

CONCEPTS, METHODS, AND TOOLS FOR DESIGNING AND VALIDATING CYBER-PHYSICAL ENERGY SYSTEMS



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BACKGROUND AND MOTIVATION

- Challenges and drivers



- Climate change
- Deep decarbonisation
- Energy transition



- Industrial competitiveness
- Business Innovation
- Digitalisation



- Urban Transformation
- Infrastructure needs
- Societal changes

BACKGROUND AND MOTIVATION

- Global policy
 - Paris Agreement (COP21): long-term, limit temperature increase to 1.5°C
 - UN Sustainable Development Goals: pathway for future research and innovation activities
 - Mission Innovation: global initiative to accelerate clean energy innovation
- Europe policy
 - European Green Deal: climate-neutrality by 2050
 - EC Roadmap Low-Carbon Economy 2050: EU GHG emissions towards an 80% domestic reduction
 - EC Hydrogen Strategy and Sector Integration: renewable hydrogen electrolyzers

HIGHER COMPLEXITY IN SMART GRID 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
 - Digitalisation of power grids
 - Deeper involvement of consumers and market interaction
 - Linking electricity, gas, and heat grids for higher flexibility and resilience

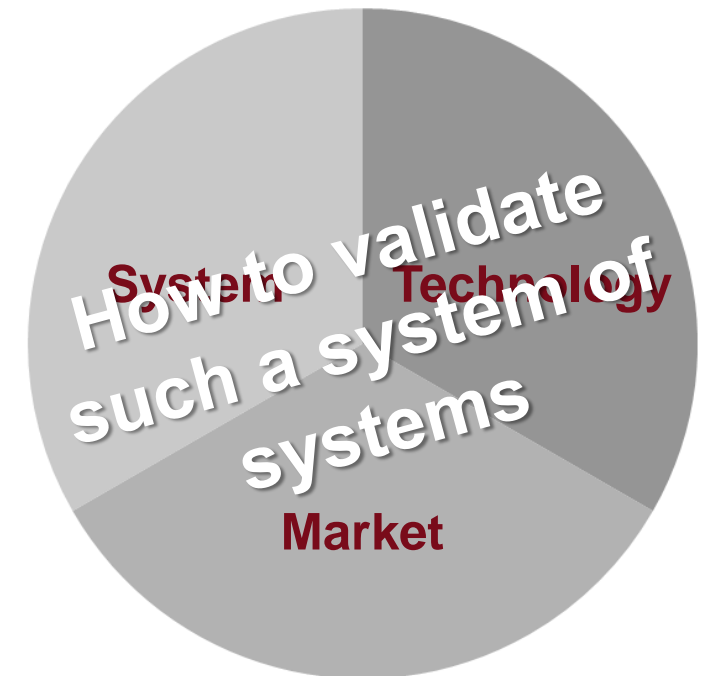
→ *Smart Grid or Cyber-Physical Energy Systems*



Source: AIT

HIGHER COMPLEXITY IN SMART GRID 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)

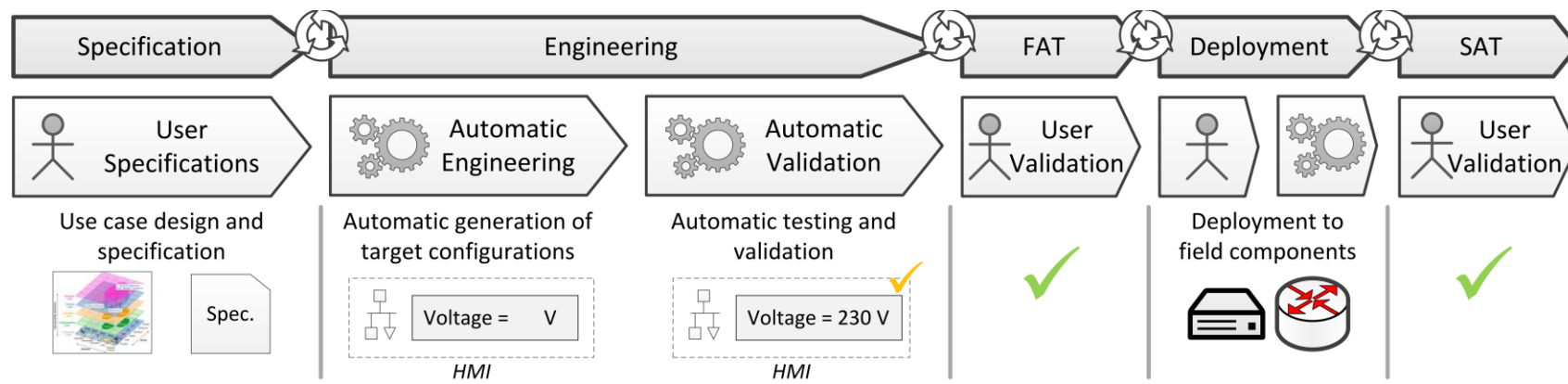


Source: AIT

ENGINEERING ISSUES AND NEEDS

- Targets and goals
 - Reduction of manual steps necessary to handle complex smart grid configurations
 - 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

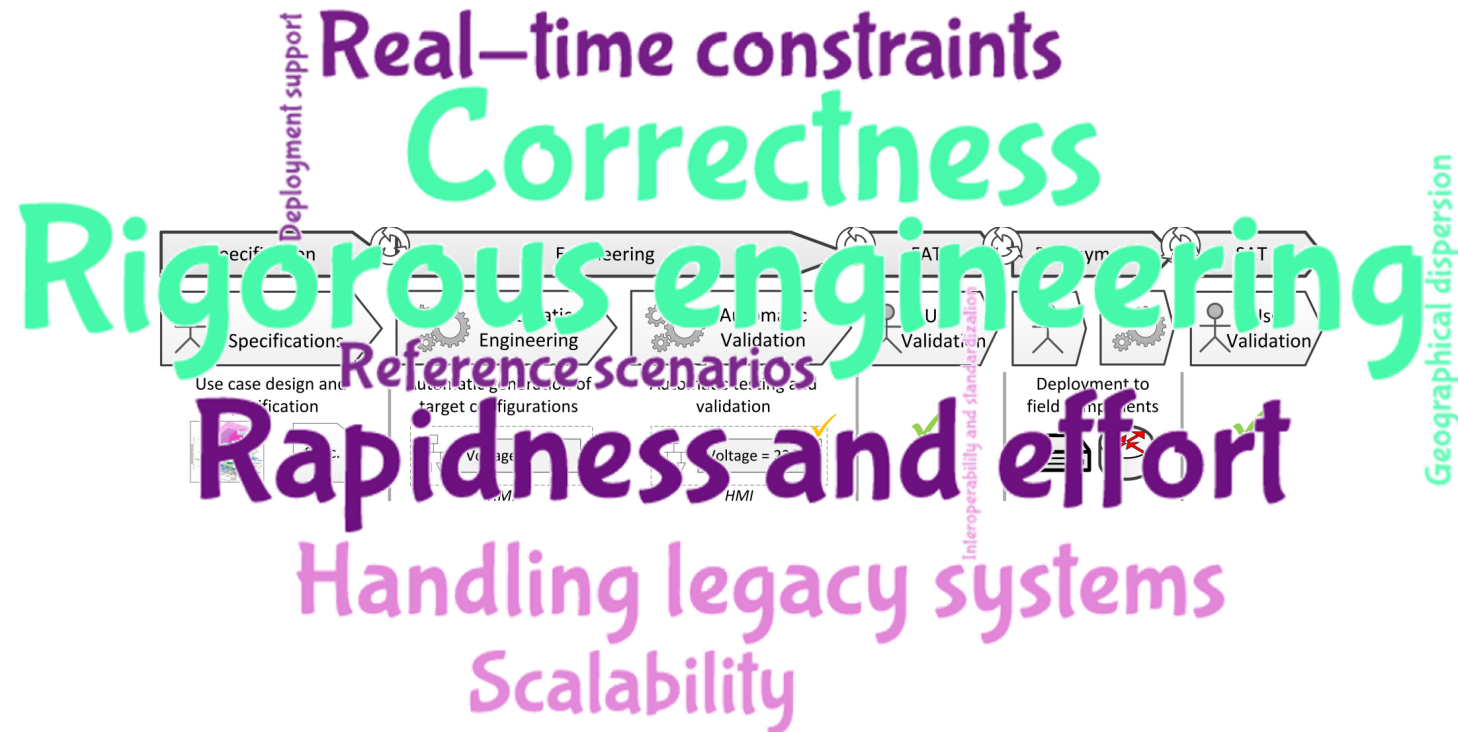
→ *Providing support from design to implementation and installation*



