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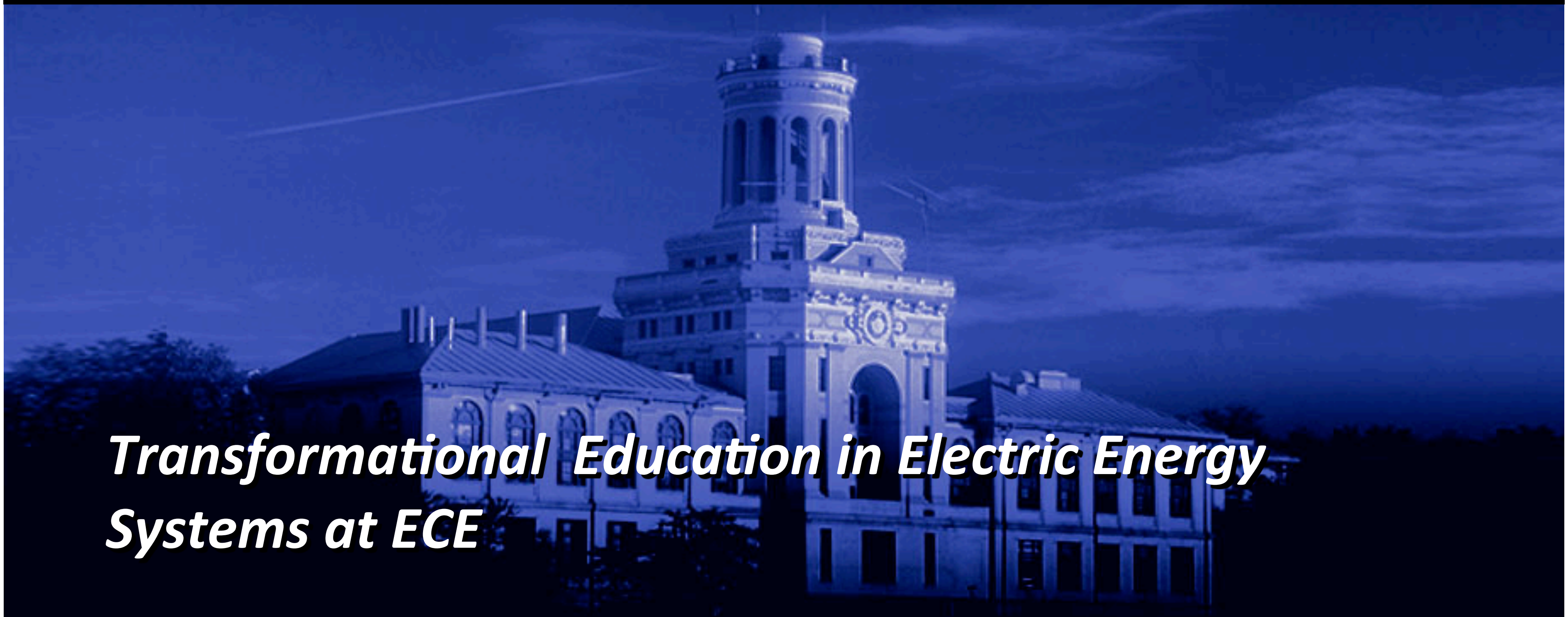

Transformational Education in Electric Energy Systems at ECE

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September 23, 2014

18-200 presentation

09/23/2014 CMU

Carnegie Mellon

Electric Energy Systems Group (EESG)

http://www.eesg.ece.cmu.edu

- ***A multi-disciplinary group of researchers from across Carnegie Mellon with common interest in electric energy.***
- ***Truly integrated education and research***
- ***Interests range across technical, policy, sensing, communications, computing and much more; emphasis on systems aspects of the changing industry, model-based simulations and decision making/control for predictable performance.***
- ***Past home of the SRC Smart Grid Research Ctr***
- ***Home of Smart Grid in a Room Simulator***

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EESG group circa 2012 –home of ECE Energy Systems Research

Noha Abdel-Karim Sanja Cvijic Prof. Franchetti Prof. Ganger Prof. Gabriela Hug Andrew Hsu Prof. Marija Ilic Jhi-Young Joo Soummy Kar

Prof. Bruce Krogh Prof. Lester Lave Qixing Liu Brandon Mauch Prof. Jose' Moura Masoud Nazari Prof. Rohit Negi Luca Parolini Nipun Popli

Marija Prica Prof. Dan Siewiorek Prof. Bruno Sinopoli Nermeen Talaat Prof. Ozan Tonguz Le Xie Rui Yang Yi Zhang Dinghuan Zhu

NOT PICTURED: Milos Cvetkovic, Jovan Ilic

Undergraduate sequence

- ***Courses that are currently being taught are:***
- ***Fall:***
  18-372 Fundamentals in Electric Power Systems
  18-473 Computational Methods for Smart Grids
  18-587 Electrical Energy Conversion, Control and Management (capstone course)
  18-618 Smart Grids and Future Electric Energy Systems
- ***Spring:***
  18-418 Electric Energy Processing: Fundamentals and Applications

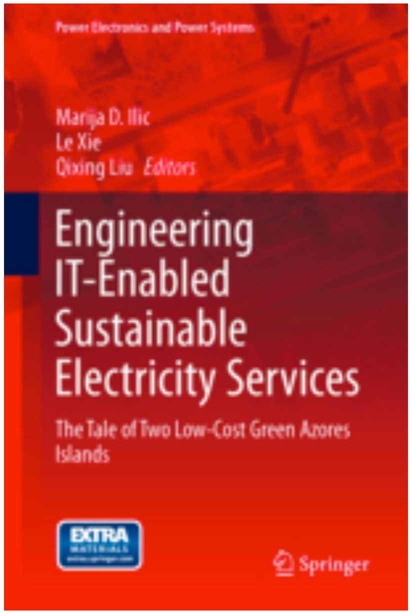
Graduate course sequence

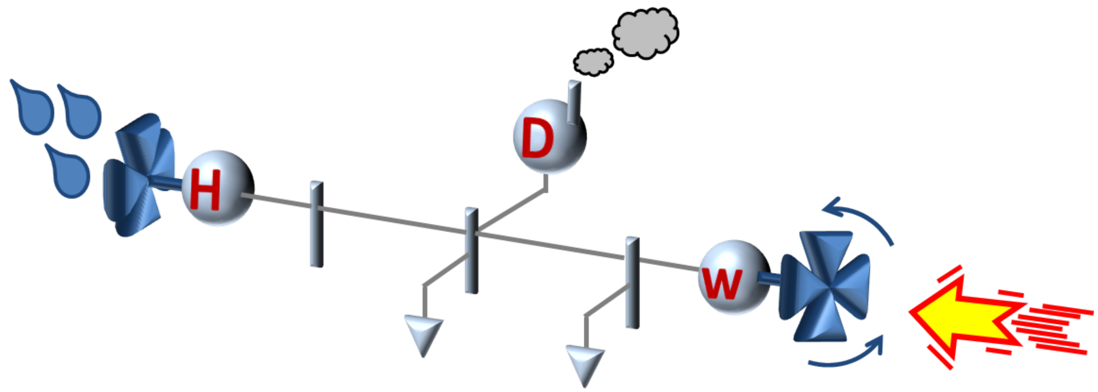
- ***Fall:***
  18-618 Smart Grids and Future Electric Energy Systems
  18-882 Power Electronics for Electric Power Systems
- ***18-875 Engineering and Economics for Electric Energy Systems***
- ***Spring:***
  18-879M Optimization in Electric Energy Systems
  18-777 Large Scale Dynamic Systems
  18-819B Introduction to Solar Arrays: Modeling, Analysis, and Design

