Making the Concepts of Robustness, Resilience and Sustainability Useful Tools for Power System Planning, Operation and Control

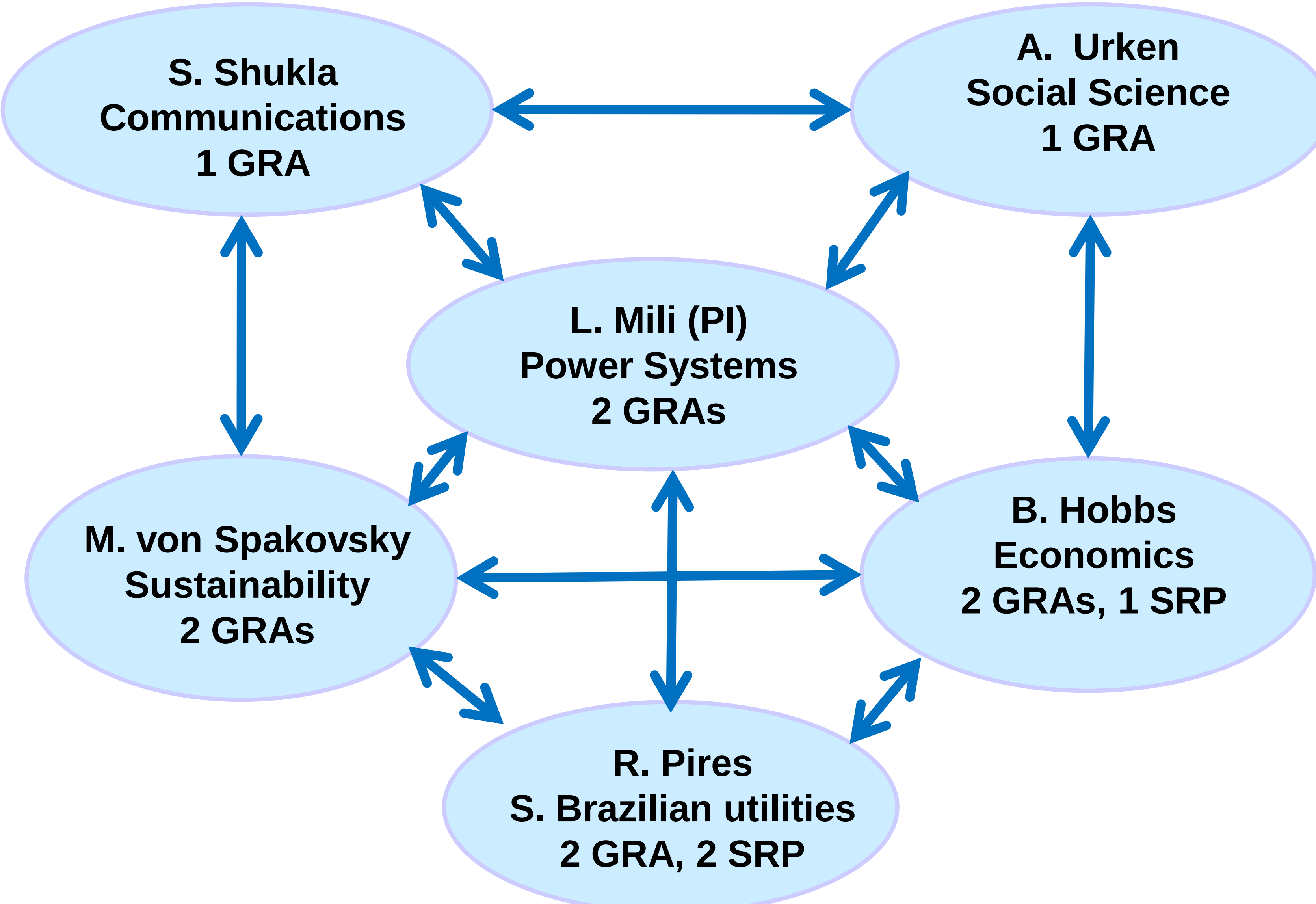
Lamine Mili

Bradley Department of Electrical and Computer Engineering

Virginia Tech, Northern Virginia Center

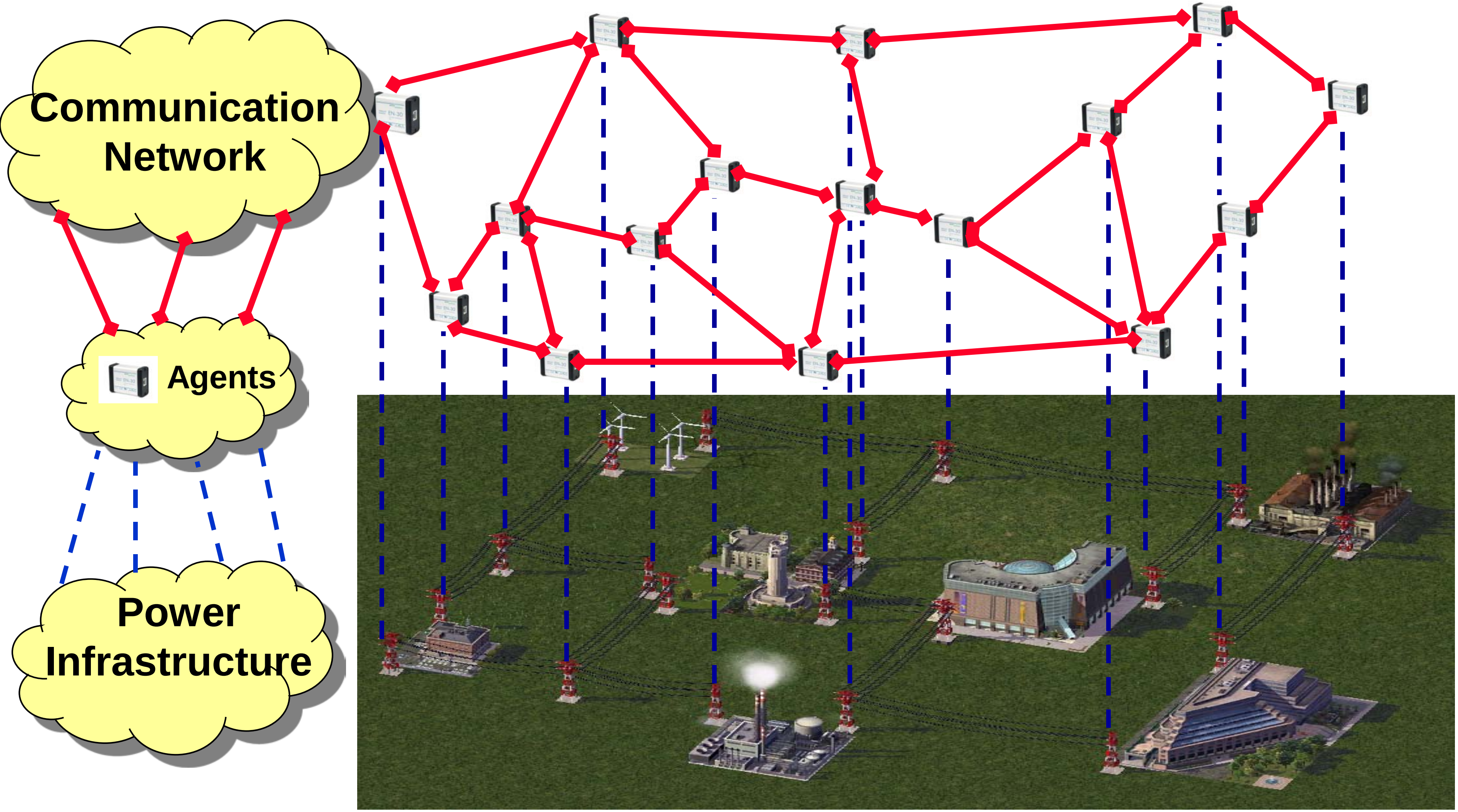
Falls Church, VA 22043, USA

NSF EFRI Grant 0835879

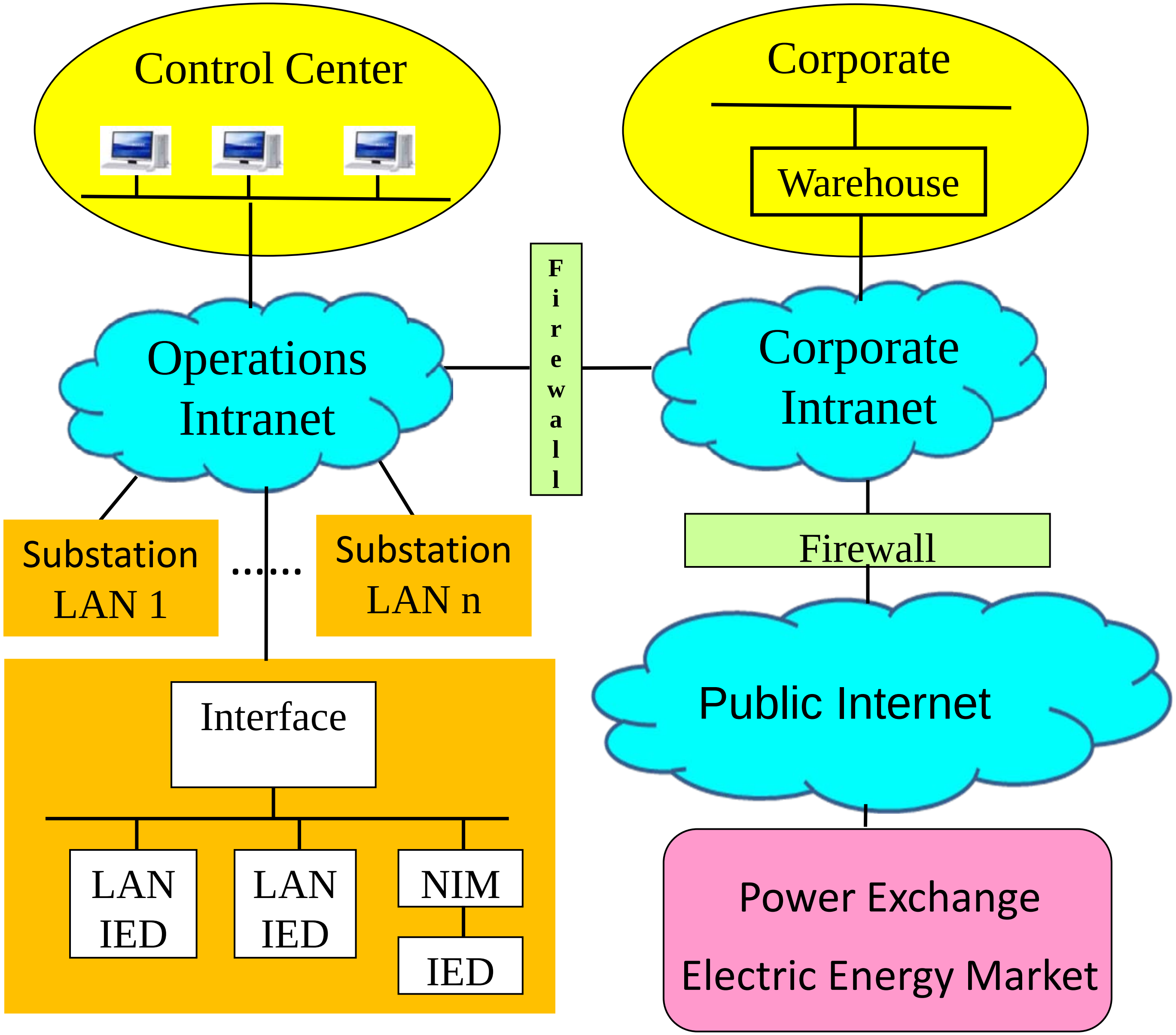


Power and Communication Infrastructure

NSF EFRI: Resilient and Sustainable Interdependent Electric Power and Communications Systems



Power and Communication Infrastructure



Networking, Computing, and Stability Analysis

- **Study a power system and its communications network as a Cyber Physical System with cohesive interdependence between computing, networking, and system dynamic responses to perturbations.**