Source: AIT

FAT: Factory Acceptance Test
SAT: System Acceptance Test

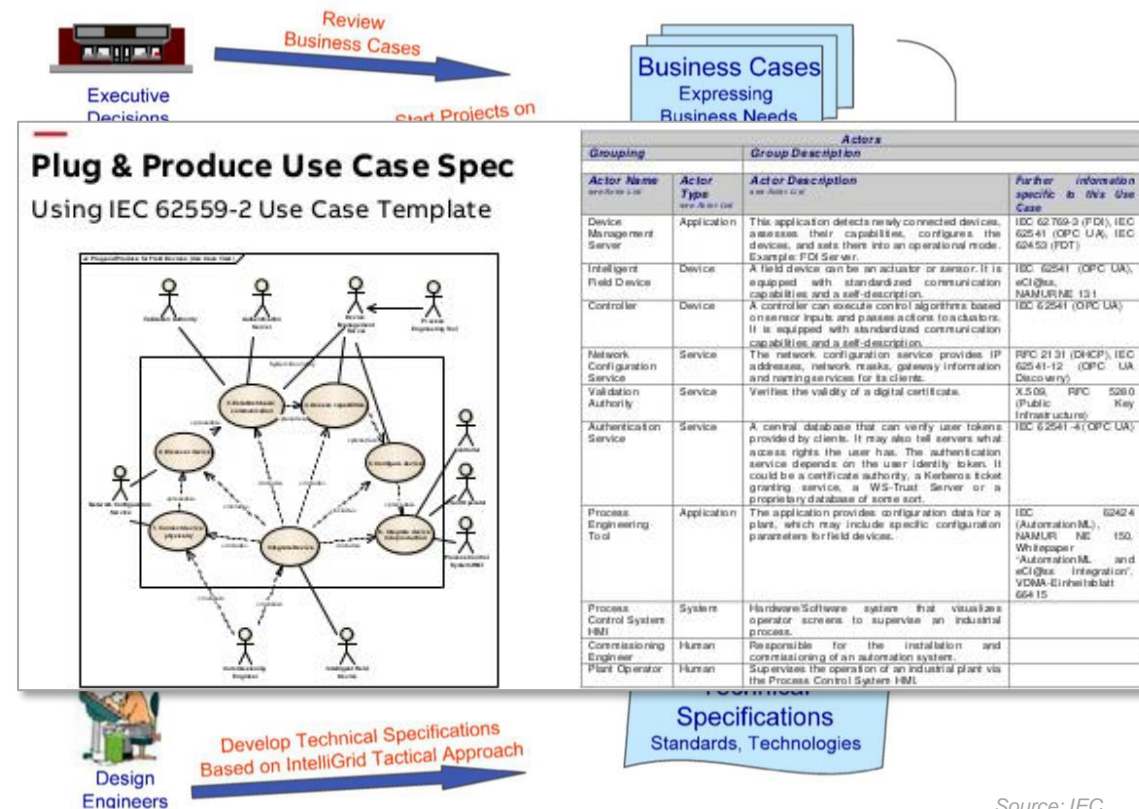
ENGINEERING ISSUES AND NEEDS



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

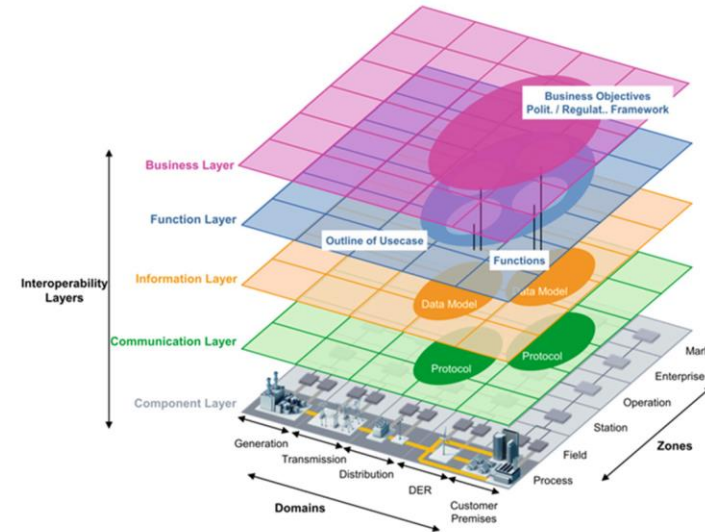
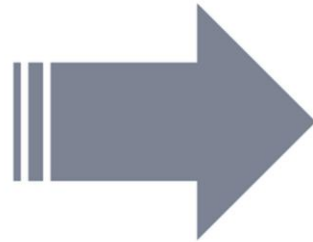
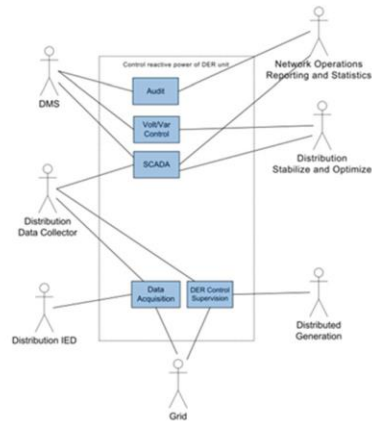


Source: IEC

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



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)*

STATUS QUO IN RESEARCH AND DEVELOPMENT

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

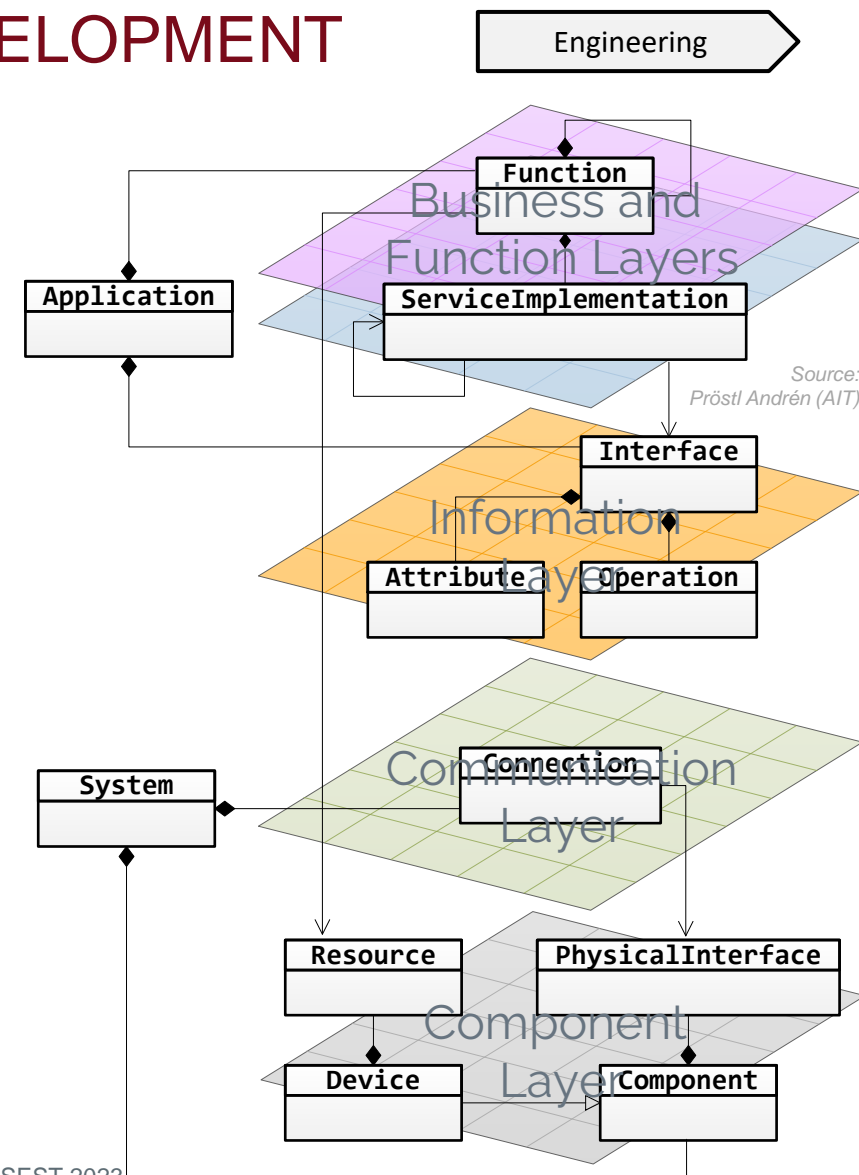
```

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

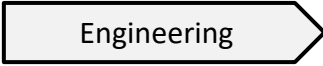
```

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

  connect DSOComputer.eth0 with StationRouter
}
    
```

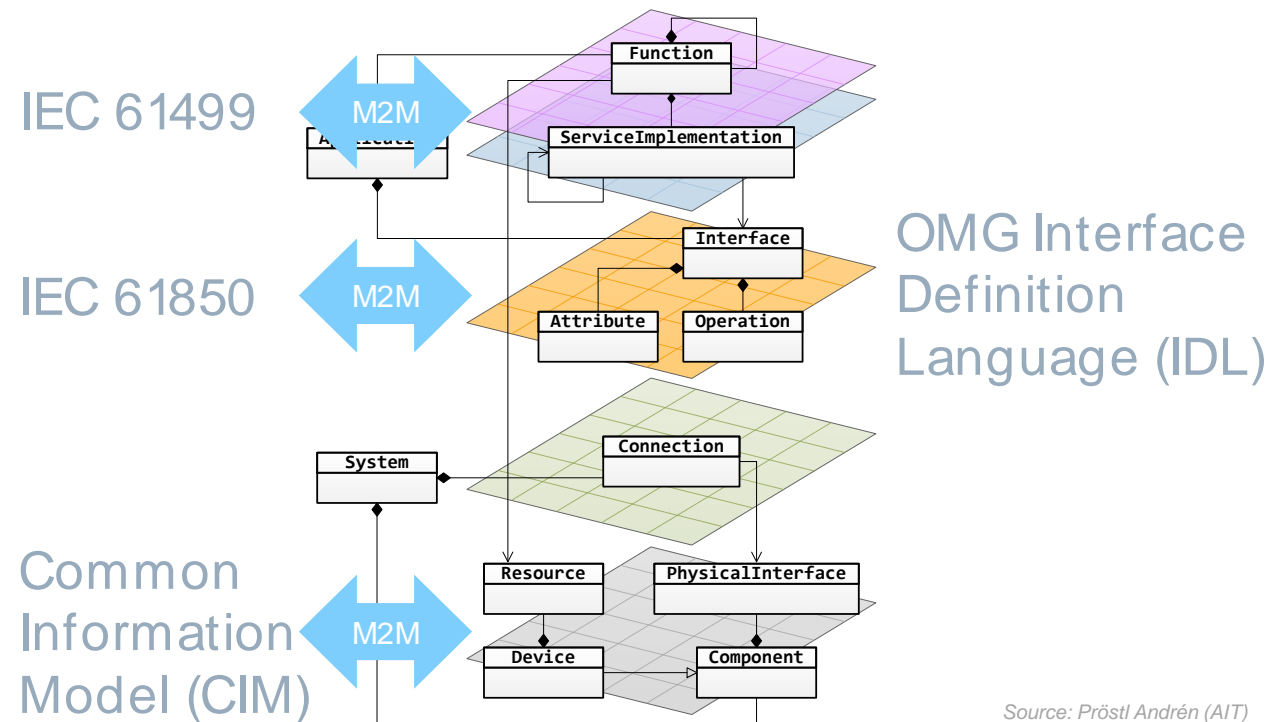


STATUS QUO IN RESEARCH AND DEVELOPMENT



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

SGAM for the approach



STATUS QUO IN RESEARCH AND DEVELOPMENT



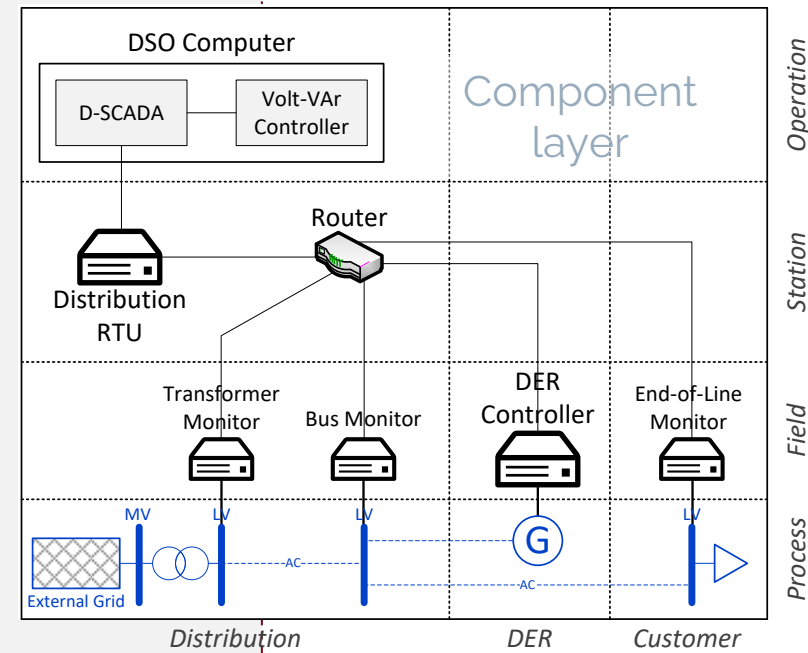
- PSAL model-based engineering for smart grids
 - Application example

