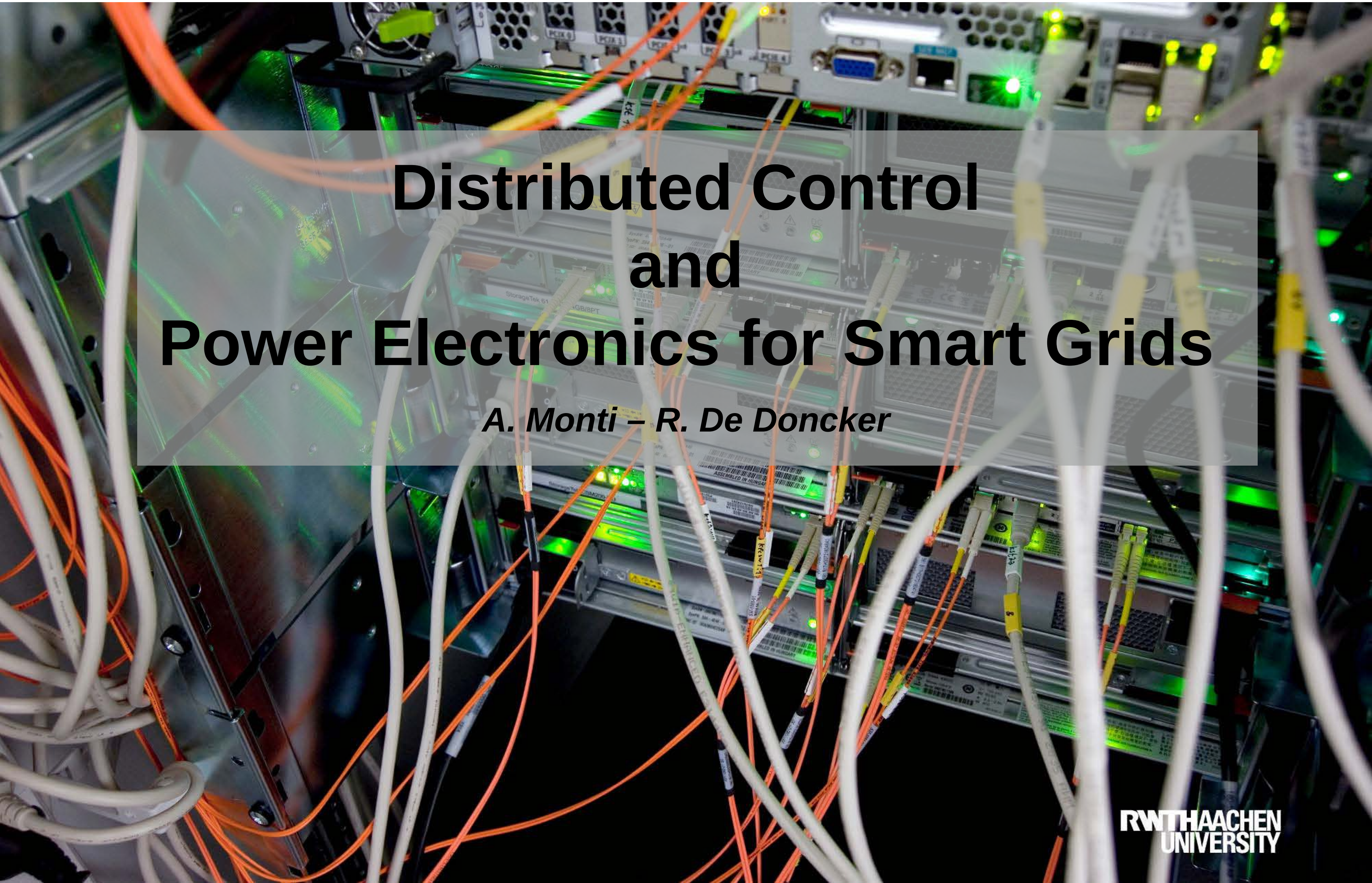


Distributed Control
and
Power Electronics for Smart Grids

A. Monti – R. De Doncker

RWTH AACHEN UNIVERSITY

Summary

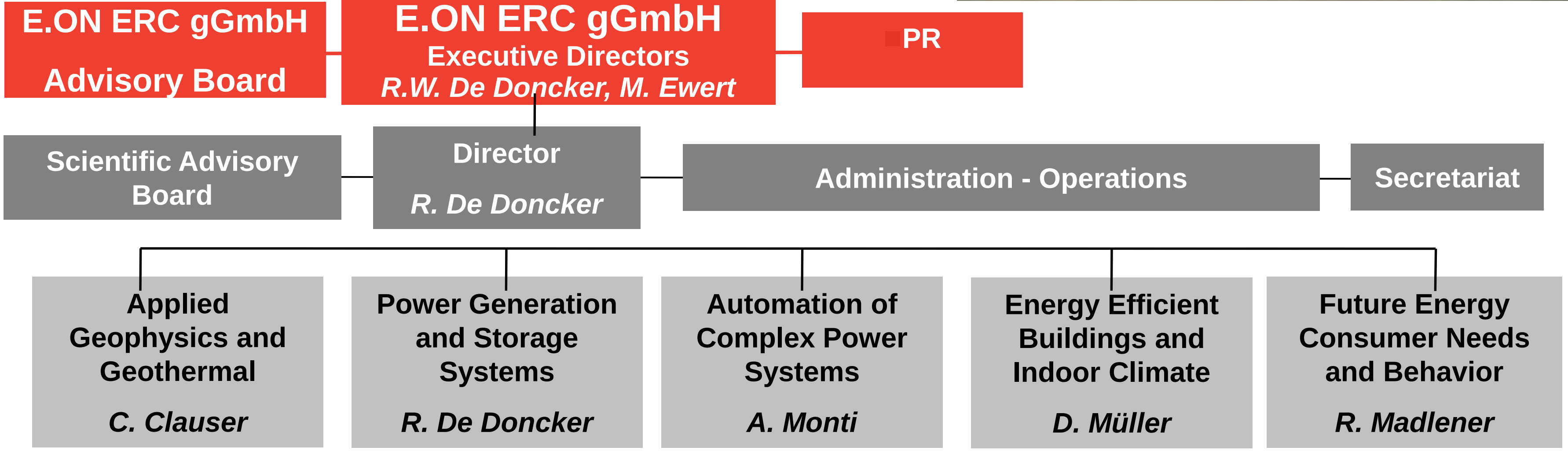
- E.ON ERC
- Global Vision
- The network today, the network of the future
- The role of DC systems
- Looking ahead
- Smart Grids and Standard
- Conclusion

Co-operation between RWTH and E.ON

June 2006: the largest research co-operation in Europe between a private company and a university was signed

Five new professorships in the field of energy technology were defined across 4 faculties

Research Area: Energy savings, efficiency and sustainable power sources



E.ON ERC gGmbH
Advisory Board

E.ON ERC gGmbH
Executive Directors
R.W. De Doncker, M. Ewert

PR

Scientific Advisory Board

Director
R. De Doncker

Administration - Operations

Secretariat

Applied Geophysics and Geothermal
C. Clauser

Power Generation and Storage Systems
R. De Doncker

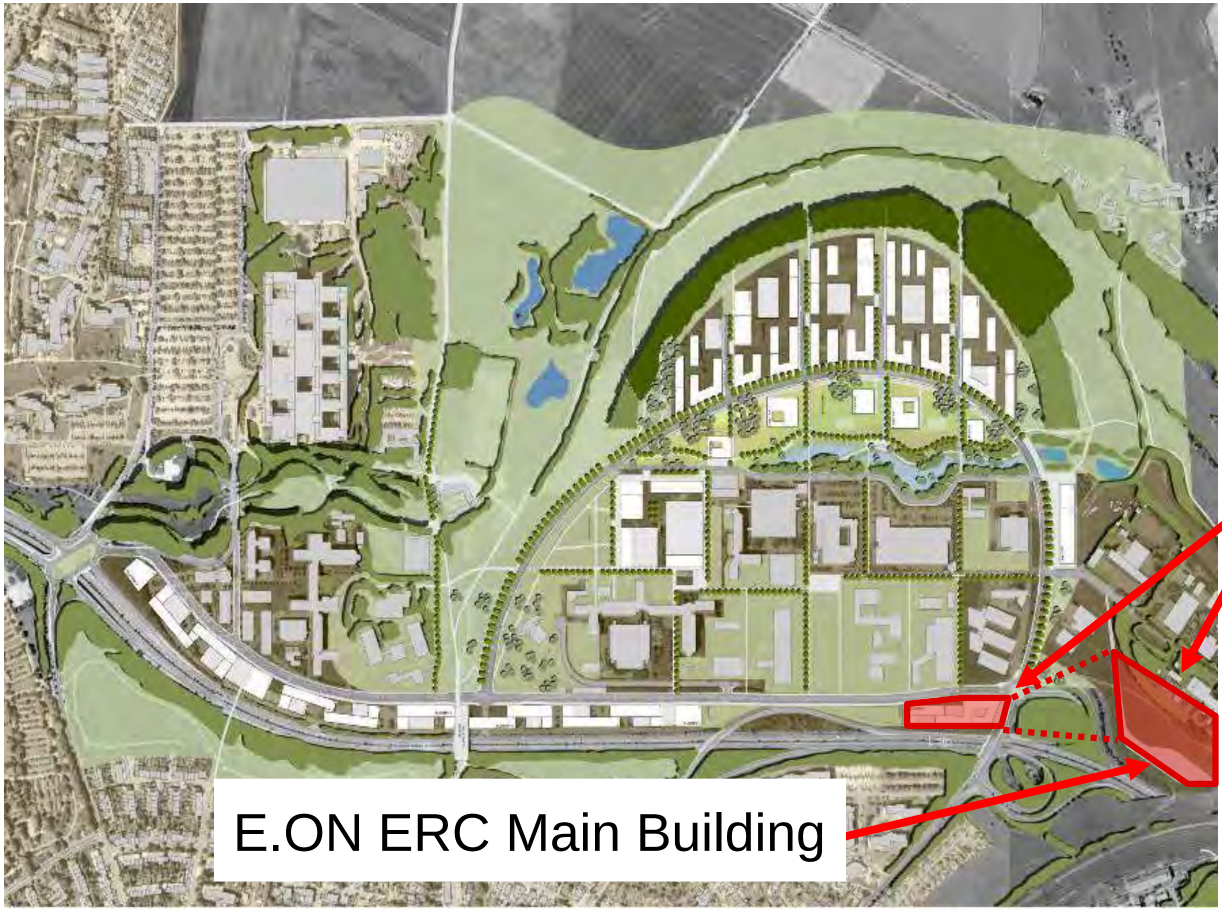
Automation of Complex Power Systems
A. Monti