- **Investigate the modes of cascading failure in computer and power networks and mitigate their impacts.**

- **Enhance the robustness and resilience of interdependent power and communications systems.**

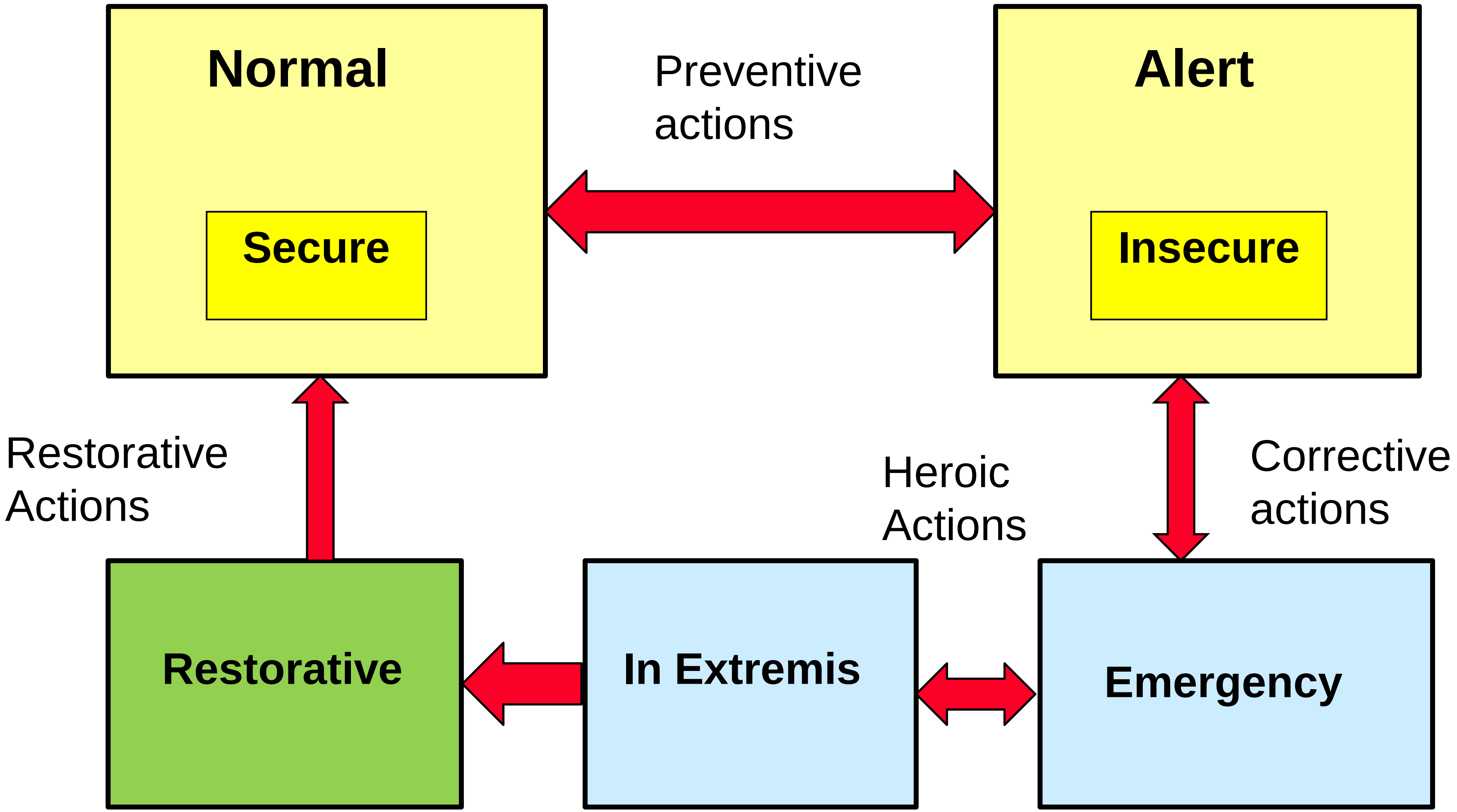
- **Enhance the sustainability of the smart grid by decreasing its impact on the environment.**

Jean de La Fontaine's Fable (1622-95)

- The oak is <u>robust</u> but <u>fragile</u> because it can be uprooted by a strongly enough wind.

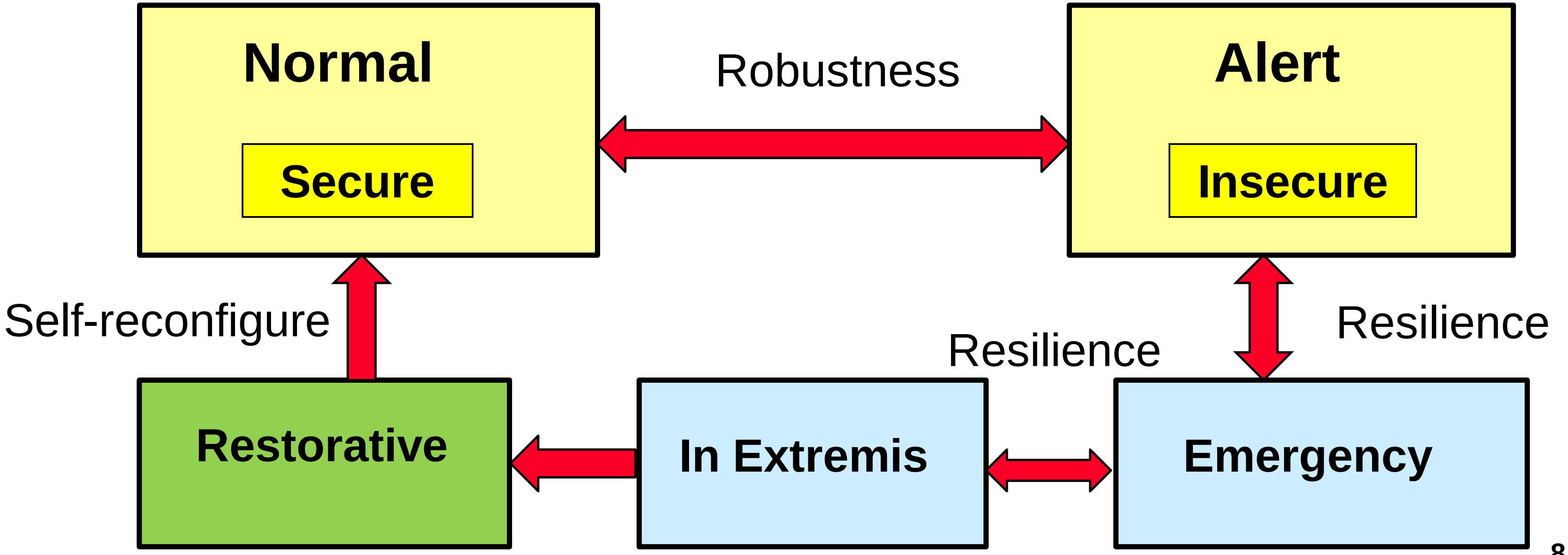
- The reed is <u>resilient</u> but <u>weak</u> because it bends down to any wind and then it restores its shape once the wind has ceased.