```

application VoltVArControlCentralized {
  function DERController at DERController.AncillaryServices {
    provides Measurements.GridMeasurements measurements
    requests DERCtrlInterfaces.DERDirectControls derDirectControls
  }
  ...
}
function VoltVArController {...}
function DSCADA {...}
function DistributionRTU {...}
function DERGenerator {...}
function TransformerMonitor {...}
function BusMonitor {...}
function EndOfLineMonitor {...}

module Measurements {
  interface GridMeasurement {...}
  eventtype AggregatedMeasurement {...}
}
module DERCtrlInterfaces {...}

connect DERController.derDirectControls
  with DERGenerator.directControls
...
}
    
```



Source: Prössl Andrén (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT



- PSAL model-based engineering for smart grids
- System example

```

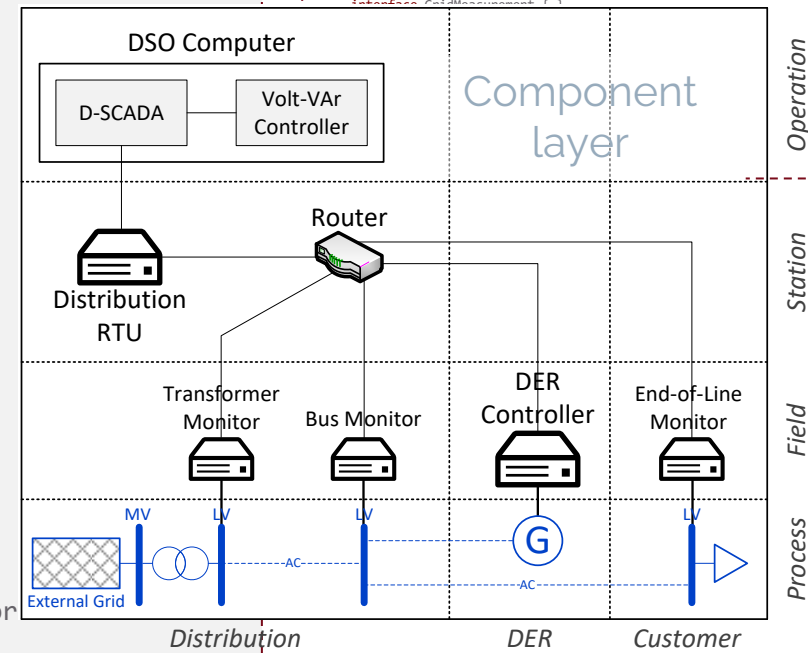
system DistributionSystemVW {
  @DER @Field
  device DERController {
    ethernet eth0 {ip = "10.0.0.1"}
    ethernet eth1 {ip = "192.168.0.2"}
    resource AncillaryServices
  }
  device DSOComputer {...}
  device DistributionRTU {...}
  router StationRouter
  device TransformerMonitor {...}
  device BusMonitor {...}
  device EndOfLineMonitor {...}
  generator ExternalSystem {...}
  busbar MVBus {...} ...
  generator DERGenerator {
    ethernet eth0 {ip = "192.168.0.1"}
    terminal LVBus2
    resource DERResource
  }
  ...
  connect DERController.eth1 with DERGenerator.eth0
  connect DERGenerator.LVBus2 with LVBus2.DERGenerator
}

```