Challenges you could tackle in your career

- Being on a beautiful Azores Island with a dirty diesel plant polluting it.. Someone asks you to use ECE knowledge to replace the plant with wind power/solar/geothermal and still make sure people have electricity.
- Being part of a deep space manned Mars exploration by NASA and someone asking you to make sure power supply doesn't fail (Gravity movie)
- Being a large ship in the middle of the sea (for fun or defending your country)
- Being part of a design of modern cars..
- Being a pilot on Boeing's dream-liner and making sure no power failures.
- Being in a small village in Africa or India and designing small micro-grids..
- Working in power companies which serve cleaner and cheaper power without unintended power interruption.
- Working for NIST to design standards for new equipment and software

Making islands sustainable…

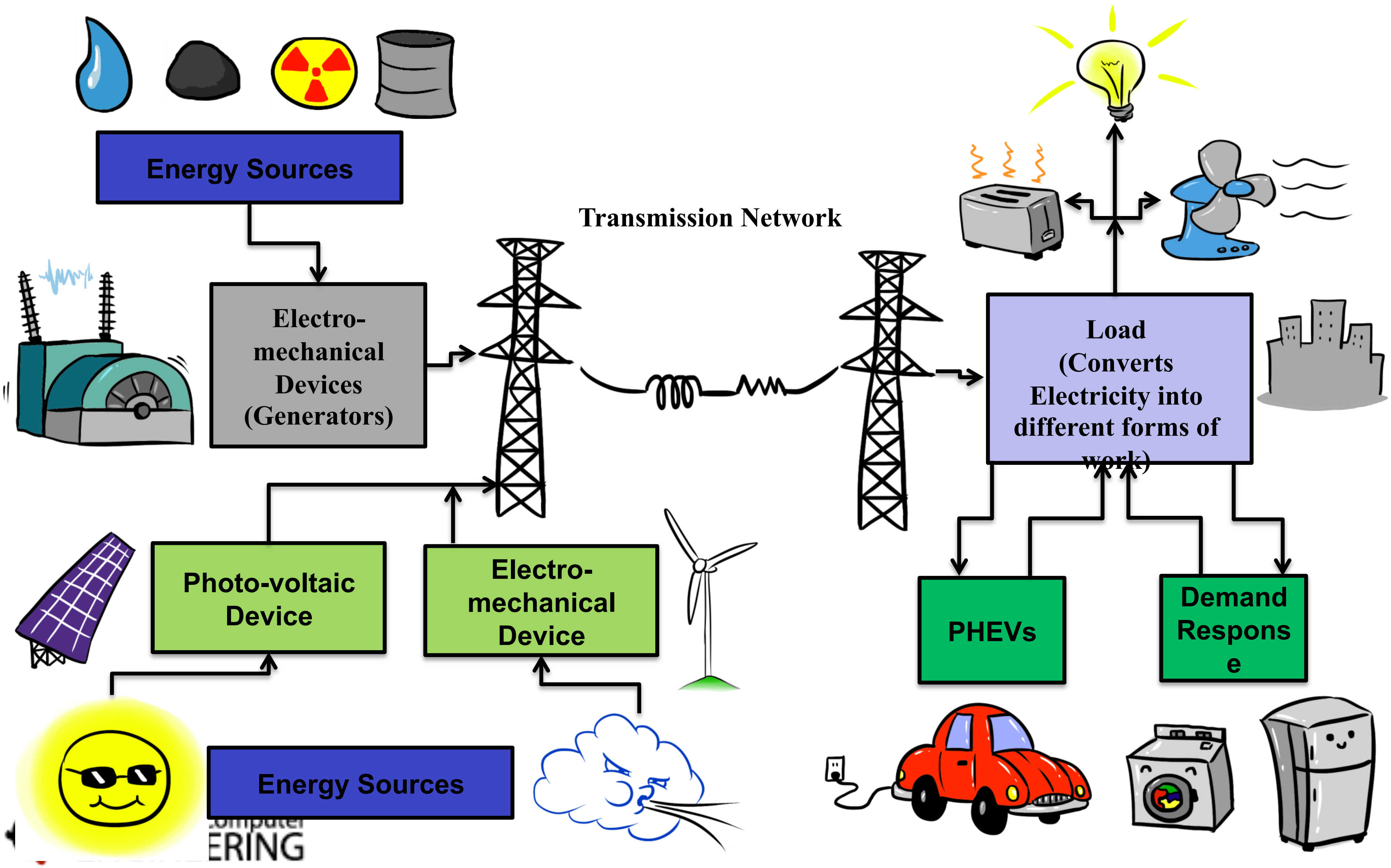




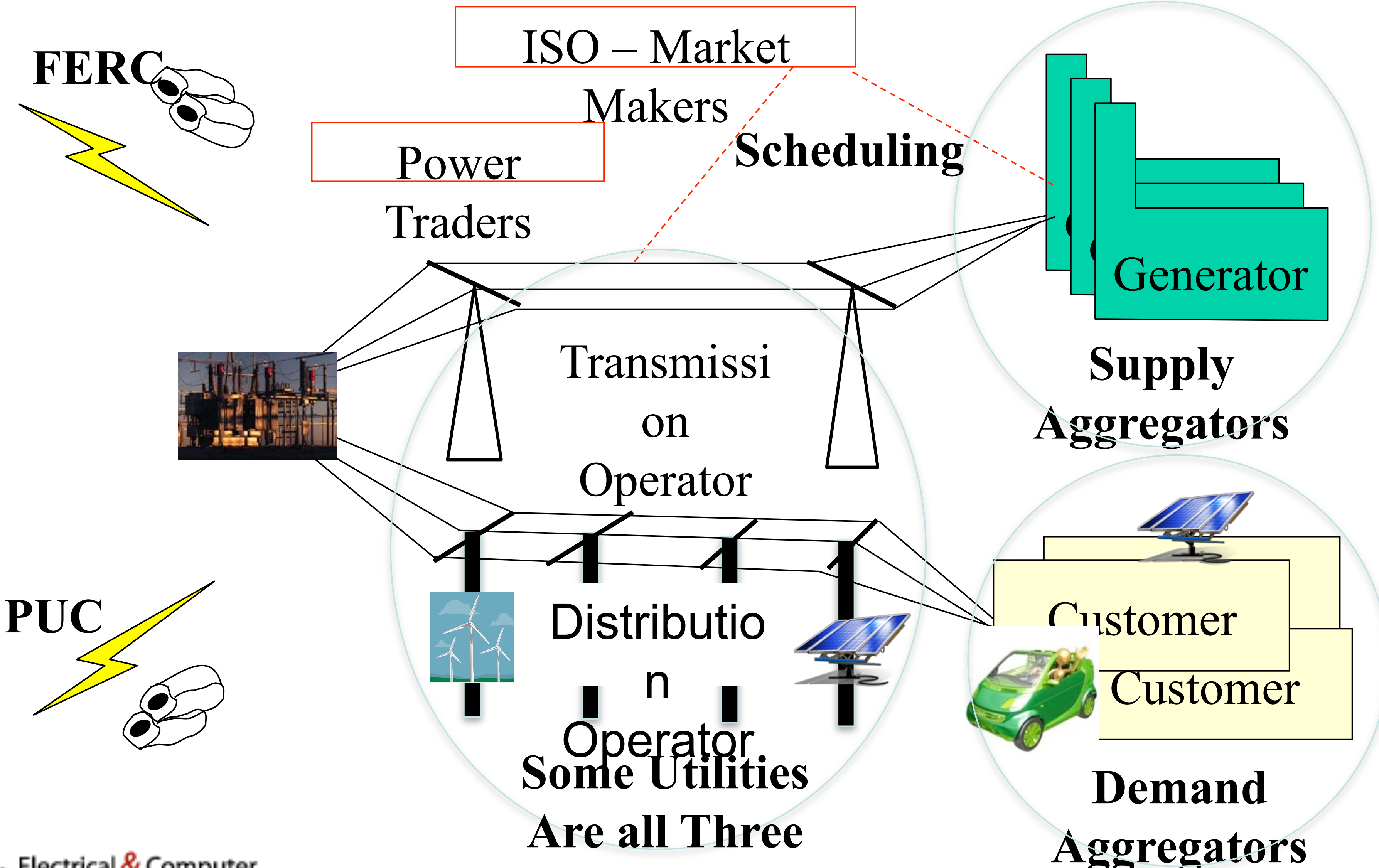
H – Hydro
D – Diesel
W – Wind

http://www.springer.com/energy/systems,+storage+and+harvesting/book/978-0-387-09735-0

Fundamental challenges in the new industry (hardware unbundling—AC to AC/DC, DC/DC)



Fundamental challenges in the new industry (organizational unbundling)



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Bulk power grids of today.

Transformational changes in energy systems

- ***Rethink how to plan, rebuild and operate an infrastructure which has been turned upside-down from what it used to be***
- ***Leaders must understand***
  - *3ϕ physics (the basic foundations)*
  - *Modeling of complex systems (architecture-dependent models, components and their interactions, performance objectives)*
  - *Dependence of models on sensors and actuators; design for desired system performance (defined by economic policy and engineering specifications)*
  - *Numerical methods and algorithms; embedded software*
