NATIONAL RENEWABLE ENERGY LABORATORY

NREL is a national laboratory of the U. S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

An Integrated Approach to Design and Analysis of Intelligent Future Energy Systems

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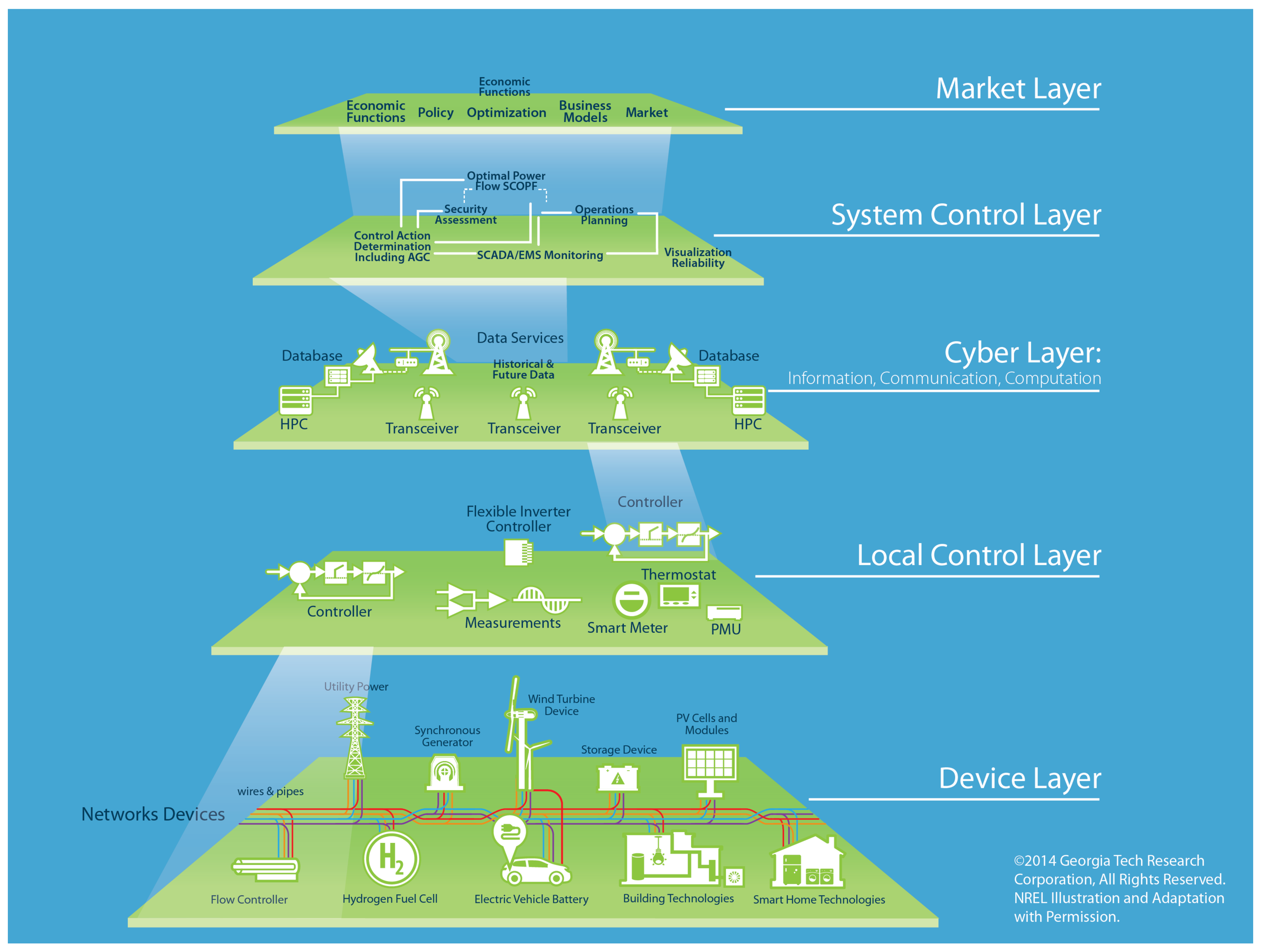
2014 NSF Young Professional Workshop on Exploring New Frontiers in Cyber-Physical Systems