```

application VoltVarControlCentralized {
  function DERController at DERController.AncillaryServices {
    provides Measurements.GridMeasurements measurements
    requests DERCtrlInterfaces.DERDirectControls derDirectControls
  }
  ...
  function VoltVarController {...}
  function DSCADA {...}
  function DistributionRTU {...}
  function DERGenerator {...}
  function TransformerMonitor {...}
  function BusMonitor {...}
  function EndOfLineMonitor {...}
}
module Measurements {
  interface GridMeasurement {

```

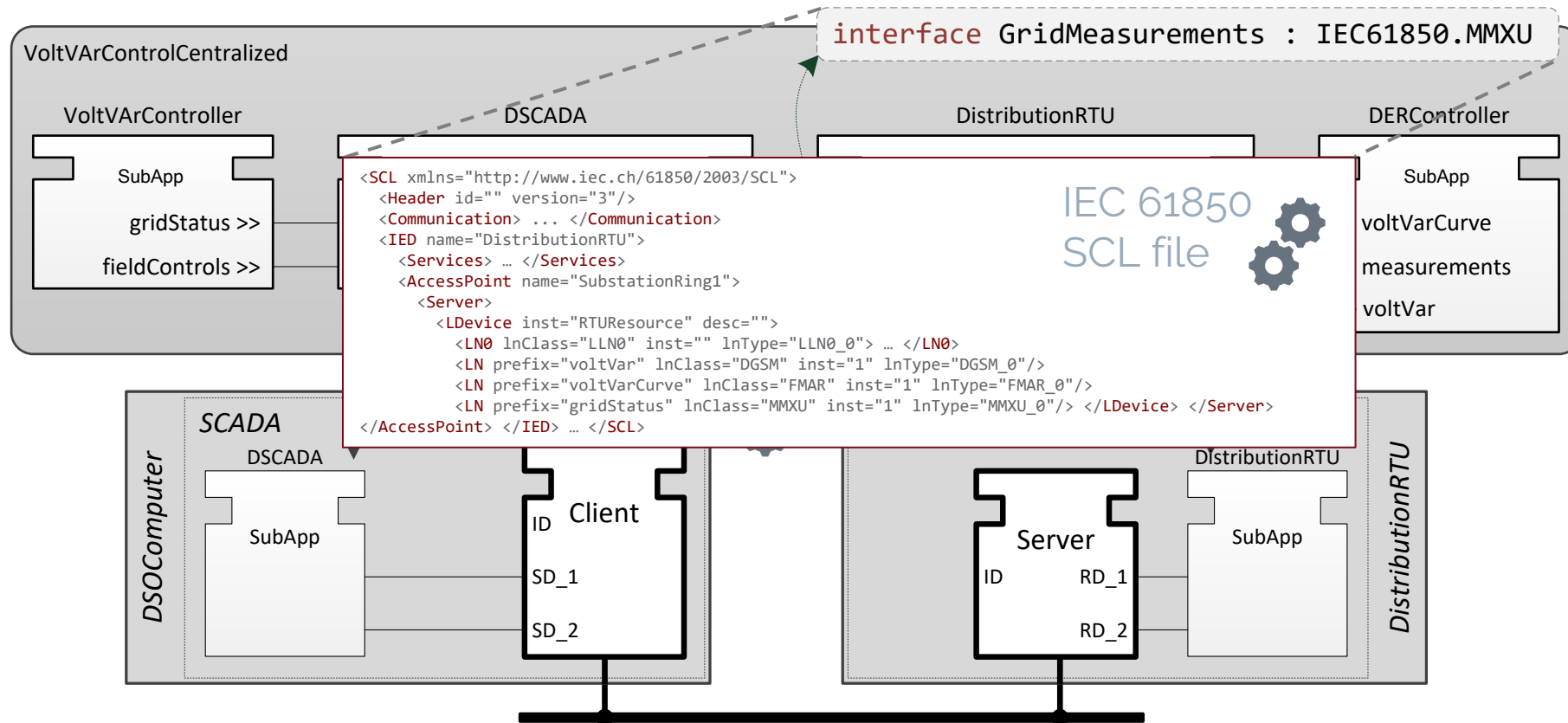


Source: Prössl André (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

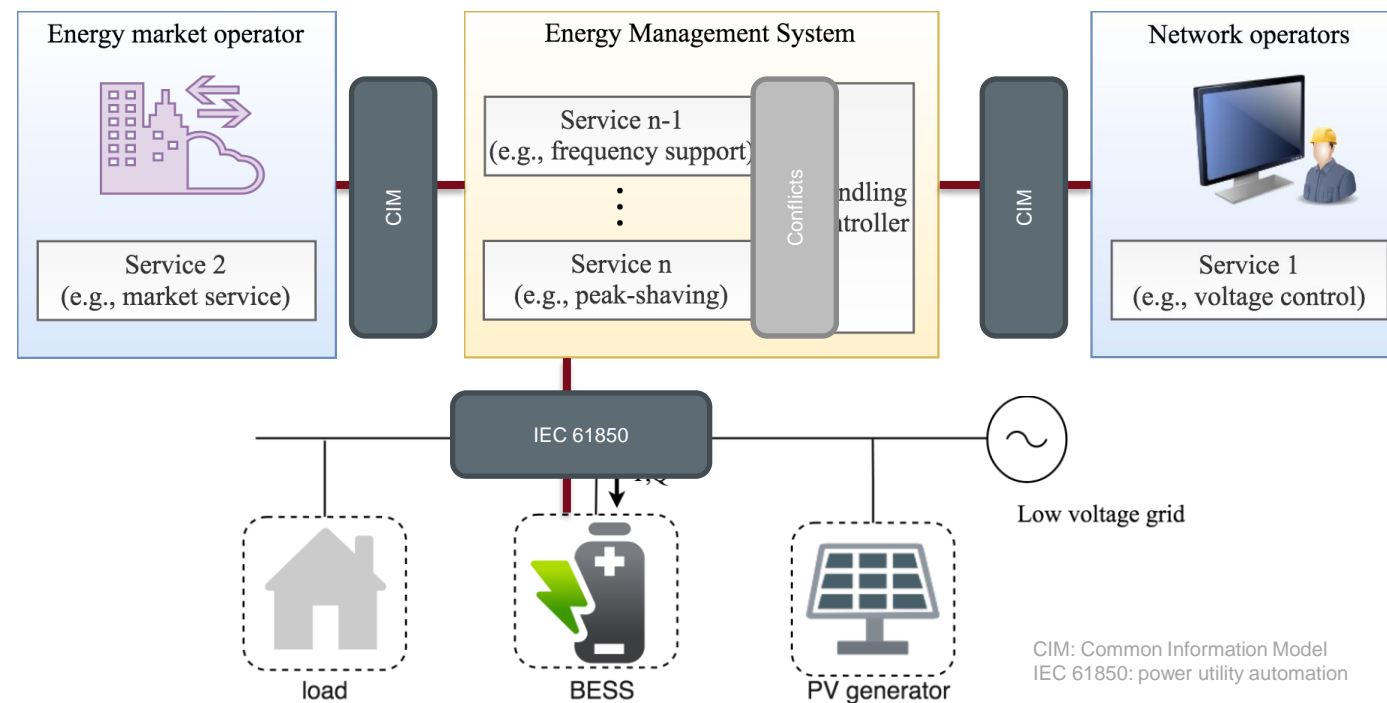
- PSAL model-based engineering for smart grids
 - Generation of IEC 61499 code



STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)



1. Conflicts between services
2. Lack of data interoperability

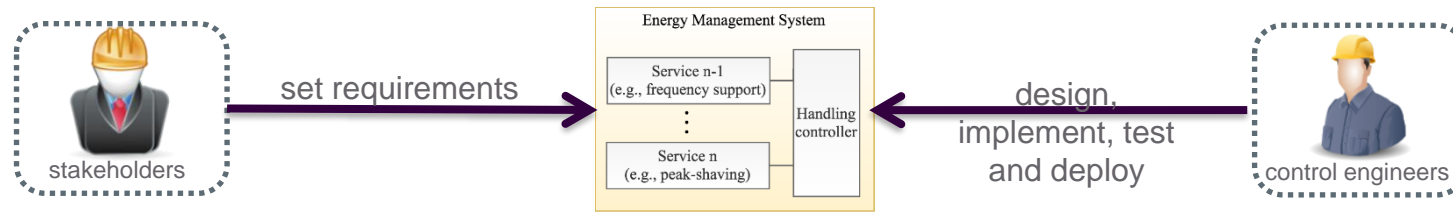
Source: Zanabria (AIT)

Source: C. Zanabria, Adaptable Engineering Support Framework for Multi-Functional Battery Energy Storage Systems, Doctoral Thesis, TU Wien, supervisor T. Strasser, 2018

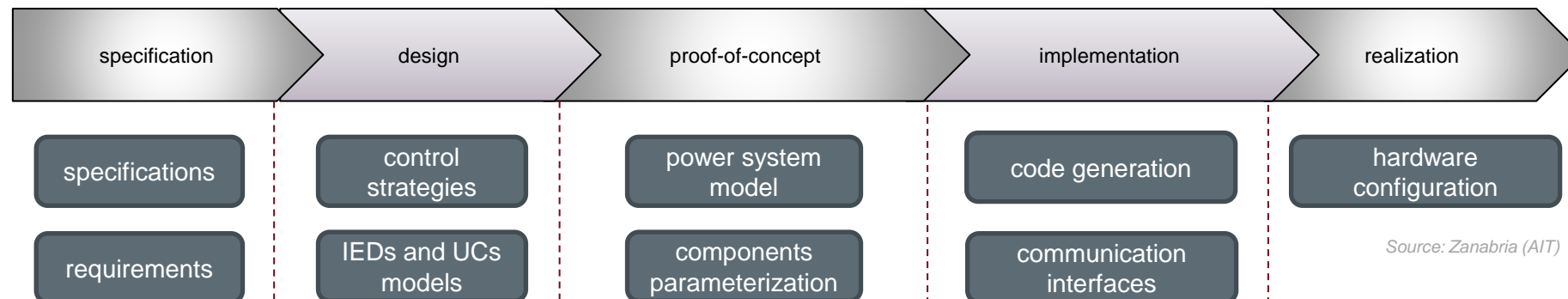
STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
 - Energy Management System (EMS) core element (multi-functional usage)



- Complex EMS engineering process



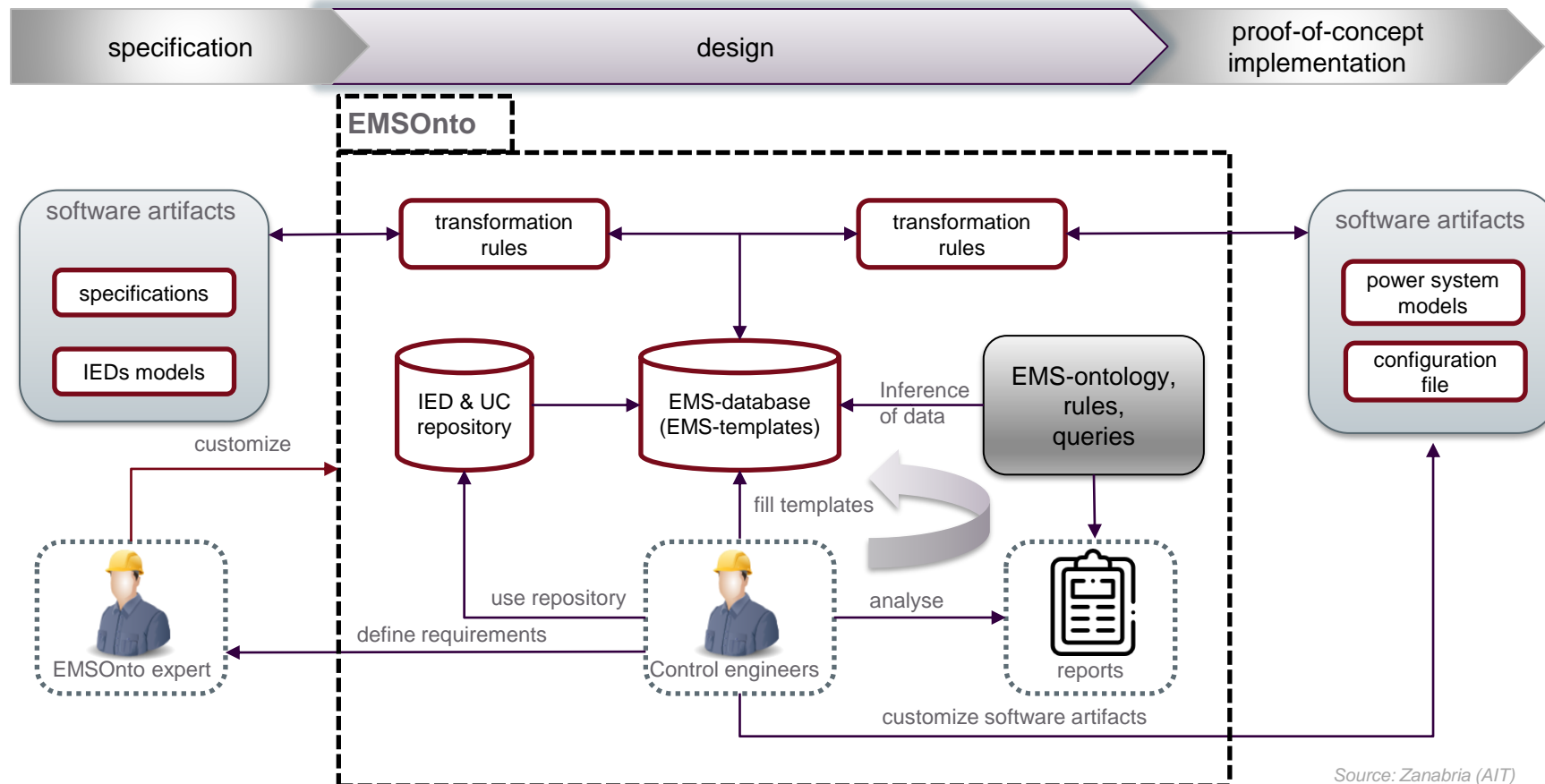
- 3. Lack of a vendor-independent solution
- 4. Error-prone engineering process

IED: Intelligent Electronic Device
UC: Use Case

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)



Source: Zanabria (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

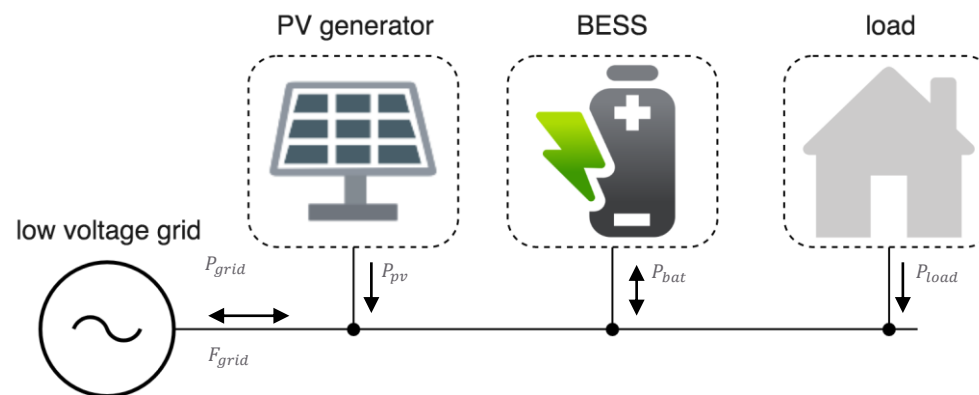
Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
 - Conflict handling: different types considered

<i>service</i>	<i>manipulate</i>	<i>control</i>	<i>control goal</i>
frequency-watt(FW)	P_{bat}	P_{bat}	$P_{bat} = \gamma F_{grid} + \theta$
self-consumption (SC)	P_{grid}	P_{bat}	$P_{grid} = 0$

$$P_{grid} + P_{bat} + P_{PV} + P_{load} = 0$$

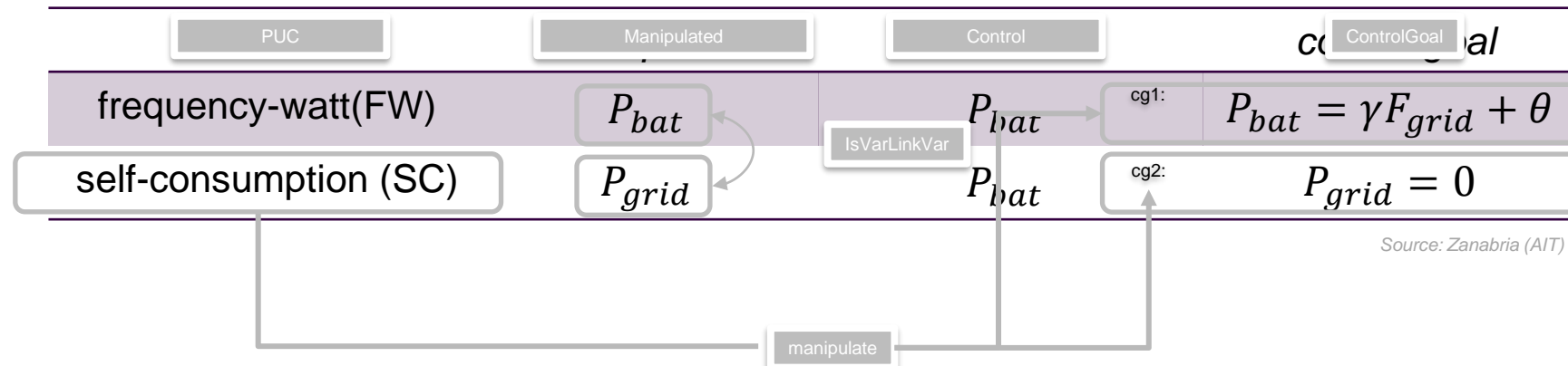
Source: Zanabria (AIT)



STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