Energy Efficient Buildings and Indoor Climate
D. Müller

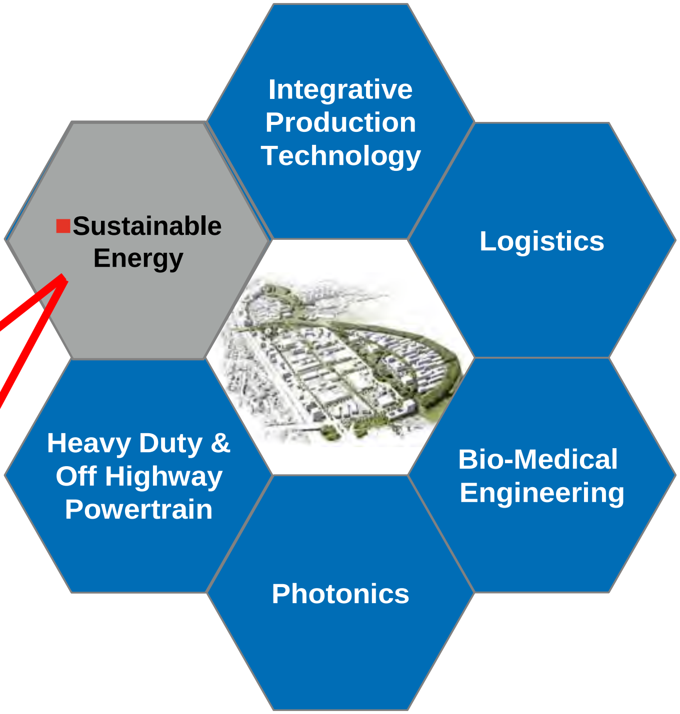
Future Energy Consumer Needs and Behavior
R. Madlener

RWTH Aachen Campus

The six starting clusters of RWTH Aachen Campus at Melaten: E.ON ERC leads the Sustainable Energy Cluster



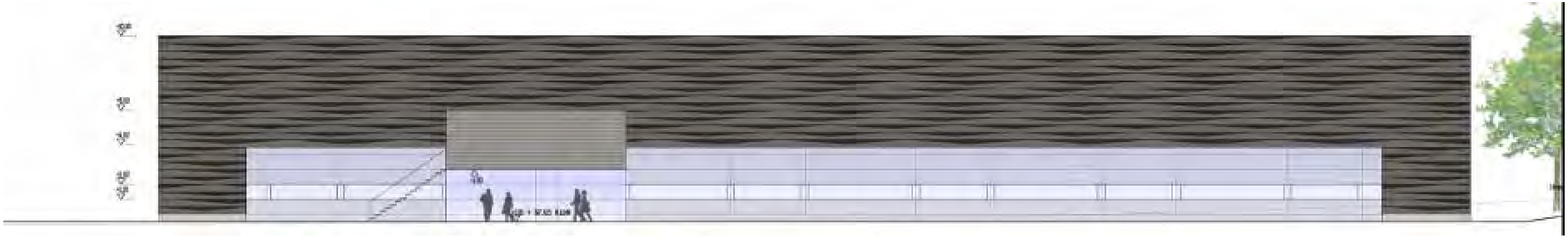
🟥 Quelle: RWTH



E.ON ERC Test Hall

Construction started Jan. 2009

- Front view - Mathieustraße

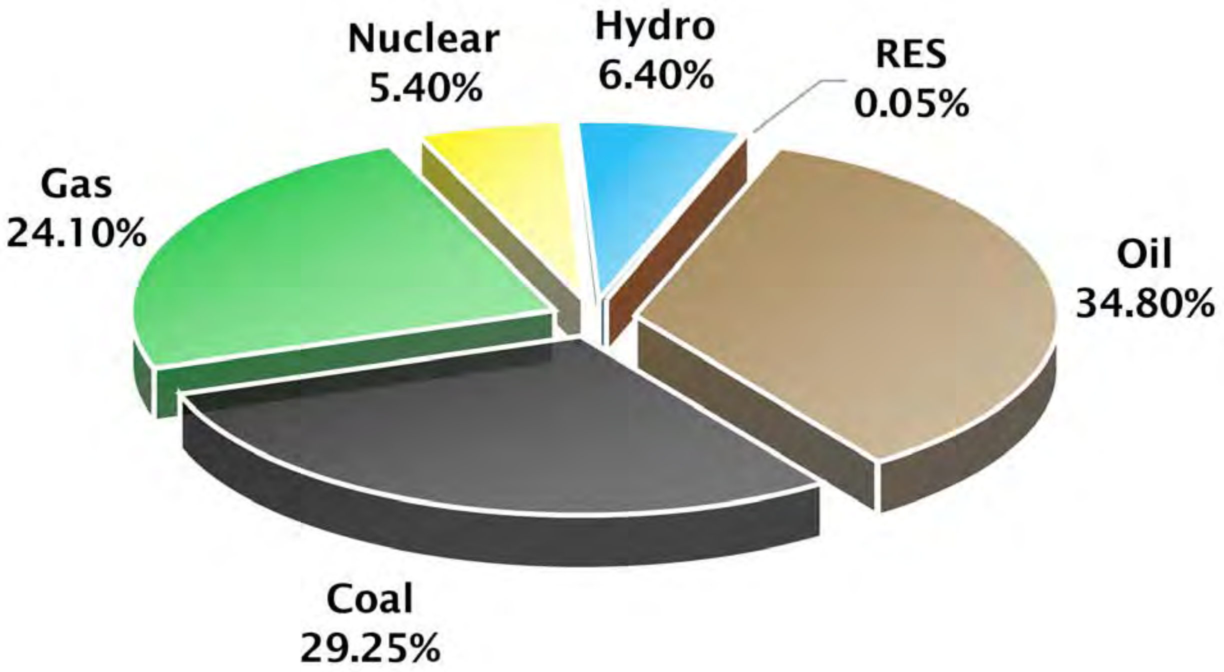


- Rear view - side E.ON ERC Main Building

Design Fischer Architects

	Building Ready	Useful area
Main Building	December 2010	3.100 m²
Test Hall	October 2009	1.000 m²
New Building	July 2009	1.550 m²