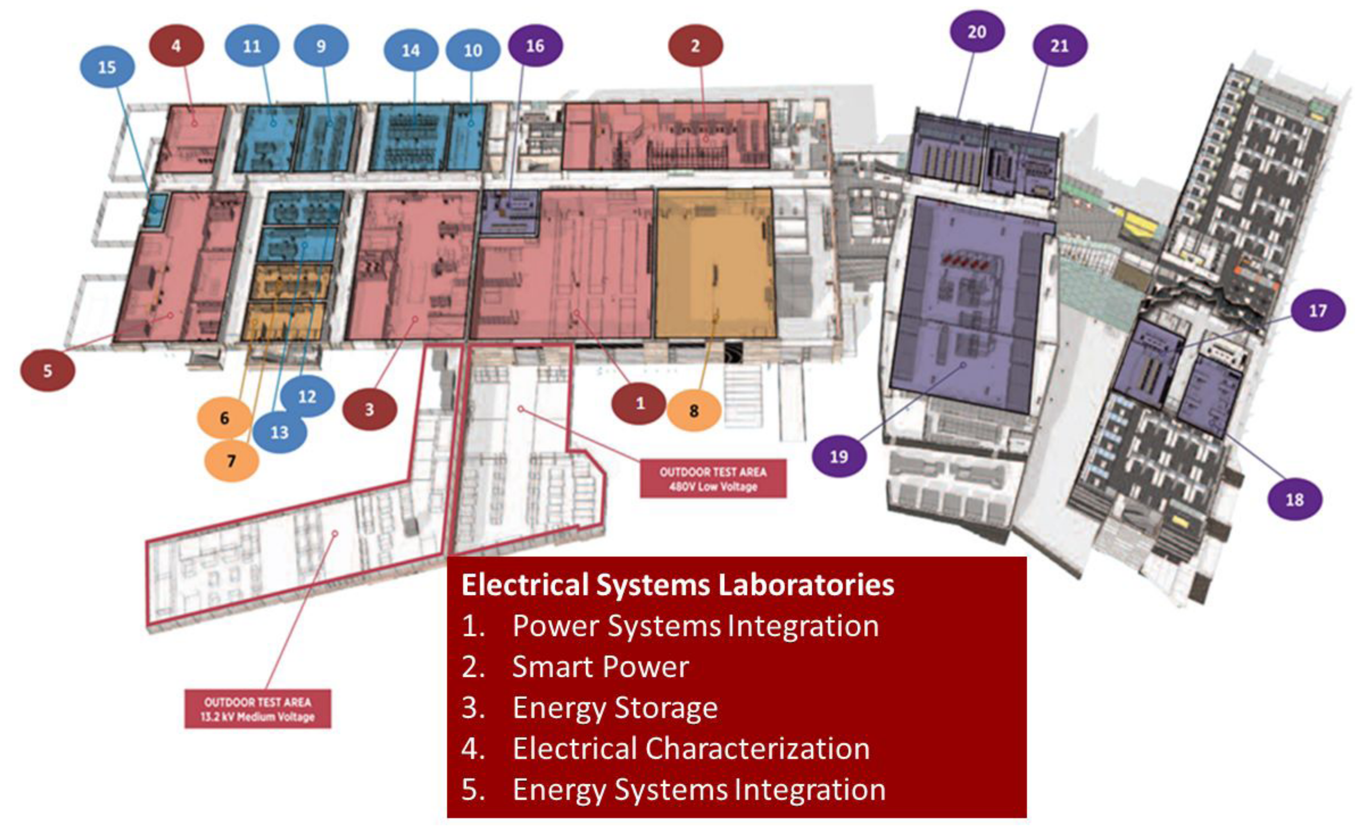


I. The Future Energy Infrastructure

- *The energy industry is currently undergoing a fundamental transformation in the way energy is generated, delivered, and consumed. Energy infrastructures constitute phenomena across large and small geographic regions - from transmission networks which stretch across continents to individual loads.*
- *Given the unprecedented scale and complexity of the challenges in cyber-physical energy systems, we anticipate that these problems cannot be addressed by ad-hoc industry developments.*
- *In contrast to conventional approaches which tend to focus exclusively on modeling, a theory-to-demonstration approach is advocated which recognizes the pivotal importance of cyber-physical test-beds in accelerating industry adoption.*
- *A coordinated and integrated investigation is needed which takes into account interactions across relevant energy and cyber subsystems as shown above.*