 - Conflict handling: ontology-based modelling of engineering conflicts



- *Tbox*
(Terminological component)
- Inferred assertions
- Query to identify a conflict type
- Conclusion

$hasFctVar \circ IsVarLinkVar \sqsubseteq hasFctVar,$
 $hasFctVar \circ hasFctVar^- \sqsubseteq IsFcLinkFc,$
 $manipulate \circ IsFcLinkFc \sqsubseteq manipulate$

$manipulate(SC, cg1)$

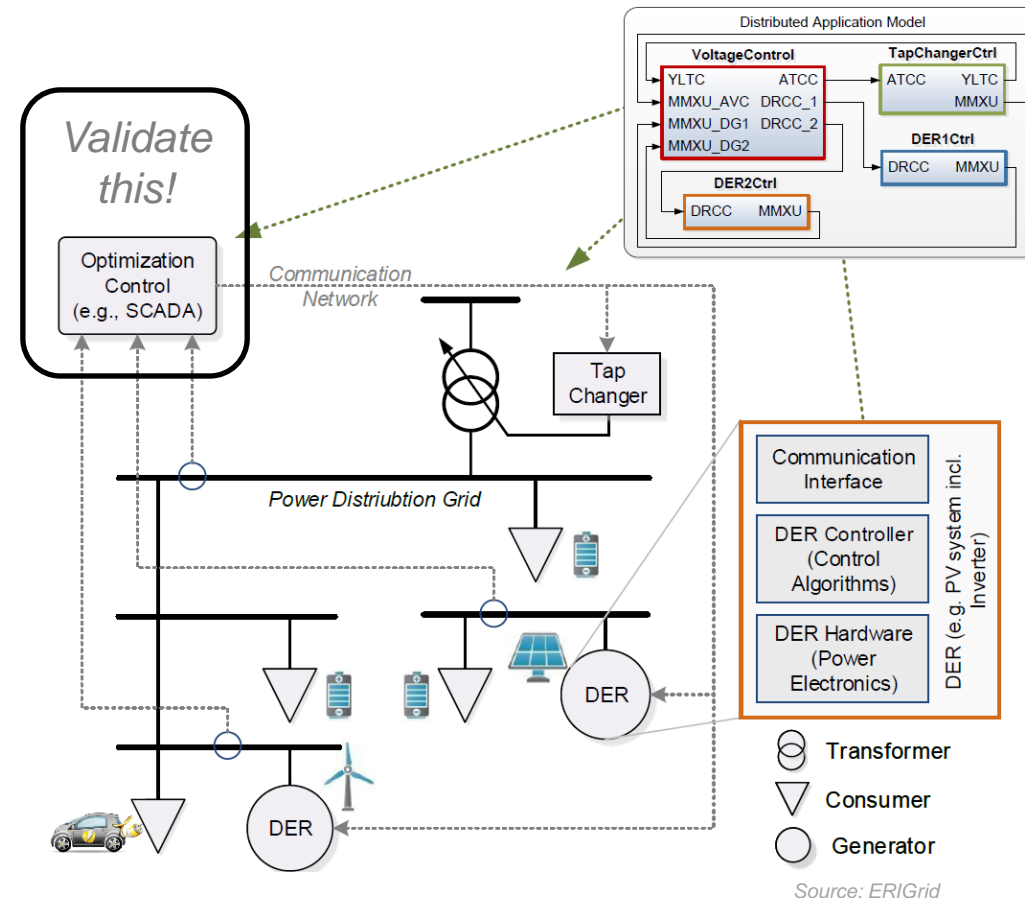
$ControlGoal \sqcap 2manipulate^- . PUC$

FW and SC are in conflict

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

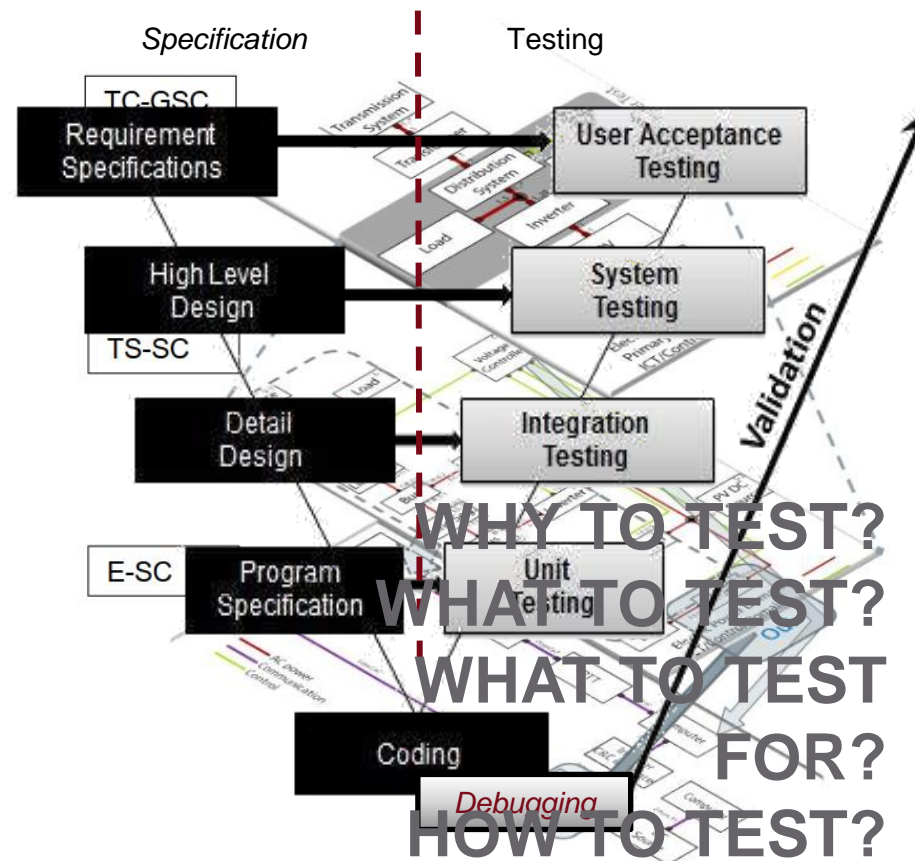
- ERIGrid holistic testing approach for smart grid systems
 - Testing of smart grid components and concepts
 - Many domain involved (holism)
 - Setups and workflows differ across Research Infrastructures (RI)
 - Experiments are often hardly reproducible
 - Often limited by RI capabilities



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems
 - Formalize testing process
 - Testing → documented and reproducible
 - Basis for knowledge exchange
 - Formal process covering all stages of test planning
 - Overview of resources
 - Consider state-of-the-art
 - Operationalize, refine

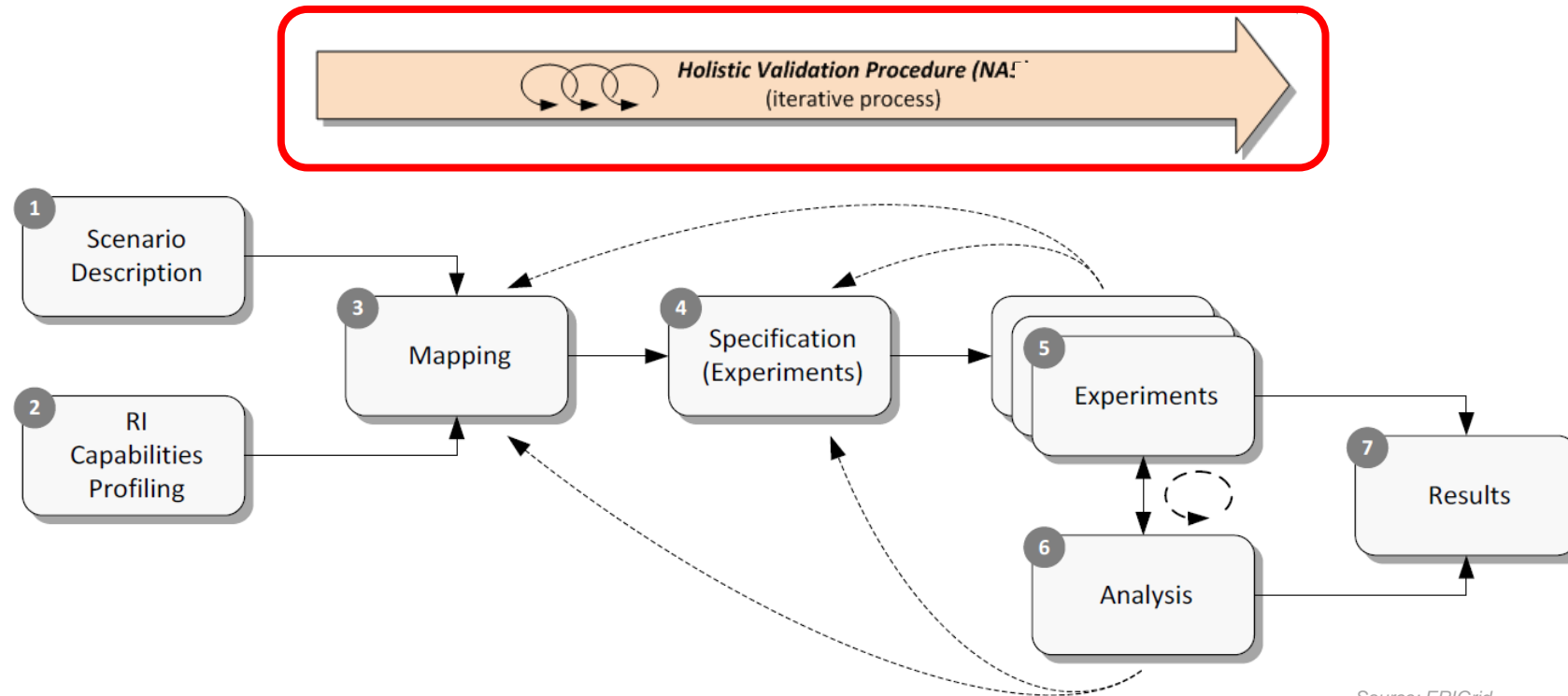


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems



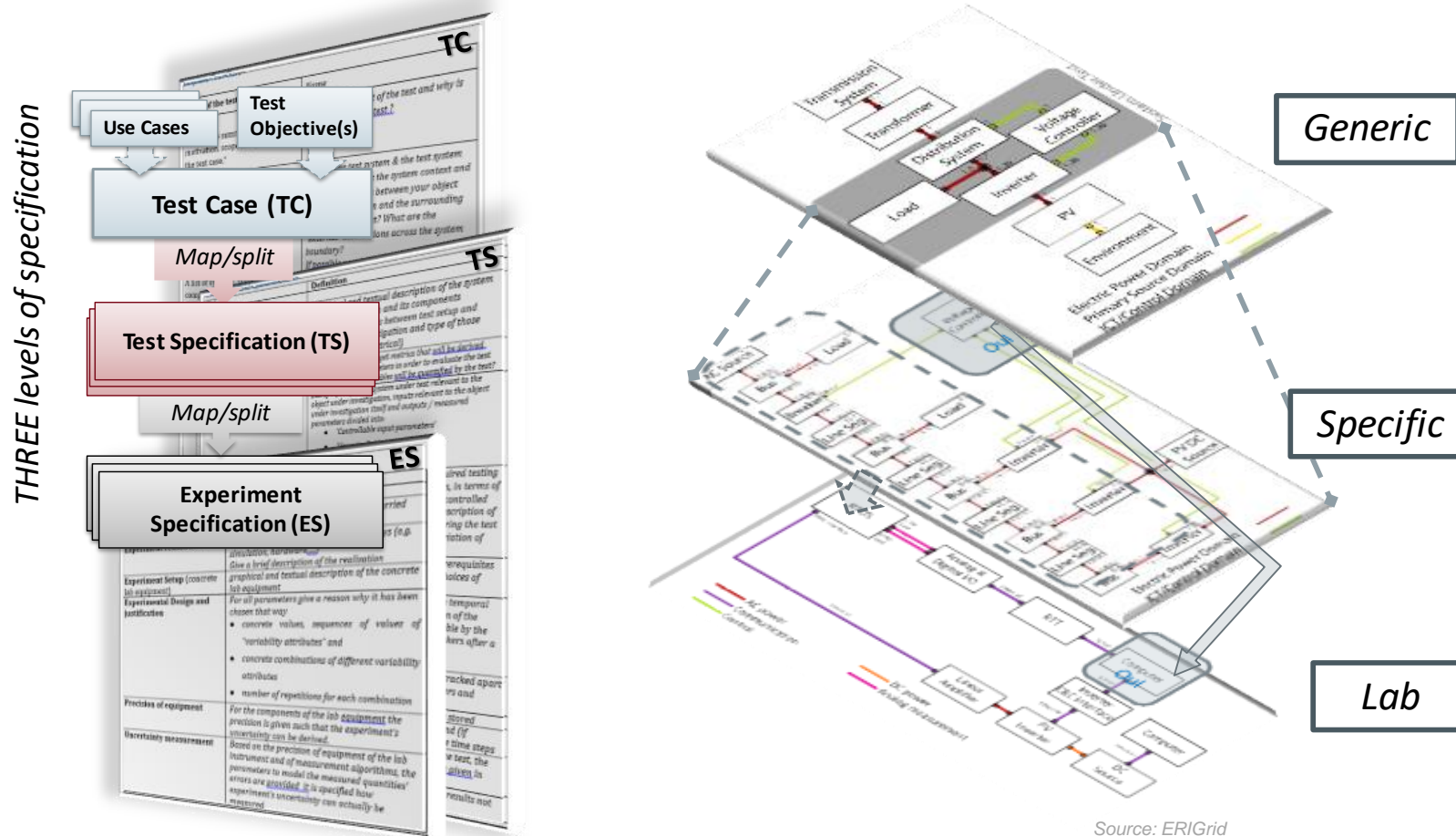
Source: ERIGrid

“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”

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

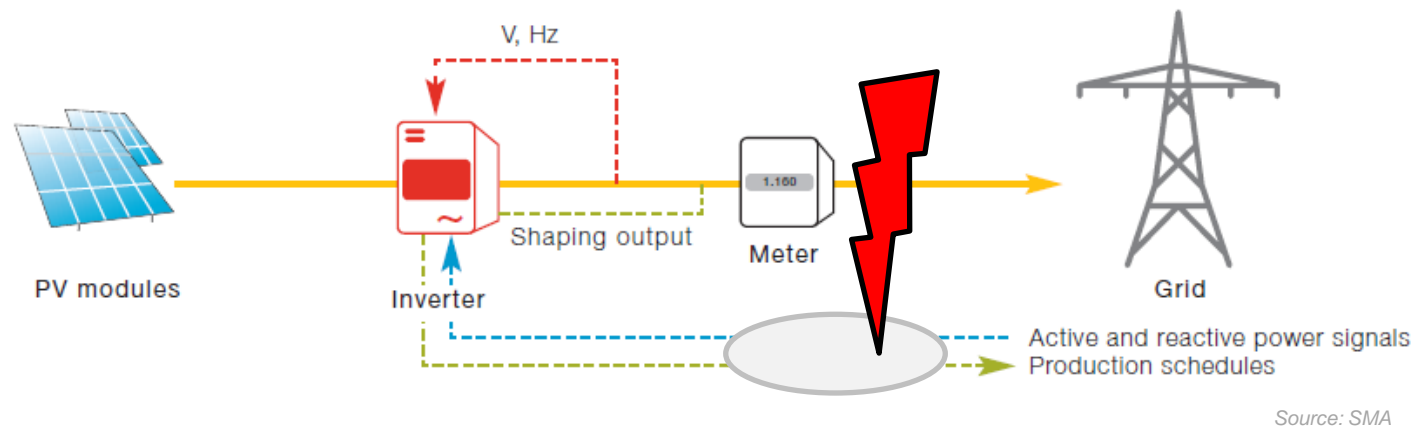
- ERIGrid holistic testing approach for smart grid systems



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

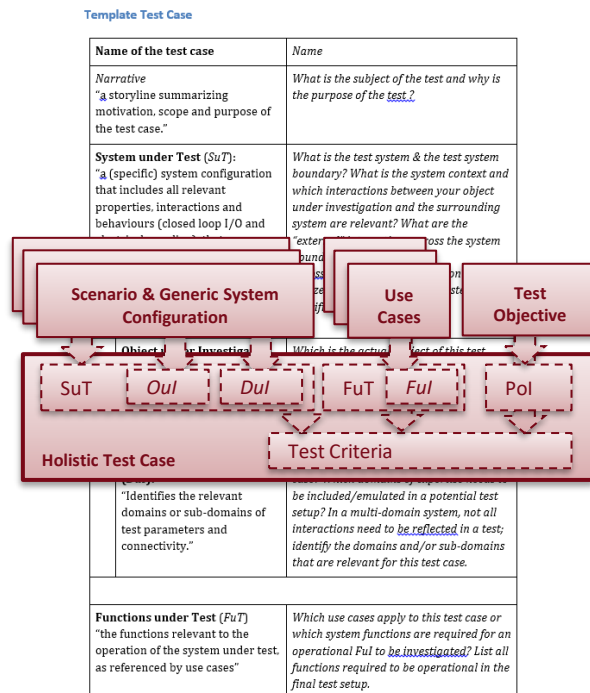
- ERIGrid holistic testing approach for smart grid systems
 - Example: cyber-security analysis
 - Analysing the influence of the attack on the energy infrastructure
 - IEC 61850 remote controlled inverter-based DER
 - Man-in-the-Middle attack scenario



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems
 - Example: cyber-security analysis
 - Formalized test case description



Template test specification

Title	Definition
Ref. Holistic test case	