The Five Operating States of a Power System



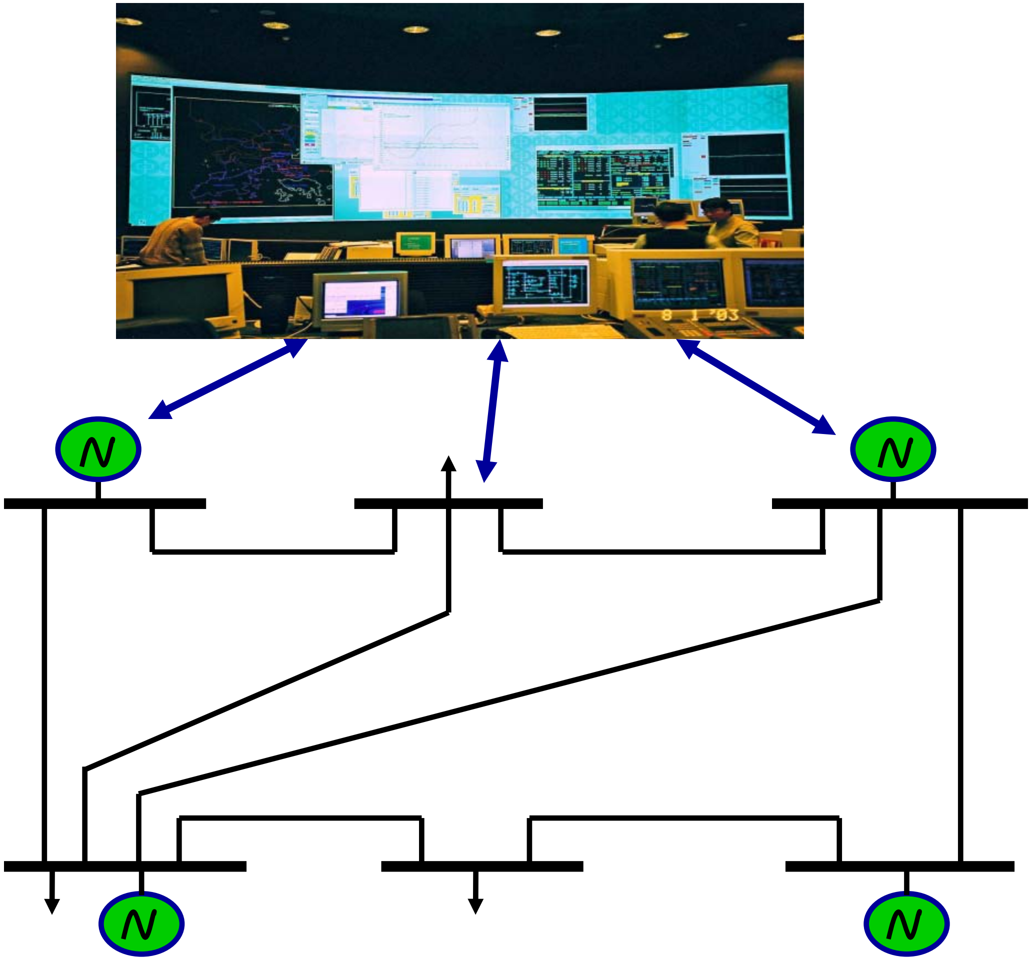
Definition of Robustness and Resilience

- **Robustness** to a class of disturbances is defined as the ability of a system to maintain its function (normal state) when it is subject to disturbances of this class.
- **Resilience** to a class of **unexpected** extreme disturbances is defined as the ability of a system to gracefully degrade and to quickly **self-recover** to a normal state.



Achieving Robustness and Reliability

- Robustness and reliability are achieved via equipment redundancy, strong coupling between system components, and centralized hierarchical control.



Achieving Robustness

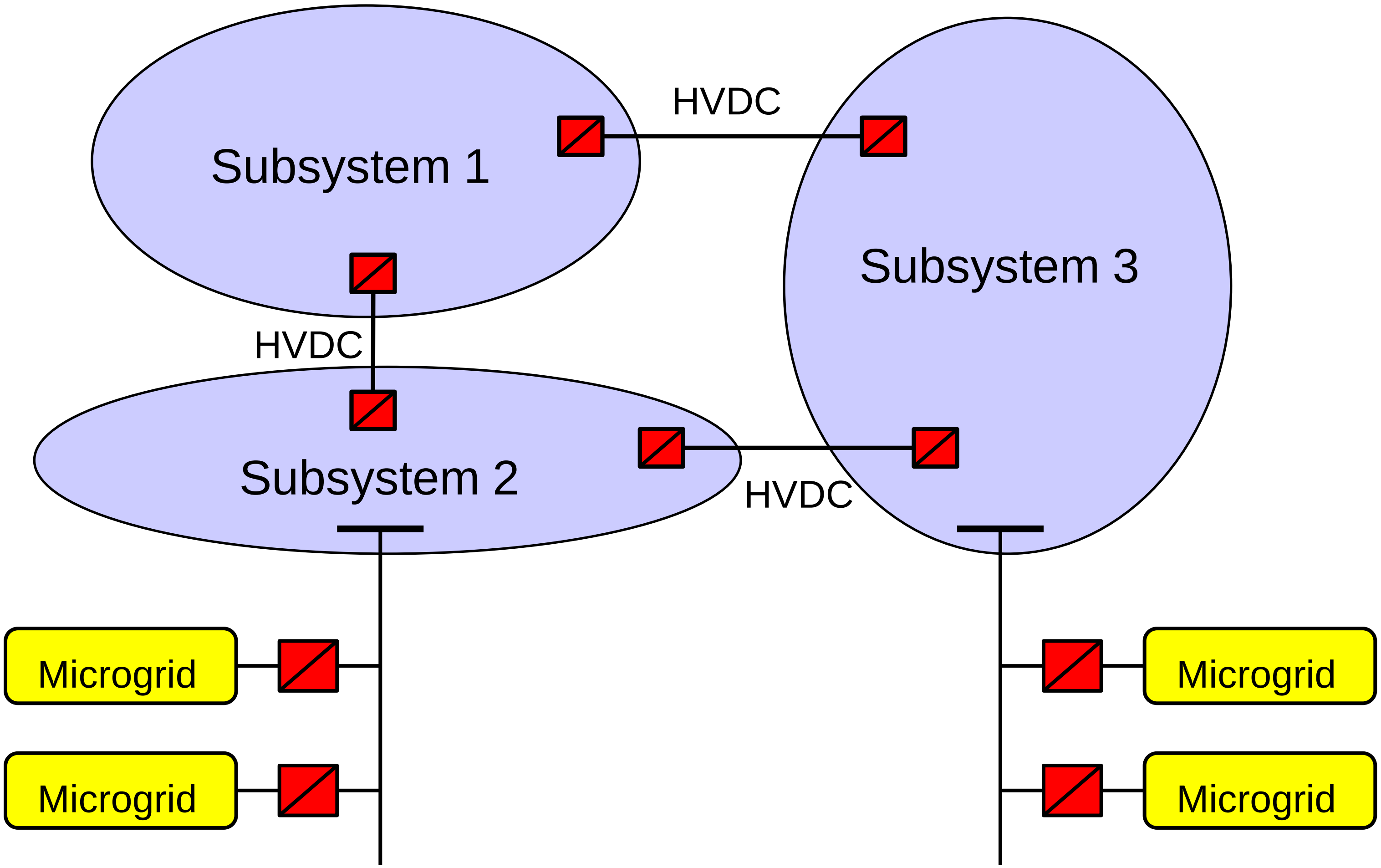
- Robustness is achieved via
  - the addition of redundant equipment in the system, for instance by adding lines, transformers, power plants. This will increase the stability margins of the system;
  - the implementation of control actions such as line switching or generation redispatch to alter the load pattern on the network. These actions will modify the operating point of the system to a more secure state.
  - the adaptive adjustment of the setting of the digital relays as the system operating state evolves.