  - *The key role and value of IT*

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Objectives for modern electric energy systems programs

- ***Not only a novel education, but multi-disciplinary coverage across ECE and beyond***
- ***Provide conceptual problem formulations (understand how models, sensing, control and communication are different for sample systems: 1) old centralized infrastructure; (2) deregulated industry; and, (3) industry with lots of distributed sensors, controllers, intermittent generation, demand-side.)***
- ***Introduce novel simulators/graphics/visualization to teach these concepts.***

An illustrative future electric grid

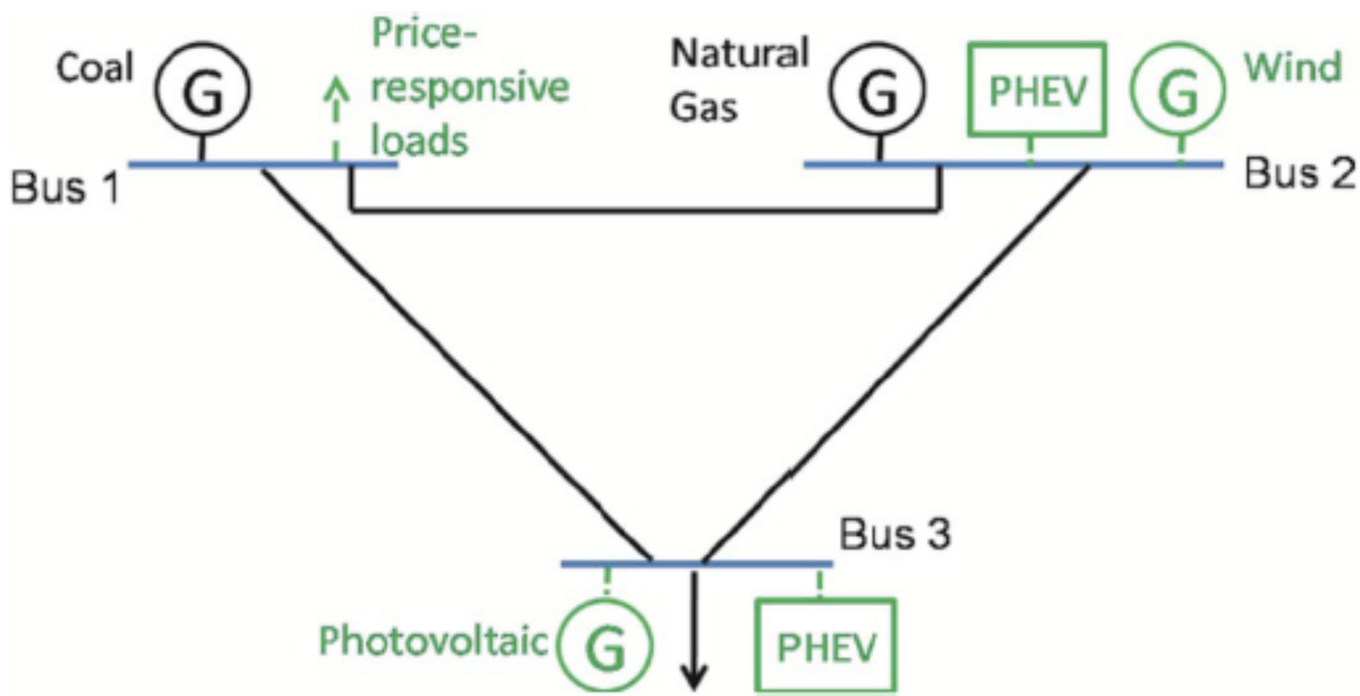

Fig. 5. Small example of the future electric energy system.

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Marija Ilic

ECE and EPP

irector, Electric Energy Systems Group

http://www.eesg.ece.cmu.edu

General area: Multi-layered Large-scale Dynamic Network Systems

- **Nonlinear dynamics, SP for transforming time-varying models to LTI models, designing controllers and observers.**
- **Nonlinear control design for stabilizing large-scale networks. Power electronics-based switching.**
- **Distributed sensing and control of stored energy in RLC networks**
- **Cyber-Physical Models for New Sensing and Control; Policy Design to Induce Just-in-Time and Just-in-Place Control**
- **Cyber-Physical Protocols**

Domain applications: FUTURE ENERGY SYSTEMS

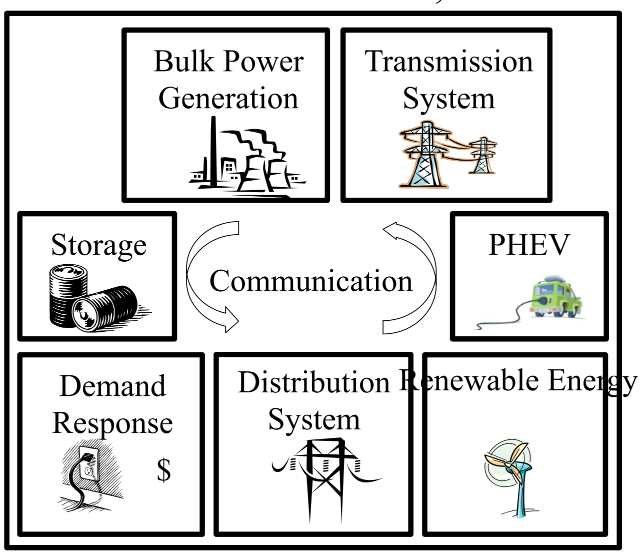
- **Energy Micro-grid: Control and Power Electronics**
- **Unified modeling and control of frequency and voltage dynamics in future electric energy systems**
- **Nonlinear FACTS and HV DC Light Control for Meshed Electric Power Grids**
- **Fast Flow Control in Nonlinear RLC Electric Networks**
- **Integration of Intermittent Energy Resources—Large Penetration of Wind**
- **Engineering Customer Choice**