Test System Setup (also graphical)	Graphical and textual description of the system under investigation and its components including interfaces between test setup and Object under investigation and type of those interfaces (e.g. electrical)
Target measures	Specification of the target metrics that will be derived, from measured parameters in order to evaluate the test objectives. Which variables will be quantified by the test? List of inputs for the system under test relevant to the object under investigation, inputs relevant to the object under investigation itself and outputs / measured parameters divided into: <ul style="list-style-type: none"> • 'Controllable input parameters' • 'Uncontrollable input parameters' • 'Measured parameters'
Input and output parameters	
Test Design	The choice of mapping between required testing target and available test parameters, in terms of

Test Specification
Test Design, Test System Config., Input & Output

Template experiment specification

Title	Definition
Ref. Test Spec.	
Research Infrastructure	Specify the RI where the experiment is carried out
Experiment realisation	The setup can be realised in different ways (e.g. simulation, hardware,...) Give a brief description of the realisation
Experiment Setup (concrete lab equipment)	graphical and textual description of the concrete lab equipment
Experimental Design and	For all parameters give a reason why it has been

Experiment Specification
Experiment Design, Experiment setup

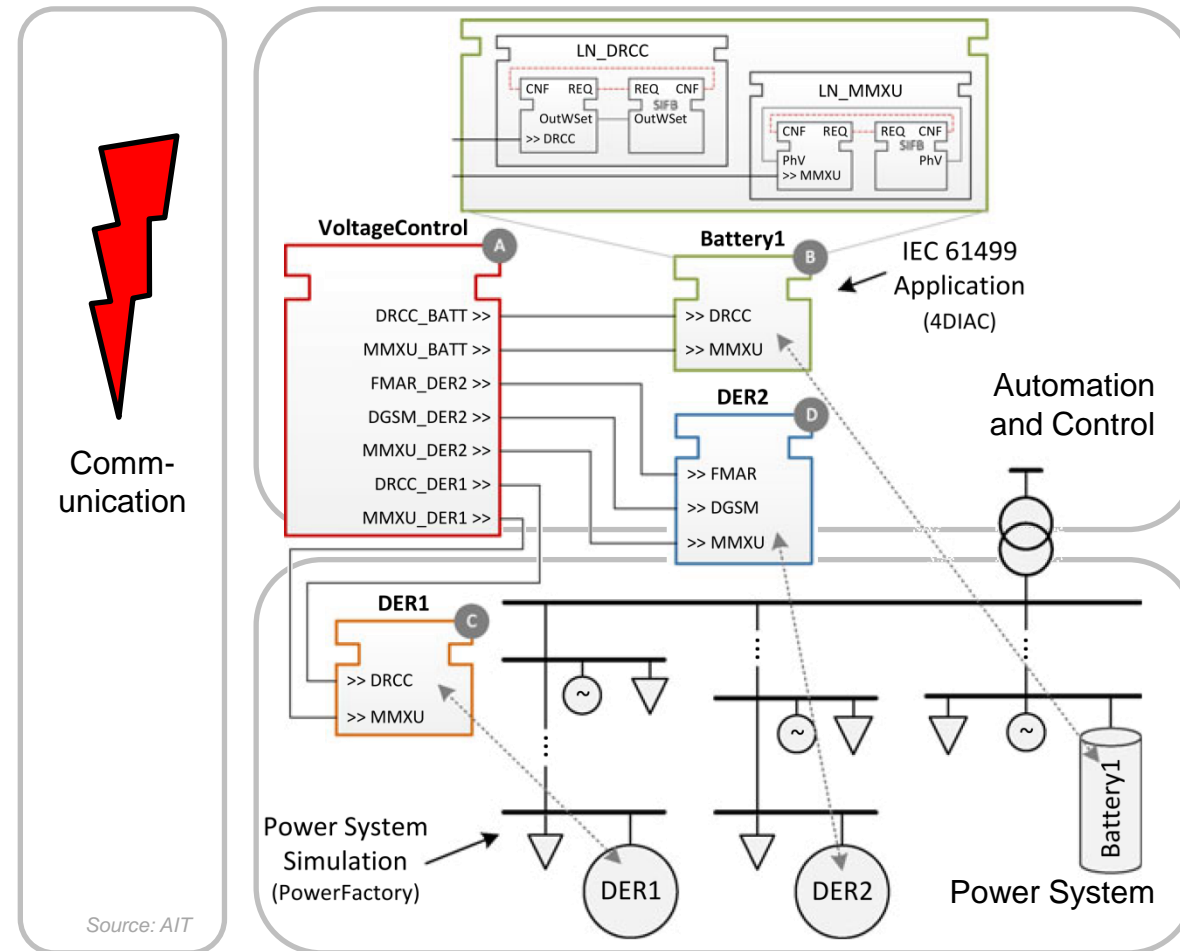
	attributes • number of repetitions for each combination
Precision of equipment	For the components of the lab equipment the precision is given such that the experiment's uncertainty can be derived.
Uncertainty measurement	Based on the precision of equipment of the lab instrument and of measurement algorithms, the parameters to model the measured quantities' errors are provided. It is specified how experiment's uncertainty can actually be measured.

Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

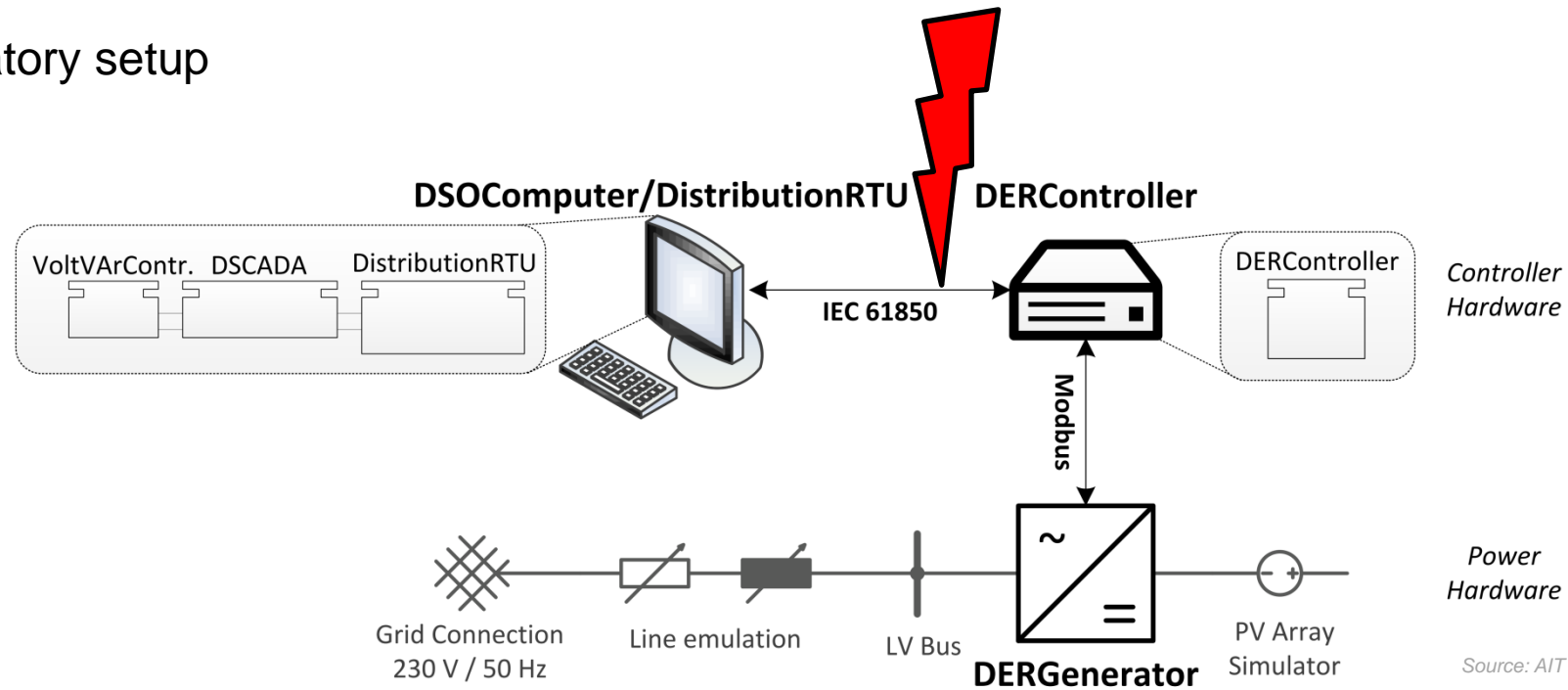
- ERIGrid holistic testing approach for smart grid systems
 - Example: cyber-security analysis
 - Simulation-based analysis
