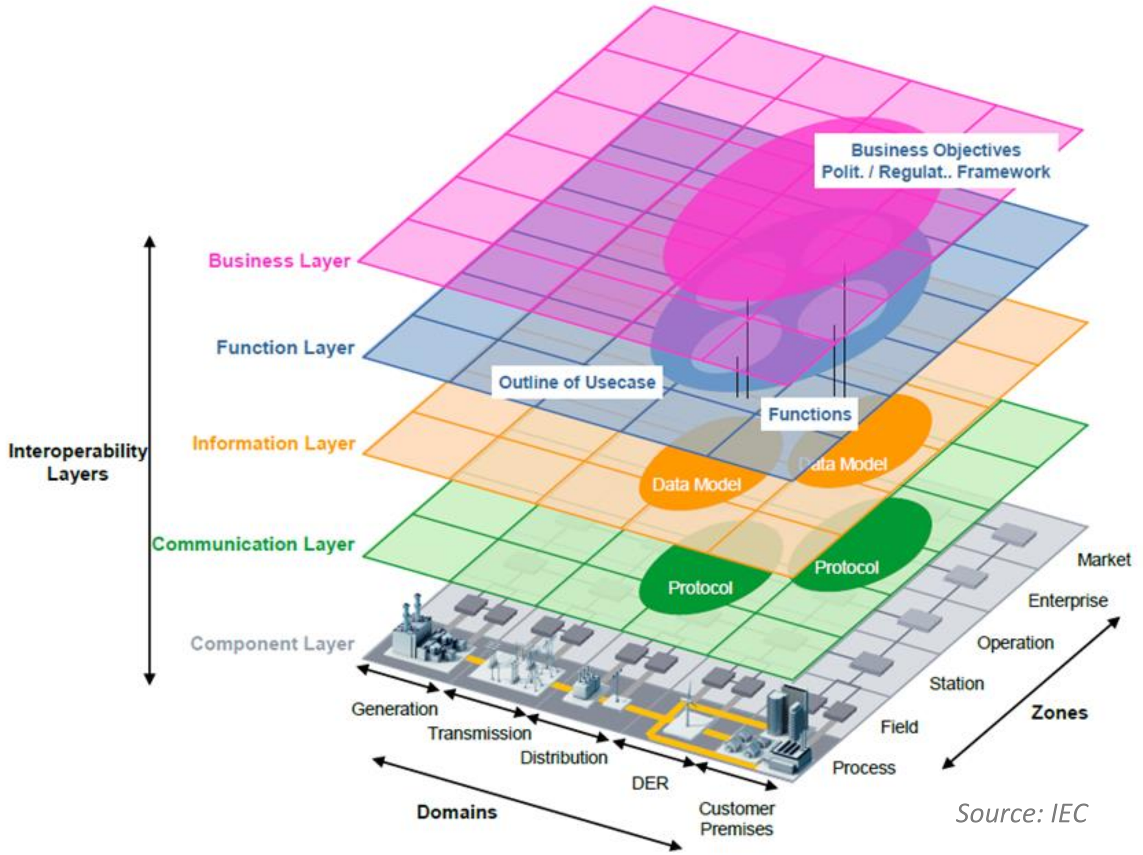




Interoperability Testing

Why interoperability?

- Interoperability of various building blocks is necessary
- Full interoperability of components from different vendors with systems of various energy providers are required
- Competition can then flourish
- This requires not only political will, but also suitable technical solutions and an appropriate standardisation framework



Source: IEC

EU H2020 Programme GA No. 870620
doi:10.5281/zenodo.10676588

Interoperability Testing

Why interoperability?

- Key challenge
  - Convergence of many industrial sectors with different standards, culture and technical background
  - Single/multi-vendor devices, components should be able to inter-work
- Definition CEN-CENELEC-ETSI SG-CG: Interoperability is the "ability of two or more networks, systems, devices, applications, or components to interwork, to exchange and use information in order to perform required functions"
  - SGAM reference architecture: interoperability across all the 5 layers
  - Interwork at power level?

Interoperability Testing

Why interoperability?