Achieving Resilience via Modularity

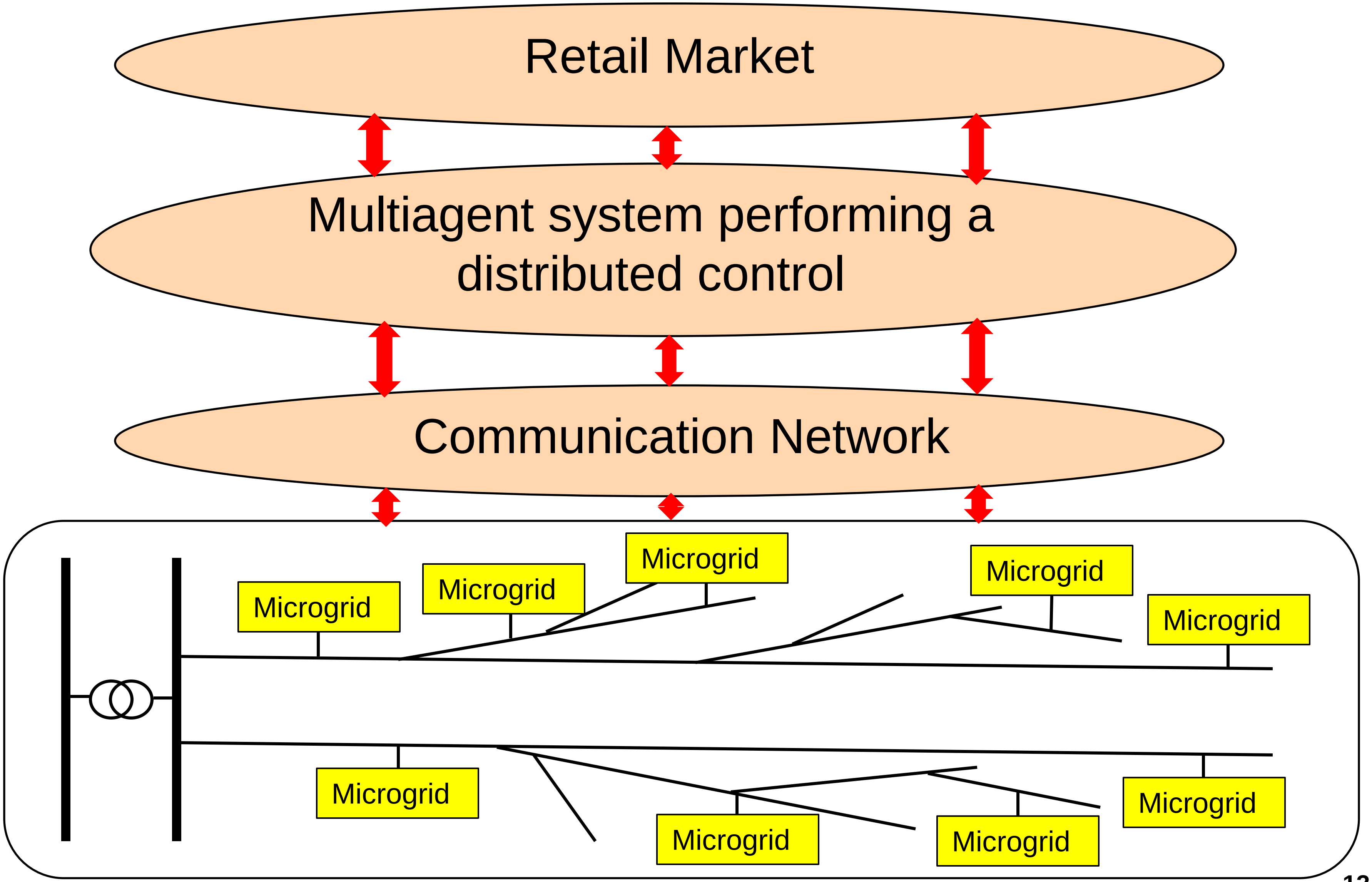
- **Resilience is achieved**
  - **via a segmentation of the system into weakly coupled subsystems to prevent the propagation of local failures to large areas via cascading events;**
  - **via distributed and coordinated control actions. This control is emergent in that it results from the collective action of many agents.**
    - **The agents have to assess the level of the stress of the system and decide collectively the type of actions that they have to initiate.**

Power System Segmentation (EPRI)

Resilience is achieved via a segmentation of a power system into weakly coupled subsystems.



Multiagent System for Microgrid Control

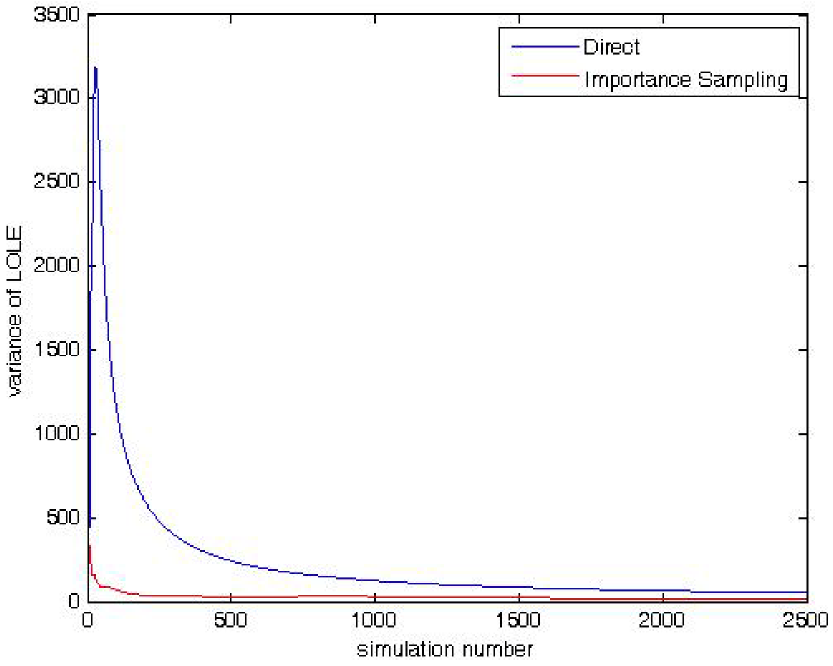


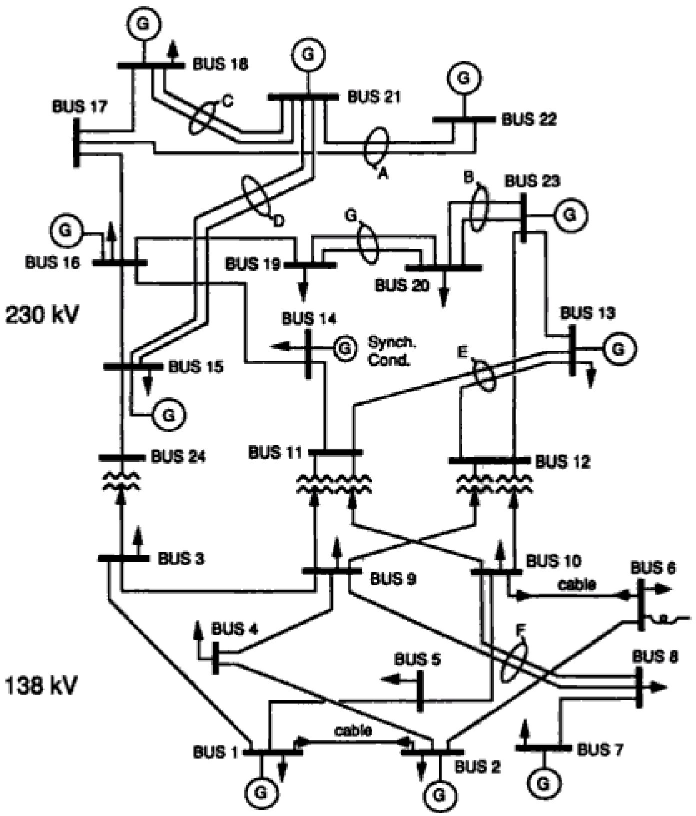
Robustness and Resilience Tradeoff

- A trade-off between robustness and resilience can be formulated as an optimization problem subject to a bound on the cost.
- This optimization will indicate where to segment the transmission system via HVDC links and will give us the desired level of penetration of microgrids.