II. NREL's Energy Systems Integration Facility (ESIF)

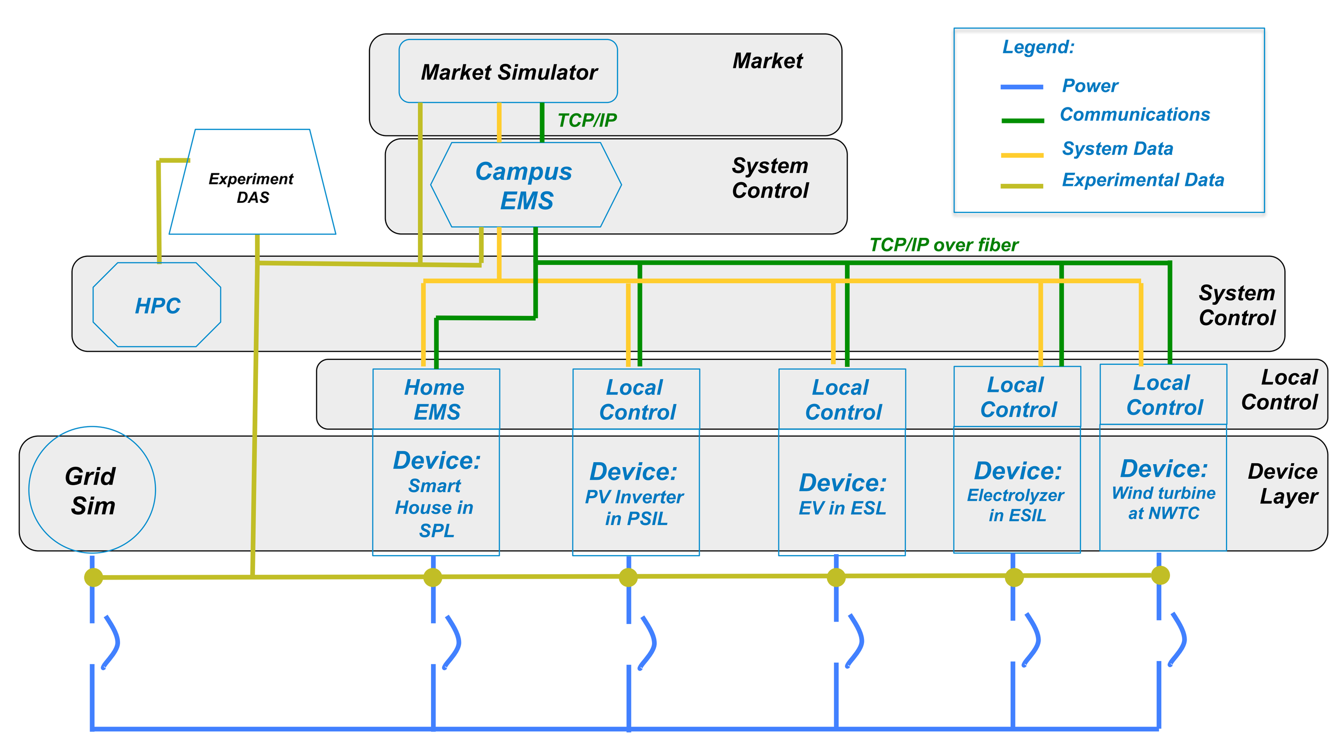
- *ESIF is a new state-of-the-art facility on the NREL campus which offers a suite of laboratories focused on power electronics, EVs, battery storage, fuel-cells, power systems, high-performance computing, and smart-grid research.*
- *To leverage the unique capabilities of each laboratory within ESIF, a research electrical distribution bus allows for multiple labs to be interconnected in complex cyber-physical experiments.*



III. Power System Laboratories

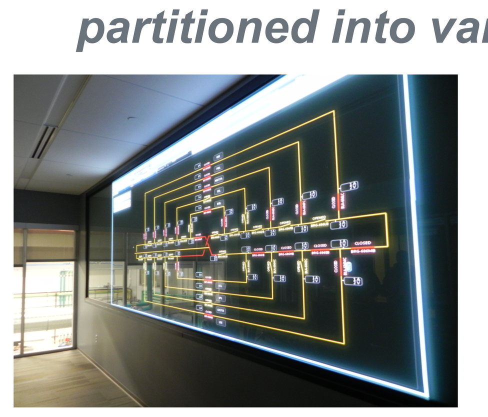
The multiple electric power and smart-grid laboratories within ESIF are illustrated above and described below.

- *__Power Systems Integration Lab__: Emphasis is on distributed energy resources such as PV, wind, and diesel/gas generators and hardware-in-the-loop for microgrids and grid-connected systems.*
- *__Smart Power Lab__: Research focus is on communication networks with applications to grid metering, data acquisition, and systems control development.*
- *__Energy Storage Lab__: Development of energy storage devices. Emphasis on EV batteries and ultracapacitors.*

