U.S.-PAKISTAN CENTER FOR ADVANCED STUDIES IN ENERGY (USPCAS-E)

Smart Grid Architecture
ESE-909 (Core)
Lecture 1 (An Introduction)
Basics of Smart Grid

By

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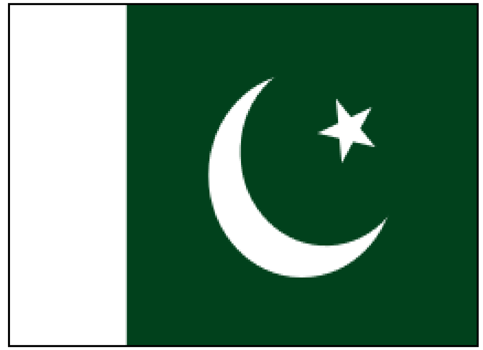
Lecture Overview

1. ***SG Definition***
2. ***Traditional grid Vs. Smart grid comparison***
3. ***Prominent Smart grid features (+ Additional Info)***
4. ***IEEE version of Smart grid***
5. ***SG Domains (By NIST Model)***
6. ***Aimed research areas & 5 key aspects of SG D&D***
7. ***5 key aspects of SG D&D (Important points)***
8. ***Stakeholder roles and function***
9. ***Representative SG architecture***
10. ***SG Components & their functions***

NUST
Defining Futures



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"The scientific man does not aim at an immediate result. He does not expect that his advanced ideas will be readily taken up. His work is like that of the planter — for the future. His duty is to lay the foundation for those who are to come, and point the way. He lives and labors and hopes." **Nikola Tesla**

NUST Defining Futures

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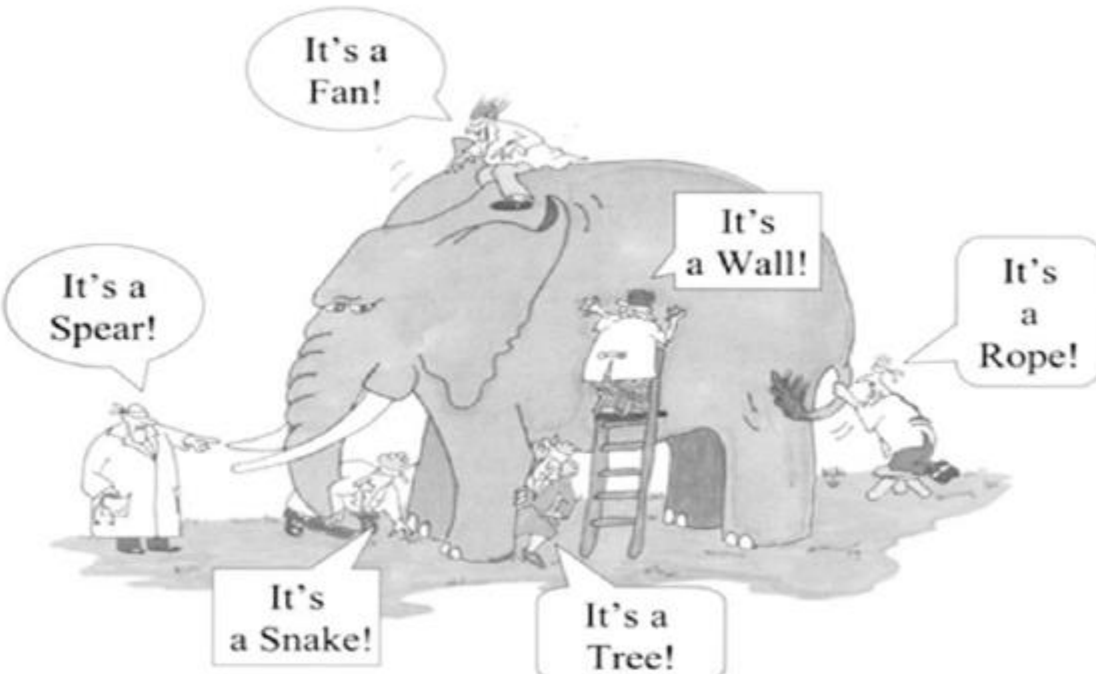
What is Smart Grid? It depends on the way we look at it!

Core objective: It is to have Smart/optimal utilization of all the available resources.



Smarter (NIST Model) in:

1 Generation
2 Transmission
3 Distribution
4 Customer participation
5 Operations
6 Markets
7 Service Providers

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Definitions:

National Institute of Standards and Technology (NIST), USA:

A modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications.

IEEE:

- Smart grid is a large 'System of Systems', where each functional domain consists of three layers:
  - ✓ (i) The power and energy layer,
  - ✓ (ii) The communication layer, and
  - ✓ (iii) The IT/computer layer.
- Layers (ii) and (iii) above are the enabling infrastructure that makes the existing power and energy infrastructure 'smarter

Smart Grid

Question

Answer

What is Smart Grid??

Smart Grid

=

Information & Communication Technologies (ICT)

+

Electric Grid Modernization

+

Asset Optimization

+

Integration of New Emerging Concepts

Working Smart Grid Definition

The smart grid is an advanced digital two - way power flow power system capable of self - healing, and adaptive, resilient, and sustainable, with foresight for prediction under different uncertainties. It is equipped for interoperability with present and future standards of components, devices, and systems that are cyber - secured against malicious attack.

Motivation and Aim for Smart Grid

- Wide geographical spread
  - Due to typical large distance between major load centers & conventional sources of energy.
- Large number of interconnections
  - Due to political, economic, environmental, reliability, and stability issues.
- Rapid growth in the demand of electricity
  - Due to increase in population, standard of living, development of townships.
- Power system components are being operated closer to their designed limits
  - More investment needed in the electrical infrastructure.
- High penetration of renewable energy sources
  - Intermittency, relay coordination, power quality, system stability.
- Competitive electricity market
  - Needs real time monitoring and strict regulation

Objectives

- Understand the need for overhaul and modernization of the existing power system
- Appreciate the necessity of Smart grid
- Understand the key components of the Smart grid and its implementation
- Know the benefits and the challenges involved in the Smart grid

Global Warming - The Threat !!

- Improving Energy efficiency
- Renewable Energy sources
- Carbon capture and sequestration
- Reducing Peak demand

The Traditional Power System

- The present infrastructure is overstrained and inter region bulk transfer is limited
- Cannot fully support the integration of renewable energy
- Low reliability of Power - Outage
- Fluctuating quality of Power
- Major source is fossil fuel
- Efficiency of Power transmission
- Almost zero customer participation
- Low Billing and collecting efficiency

Smart Grid - What is it??

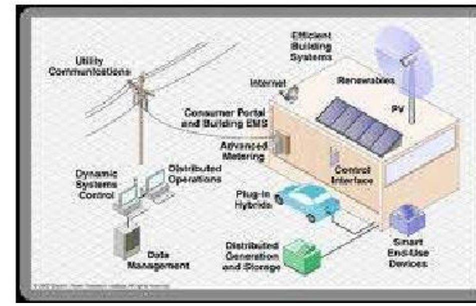
- Network created through the combination of Information Technology, Communication Technology and Electrical Power System.
- A grid remarkable in its intelligence and impressive in its scope which offers valuable technologies that can be deployed within the very near future or are already deployed today
- It simply means, a “smarter “ power grid

What Smart Grid does??

- Decentralization of Generating resources
- Integration of all sources of energy, mainly renewable
- Continuous monitoring and feedback from the network
- Anticipation of faults and helps in fault prevention
- Establishes a two-way communication between the utilities and the consumers
- Reduces the stress on the power system infrastructure
- Reduces and shifts the peak demand
- Continuous self-learning

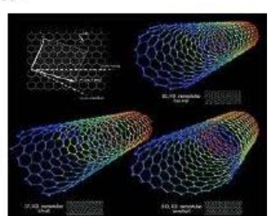
Enabling Smart Grid

- Local Energy Networks
- Energy Storage
- Electric Transportation
- Robust and cheap network devices
- Large Data storage



Energy Storage

- Ultra-capacitors, Li-ion, Vanadium redox batteries and Fuel cells
- Used in PHEVs and storage of intermittent renewable energy
- Flywheels and Pump storage - Mechanical