Gabriela Hug

Control and Optimization in Electric Power Systems

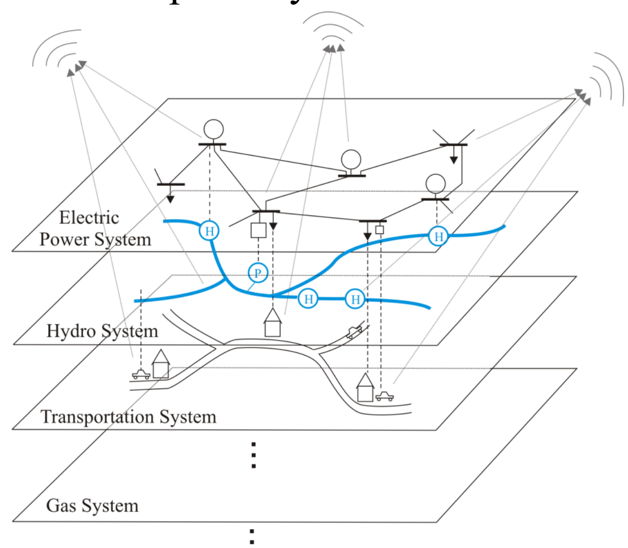
Future Electric Power Grid ("Smart Grid")

Electric power system is going through major transition: integration of renewable generation, from centralized to distributed generation and control, …



Predictive Control of Inter-coupled Systems

Goal: take advantage of available information and models to predict behaviour of the systems and optimally coordinate as a whole



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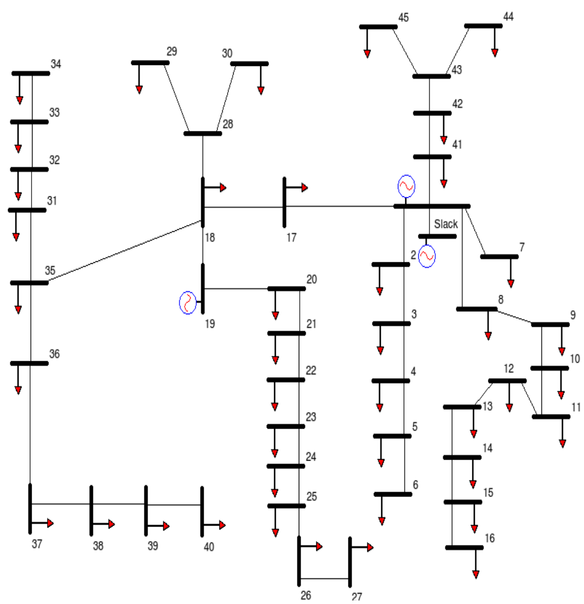
Jovan Ilic

Electric Power Systems Economics, FACTS, Energy Conversion

Electrical Power Systems Economics

Teaching a course on the interdependence between public



Power Electronics for Power System

Teaching course on steady state and dynamic analysis and optimization of FACTS use at the transmission level

Energy Conversion Principles

Teaching a course on energy conversion principles including electromagnetic field theory and control of dynamic systems.

Electrical Energy Conversion , Control and Management

Teaching a capstone course with a focus on energy management systems and energy conversion

Projects: Smart Grid in a Room, NIST sponsored project for exploring smart grid simulation and real life integration. Development of steady state software for teaching and research.

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18-882 Power Electronics for Power Systems

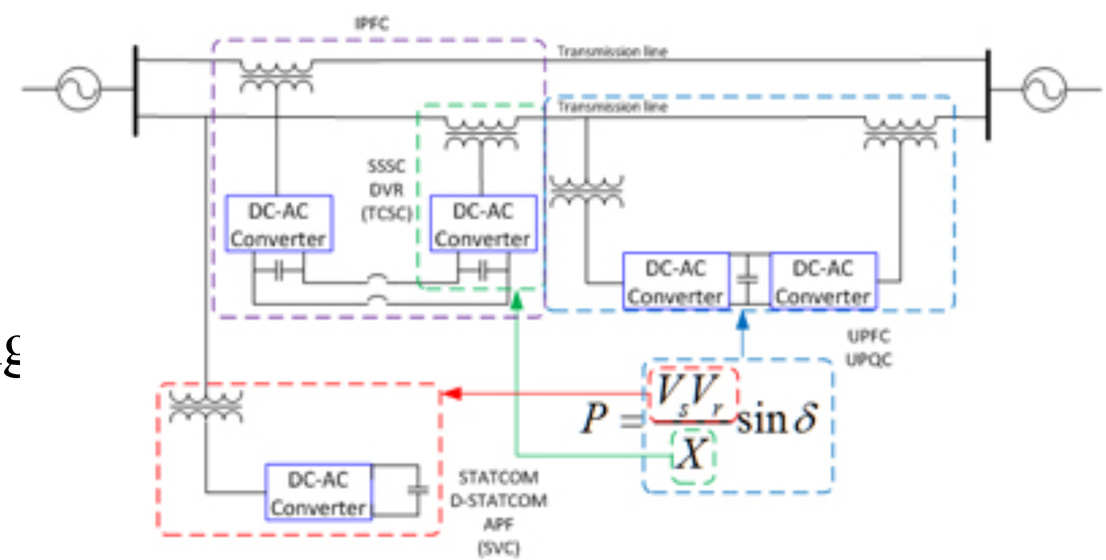
Route very high amounts of power like data packets in the Internet?

Disobey Kirchhoff's voltage and current laws? Almost but not quite!

Use high speed WAN communications to control power flow.

Multidisciplinary area:

- power systems
- power electronics
- communications
- digital signal processing
- control systems