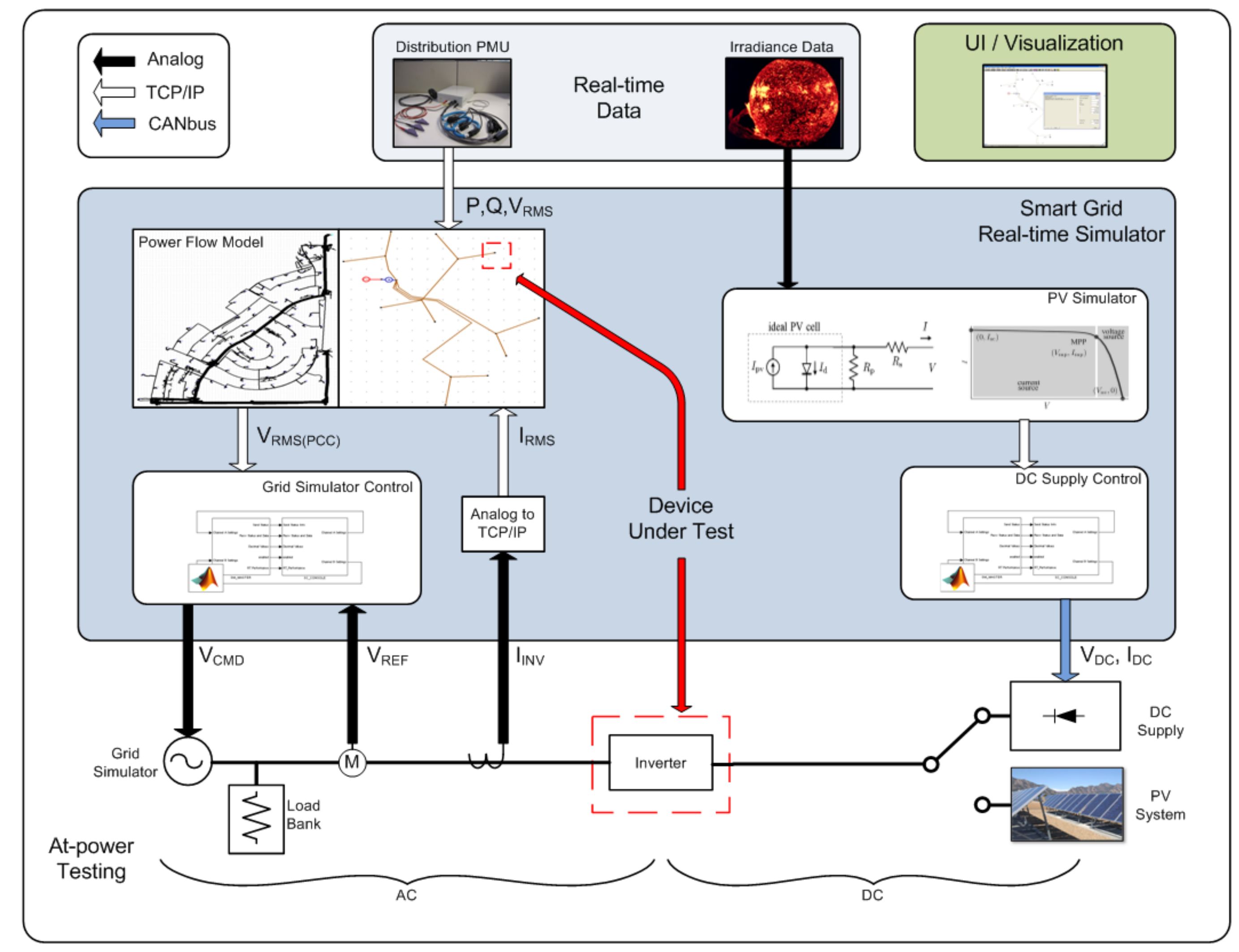


IV. Cyber-Physical Testbeds

- *Combining expertise in computing, markets, power systems, and power electronics, staff at ESIF are developing residential-scale and campus-scale cyber-physical energy testbeds.*
- *To enhance modularity and scalability, systems will be partitioned into various cyber and physical subdomains.*



- *A SCADA-equipped control room will be used to coordinate experiments which are interconnected throughout the laboratory.*
- *Residential-scale and utility-scale PV inverters and PV simulators will be used to analyze system behavior and design advanced power electronic controls.*



V. Physical Hardware and Co-Simulation of System Behavior

- *To analyze system-level phenomena and experimental hardware in a unified environment, hardware-in-the-loop technologies will be used to perform real-time system-level emulation.*
- *In such a setting, the real-time emulator will control a full-power 3-phase grid simulator which is connected to a laboratory experiment.*
- *As a result, power system hardware will interact in real-time with a large-scale network model in a single laboratory setting.*

VI. Concluding Statements

- *To develop the technologies necessary for emerging energy infrastructures, advancements within the fields of computer science, informatics, complex networks, power systems, economics, dynamics, controls, and power electronics will need to be unified.*
- *Given the scope of the challenges which lie ahead, a coordinated effort across industry, government, and academia will be needed.*
- *The intelligent future energy systems testbed at NREL will be a national asset to facilitate these collaborations and to reach the goal of developing a sustainable, reliable, and cost-effective energy infrastructure.*

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