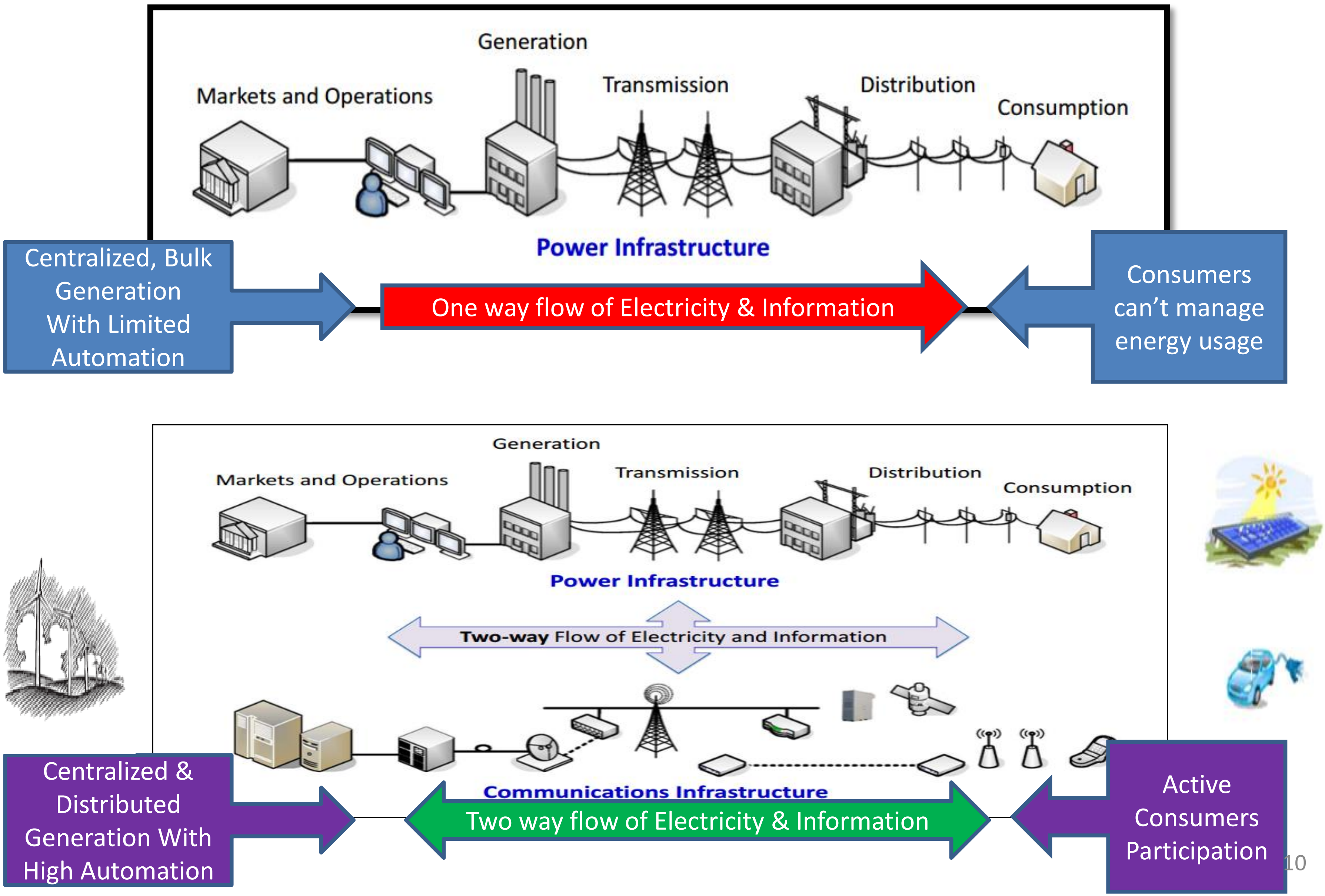


Electric Transportation

Plug-in Hybrid Electric Vehicles(PHEVs)

- Efficient means of transportation
- Can be recharged at night during low cost periods
- Can provide grid support during peak periods
- Reduces oil imports and pollution drastically

Traditional Grid Vs. Smart Grid



Prominent Smart Grid Features

Anticipated Characteristics	Traditional Grid	Smart Grid
Consumer participation	**Limited**	**Active** with DR & DERs
All types of generation & storage Accommodation	Dominated by **Central**	**High DER** with plug and play (focus on renewables)
New products, services & markets	**Limited**, poorly integrated wholesale markets	**Mature**, well integrated markets (focus: consumers)
Power Quality	Focus: Outages & **slow** response to PQ issues	**Rapid resolution** & Priority based price/quality option
Asset Optimization & Operational Efficiency	**Little** integration of concerned data with asset management	**High** data acquisition, Focus: Minimize impact to consumer
Self-Healing	**No**, follows post fault	**Yes**, indicate, isolate and trouble shoot fault quickly
Resiliency	**Vulnerable** with slow response	**Resilient** and rapid restoration capability

Additional Info: TG Vs. SG

Table 1 Distinct comparison between Traditional Grid (TG) Vs. Smart Grid (SG)

S.#.	Prominent Features/Indicators	Traditional Electrical Grid	Future Smart Grid
1	Power Flow	Unidirectional	Bidirectional
2	Communication Flow	Unidirectional	Bidirectional
3	Power Generation structure	Central	Distributed
4	Distribution Network Topology	Radial	Interconnected (Loop/Mesh)
5	Distribution Network Boundaries	Defined Role	Initiation of New Concepts
6	New consumption Models	No	Realizable
7	Distributed Generation	No or Less	High Penetration (Renewable)
8	Back-end key enabler equipment	Electromechanical	Digitalized
9	Number of sensors	Few in number	Large in number
10	Monitoring	Less or no automation	High Automation, Self-Monitoring
11	Control	Manual	Automatic and Advanced
12	Restoration/Recovery	Manual	Automatic, Self-Healing
13	Protection (Blackouts/Failures)	High need of Human attention	Less (with Adaptive protection)
14	Islanding	No	Yes (New paradigm i.e. Micro-grid)
15	Customer choices/Participation	Few	High
16	Customer Participation in Decision	Less	Extensive
17	Privacy and Security Concerns	Few	High
18	Production Reserve	Immediate production/consumption	Optimal use of storage system
19	Response to Emergencies	Slow	Fast
20	Data Management	Simple	Complex and optimized
21	Information and Communication	Less	Extensive use
22	Metering	Manual (High Human attention)	Smart/Advance infrastructure
23	Market	Regulated	Unregulated (New Models)
24	Focused solution strategy	Feasible economic solutions	Technical, economic, environment
25	Distribution network planning tools	Developed	In progress