 - Coupling of different domains (power, ICT, control & automation)



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

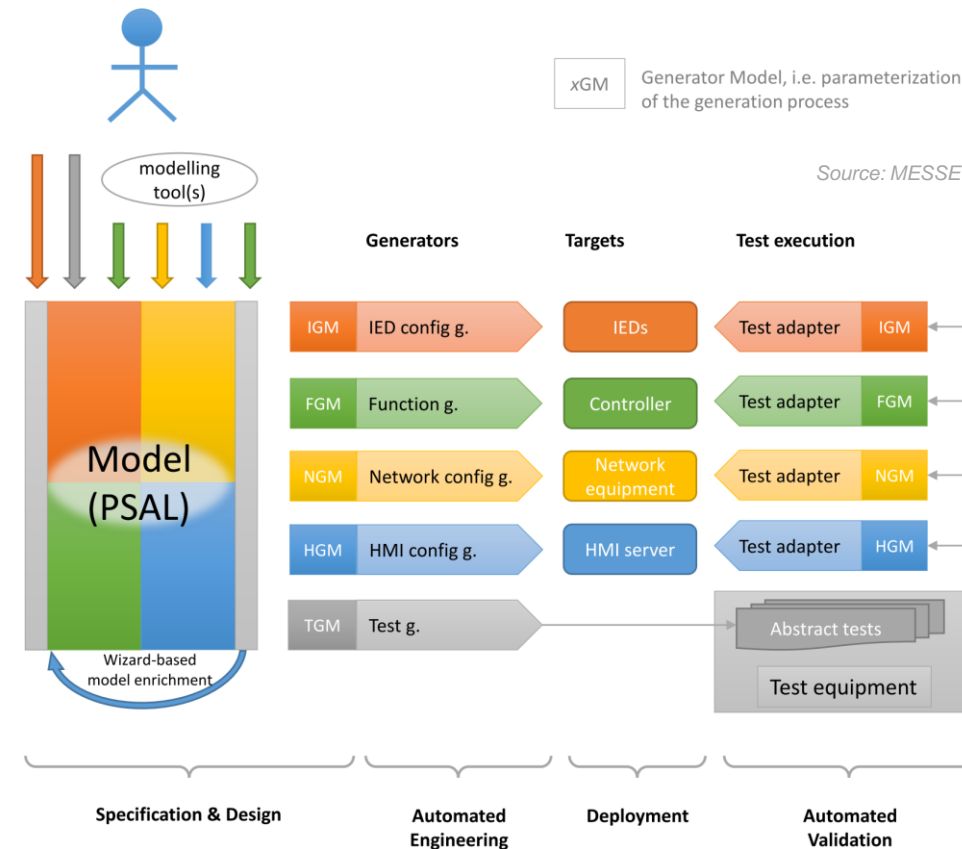
- ERIGrid holistic testing approach for smart grid systems
 - Example: cyber-security analysis
 - Laboratory setup



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

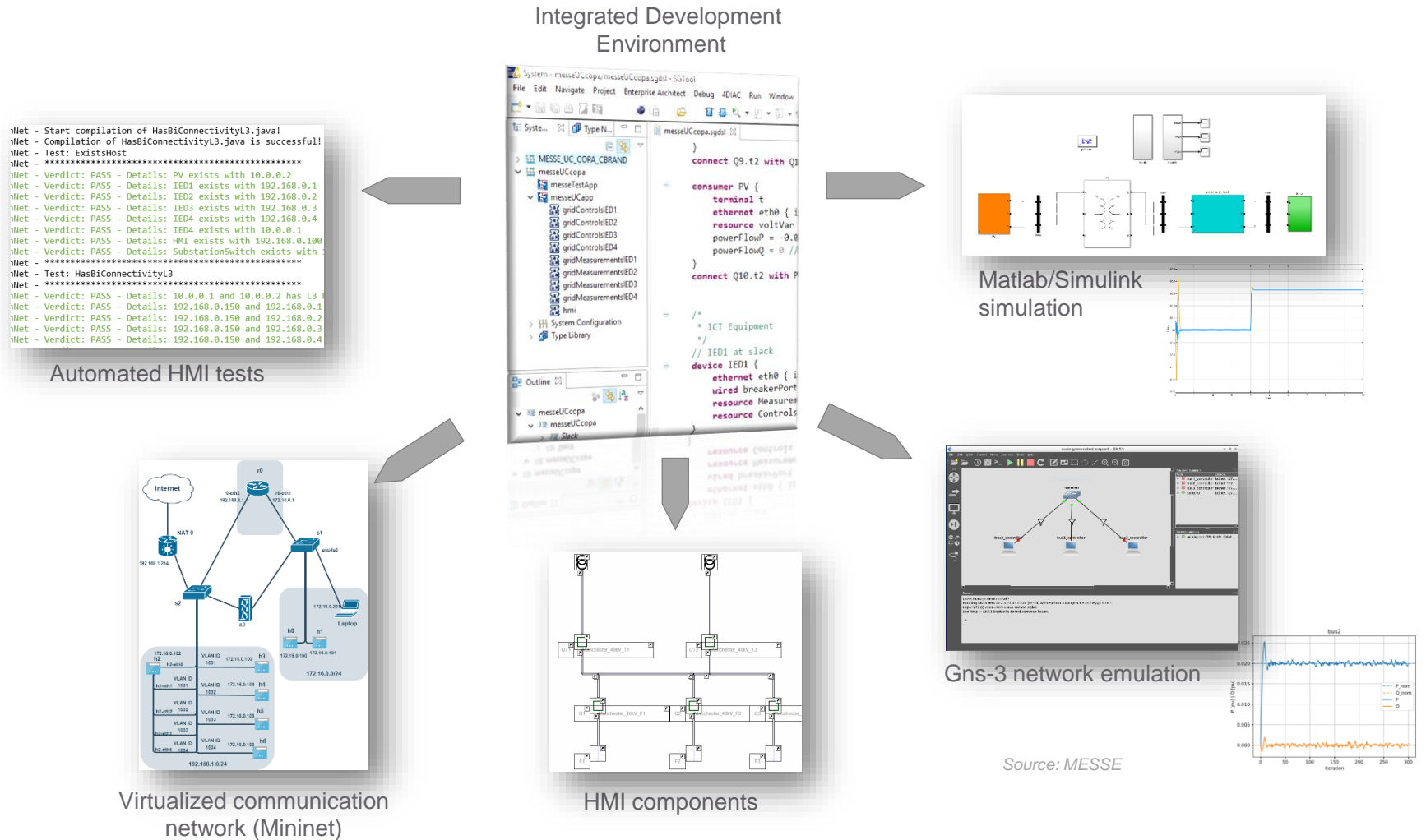
- MESSE holistic engineering, validation, and deployment support system
 - Automation of the engineering and validation process
 - Usage of MDE
 - Covers different domains (power, ICT, HMI)
 - Generation support for
 - Code (PLC, SCADA)
 - Testing scenarios



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

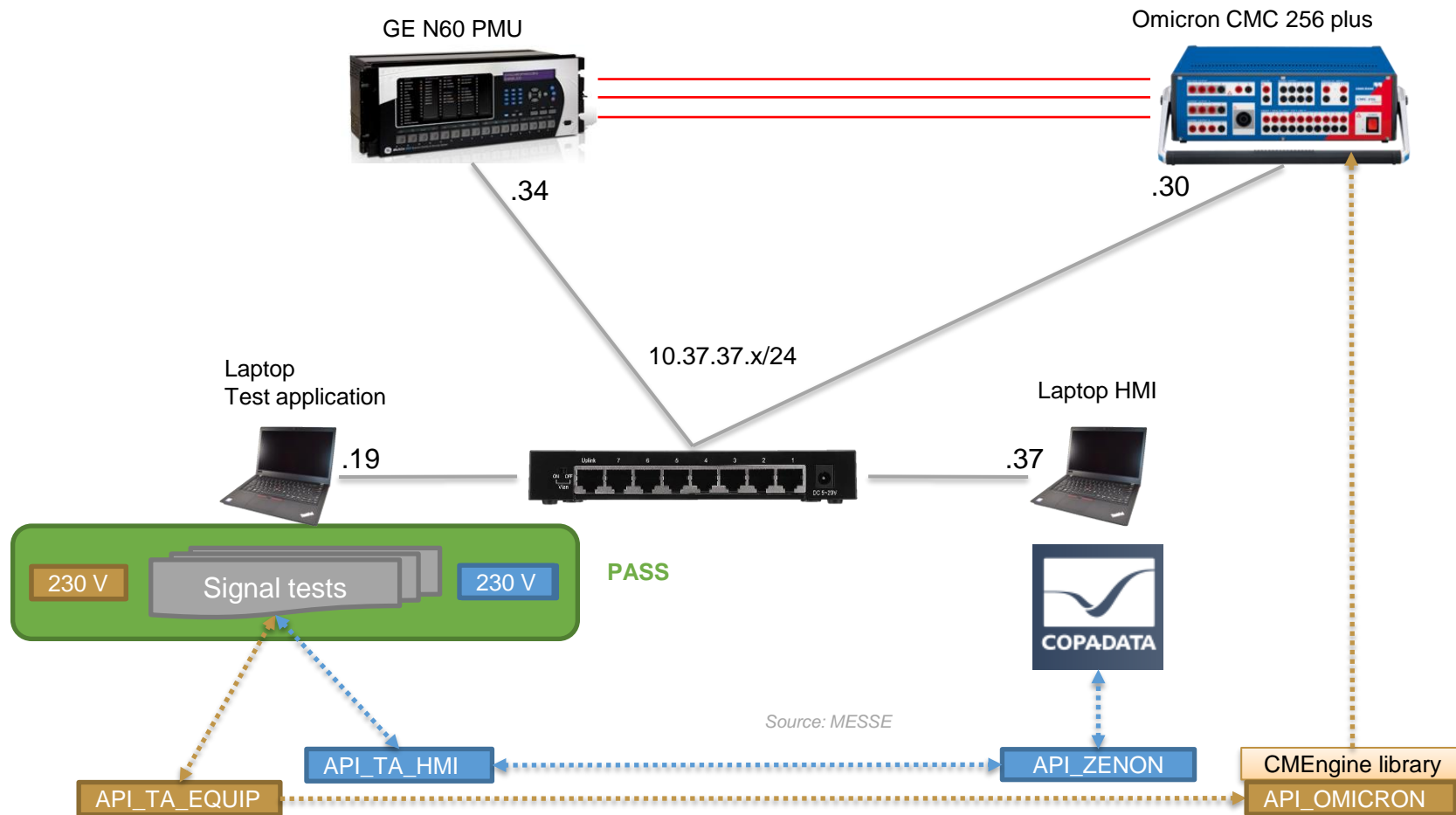
- MESSE integrated engineering, validation, and deployment support system



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- MESSE integrated engineering, validation, and deployment support system



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- MESSE integrated engineering, validation, and deployment support system

Test setup in reality

1. Abstract Test triggered by Java test application, triggers Omicron Test Adapter
2. Omicron Test Adapter (using Test Engine) sets Voltage level on CMC-Outputs
3. Omicron CMC provides Voltage on GE N60
4. GE N60 sends values via IEC 61850 to zenon HMI
5. zenon API provides voltage values – read by Test Adapter of Java test application for comparison

CONCLUSIONS AND OUTLOOK

- Formalized processes and approaches for smart grid systems development necessary
- Integrated analysis of power and ICT needed
- Methods for system-level testing required
- Integrated analysis of power and ICT needed
- Several solutions available but several points still partly solved
 - Harmonization of existing approaches
 - Large-scale examples and scenarios
 - Integration with traditional engineering approaches
 - Introducing new abstractions and modelling options

phase approach	design					proof	impl.	rapid prot.
	function	inform.	comm.	comp.	inconst.	function	function	
UML	☹️	✘	✘	✘	✘	✘	👎	✘
SysML	☹️	👎	✘	✘	✘	✘	👎	✘
IntelliGrid	👎	✘	✘	✘	✘	✘	✘	✘
SGAM-TB	☹️	✘	👎	👎	✘	✘	👎	👎