Modeling of Cascading Failure in Power Systems

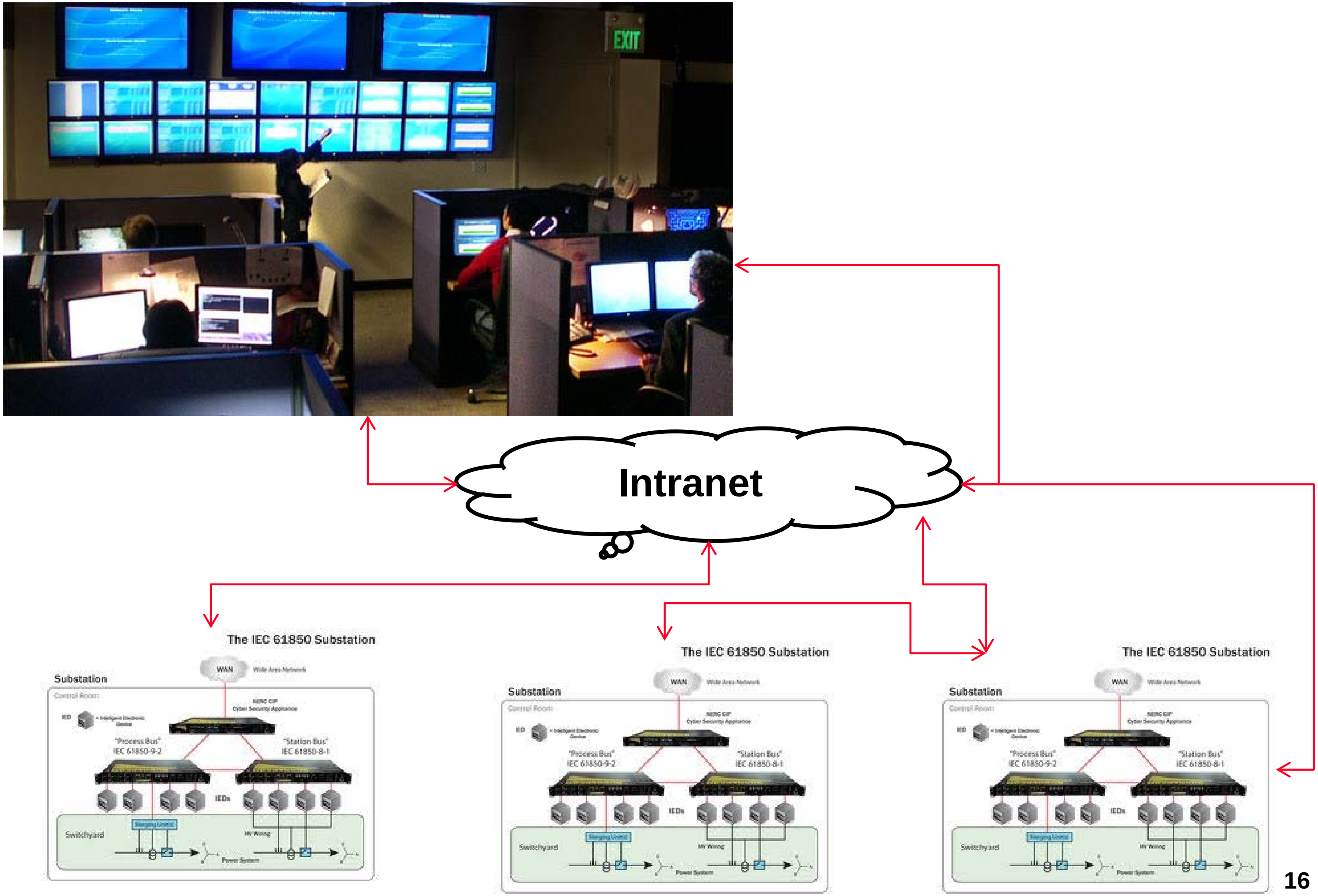
The IEEE reliability test system has 9 different types of 32 generating units ranging from 12MW to 400MW.



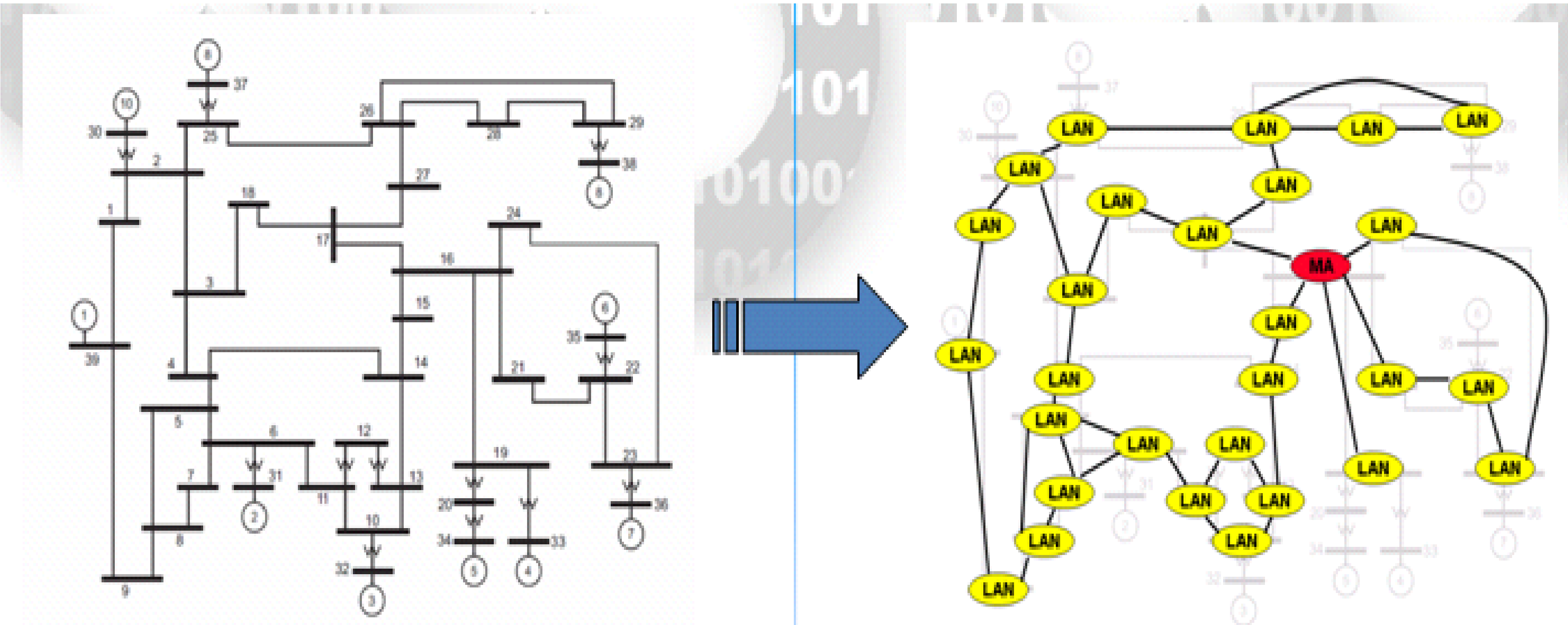


The variance of the Loss of Load Expectation (LOLE) for the direct method and the importance sampling algorithm

Control Center for Monitoring Substation IEC 61850



Agent Based Supervision of Zone 3 Relays



IEEE 39-Bus System and Communication Infrastructure

- Master agents co-ordinate with slaves in a peer-to-peer manner
- Monitor and control power system through interconnected network

Maximum Delays in the Network

Maximum delays in the network sharing same topology with the power lines

	PLC	Copper	Fiber
UDP without Traffic	160.4ms	2ms	0.416ms
TCP without outTraffic	640.4ms	4.8ms	0.464ms
UDP with Traffic	N/A	3.6ms	0.432ms
TCP with Traffic	N/A	5.2ms	0.448ms

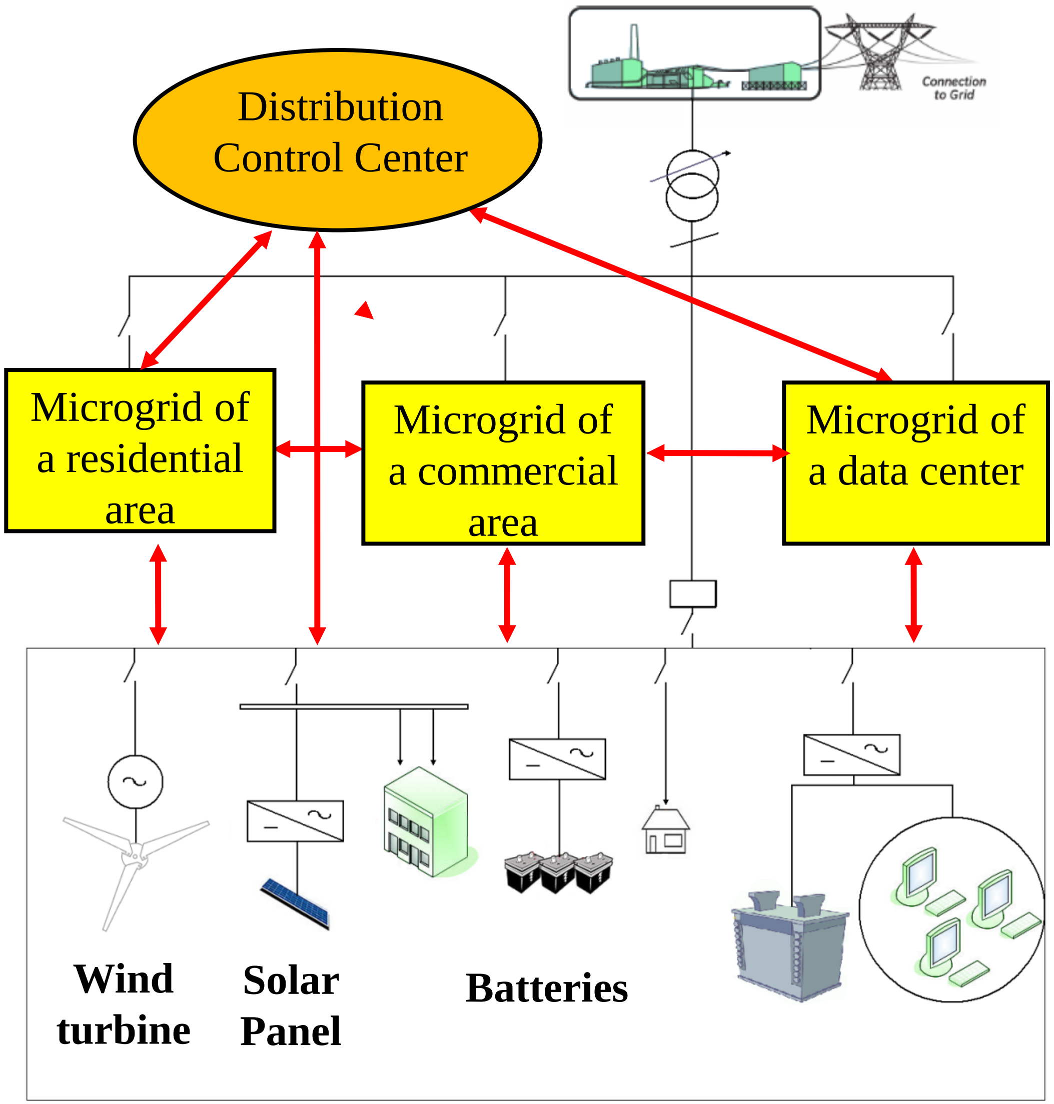
Maximum delay in the hierarchical network with LANs in the substation