IEEE Version of Smart Grid

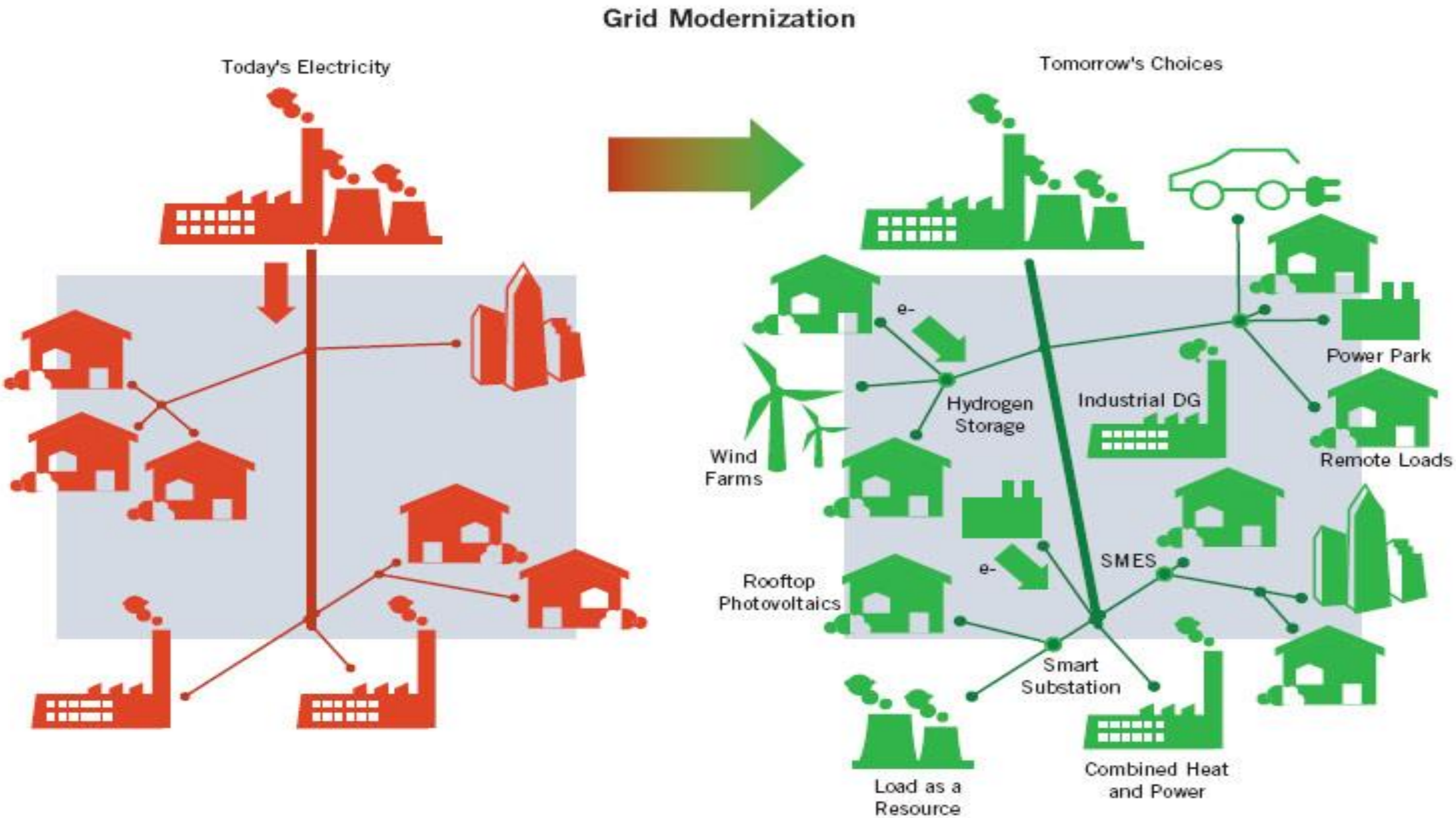
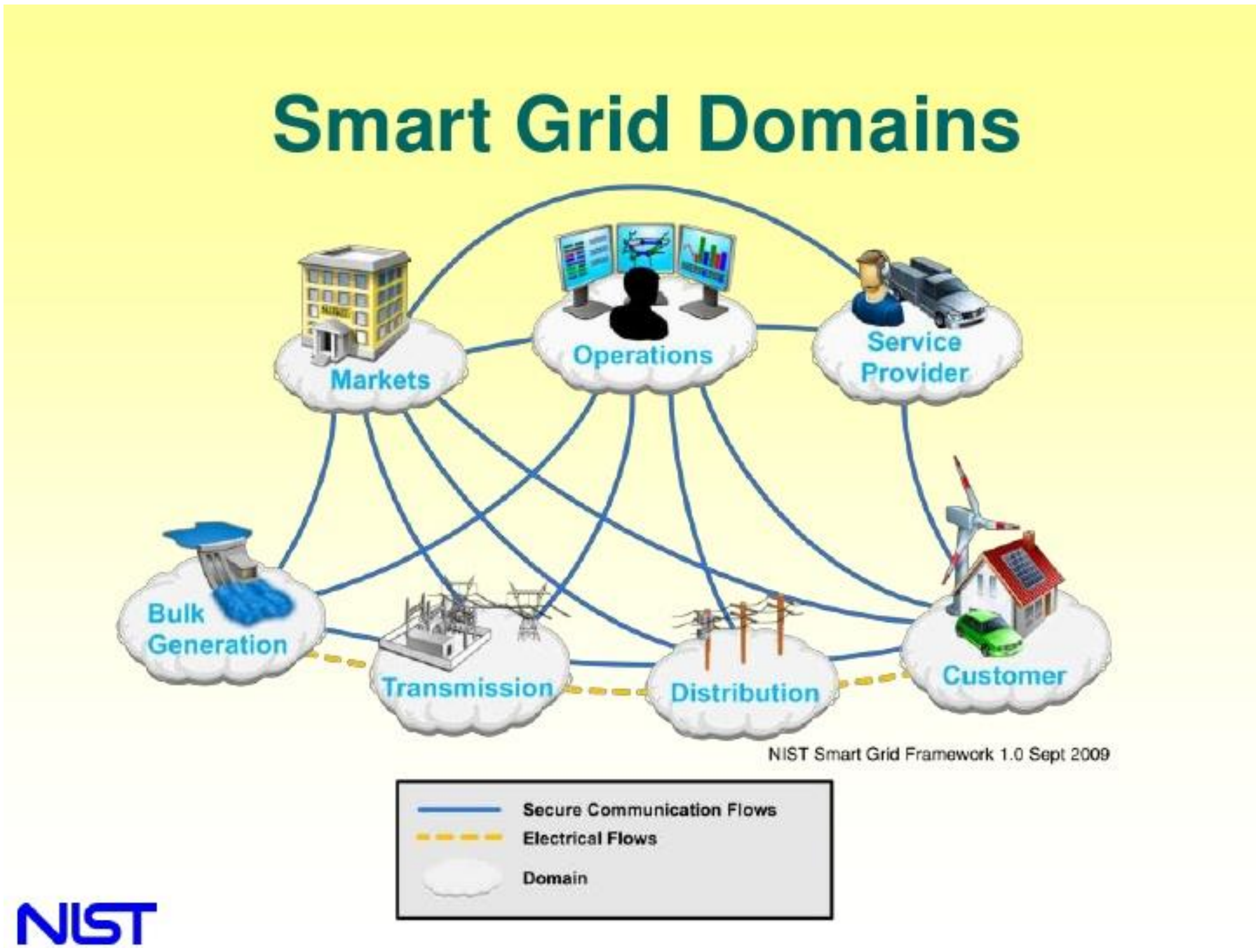


Fig. 1. The IEEE's version of the Smart Grid involves distributed generation, information networks, and system coordination, a drastic change from the existing utility configurations.

http://powerelectronics.com/power_systems/smart-grid-success-rely-system-solutions-20091001/

Smart Grid Domains by NIST



Smart Grid Domains

- *Generation*
  - Co-existence of various types of renewable and non-renewable generating technologies.
  - System operator has to coordinate the operation of the generation plants, and ensure the stable and secure operation of the system.

- *Transmission*
  - Energy-efficient transmission network will carry power from the bulk generation facilities to power distribution systems
  - The transmission network needs to be monitored in real-time, and protected against any potential disturbance.
  - The power flow and voltage on the lines need to be controlled in order to maintain stable and secure operation of the system.

Smart Grid Domains, Contd.