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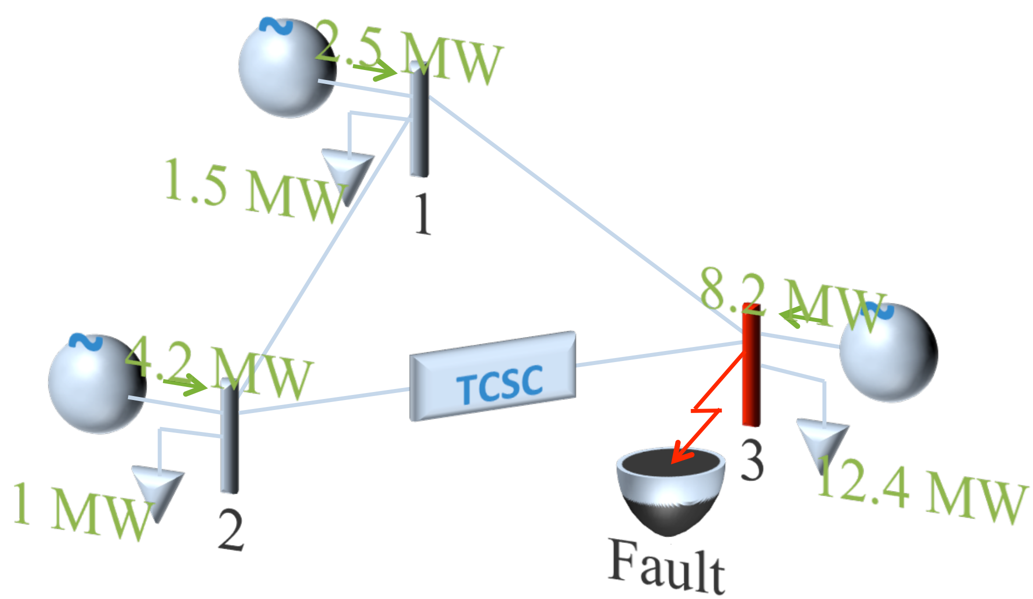
Nonlinear control for storage devices (FACTS,flywheels)

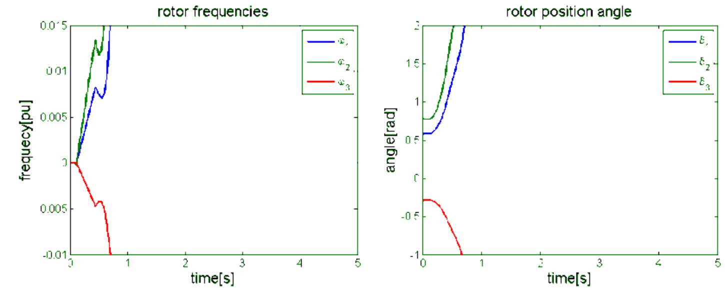


Fault:
- a short circuit at Bus 3
- created at $t = 0.1s$
- cleared at $t = 0.43s$

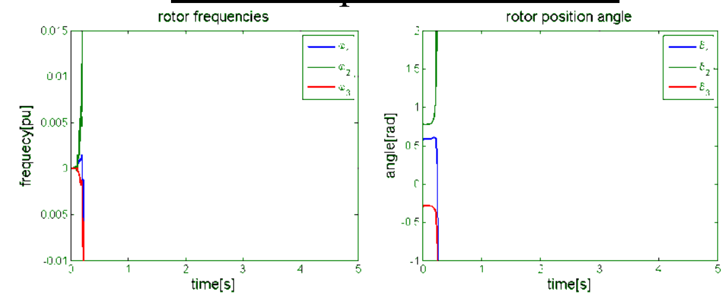
Critical clearing time:

$$T_{CCT} = 0.25s$$

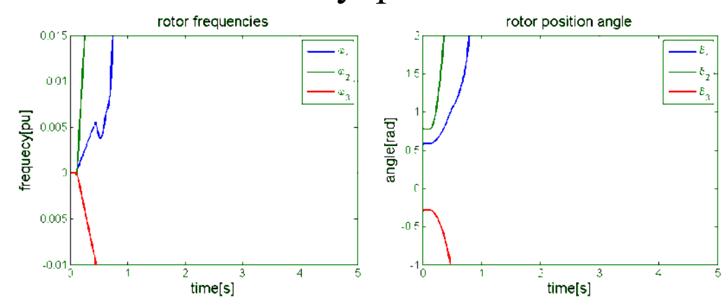
No controller on TCSC



Linear PI power controller[2]

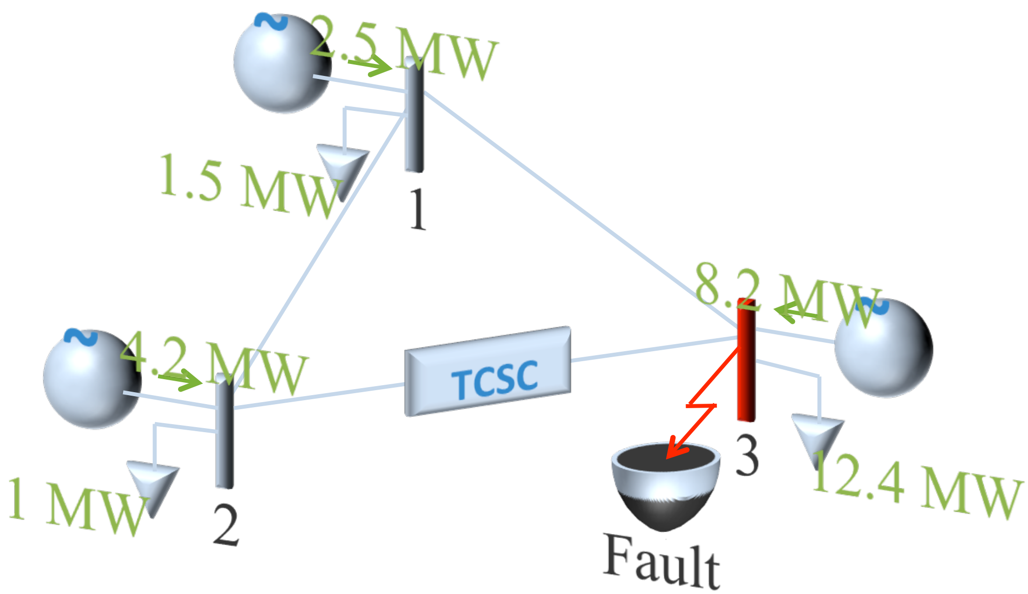


Nonlinear Lyapunov controller[3]

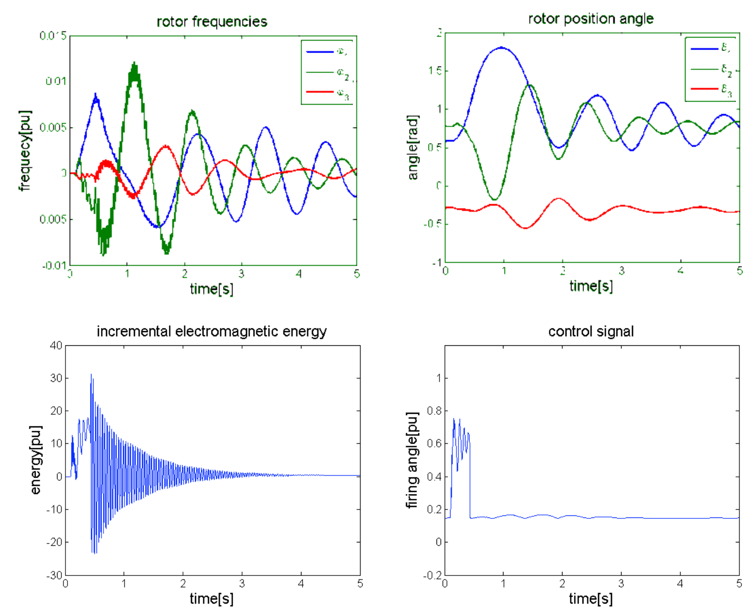


[1] The test system: L. W. Chapman, *"Power System Control for Large Disturbance Stability: Security, Robustness and Transient Energy"*, Ph.D. Thesis: Massachusetts Institute of Technology, 1996.
[2] Linear controller: L. Angquist, C. Gama, *"Damping Algorithm Based on Phasor Estimation"*, IEEE Power Engineering Society Winter Meeting, 2001
[3] Nonlinear controller: M. Ghandhari, G. Andersson, I. Hiskens, *"Control Lyapunov Function for Controllable Series Devices"*, IEEE Transactions on Power Systems, 2001, vol. 16, no. 4, pp. 689-694