Global Status

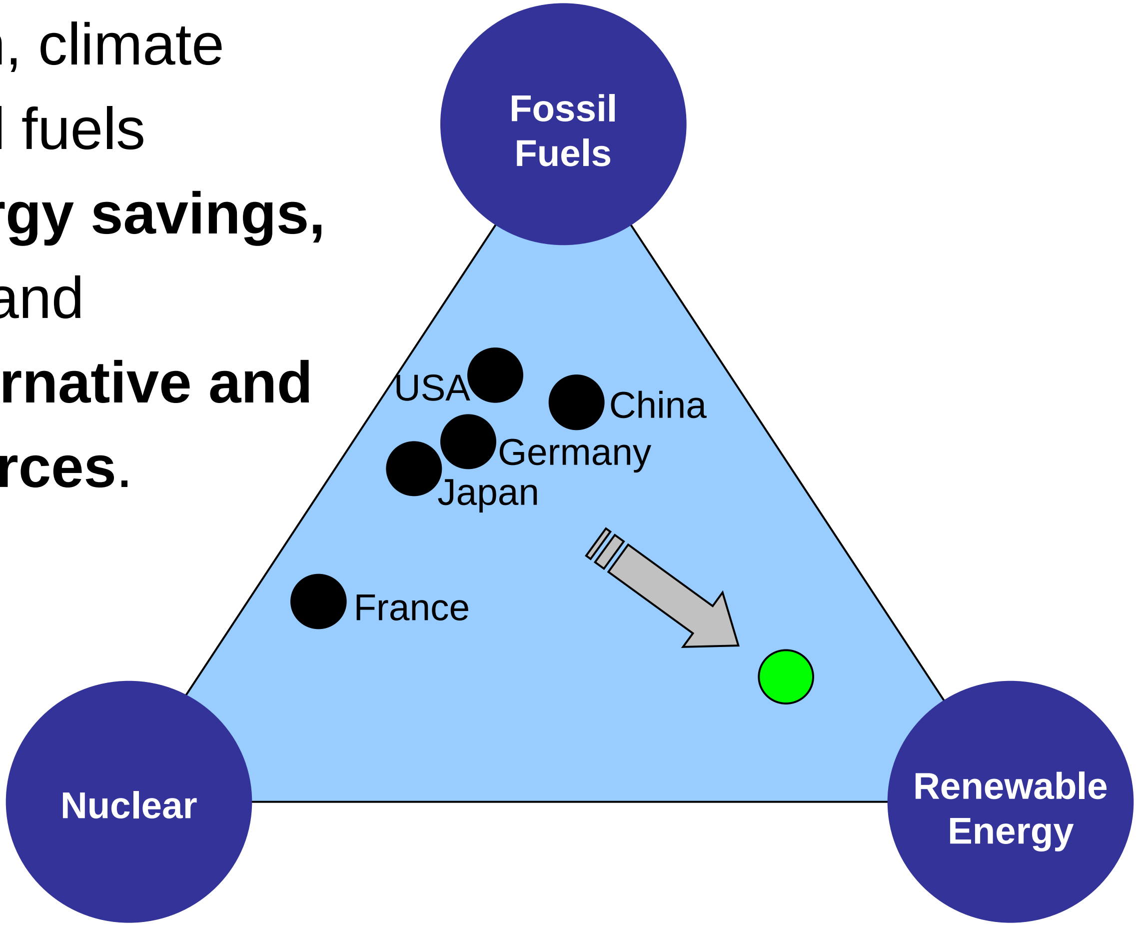


Global Primary Energy Consumption
Source: BP Report June 2009

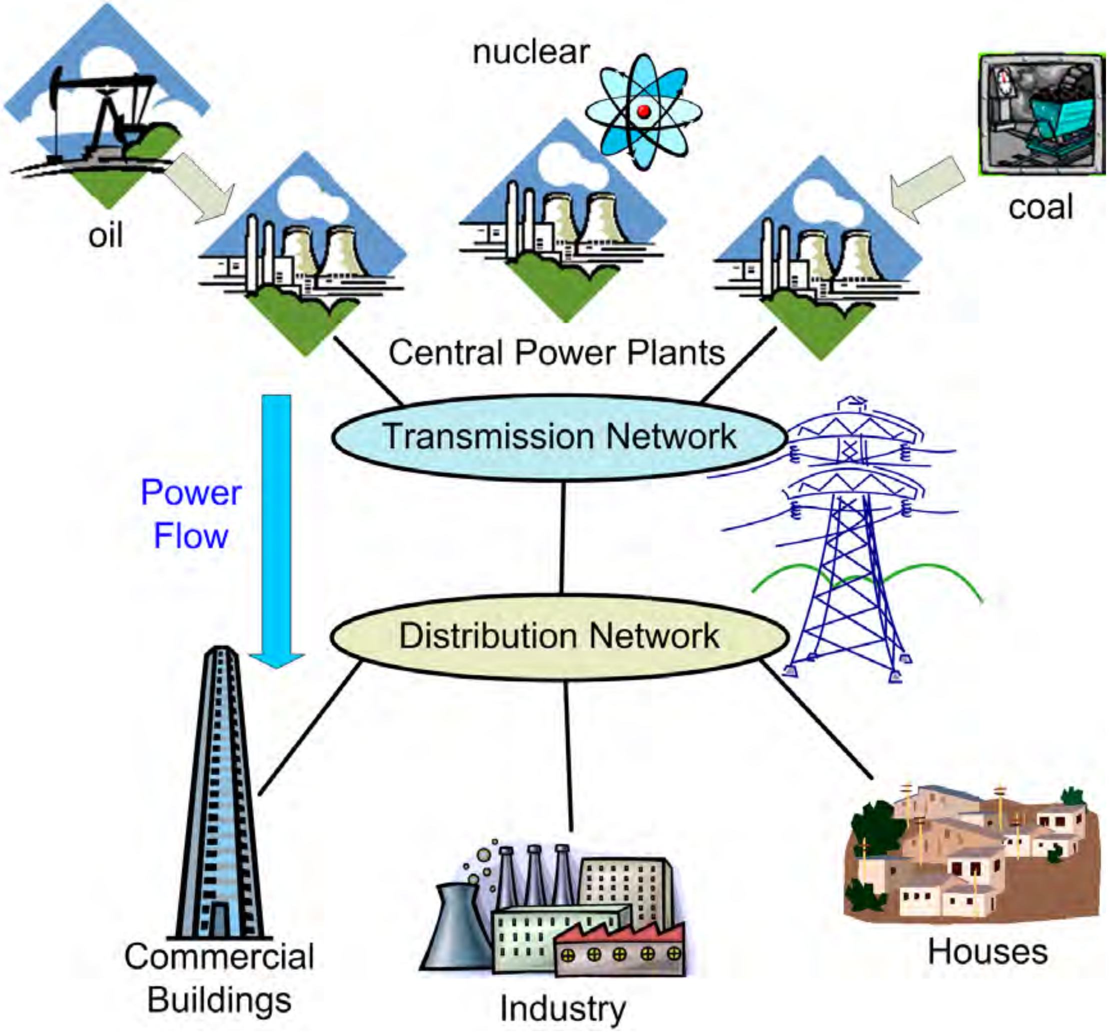
Reserves – how much time left?

Global Vision

Increasing urbanization, climate change, declining fossil fuels reserves enforces **energy savings, improving efficiency** and **increasing use of alternative and renewable power sources**.



Power Systems Today



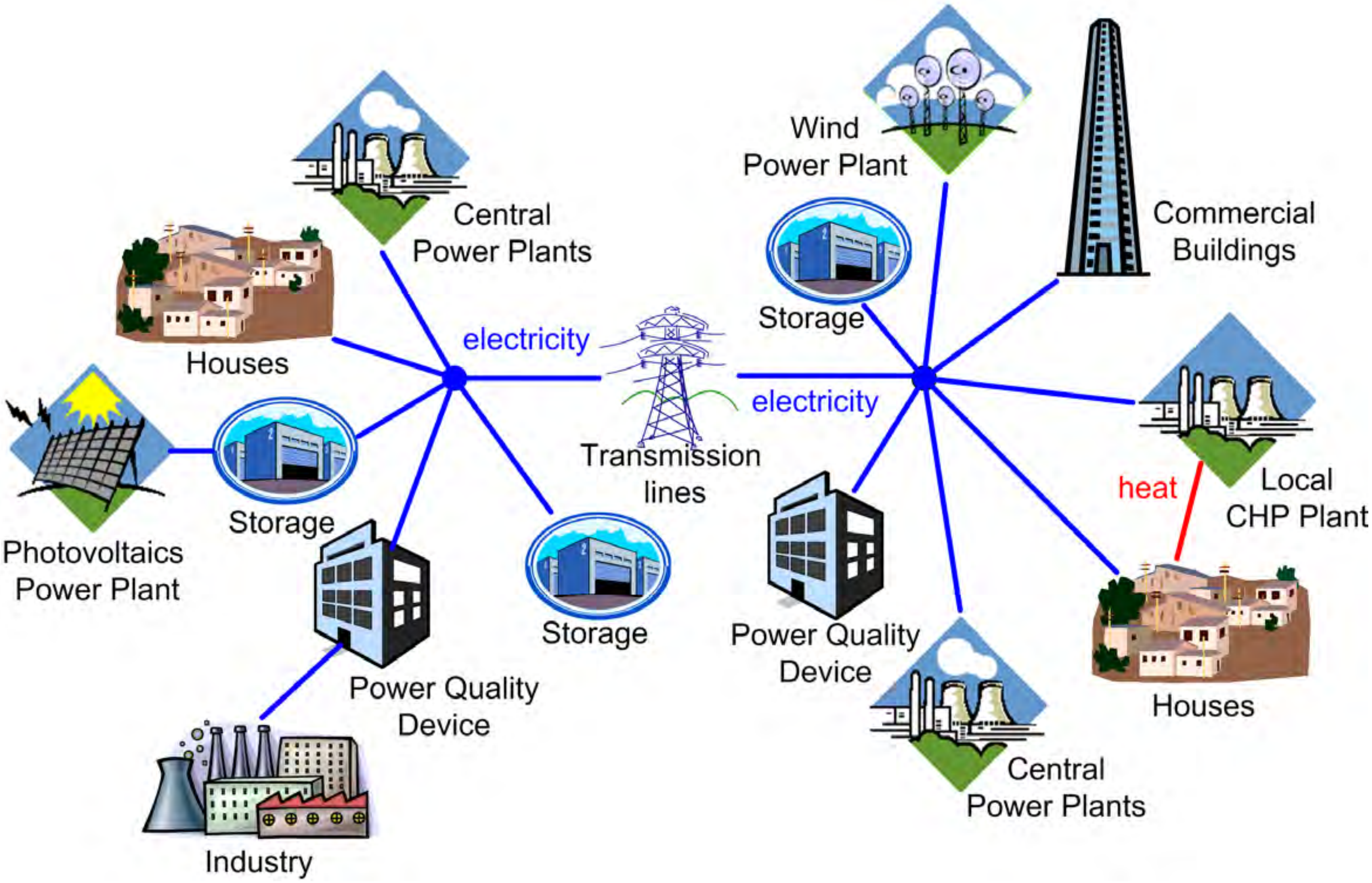
Source: IET, Aalborg University

Characteristics of the present

- Generation highly concentrated
- System is quasi-static
- Generation is “totally” under control
- Load are statistically predictable
- Flow of energy from transmission to distribution is unidirectional
  - Distribution is a totally passive system