PSAL	☹️	☹️	✓	✓	✘	✓	✓	☹️
MATLAB	☹️	👎	✘	👎	✘	✓	✓	☹️
IEC 61499	☹️	👎	✓	✓	✘	✓	✓	✘
IEC 61131-3	☹️	👎	✓	👎	✘	✓	✓	✘
EMSOnto	☹️	✓	✘	✘	✓	✓	✓	✓

Source: Zanabria (AIT)

CONCLUSIONS AND OUTLOOK

FREE PHYSICAL AND VIRTUAL LAB ACCESS

The ERIGrid 2.0 project invites all interested engineers in the domains of power system testing, smart grids and smart energy to receive free funding to access the best laboratories and services of Europe for their own experimental research. Physical lab access can be organised either on-site or remotely. Furthermore, ERIGrid 2.0 provides virtual access to 8 facilities and services without applications required.

USERS WILL RECEIVE:

- on-site or remote access to 21 first-class laboratories or application-free virtual access to 8 services of ERIGrid partners
- in case of physical access: funding for their complete research stay at the location of the selected laboratory, including coverage of expenses for travelling, accommodation and lab operation costs
- access to concentrated know-how and best practices in the field of smart grids and energy systems components characterisation and evaluation, smart grid ICT / automation validation, co-simulation, real-time simulation and Power/Controller Hardware-in-the-Loop (HIL), and others
- opportunity to advance their own research and solutions
- working with the top smart grid and energy systems experts
- chance to impact EU industry
- promotion of their research through ERIGrid 2.0 channels

Find detailed descriptions of labs and services and all further details at erigrid2.eu/lab-access.

apply every 3 months for physical lab access

access virtual services anytime no application required

CONNECTING EUROPEAN SMART GRID RESEARCH INFRASTRUCTURES

FREE ACCESS TO EUROPE'S BEST SMART GRID AND ENERGY SYSTEMS LABS

@ERIGrid 2.0 Project

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ACKNOWLEDGEMENTS

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- MESSE Consortium (FFG No. 861265)

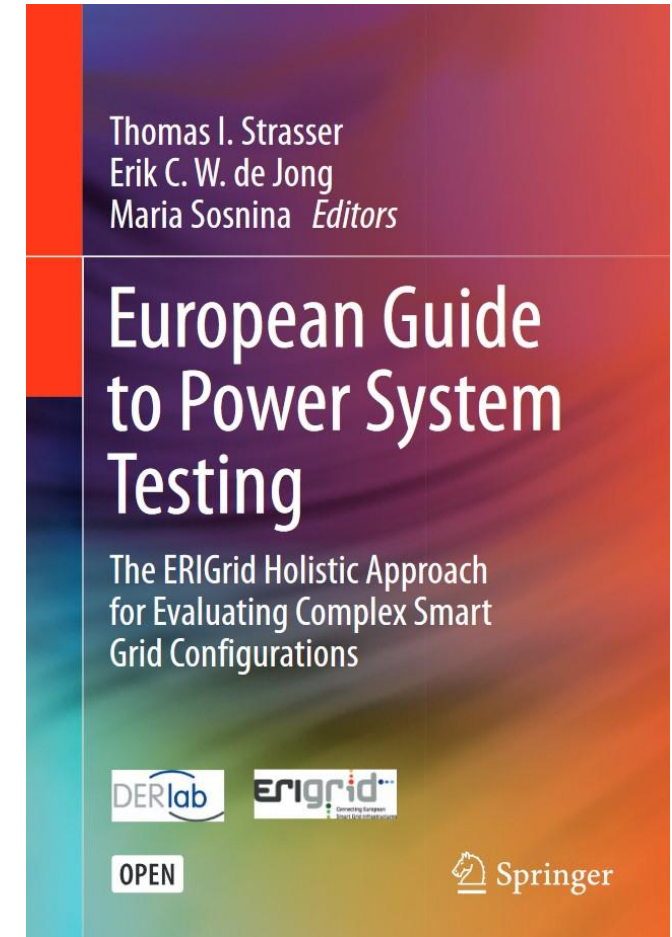


- ERIGrid/ERIGrid 2.0 Consortia (H2020 GA 654113 and 870620)



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