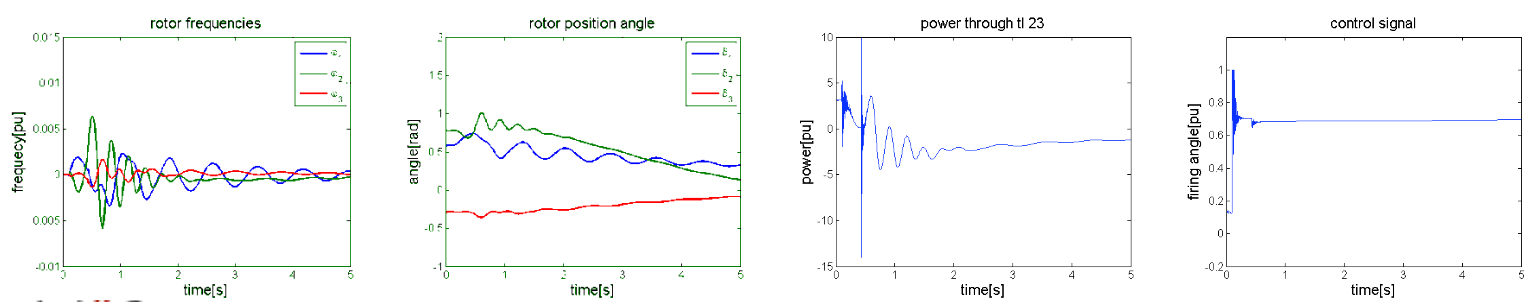
Use of interaction variables in strongly coupled systems



Interaction variable choice 1:



Interaction variable choice 2:



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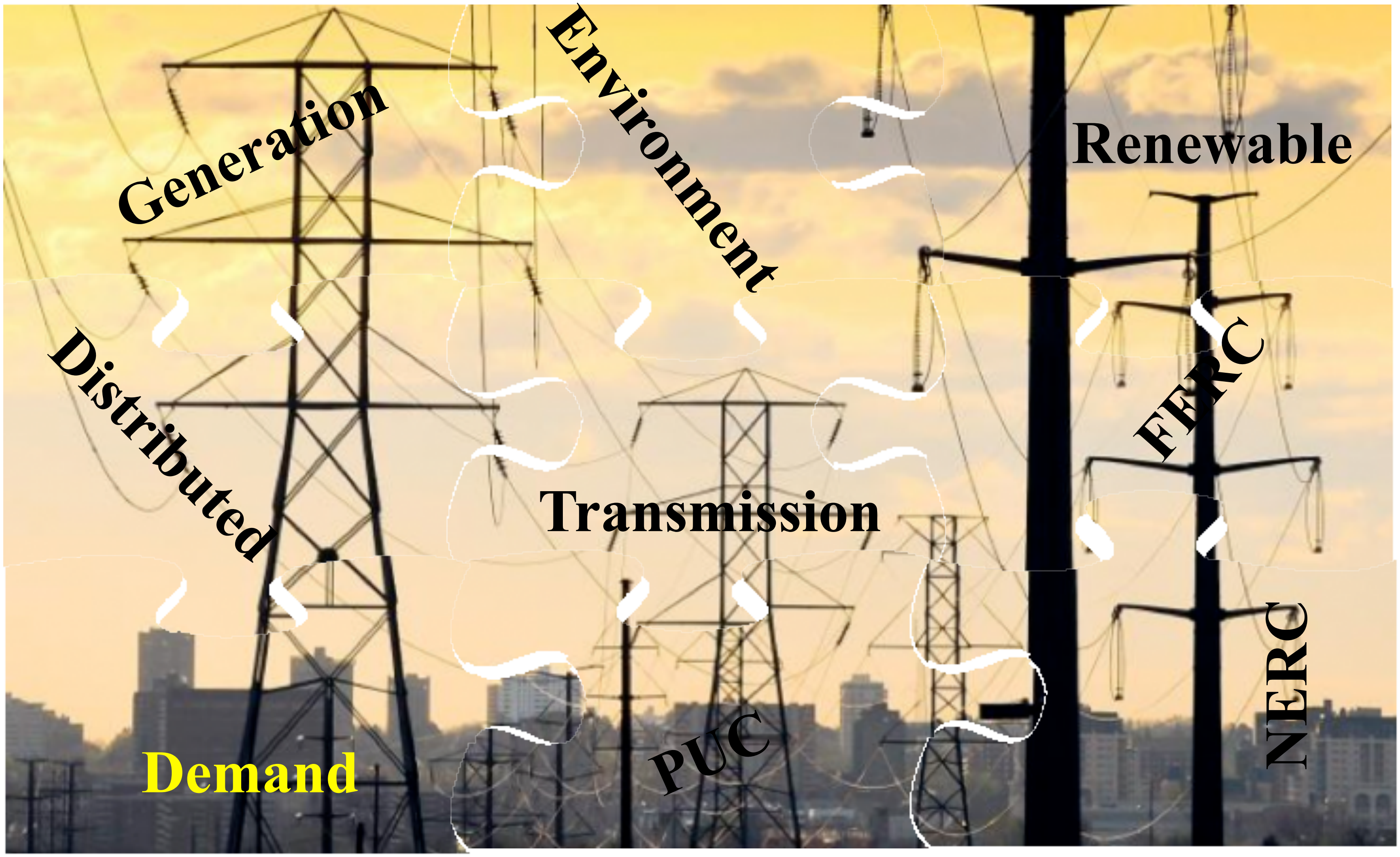
18-875 Power Systems Economics