	PLC	Copper	Fiber
UDP without Traffic	1082.588ms	12.188ms	2.684ms
TCP without outTraffic	2002.748ms	22.748ms	3.024ms
UDP with Traffic	N/A	48.4ms	3.014ms
TCP with Traffic	N/A	50.8ms	3.104ms

What is a Microgrid ?

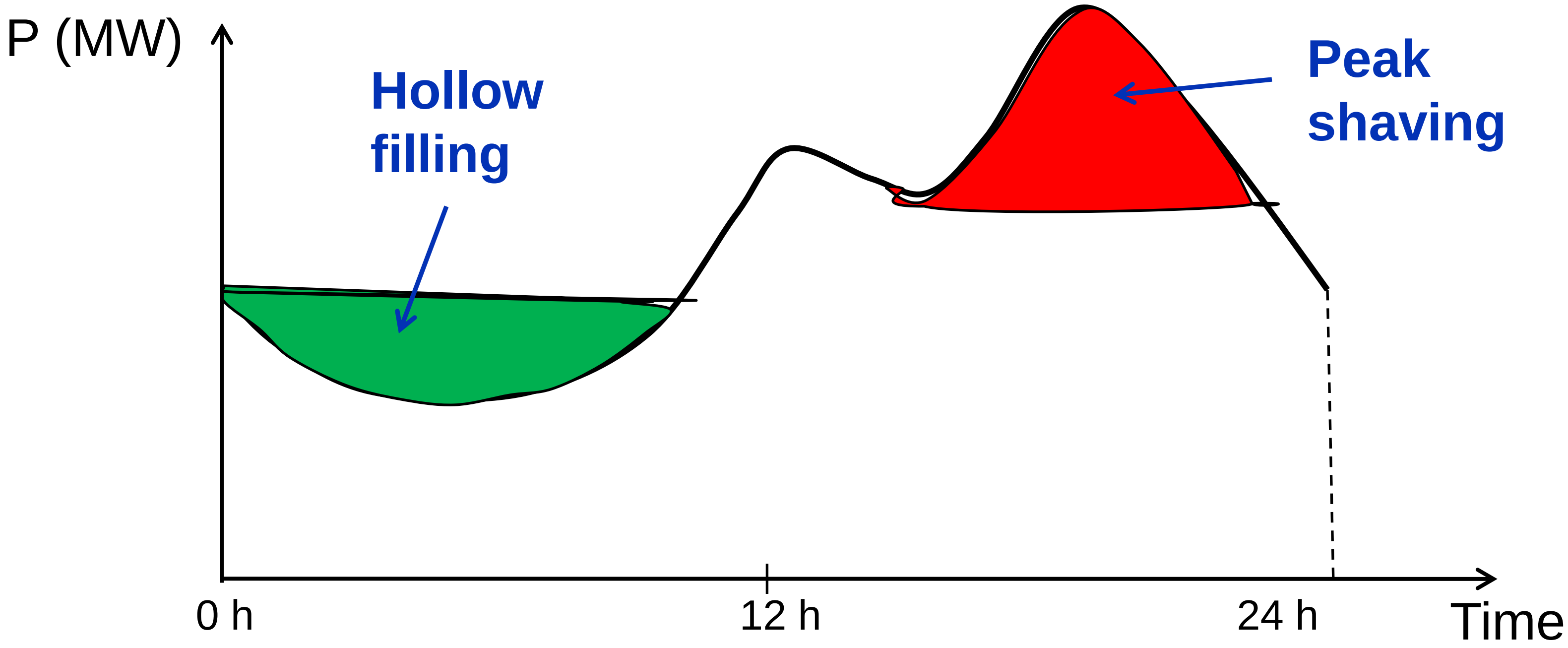
- **A microgrid is a small-scale DC/AC electric power system that interconnects generation units and storage devices to residential, commercial or industrial loads via inverters, converters or rectifiers.**
- **It may include AC and/or DC networks.**
- **It can be operated either in an islanded mode or in a grid-interconnected mode.**
- **It can be connected to a single-phase or a three-phase feeder at 480V- to 35 kV-voltage levels via fast responding power electronic conversion devices.**
- **It can provide electricity and heat energy (CHP).**