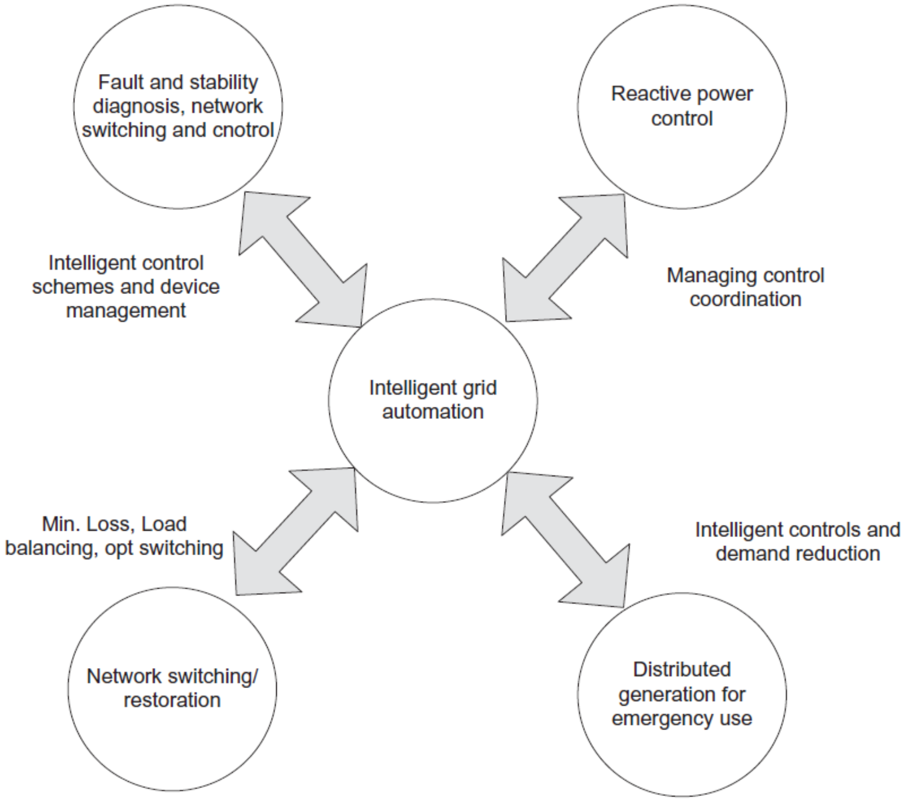


Figure. Intelligent grid automation at Transmission Level

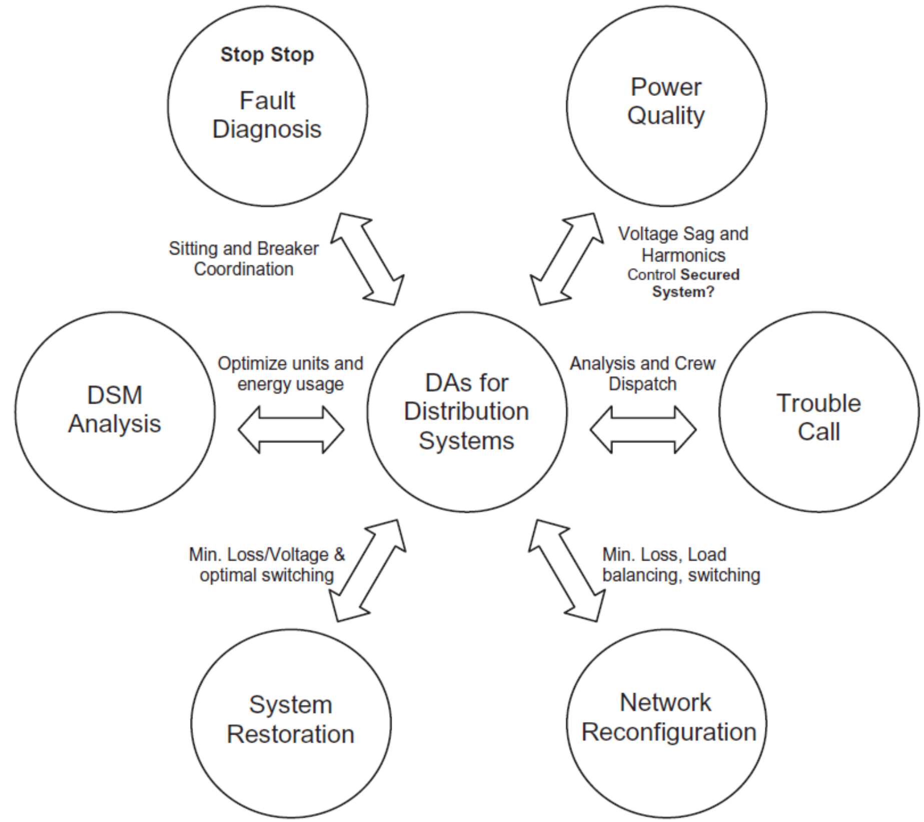


Figure. Distribution automation for distribution systems.

Smart Grid Domains, Contd.

- *Transmission*
  - System operator has to ensure optimal utilization of the transmission network, by minimizing the losses and voltage deviations, and maximizing the reliability of the supply.
- *Distribution*
  - Substation automation and distribution automation will be the key enablers for the smart distribution systems
  - Increasing use of distributed energy resources (DERs) will be an important feature of future distribution systems.
  - An important job of the distribution system operator is to control the DERs in a coordinated way to ensure stability and power quality of the distribution system.

Smart Grid Domains, Contd.

- *Customer*
  - Customers can be classified into 3 main categories:
    - Residential, commercial, and industrial.
  - In smart grids, customers are going to play a very important role through demand response.
    - By peak-load shaving, valley-filling, and emergency response, customers are going to play an active role in better operation of the distribution system
  - Building or home automation system will monitor and control the power consumption at the consumer premises in an intelligent way.

Smart Grid Domains, Contd.

- ***Operators***
  - Smart grid operations require communication interface with the bulk generating facilities, transmission system, substation automation, distribution automation, consumers, & market.
  - Metering, recording, and controlling operations come under the purview of the smart grid operations.
  - Real-time information exchange with the power market needs to be established in order to implement power trading and scheduling.
  - The operators need to interact with various service providers for ensuring proper functioning of the smart grid.

Smart Grid Domains, Contd.

- ***Markets***
  - The communication infrastructure integrating the bulk generation, transmission, distribution, consumers, markets, and service providers is the key to the success of the power market in a smart grid.
  - Appropriate regulatory policies need to formulated for seamless integration of the various domains, including the storage and DER aggregators into the smart grid market.
  - The pricing information has to be made available online for shorter intervals (hours or even minutes).

Smart Grid Domains, Contd.

- ***Service Providers***
  - Various service providers will emerge, as the smart grid business model matures.
  - Communication interface with the operator, market, and consumers will be needed for the service providers.
  - Examples of services:
    1. Forecasting for renewable generation.
    2. Billing and customer complain management.
    3. Building and home management.
    4. Installation and commissioning services.
    5. Account management.

5 Aimed Research Areas & 5 Key Aspects of SG Development & Deployment

1. SG R&D program (development & deployment)
2. SG standards and protection (widely accepted)
3. R&D of infrastructure (enable SG deployment)
4. Reliability and security (ensure certainty)
5. Policy to encourage SG technology support(GTD)

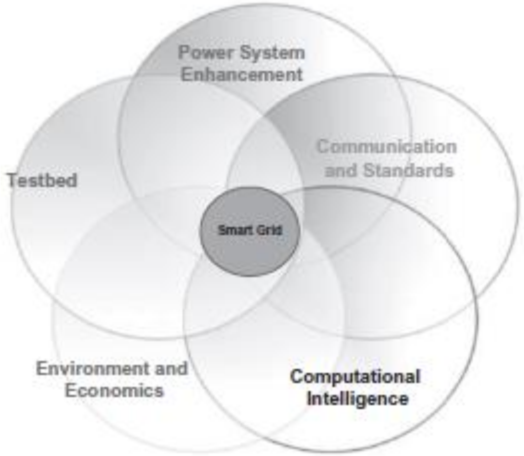


Fig. 5 Key Aspects of SG Development & Deployment

1. Computation Intelligence
2. Power system enhancement
3. Communication and Standards
4. Environment and Economics
5. Test Bed

5 Key Aspects of SG Development & Deployment (D&D)

1. Computation Intelligence

Advanced analytical tools to optimize power network

Includes:
1. Heuristic based tools
2. Evolution programming
3. Decision support tools
4. Optimization techniques

2. Power system enhancement

Includes:
1. Increased use of renewables
2. Offset impacts of carbon emissions (No thermal fuel)
3. Meet demand uncertainty
4. Increase reliability of power delivery

5 Key Aspects of SG Development & Deployment (D&D). Contd.

3. Communication and Standards

Planning horizons can be as short as 15min-1hr ahead

Includes:
1. Automations will generate vast operational data
2. Data generates under rapid decision making environment
3. Adaptive, predicting capability with foresight (New algo)
4. New protocols required for manage, operate and market

4. Environment and Economics

Includes:
1. Fully developed SG with tools (Enhanced performance)
2. New Jobs in multi-dimensional fields (1st gen. SG)
3. Difficulties in upgrading present system
4. SG integration from beginning minimize D&D issues

5. Test Beds (For research, proof of concept, etc.).

Stakeholder roles and function

An important part of the SG realization is the complete buy in or involvement of all stakeholders

1. **Utilities:** Installation/implementation of SG based technologies
   - ➢ South California Edison aims @ AMI for customer service, efficiency, etc.
2. **Policy makers:** Establishing standards for operation, monitoring & interoperability
   - ➢ US department of energy (DoE)→ GridWise Program → Interoperability
3. **Technology providers:** Development of SG technologies for the grid enhancements
   - ➢ Power system engineering research center (PSERC) →SoA technologies
4. **Researchers:** Development of tools and technologies for SG
   - ➢ Electrical power research institute (ERPI) → Intelligrid software
5. **Consumers:** Consumer's input and participation, etc.
   - ➢ Technology companies, vendors & manufacturers aim @ grid/consumers

Representative SG Architecture

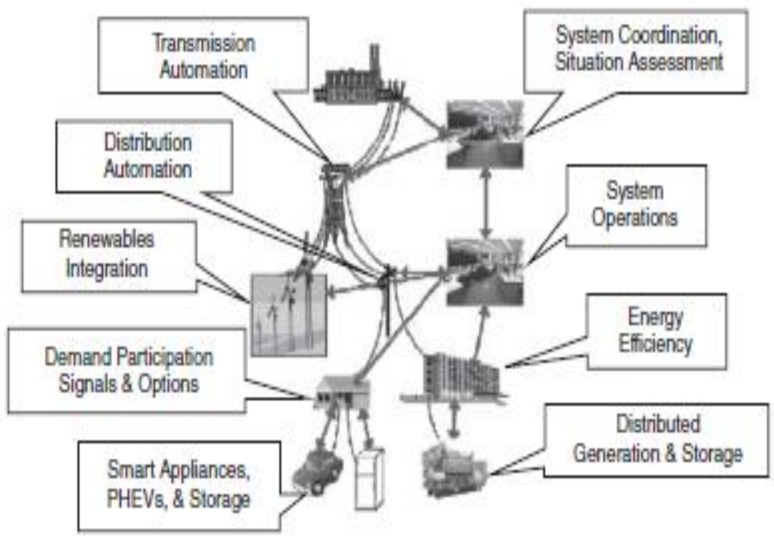


Fig. DOE Architecture of SG (First)