- Status
  - Standards and detailed experimental methods for testing the interoperability of CPES missing
  - Standards do not guarantee interoperability, even if they promote it
- The European Commission (EC) – Joint Research Centre (JRC) proposal
  - Interoperability testing methodology
  - Usage of the Design of Experiments (DoE) methodology
- The Smartgrids Austria IES proposal
  - Guidelines and software tool for interoperability testing
  - Motivated from healthcare domain

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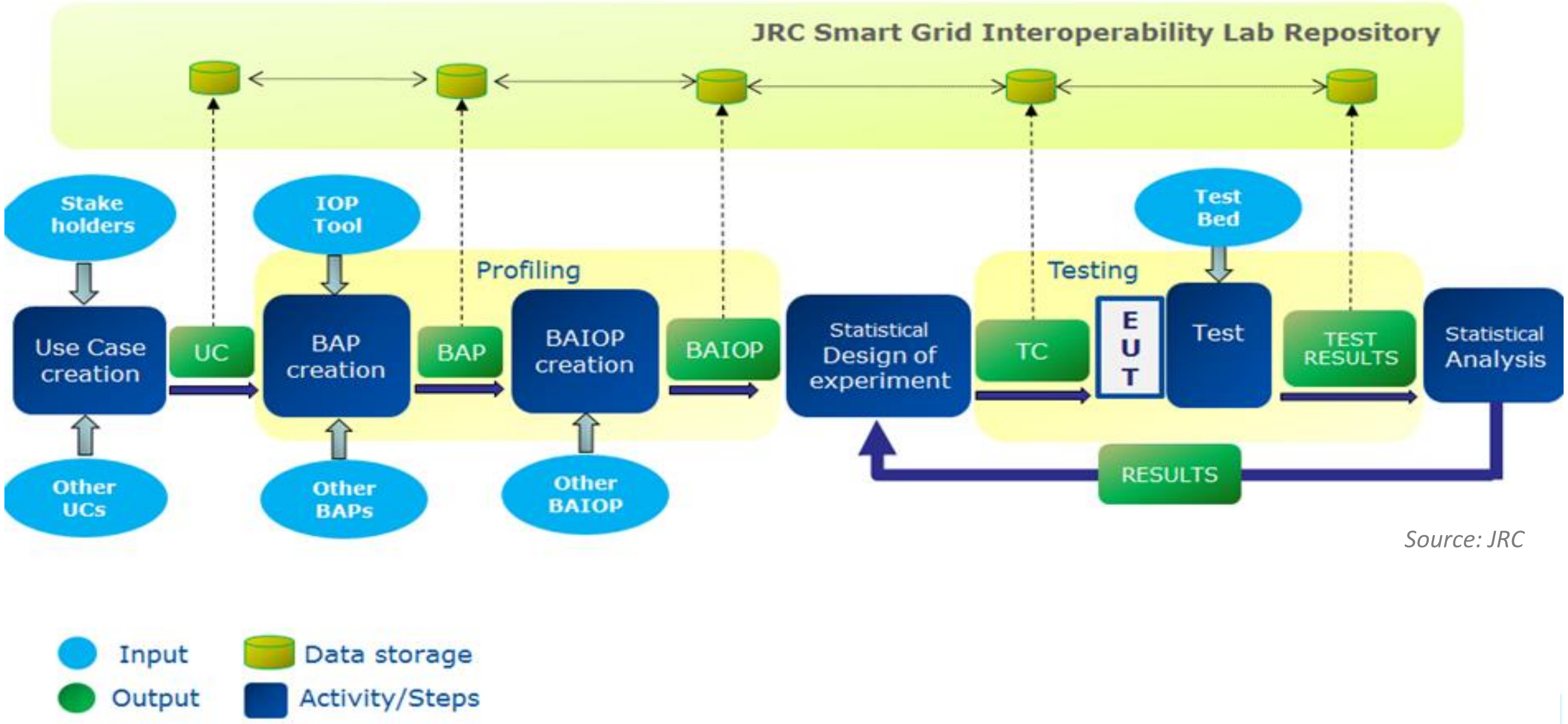
Interoperability Testing

Overview of the JRC interoperability testing methodology



Source: JRC

4. Advanced Validation and Testing Methods

Online Training Series on the Digitalisation of Smart Energy Systems

February 21, 2024, online

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tbd

- tbd

5. Summary and Conclusions

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tbd

- tbd

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