Power Systems in the Future

E.ON Energy Research Center



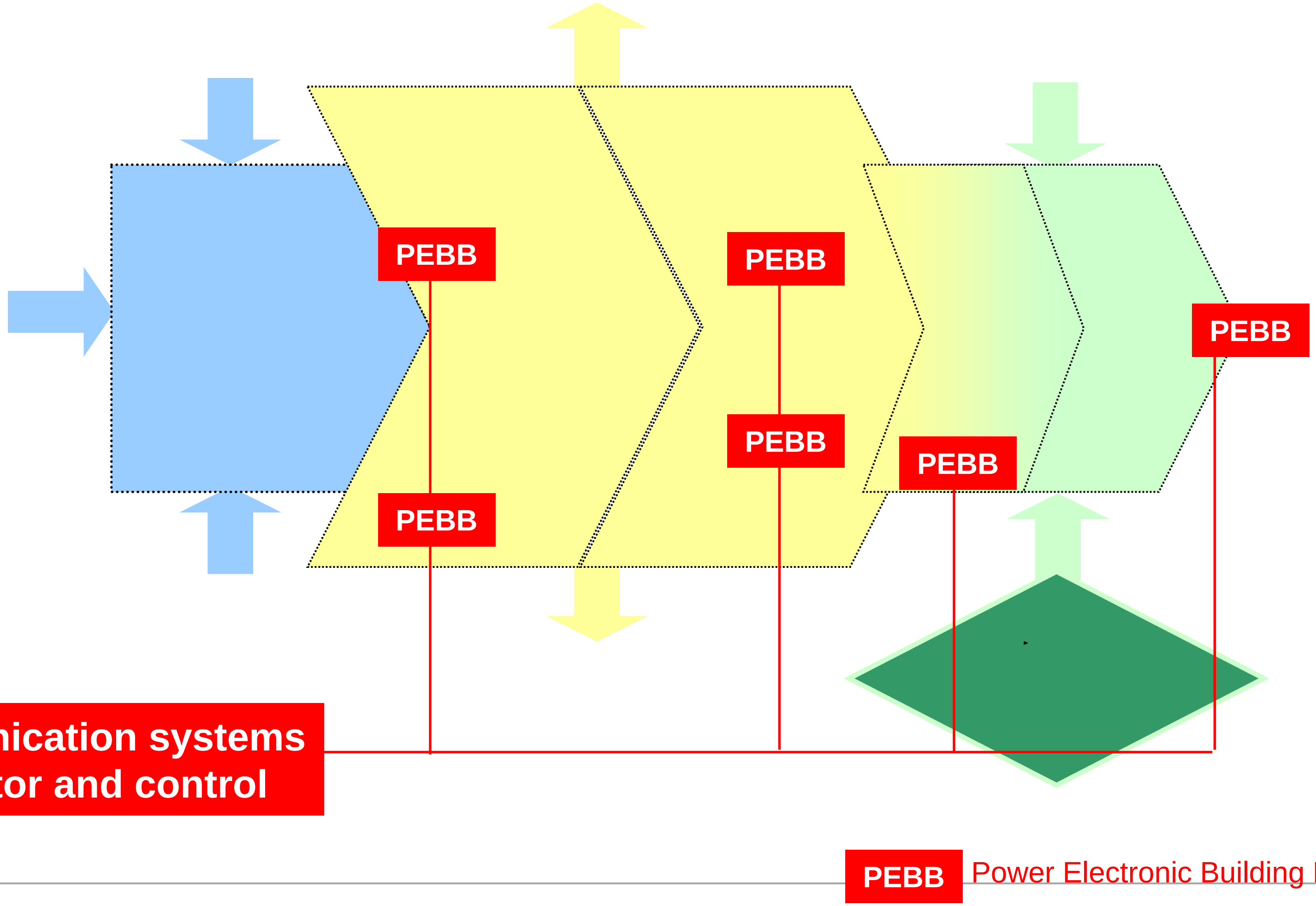
Less central power plants and more distributed power generation

- *Source*: IET, Aalborg University

Characteristics of the future

- More distributed generation
- Renewable sources are not totally predictable (uncertainty) and not under our control
- Power injection happens also at distribution level
- The system is characterized by higher dynamics
  - E.g. wind puff