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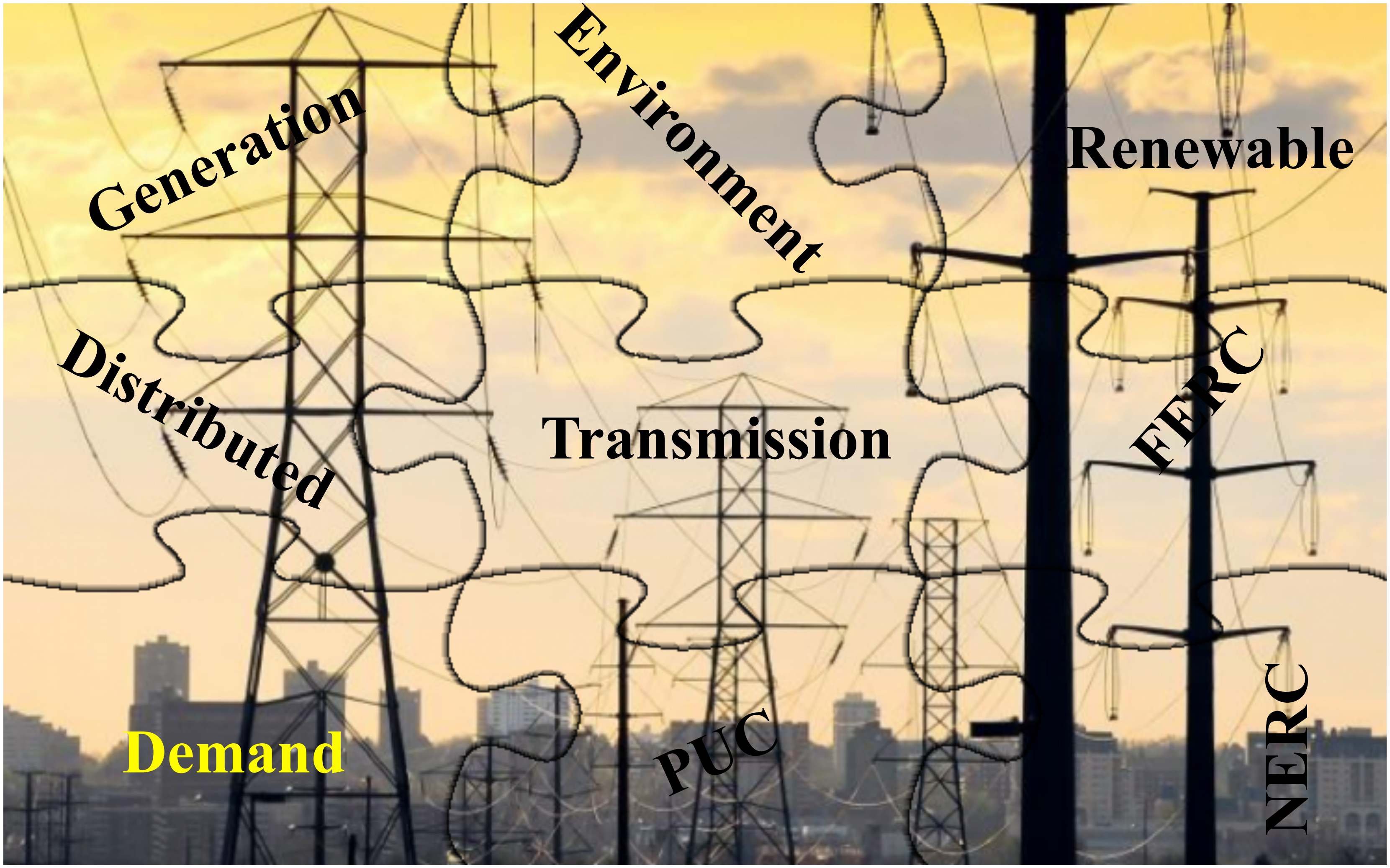
How Do We Get From There to Here



With Lots of Smarts and Hard Work

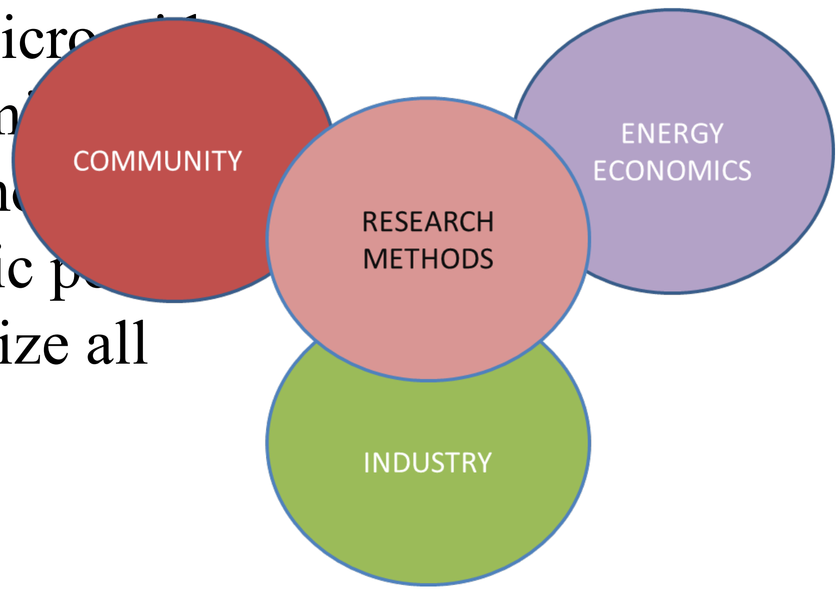
How do we incent everybody to participate?

Everybody should benefit from the new industry model.

The entire system must be fair to all participants.

Extremely complex multidisciplinary problem addressing:

- Advanced electrical power systems
- Renewable energy and environmental issues
- Smart grids and micro
- Microeconom
- Behavioral econ
- Engineering public p
- Globally optimize all



18-587 Electrical Energy Conversion, Control, and Management

Time to take the capstone? Congratulations, you are almost done with BS.

Need a helping hand
to join the future?

If you are interested in
solving some of the most
important problems we are
facing today, 18-587 is
for you.

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So, how do you make the transition to the real world?

By bringing your ideas to life in the familiar ECE environment.

Areas 18-587 covers

Nontechnical:

- project management
- protecting your intellectual property rights (IP)
- respecting others IP
- Ethics, IEEE code of conduct
- Engineering moral considerations

Technical (varies):

- energy management
- smart, NEST like, thermostats
- HVAC systems control
- energy consumption optimization and scheduling
- wind energy conversion control
- photovoltaic conversion control
- advanced communication support for the above tasks
- software optimization problems

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Future problem --sustainability