Microgrid Components

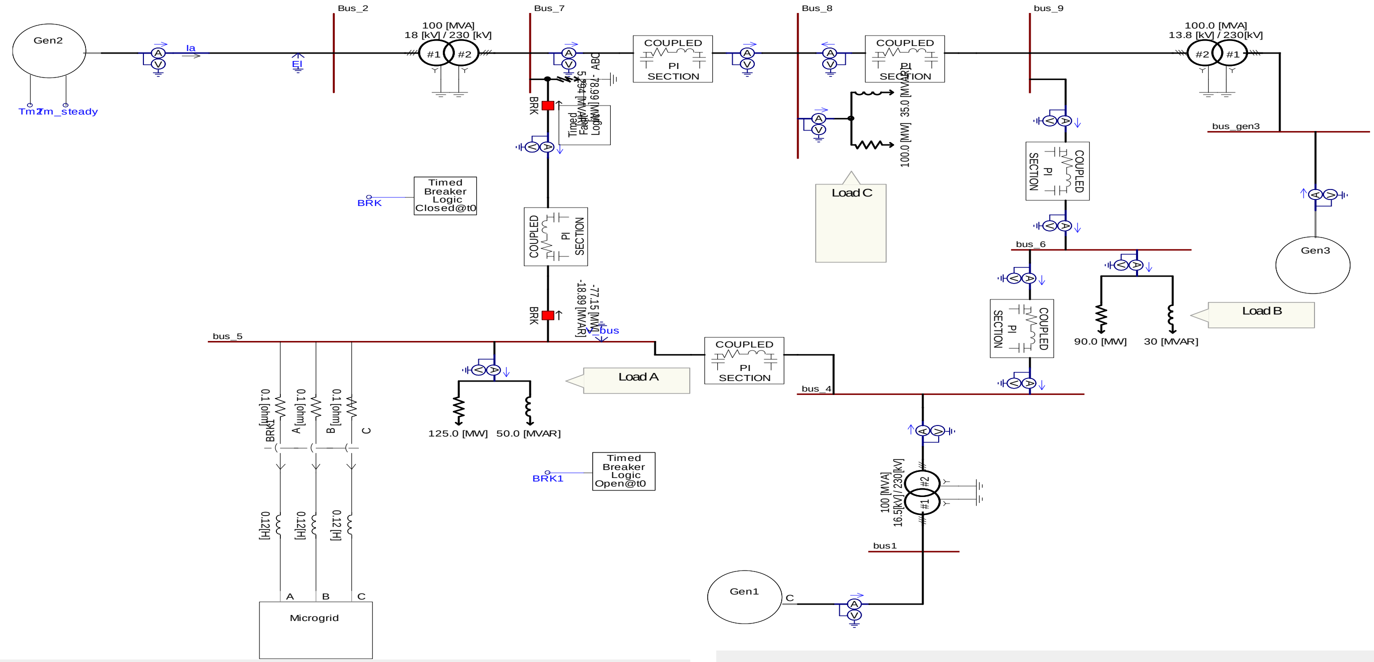


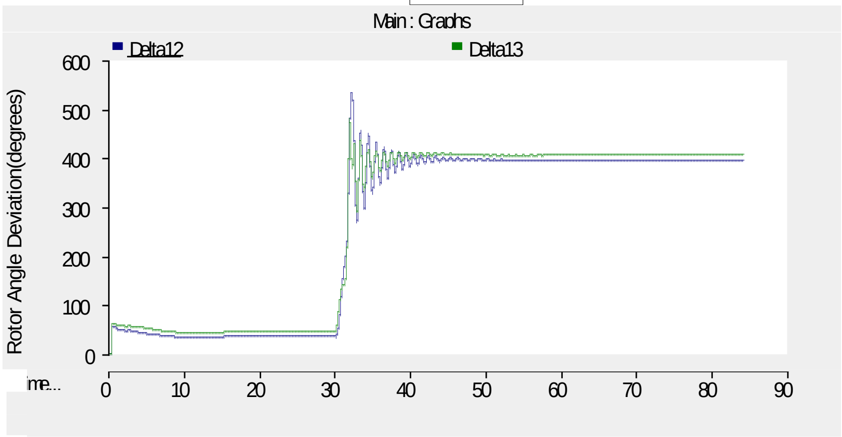
Benefit: Peak Shaving and Energy Saving

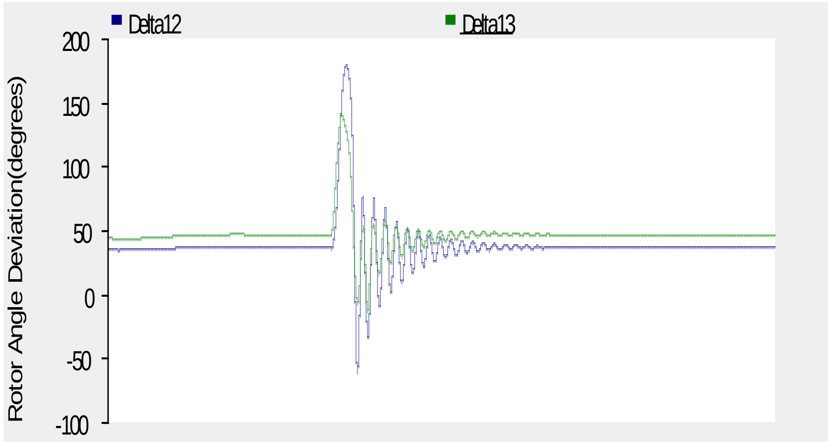
- **Microgrids can contribute to bulk power peak shaving, load curve flattening, and electric energy saving via demand displacement.**



Enhancement of the Stability Margin







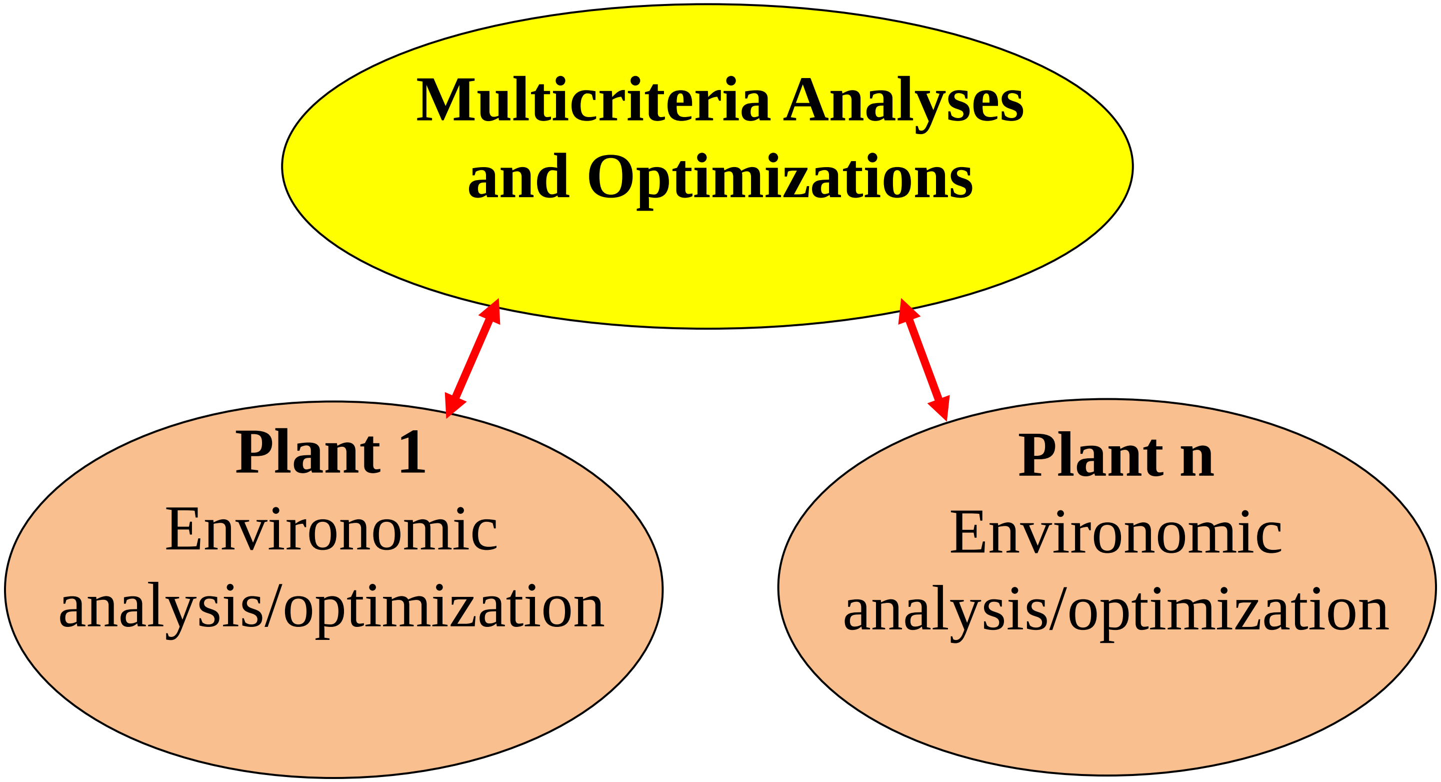
System without microgrid: critically unstable; Critical clearing time is 833 ms

The microgrid increases the stability margins. Critical clearing time is 1.3 s

Mitigating Hurricanes’ Impacts

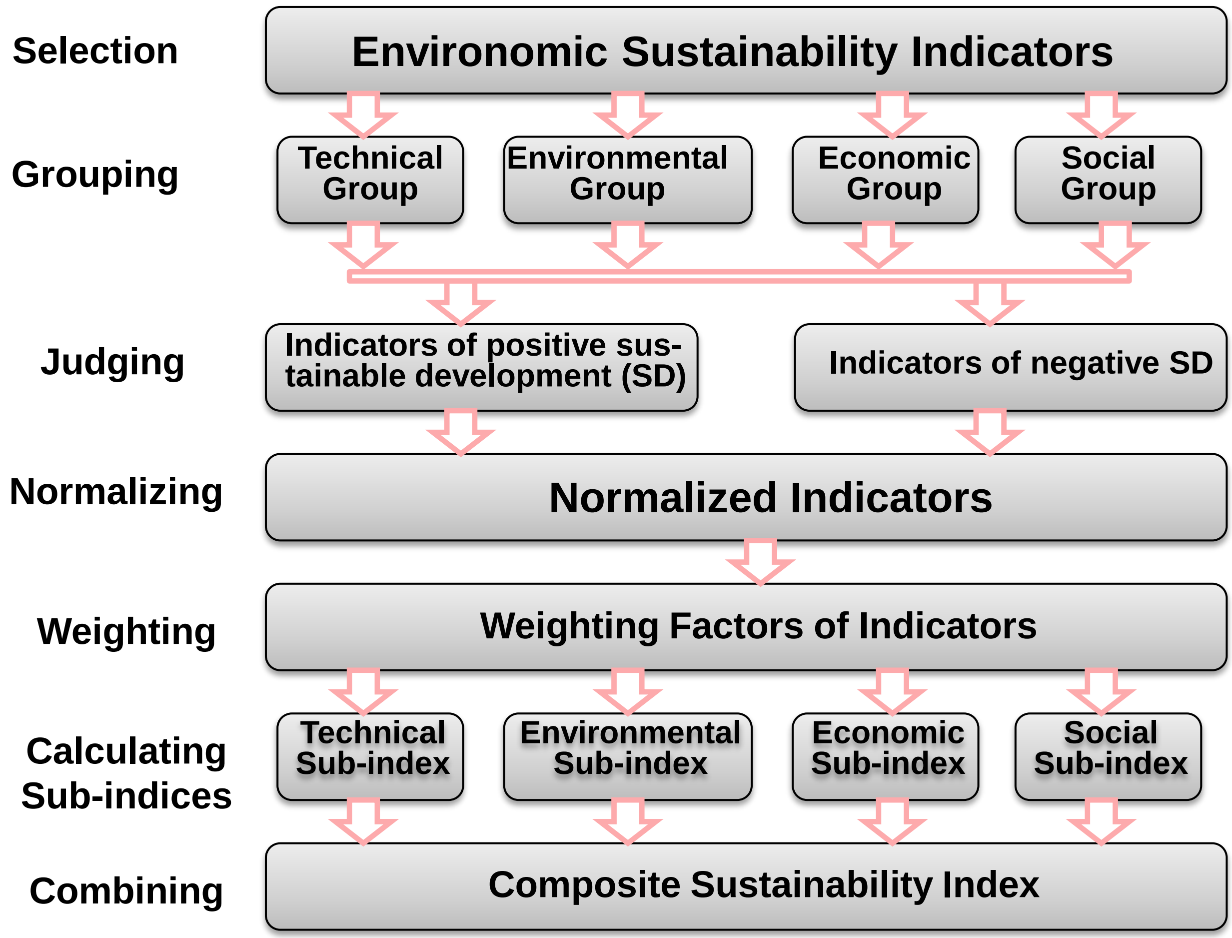
- **Following hurricanes, microgrids can provide electric energy to customers in an islanding mode for several weeks.**
- **A cost-benefit analysis is being carried out in a case study in Florida that integrates energy, transportation, water, and communications infrastructures**