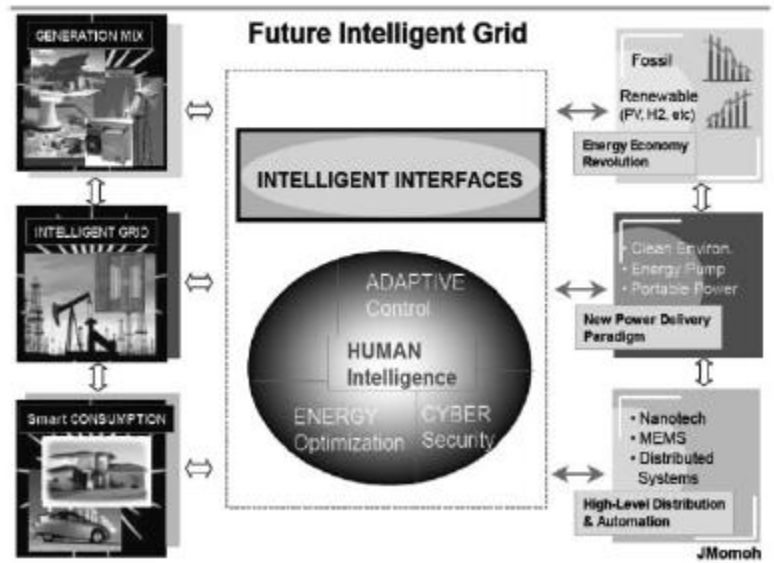
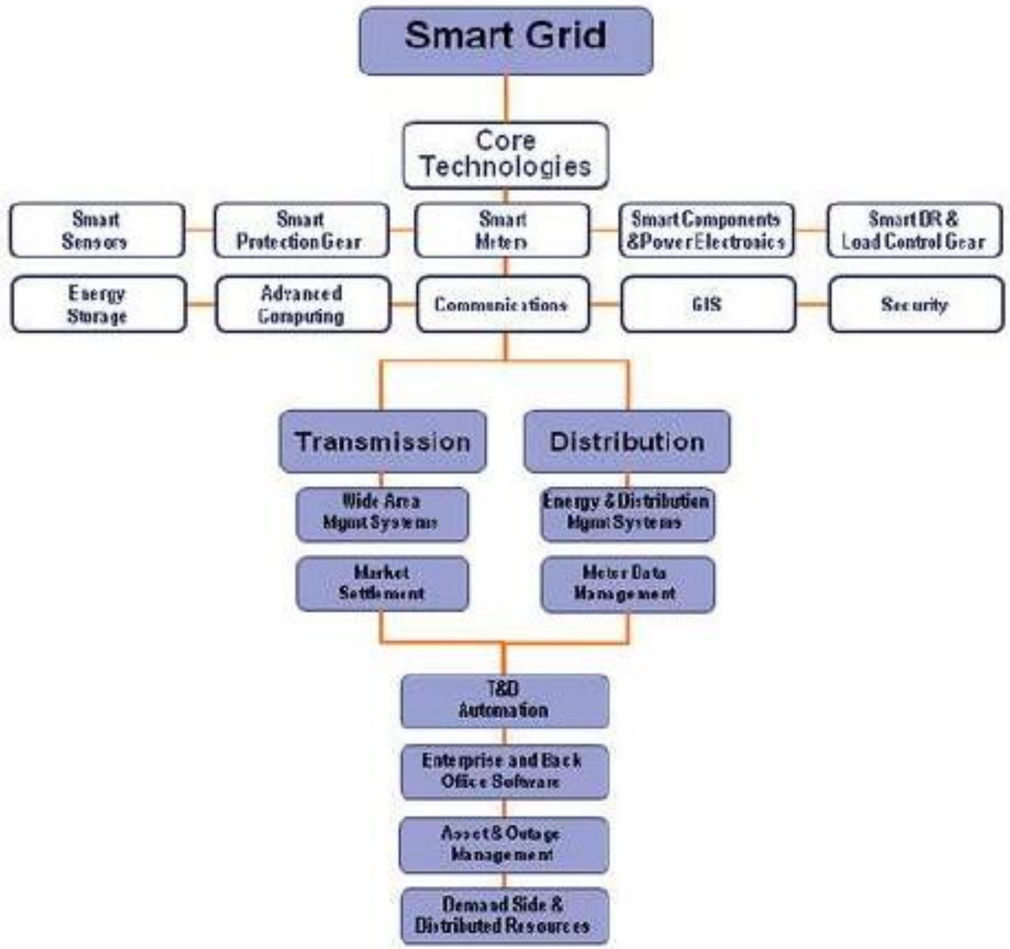


Fig. James Momoh Architecture of SG (second)

- First architecture is divided among 9 areas.
- Second architecture framework is into subsystems with layers of intelligence and technology and new tools and innovations.

A Generalized Architecture of SG

Architecture



SG Components & their Functions

1. **Smart Devices Interface Components:** Smart devices enables:
   - Real-time information process for control and monitoring of generation .
2. **Storage Component:** Storage opportunities exists in:
   - Pumped hydro, advance batteries, flow batteries, compressed air, super - conducting magnetic energy storage (SMES), super -capacitors, and flywheels.
3. **Transmission Subsystem Component:** Must tolerate:
   - Dynamic load changes & contingency without service interruption
4. **Monitoring & Control Technology Component:** Must handle:
   - Congestion, instability and reliability issues (Also allow real-time changes)
5. **Distribution Subsystem Component:** Support scheme enables:
   - Intelligent management (energy & information) among utility & consumers
6. **Demand Side Management Component:** Must enable options for:
   - Effective means of modifying the consumer demand to cut operating expenses from expensive generators and defer capacity addition

Research and scientific aspects of the SG

The Smart Grid concept is in itself an important and ambitious research program:

1. *It involves different timescales (short-, medium- and long-term)*
2. *It involves several stages including:*
   - *research,*
   - *development,*
   - *pilot demonstration,*
   - *feedback*
   - *deployment processes.*

Examples of the development of innovative concepts:

These projects are either funded by government agencies or community organizations (such as the European Commission in Europe or the Department of Energy in the US) or industrial entities and consortia.

1. *The scientific orientation is based on achievements in the field of:*
   - *automation of grid functions,*
   - *the integration of renewable energy sources,*
   - *the demand-side response,*
   - *energy-flow optimization*
   - *and the coupling of electricity infrastructure with ICTs.*

Guidelines to the development of innovative concepts

1. The distribution of intelligence:

1. *It involves self-adaptive voltage controller, decentralized decision process and intelligent protection, as examples.*

2. *These kinds of devices allow the insertion rate of distributed generators to be significantly increased within the existing network through solving specific distributed generator (DG) integration constraints.*

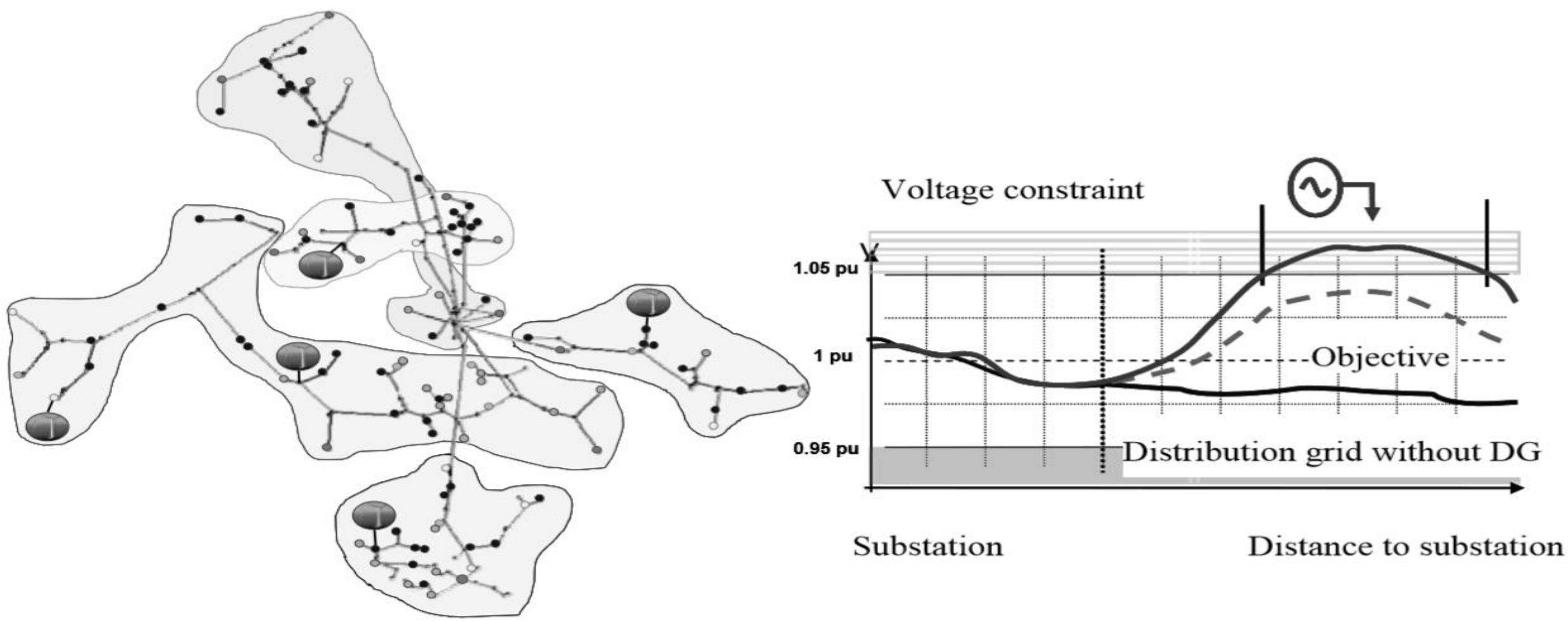


Figure 1.a. Distributed generation (DG) and voltage profile in distribution systems

Guidelines to the development of innovative concepts. Contd.