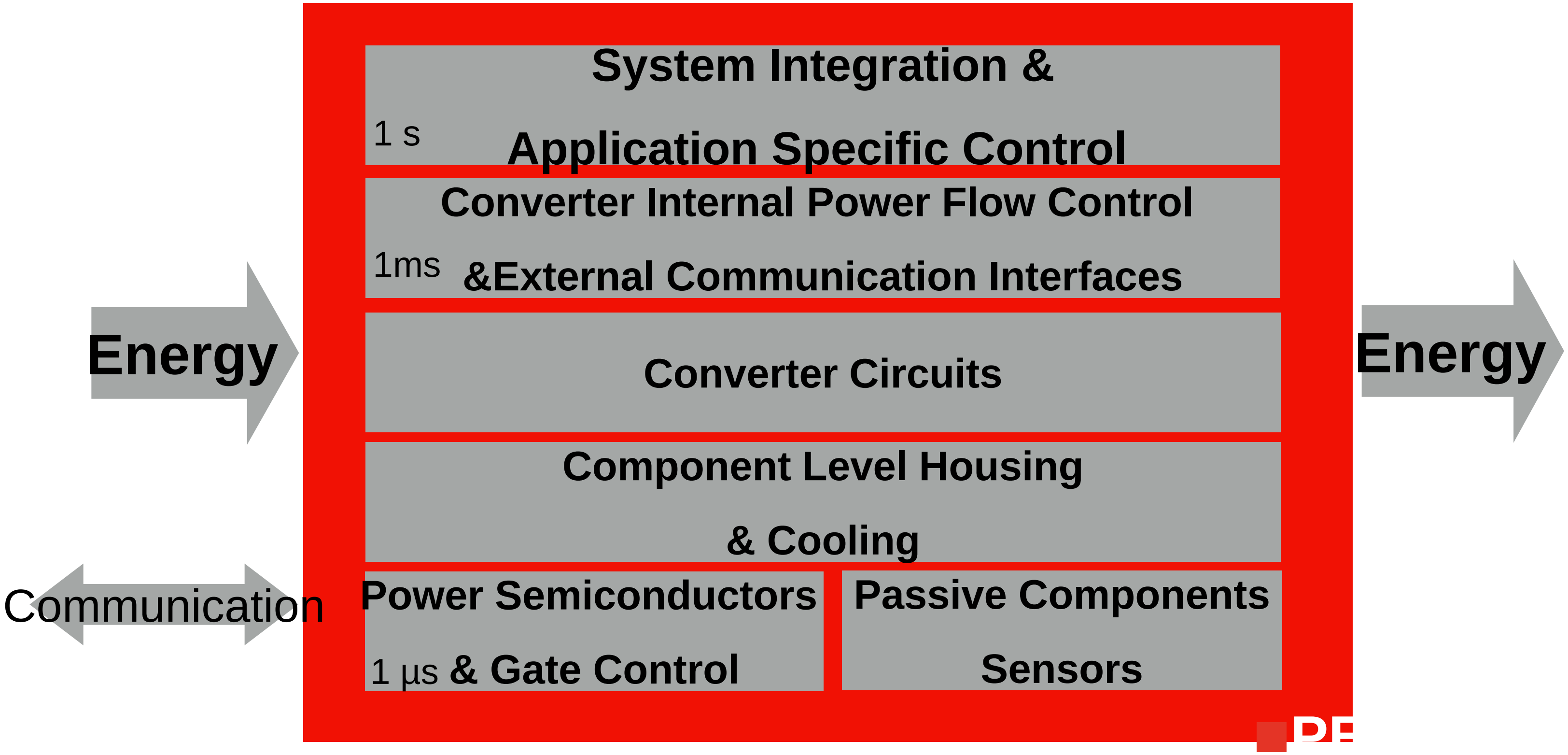
Future Technologies



PEBB Power Electronic Building Block

Power Electronic Building Blocks

PEBB Physical Layers and Design layers



System Integration &

1 s **Application Specific Control**

Converter Internal Power Flow Control

1ms **&External Communication Interfaces**

Converter Circuits

Component Level Housing

& Cooling

Power Semiconductors

1 μs **& Gate Control**

Passive Components

Sensors

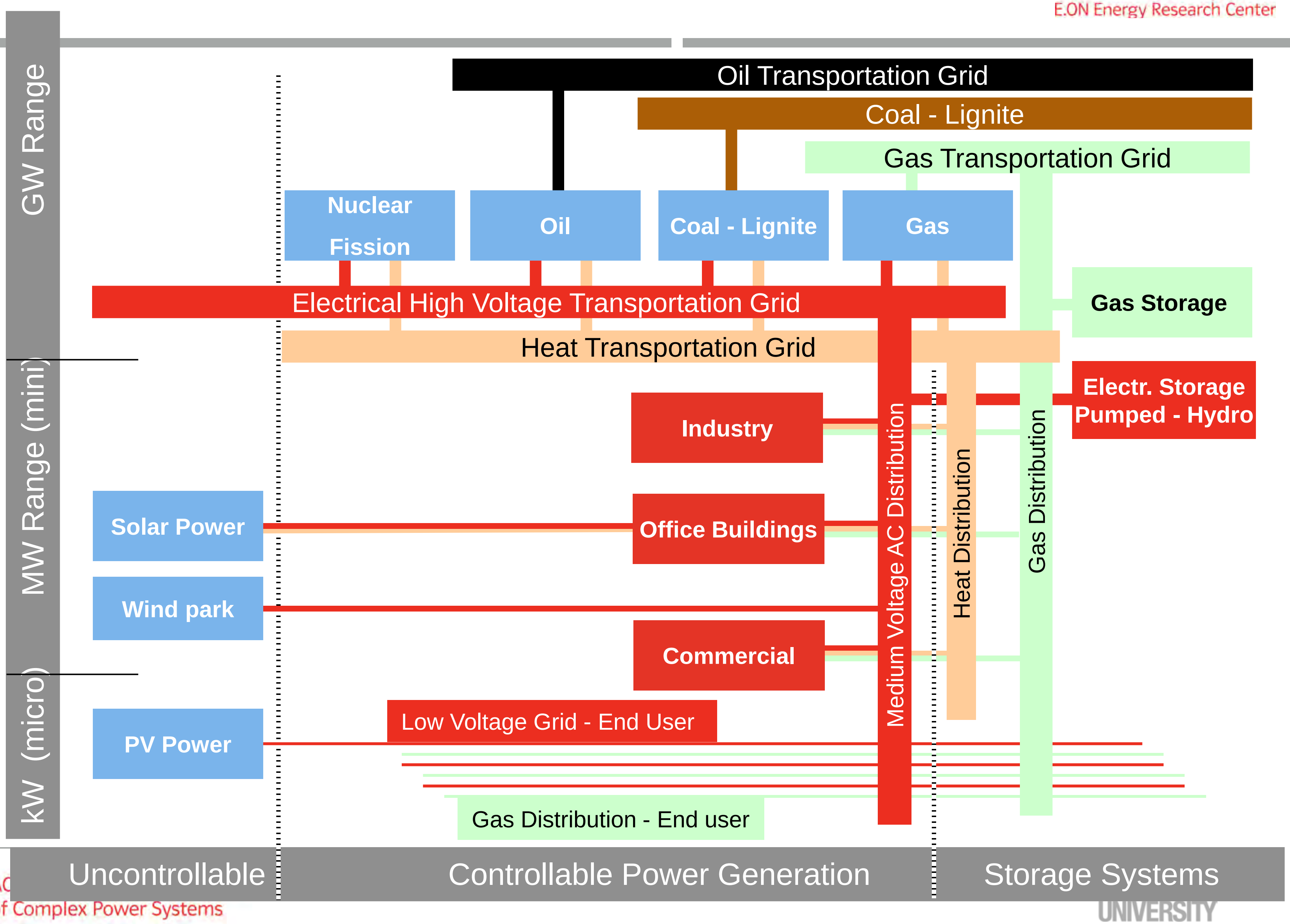
Energy

Energy

Communication

- Highly efficient energy (99%) conversion with PEBBs
- Suitable for dc-to-dc converter, generator side converters and line-side converters at medium voltage
- Scalable in power from 0.5 to 50 MW

Present Power Generation & Distribution



GW Range

MW Range (mini)

kW (micro)