- **Development of theoretical foundations of a two-level sustainability assessment framework (SAF)**



Sustainable Power System

- Selection of environomic sustainability indicators to assess the sustainability of the ***NW European regional transmission/distribution grid interacting with a set of micro-grids*** (***Frangopoulos et al., 2010***).



$$\bar{I}_{ij} = \begin{cases} 0 & if\ I_{ij} \le a_{ij} \\ \dfrac{I_{ij} - a_{ij}}{b_{ij} - a_{ij}} & if\ a_{ij} < I_{ij} < b_{ij} \\ 1 & if\ I_{ij} \ge b_{ij} \end{cases}$$

Indicators of positive SD

$$\bar{I}_{ij} = \begin{cases} 1 & if\ I_{ij} \le a_{ij} \\ \dfrac{b_{ij} - I_{ij}}{b_{ij} - a_{ij}} & if\ a_{ij} < I_{ij} < b_{ij} \\ 0 & if\ I_{ij} \ge b_{ij} \end{cases}$$

Indicators of negative SD

Weighting factors

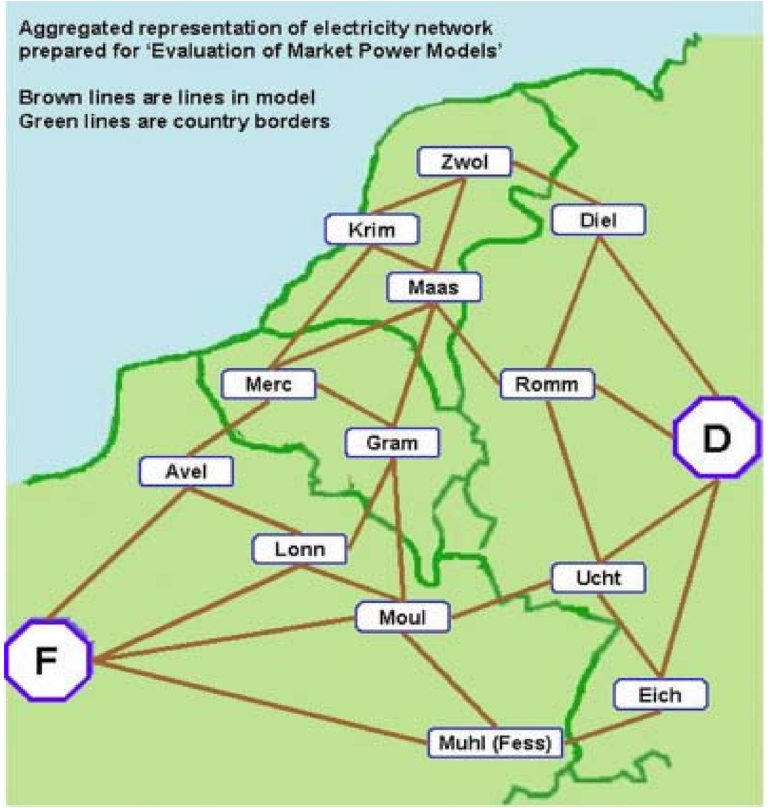
$$\bar{I}_{Sj} = \sum_i w_{ij} \bar{I}_{ij} \qquad \sum_i w_{ij} = 1, \qquad w_{ij} \ge 0$$

Sustainability Sub-index of group *j*, and relative weight of indicator *i* in group *j*.

$$I_{CS} = \sum_j w_j \bar{I}_{Sj} \qquad \sum_j w_j = 1, \qquad w_j \ge 0$$

Composite sustainability index and relative weight of the indicator in group *j*.

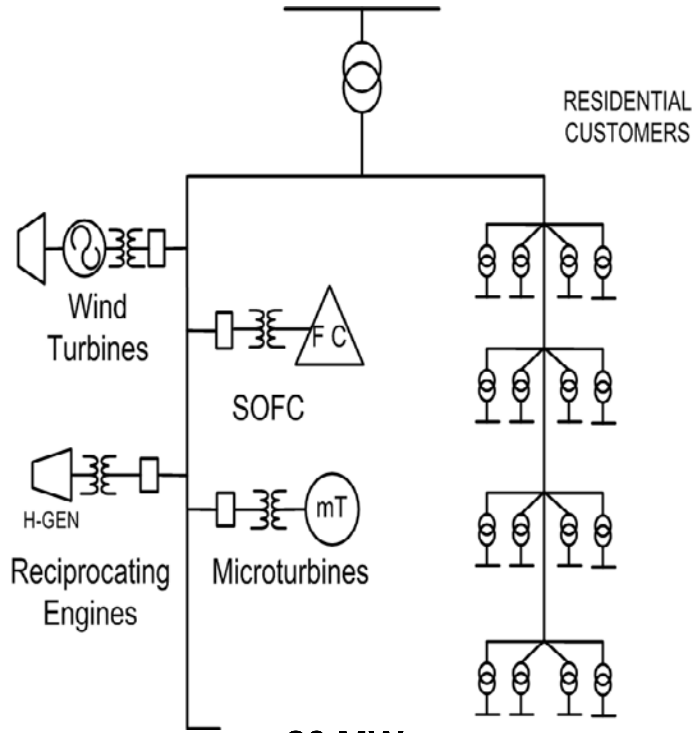
Sustainability of Microgrids in the NW European Market



- **Goal: Assess the sustainability of microgrids in the NW European market that consists of 15 nodes.**
- **Market Simulator: COMPETES (COmprehensive Market Power in Electricity Transmission and Energy Simulator) www.ecn.nl/ps/tools/modelling-systems/competes/**
- **This Model was enhanced to quantify emissions and thermodynamic efficiency**
- **Collaborators: O. Ozdemir and S. Hers, ECN (The Netherlands)**

Sustainable Power System

- Development of a 20 MW residential micro-grid configuration including renewable and non-renewable technologies with cogeneration tied to a NW European power network and used in ***an upper-level SAF***.
- 50 Residential MGs are aggregated at the node Krim in the Netherlands
- The daily load demand is divided into base load, intermediate load, and peak load.



20 MWe

Emission rates in the MG by technology (ton/MWh)

Technology	CO_2	NO_x	SO_x
SOFC	0.402	0.000007	-
Gas MT	0.778	0.000238	-
Diesel RE	0.826	0.00095	0.00163
Boiler	0.234	0.00038	-

Characteristics of MG technologies

MG technology	Capital cost ($/kW)	Useful life (years)	Unitary size (kW)	Energetic efficiency
Wind turbines	1,467	20	1,800	18%
SOFC	4,700	10	1,000	50%
Microturbine	2,500	20	60	26%
Diesel RE	350	20	180	34%

Impacts of Microgrids

- **Microgrids (MGs) lead to an improvement in the energetic and exergetic efficiency.**
- **MGs enhance the sustainability of a power system because they yield a reduction in both CO_2 and NO_x emissions.**
- **MG scenarios are *less* economically sustainable due to the high capital costs of the MG technologies, especially fuel cells.**

Application of an Upper-level SAF to the NW European Power Network

Indicator	S1	S2	S3	S4
1	0	0.46	0.54	1
2	0	0.62	0.39	1
3	0.03	0	1	0.94
Environmental sub-index	*0.01*	*0.36*	*0.65*	*0.98*
4	1	0.49	0.51	0
5	0	0.28	0.73	1
Economic sub-index	*0.50*	*0.38*	*0.62*	*0.50*
6	0.5608	0.5608	0.5635	0.5635
7	0.4561	0.4645	0.4582	0.4667
8	0.4111	0.4111	0.4132	0.4132
9	0.4453	0.4538	0.4474	0.4560
Technical sub-index	*0.4683*	*0.4726*	*0.4706*	*0.4749*
Composite sustainability index	***0.3260***	***0.4052***	***0.5776***	***0.6517***

S1 – no MG, no CO2 price **S2 – MG, no CO2 price**
S3 – no MG, CO2=25 €/ton **S4 – MG, CO2=25 €/ton**

Conclusions

- **Microgrids will allow a host of small-scale renewable energy resources to be interconnected with a power system.**
- **Microgrids will provide a power system with enhanced flexibility and agility during emergency conditions.**
- **Microgrids will represent a paradigm shift in power system operation and control. They are one of the key components of a smart grid.**