1. The distribution of intelligence:

3. Study cases and achievements can includes advanced decentralized or coordinated control function, such as voltage control per cell or islanding and automatic synchronization of portions of the grid.

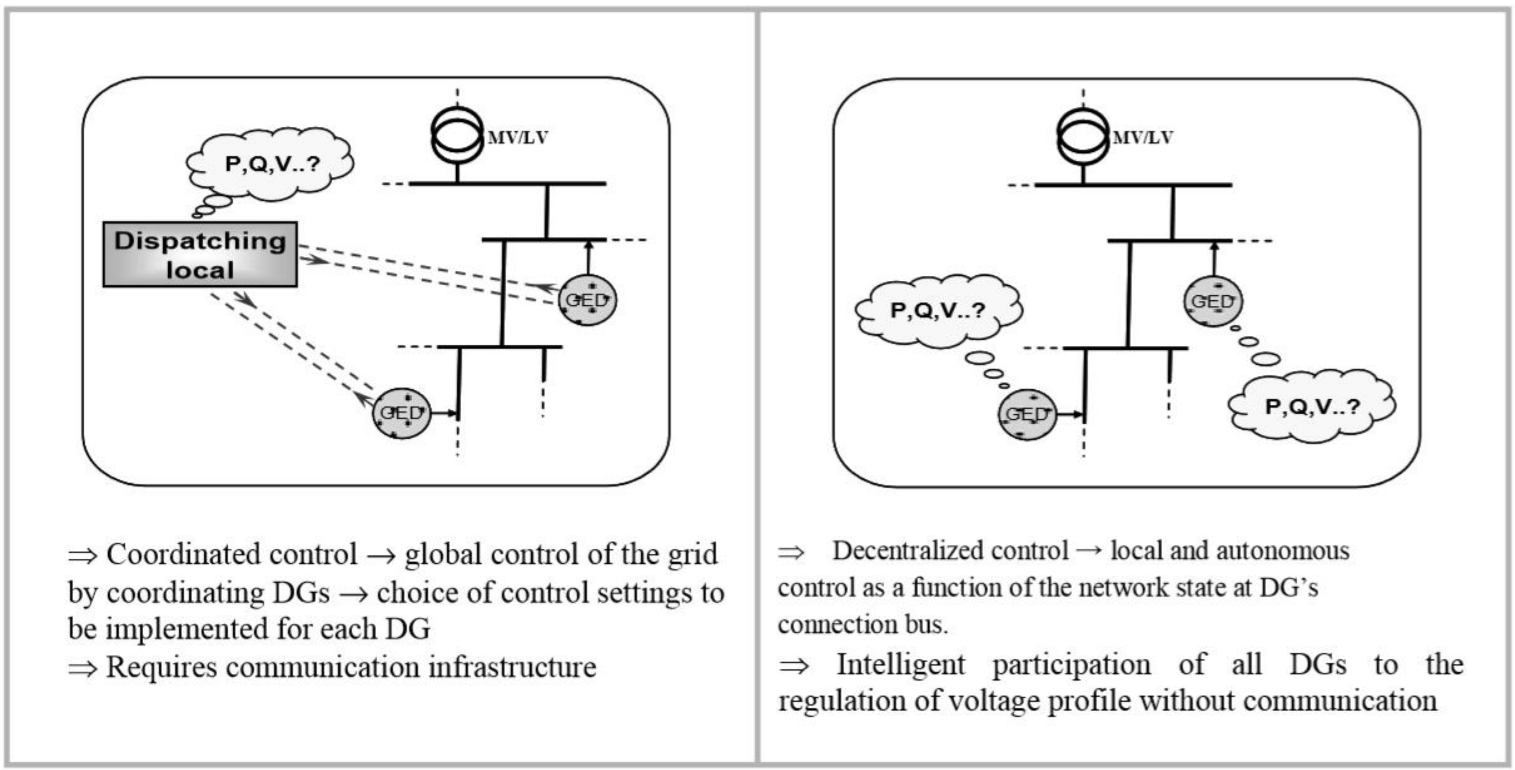


Figure 1.b. Intelligent voltage control modes in distribution systems in the presence of distributed generation

Guidelines to the development of innovative concepts. Contd.

1. The distribution of intelligence:

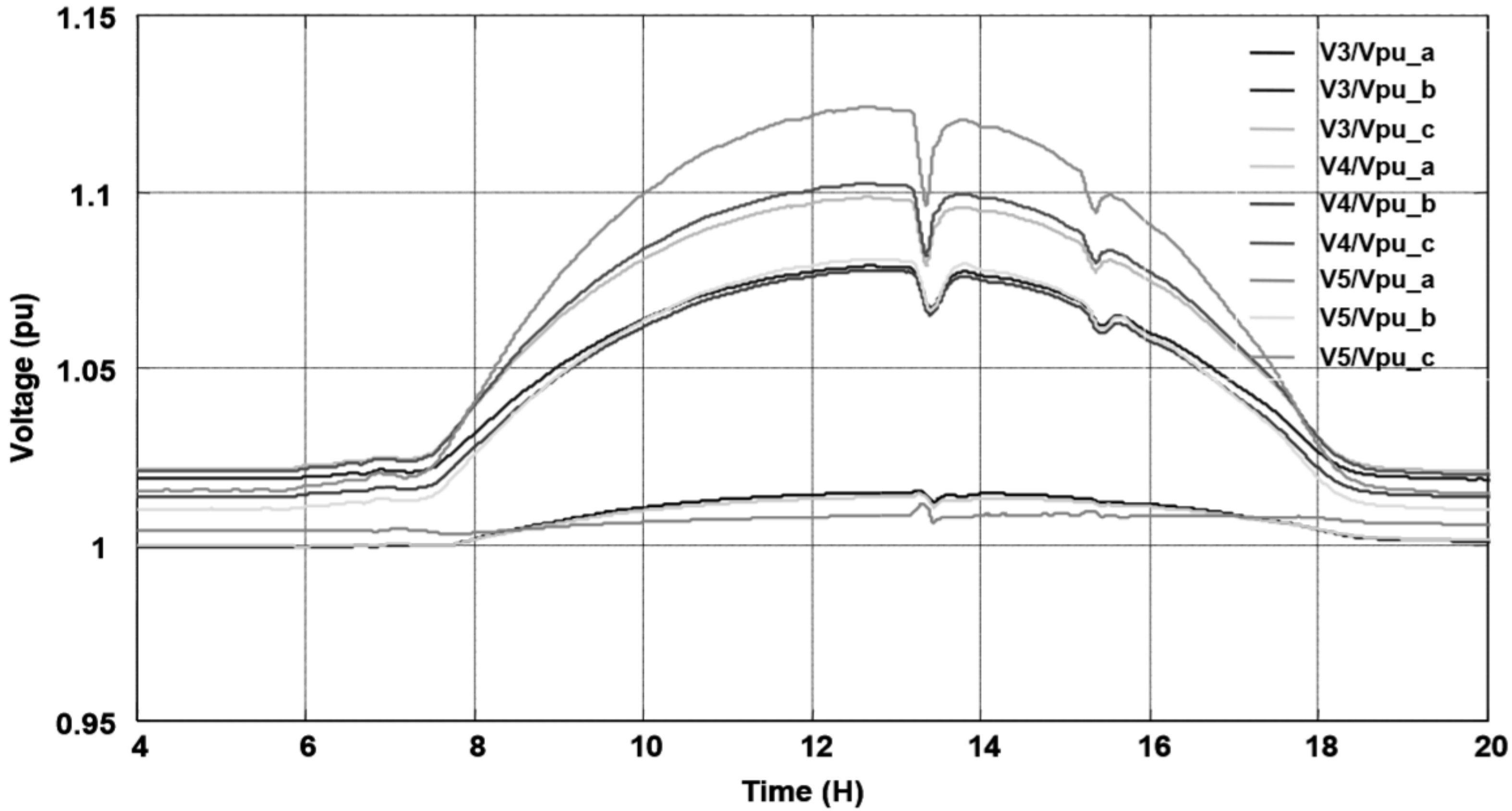


Figure. 1.c. Voltage management through conventional control (active/reactive or P/Q) on a test network

Guidelines to the development of innovative concepts. Contd.