Oil Transportation Grid

Coal - Lignite

Gas Transportation Grid

Nuclear Fission

Oil

Coal - Lignite

Gas

Gas Storage

Electrical High Voltage Transportation Grid

Heat Transportation Grid

Electr. Storage Pumped - Hydro

Industry

Solar Power

Office Buildings

Wind park

Commercial

PV Power

Low Voltage Grid - End User

Gas Distribution - End user

Medium Voltage AC Distribution

Heat Distribution

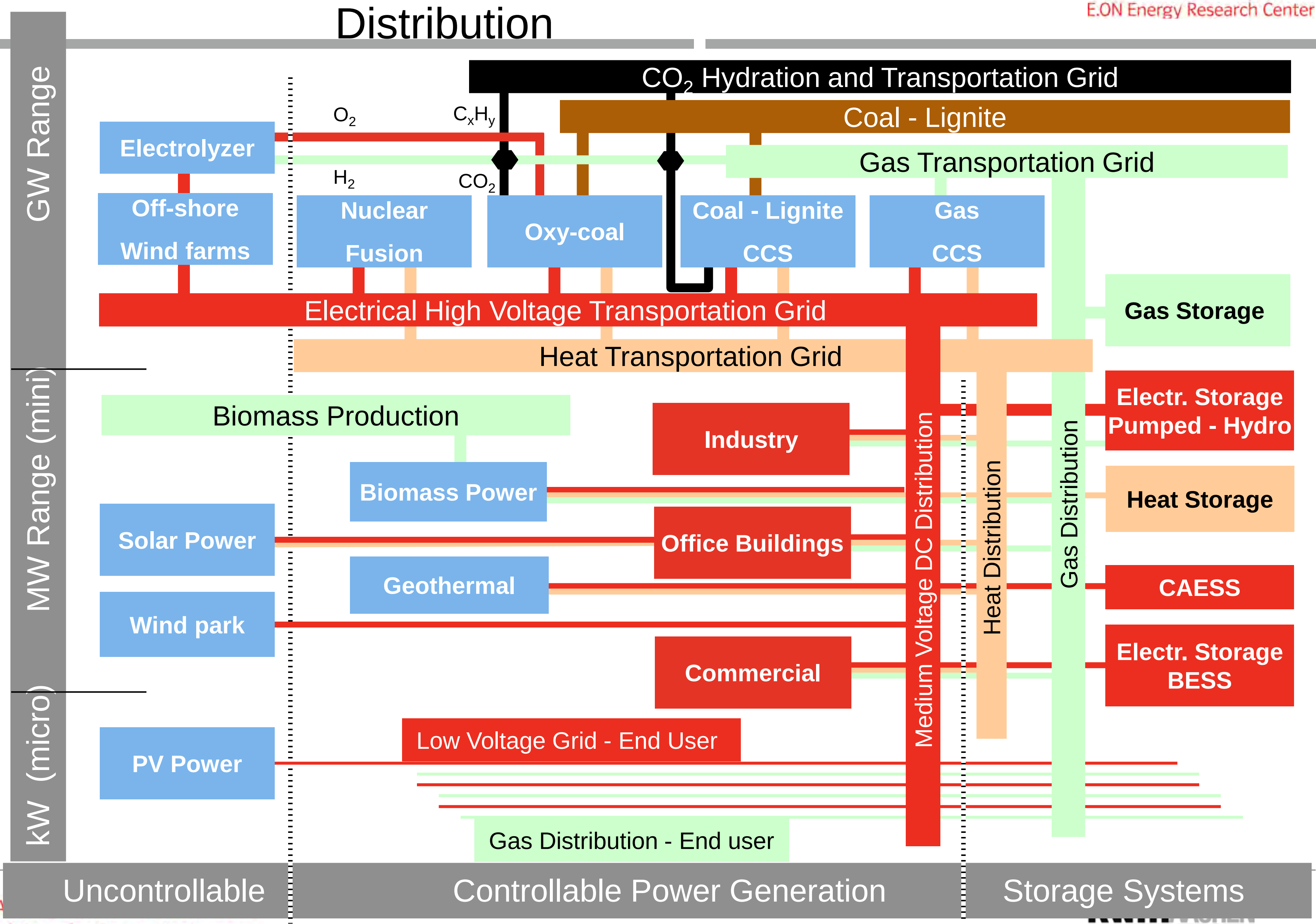
Gas Distribution

Uncontrollable

Controllable Power Generation

Storage Systems

Future Power Generation & Distribution



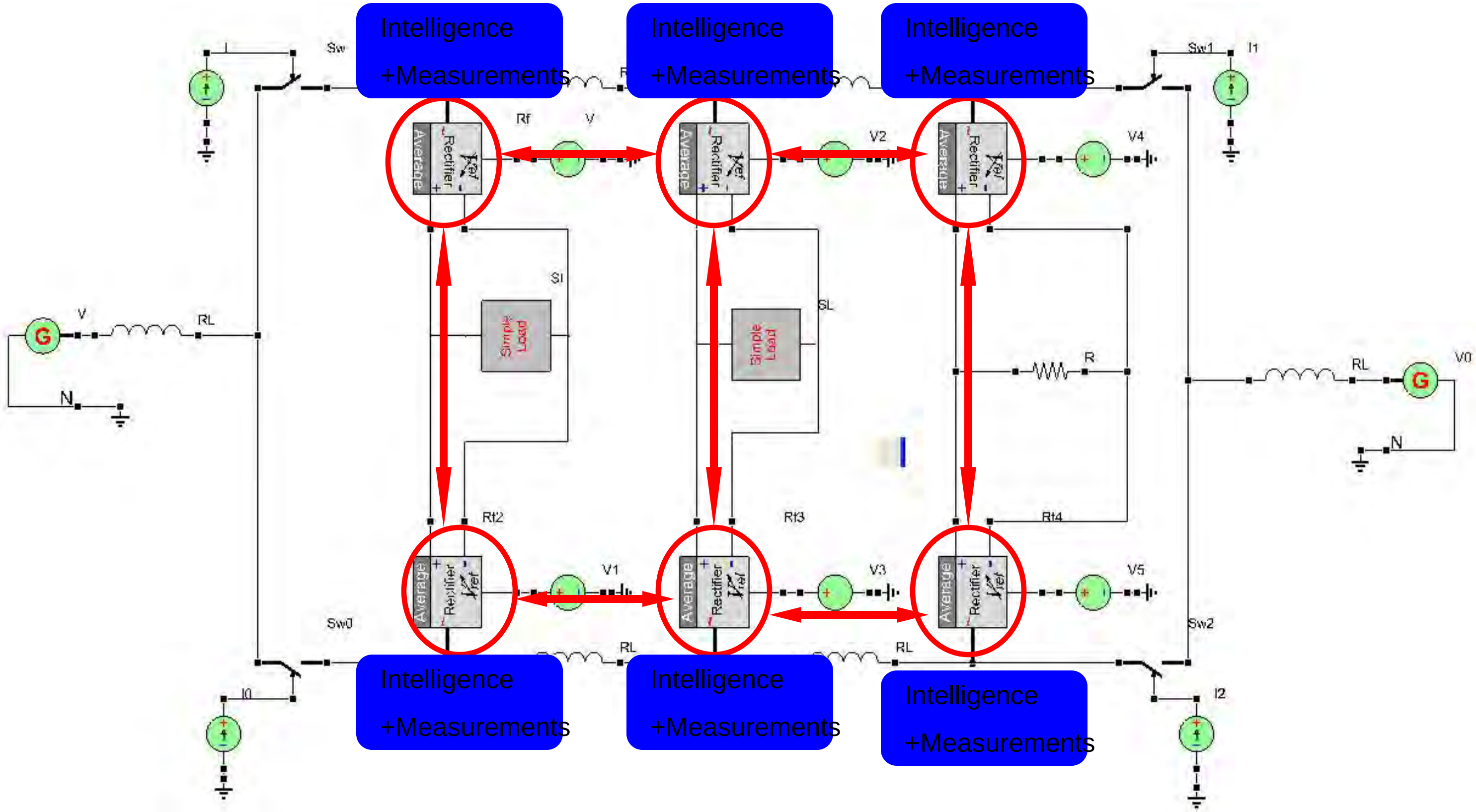
Challenges

- The Electrical energy system must be constantly balanced
  - if the sources are less predictable the balance is less predictable
  - If more sources are present and decentralized (not under the authority of one or very few companies) the balance becomes more complex
- The Distribution system is not ready for automation
  - Very limited monitoring
  - Protection designed for unidirectional flow of power
- The operation of the system are designed under the assumption of low dynamics
  - Control rooms still have man in the loop
  - Data refresh is in the order of seconds
- Possible impact at transmission level if large renewable plants are used
- Strong need for large storage systems

Open Questions

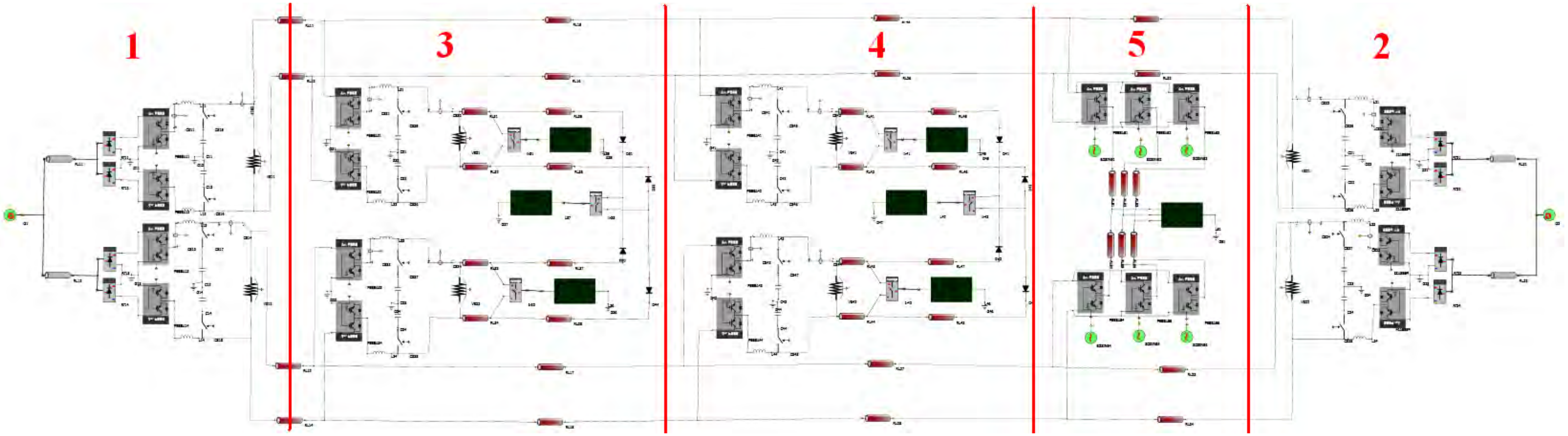
- What is the limit of stability of the network with distributed resources?
- How much renewables are we ready to absorb?
- What kind of architecture for the control of distribution?
- Who is going to be in charge?

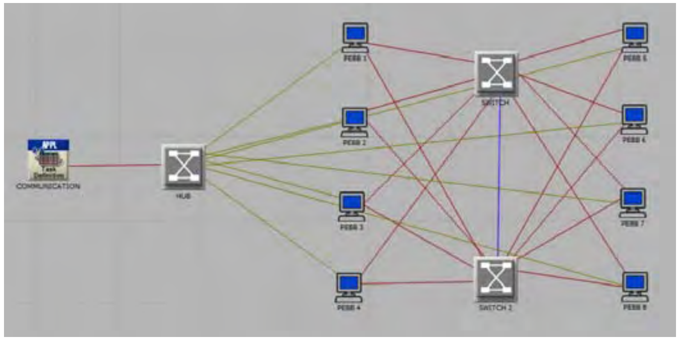
Previous lessons: Integrated Power Systems for Ships



Multi-physics Multi-domain Simulation

All Electric battleship as first example of SmartGrid: installed loads overpass generation