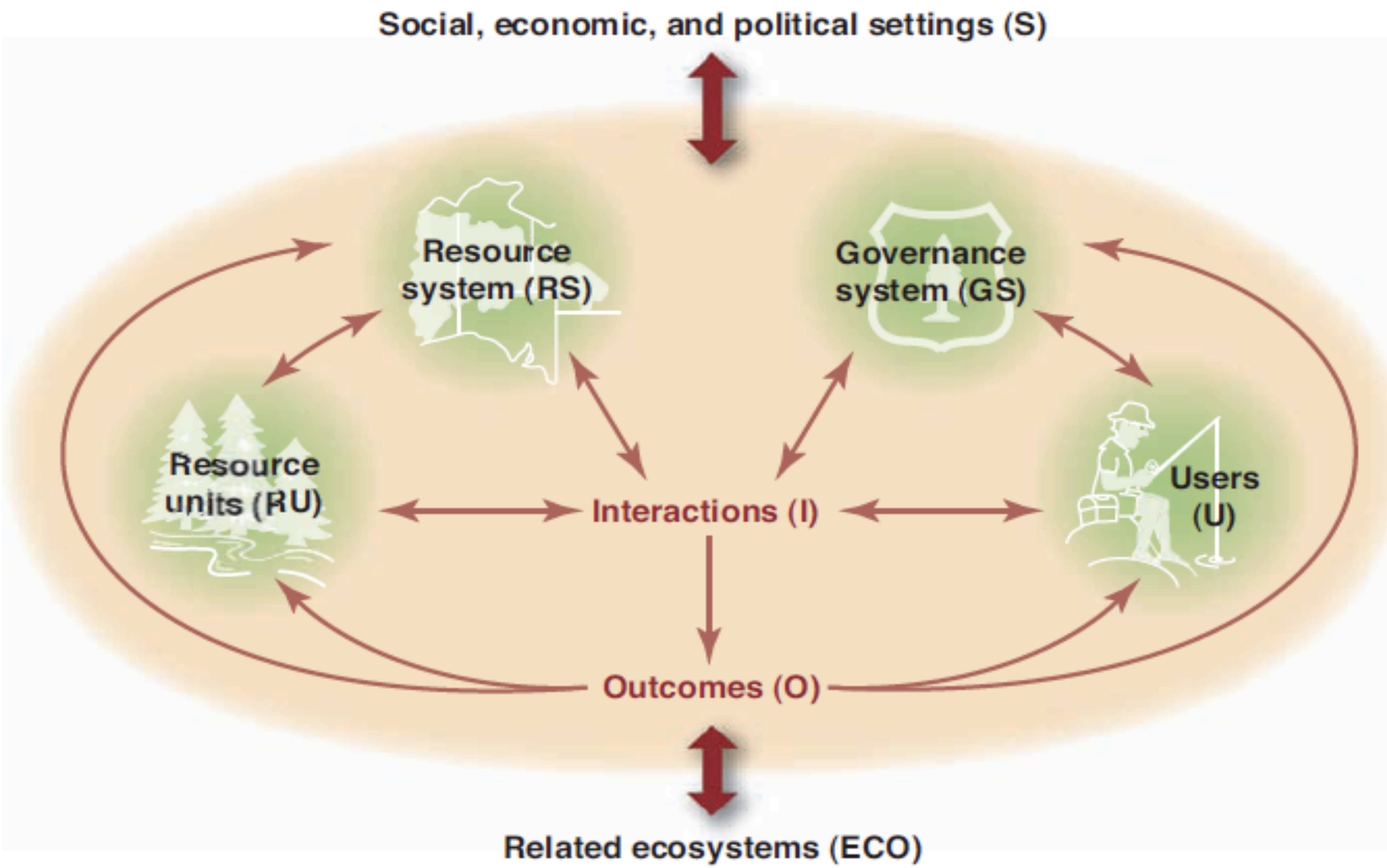

Fig. 1. The core subsystems in a framework for analyzing social-ecological systems.

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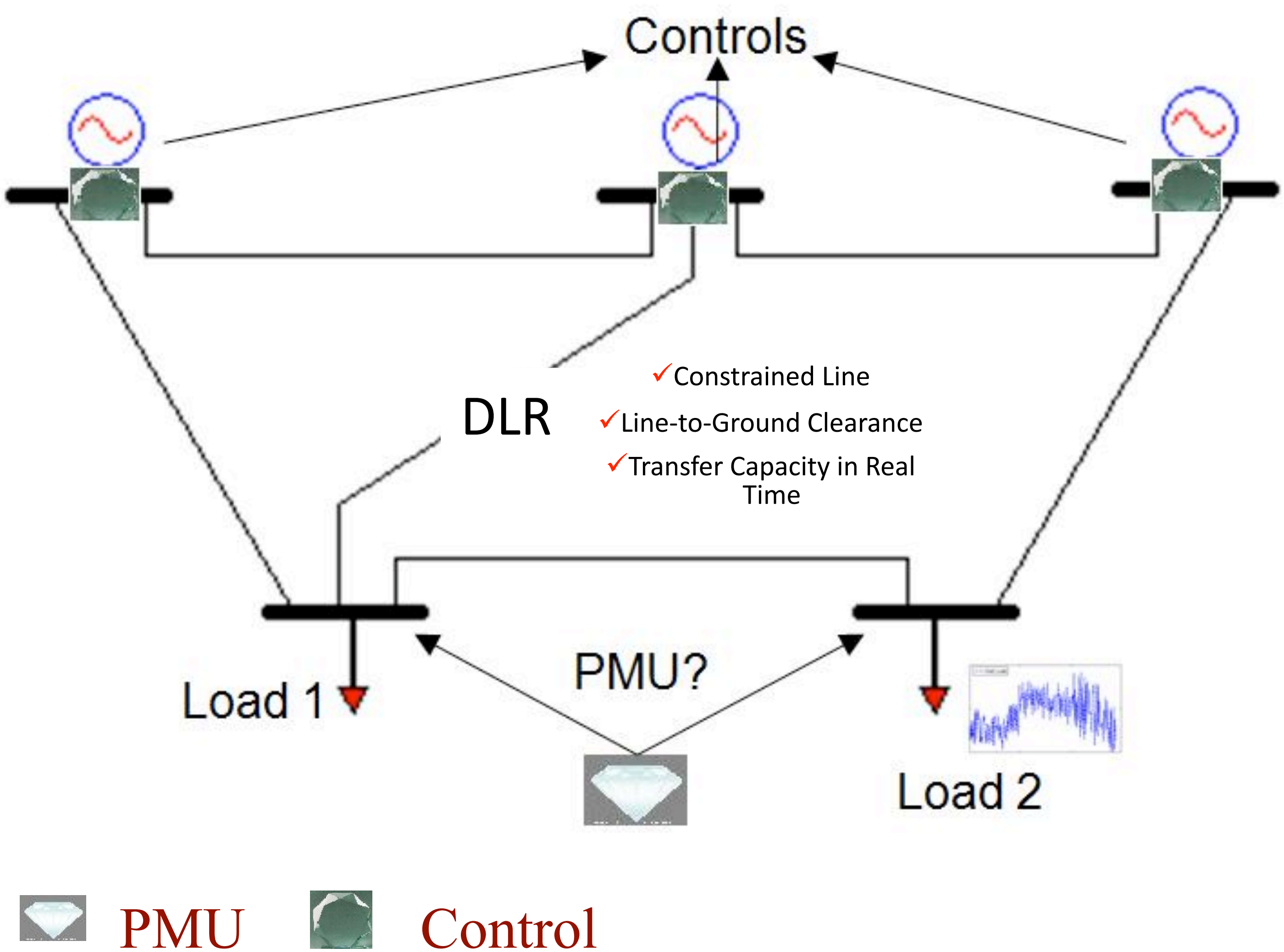
"Smart Grid" ←→ electric power grid and IT for sustainable energy SES

Energy SES	Man-made Grid	Man-made ICT
• Resource system (RS) • Generation (RUs) • Electric Energy Users (Us)	• Physical network connecting energy generation and consumers • Needed to implement interactions	• Sensors • Communications • Operations • Decisions and control • Protection

On-line automated regulation



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IT-enabled smarter energy systems

- ***Given physical energy systems, how to design the grid infrastructure and the cyber overlay to make the most out of naturally available resources?***
- ***Complex systems engineering problem (temporal, spatial, contextual)***
- ***The main challenge: What information should be collected/processed/exchanged to minimally coordinate the multi-layered physical system for provable performance?***

Closing remarks

- **There exists now a highly unusual window of opportunity to introduce modern electric energy research and education programs**
- **Obvious societal needs**
- **CMU is a great environment**
  - Boundaries across disciplines fluid
  - Very strong disciplines needed for developing embedded intelligence (CS, security, sensor networks, signal processing)
- **We will waste this rare opportunity without a full understanding of the potential of embedding IT-enabled intelligence within complex physical energy systems**

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Modern Electric Energy Systems at Carnegie Mellon/ECE

- ***Lots of fun; the number of graduate students is high and growing; the number of students taking classes is high and growing. Grass-root pressure from students.***
- ***Students genuinely interested in careers in future energy systems (drawn to the area to serve mankind while still doing engineering)***
- ***Emphasis on systems formulation (instead of on component physics); smart grid as an enabler of sustainable energy.***
- ***Much novel modeling for "translating" a physical and business system and its objectives into the language of systems, control, sensors, signal processing, computer science and IT; power electronics-enabled control.***

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