1. The distribution of intelligence:

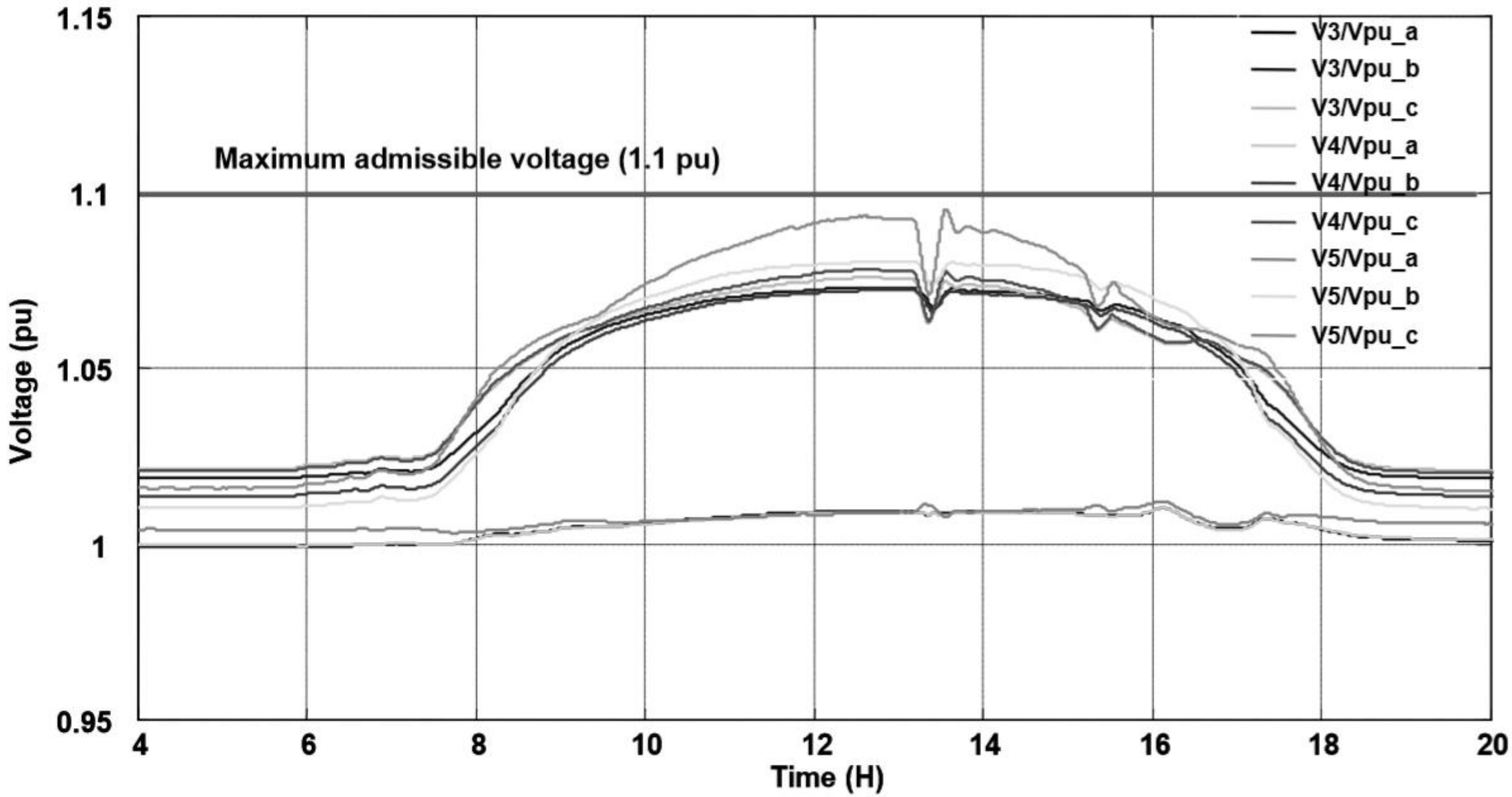


Figure. 1.d. Intelligent control of the voltage on a test network (Source: IDEA at http://www.leg.ensieg.inpg.fr/gie-idea)

Guidelines to the development of innovative concepts. Contd.

2. Self-healing power grids:

This concept concerns distribution grids.

The power grid must quickly:

Detect and even anticipate, isolate and restore safe operation in an optimal and automated way after the occurrence of a fault.

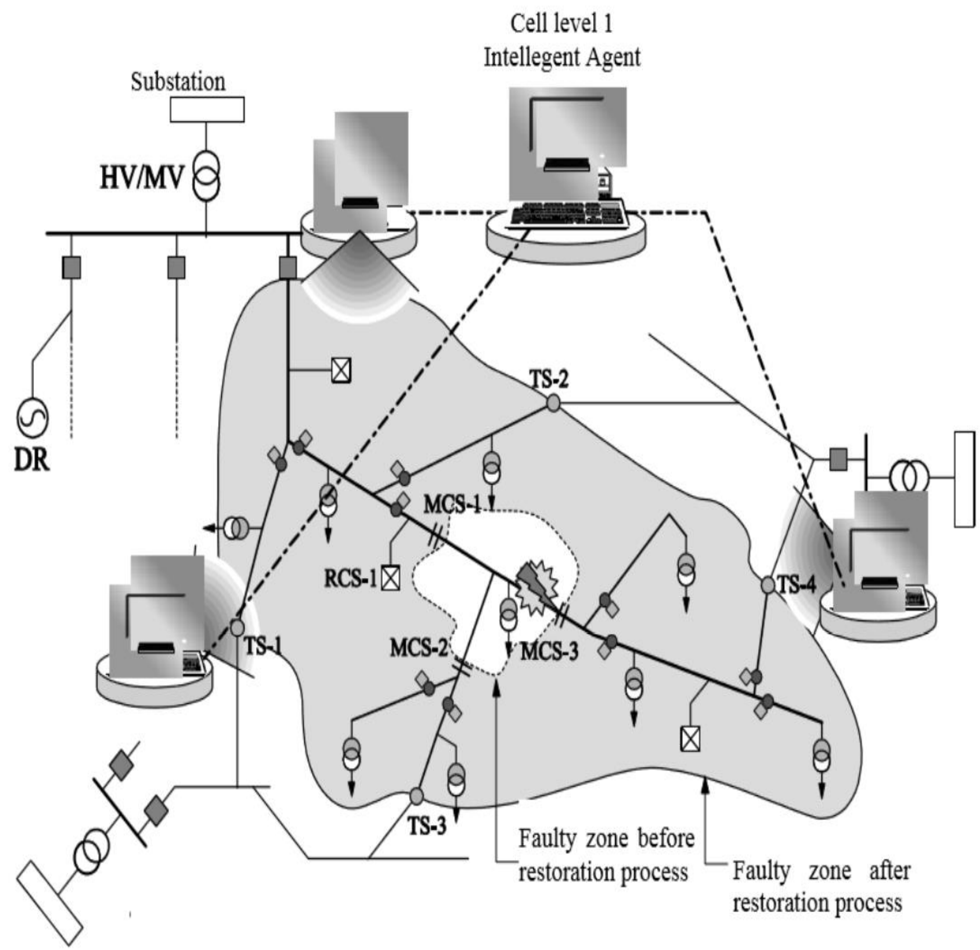
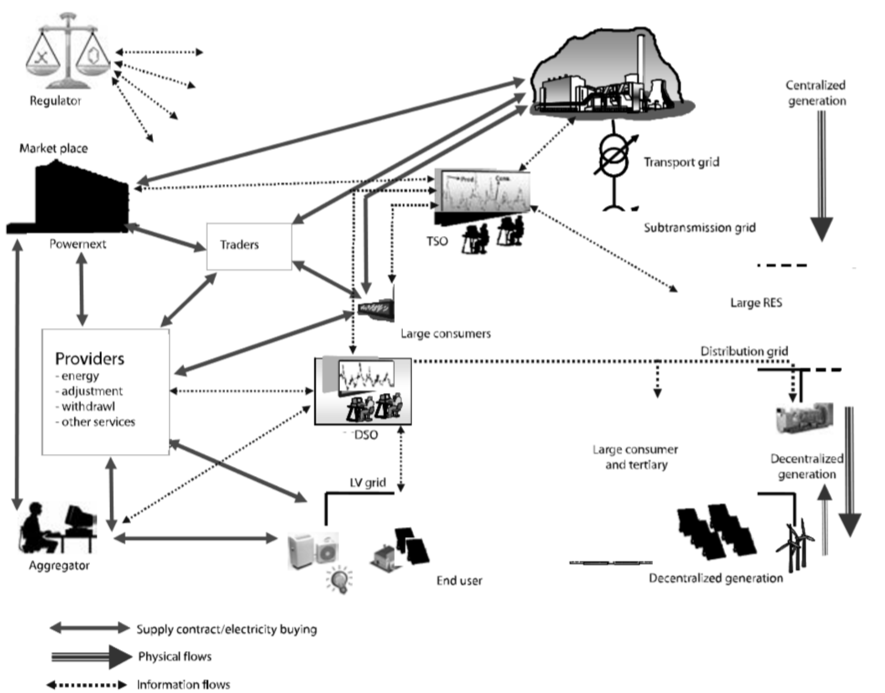


Figure 2.a. Concept of the self-healing network: detect, locate, repair and reenergize the network after a fault (Source: IDEAathttp://www.leg.ensieg.inpg.fr/gie-idea)