OpNet Communication model

VTBPro Power System Model

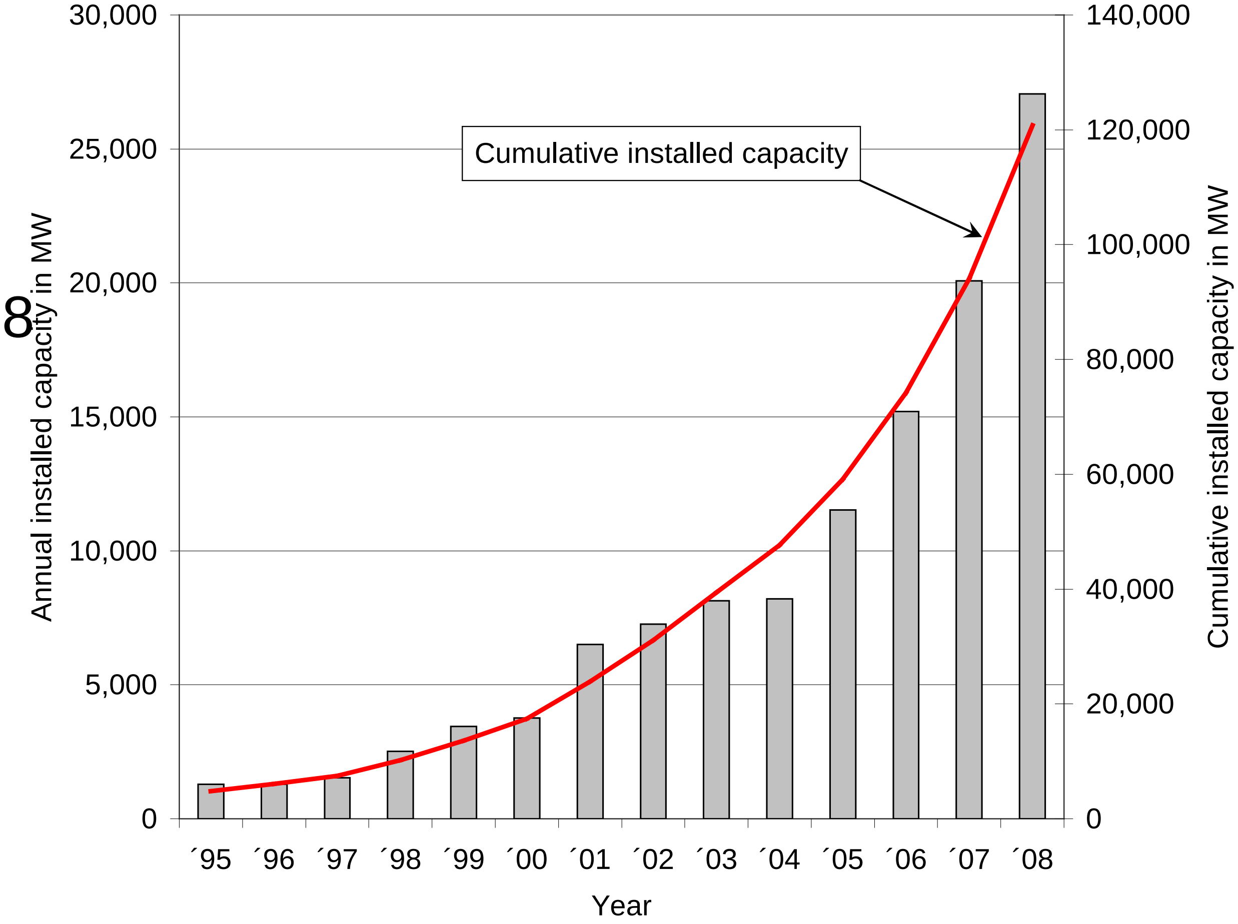
- New co-simulation approach to realistically represent communications
- Study of coordination logic among different intelligent components
- Each converter is capable of locally managing the protection but it coordinates its action with the peers
- Communication models developed according to IEC Standard

Decentralized Energy Production Combined with Base Mini-Power Stations

- Due to their low power density, regenerative energy systems are decentralized in nature
  - Wind, solar, PV
  - Biomass, hydro, geothermal
- Power electronics technology and communication is becoming mature and economically attractive to be integrated into power sources
- Co-generation: production and distribution of heat and cooling is decentralized
- Diversity in electrical energy production, service technology and reliability is critical

Wind Power – Installed Capacity Worldwide

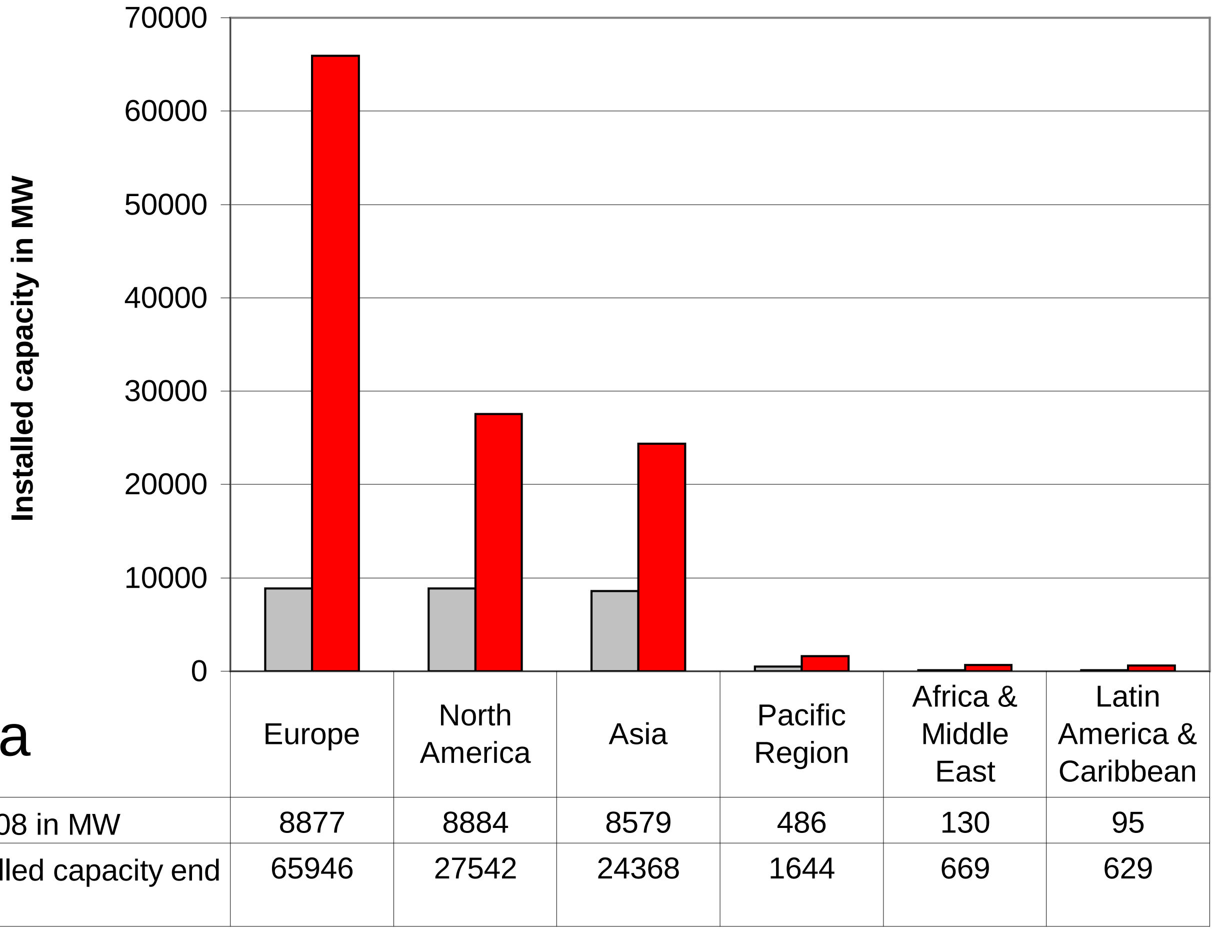
- Cumulative installed capacity approx. 121 GW (in 2008)
- New capacity in 2008 27 GW
- Increase of 36% compared to the 2007 market



Source: Bundesverband Windenergie e.V.

Installed Capacity by Region (in 2008)

- Three main drivers
  - North America
  - Europe
  - Asia
- Strong growth in Canada and the US
- Nearly a third of all new capacity has been installed in Asia

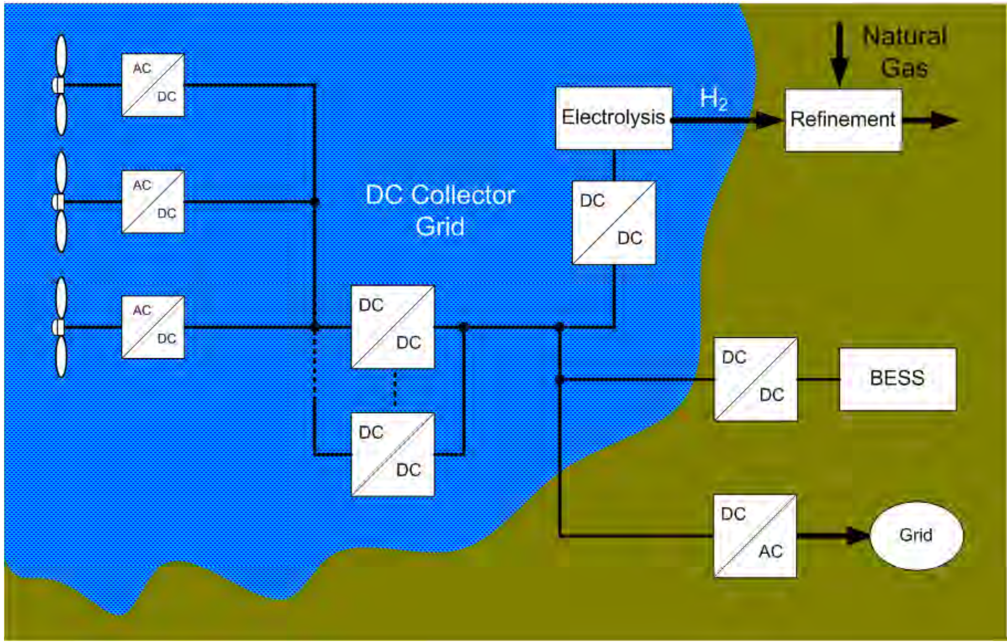


	Europe	North America	Asia	Pacific Region	Africa & Middle East	Latin America & Caribbean
⬜ New capacity 2008 in MW	8877	8884	8579	486	130	95
🟥 Cumulative installed capacity end 2008 in MW	65946	27542	24368	1644	669	629