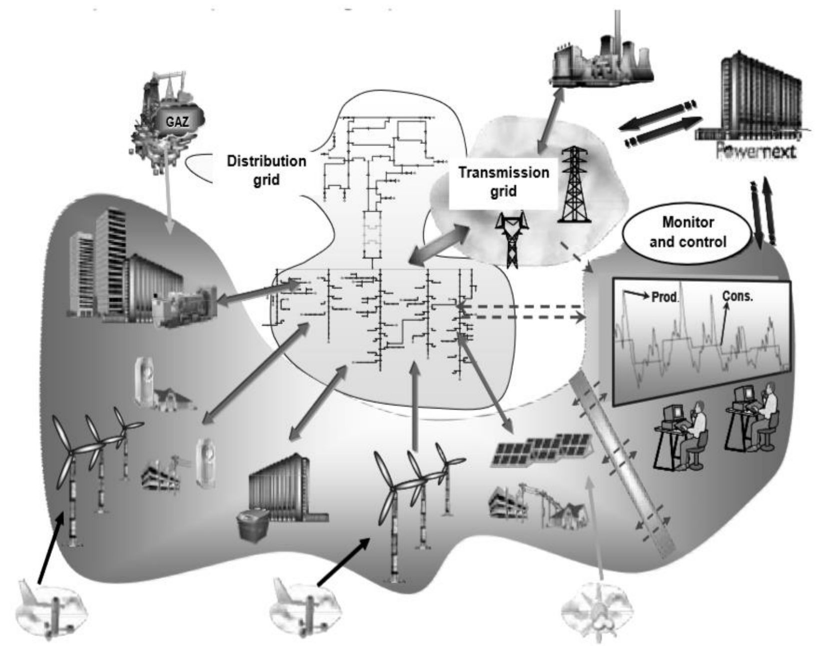
Guidelines to the development of innovative concepts. Contd.

3. The virtual power plant : *It is a concept that represents a set of methodologies for the connection and management of distributed energy resources at a large scale while taking account the intermittency.*

Figure 3.a illustrates an aggregation possibility of generation, storage and load control, as a single "virtual plant" allowing the power output of intermittent sources to be guaranteed or better controlled as in Figure 3.b.



Figue.3.a. Interaction of energy sources in VPP.



Figue.3.b. Virtual power plant: energy mix management & generation aggregation tool (Source: IDEA at http:// www.leg.ensieg.inpg.fr/gie-idea)

Guidelines to the development of innovative concepts. Contd.

***4. Observation of the power grid, particularly for distribution systems**.*

- *The transmission grid is concerned with the interconnected system and large-scale intermittent generation.*

- *The observation is an essential function for system control purposes. It can be viewed from the control center perspective and from sensors that are coupled to components and system decision processes.*

5. Reconfigurable grid architectures.

That increase the acceptable generation rate or optimize the electrical losses in the presence of distributed generation (energy efficiency).

6. Smart buildings and demand response/load control:

- *This aspect can be extended to the convergence of the electrical grid with buildings, renewable energies and PHEV.*

- ***Figure 6.a** shows possible interactions between different appliances, storage devices, local generation units, PHEV, energy boxes within a house and the electrical grid through a smart meter.*

Guidelines to the development of innovative concepts. Contd.

6. Smart buildings and demand response/load control:

- ***Figure 6.a*** *also shows that house communicates and becomes intelligent, and the step towards integrated management of all facilities (household appliances, telecommunication, electricity, safety, etc.) becomes smaller.*

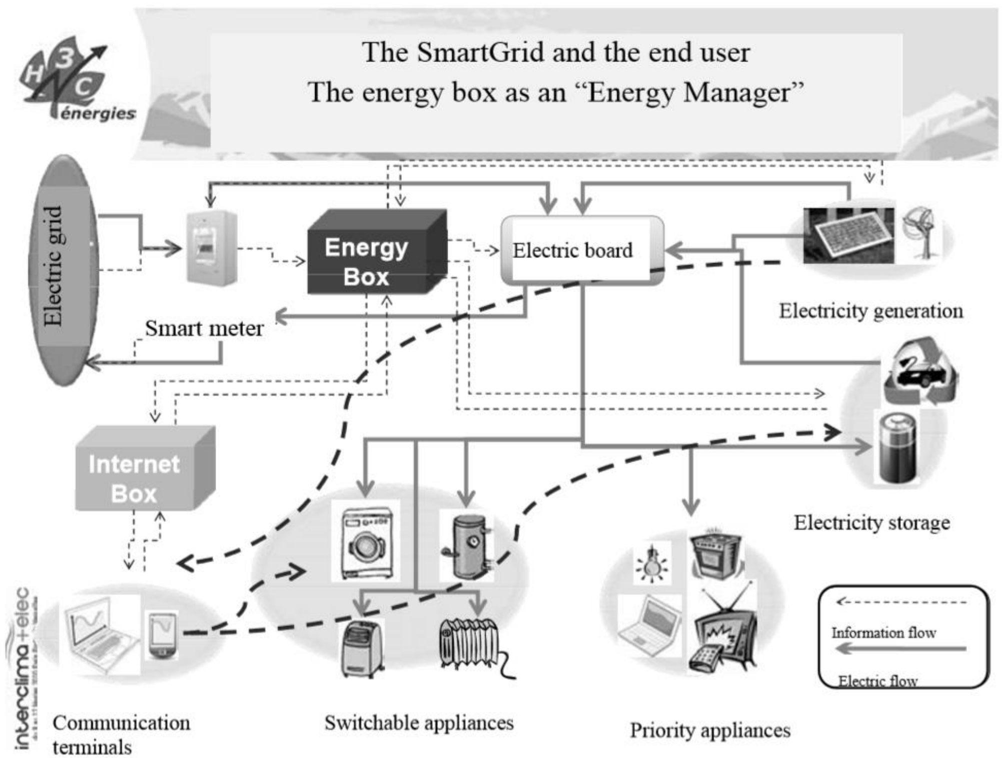


Figure 6.a. The smart house with its energy box and smart meter (source:H3C-Energiesatwww.h3c-energies.fr/)

Scientific, technological, commercial and sociological challenges.

Smart Grids allow the convergence of physical infrastructure (the electrical system) and digital infrastructure (ICTs).

It is well known that the meeting of two disciplines is a source of major innovations.

The challenges are classified into scientific, technological, commercial and sociological.

They are remarkable challenges that can only be met with the establishment of partnerships (and technological processes) involving all stakeholders in this chain.

The chain consists of the following: *(energy producers, system operators, energy service providers, electrical equipment and ICT manufacturers, solution integrators, universities and research centers, standardization bodies, energy associations and agencies).*

Of course, the final customer must also be included as an active entity and no longer as a passive consumer.

Scientific and technological Challenges

- **Integration of renewable energies** and management of intermittency for a global system balance and economics, including the participation of these energy sources in ancillary services.
- **Integration of PHEVs on the grid**, their various forms of load and interaction with the system (injection, consumption, storage, control and services).
- **Observability of the grid** with a reduced set of sensors (with appropriate accuracy) or on the basis of smart meters while taking into account real-time constraints.
  – It also includes data processing and the management of large amount of information with respect to a dynamic bidirectional communication “grid-smart meter”.

Scientific and technological Challenges. Contd.

- **Development and implementation** of “simple” and cost-effective **self-healing technologies** in the presence of distributed generation including at the low-voltage level.
- **Protection/equipment** with frequent switching capabilities, allowing multiple grid reconfigurations for better flexibility and reduced losses (better energy efficiency).
- **Coupling of load control** with new usages (PHEVs) or intermittent generation (convergence of buildings, renewable energies, PHEVs and power grids) within cell distribution grids or “eco-smart cities”.
  - This part includes coupled models and simulation tools.

Scientific and technological Challenges. Contd.

- **Understanding the interdependency between the digital (virtual) and the electrical power (physical) infrastructures**.
  - This aspect also falls within the requirement for coping with increased system complexity and ensuring system security (including cyber security) while embedding various “smart” technologies into the grid.

- **Planning of Smart-Grid investments** in an uncertain environment (appropriate models, stochastic approaches, risk management, etc.) and evolution of power grid architectures.

Commercial and sociological Challenges.

- **Business models** for diffuse and efficient demand response, including value capturing and sharing, given the responsibility partitioning of the energy value chain.
- **Levels of technological deployment** in an industry accustomed to slow evolution and transition.
- **Acceptability to customers** with respect to the intrusion of load control technologies and smart meters as well as to their “positive” behavior in participating to demand response.
- **Global optima** with new usages.

Preparing the competences needed for the development of Smart Grids

- Smart Grids **require cross-disciplinary competences** as well as the capitalization of expertise, since the future “smarter grid” will have to be built on the basis of existing power infrastructures (evolution process).
- Thus, **existing training programs** in power engineering need to incorporate knowledge on information and communication science and vice versa.
- Curricula addressing **Smart Grid competences** with new evolving education programs needed to be finalized.
- **Investment in power grid equipment** must be accompanied by a serious modernization and an effort to recruit young engineers and technicians who are well armed and motivated to build the intelligent networks of the future.