Source: Global Wind Energy Council (GWEC)

MVDC Collector Grid for Offshore Wind Farms

- Increased efficiency
  - 2% higher compared to AC systems
  - Simple, more reliable wind turbines
- Smaller and lighter transformers
  - Weight reduced to 30 %
- Reduced costs
  - Smaller off-shore platforms
  - Reduced LCC
  - Reduced installation, transportation and investment cost
  - Improved reliability

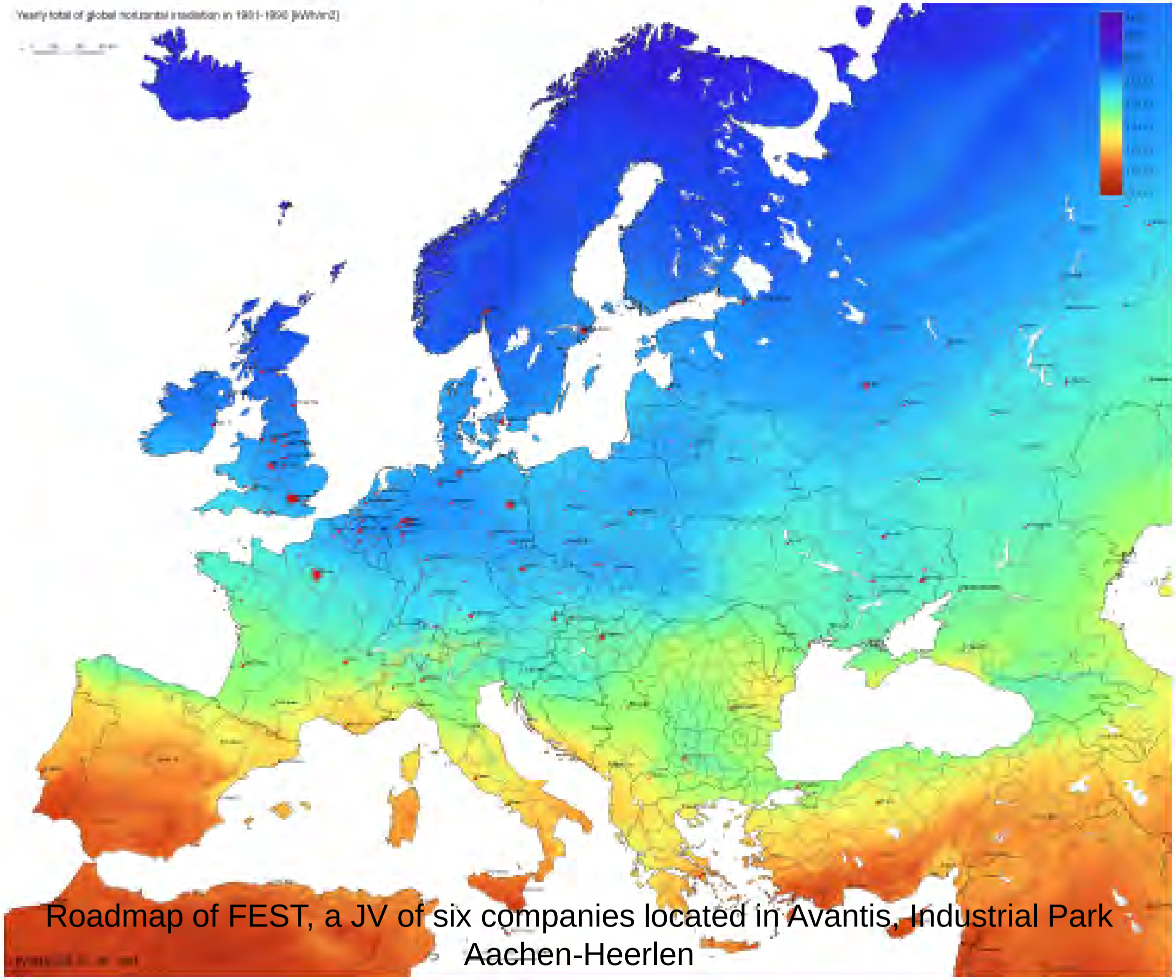


- New technology challenges
  - Protective devices
  - Electronic transformer (DC-DC converter)
- Offers development platform for future DC distribution systems

Economics of PV

Grid parity in Europe – 2007

PV module costs: 2 € /Wp



Roadmap of FEST, a JV of six companies located in Avantis, Industrial Park Aachen-Heerlen

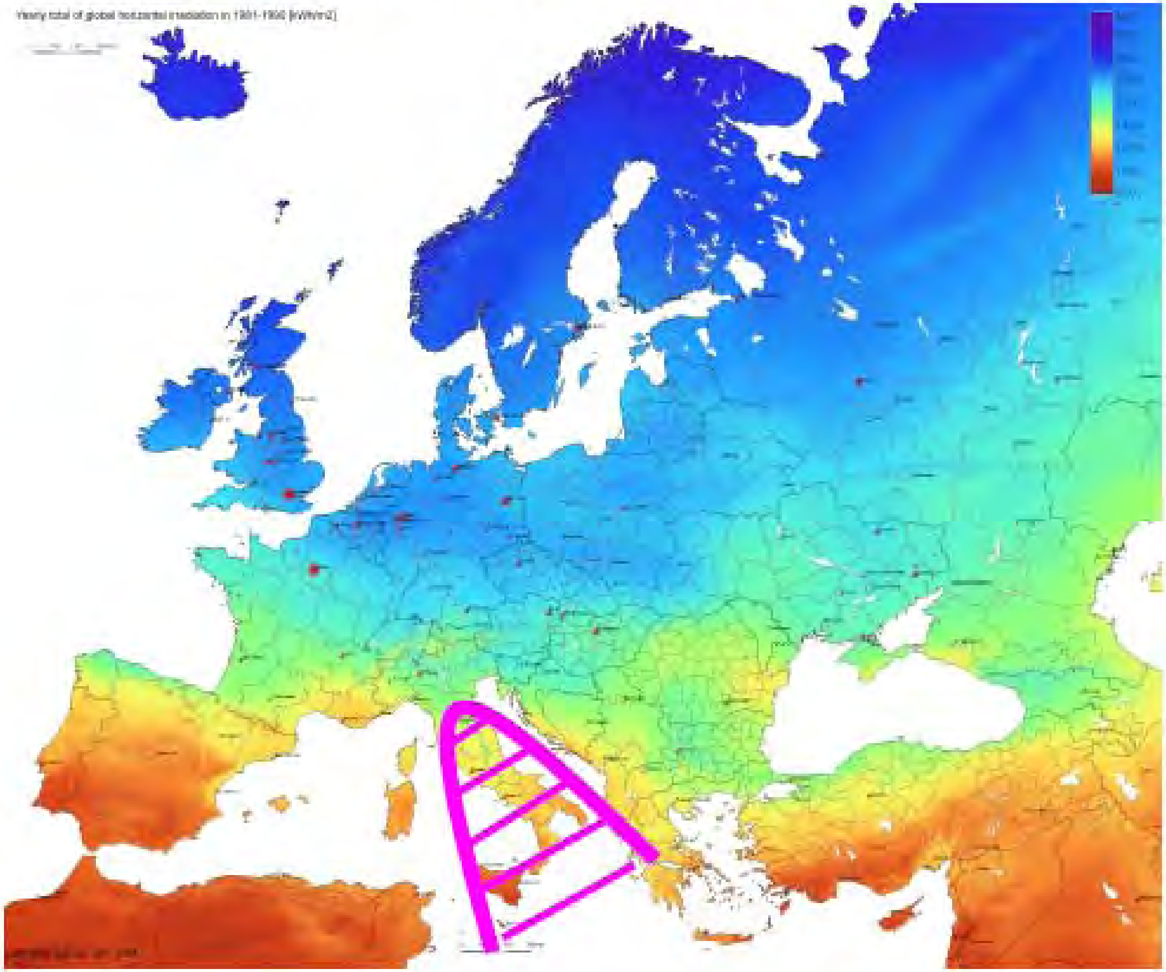
irradiation ($kWh/m^2 \cdot yr$)	**PV generation cost (€/kWh)**
600	0.83
1000	0.50
1400	0.36
1800	0.28

insolation map: Šúri M., Huld T.A., Dunlop E.D. Ossenbrink H.A., 2007. Potential of solar electricity generation in the European Union member states and candidate countries. Solar Energy (in press), http://re.jrc.ec.europa.eu/pvgis/

Economics of PV

Grid parity in Europe – 2010

PV module costs 1.2 € /Wp

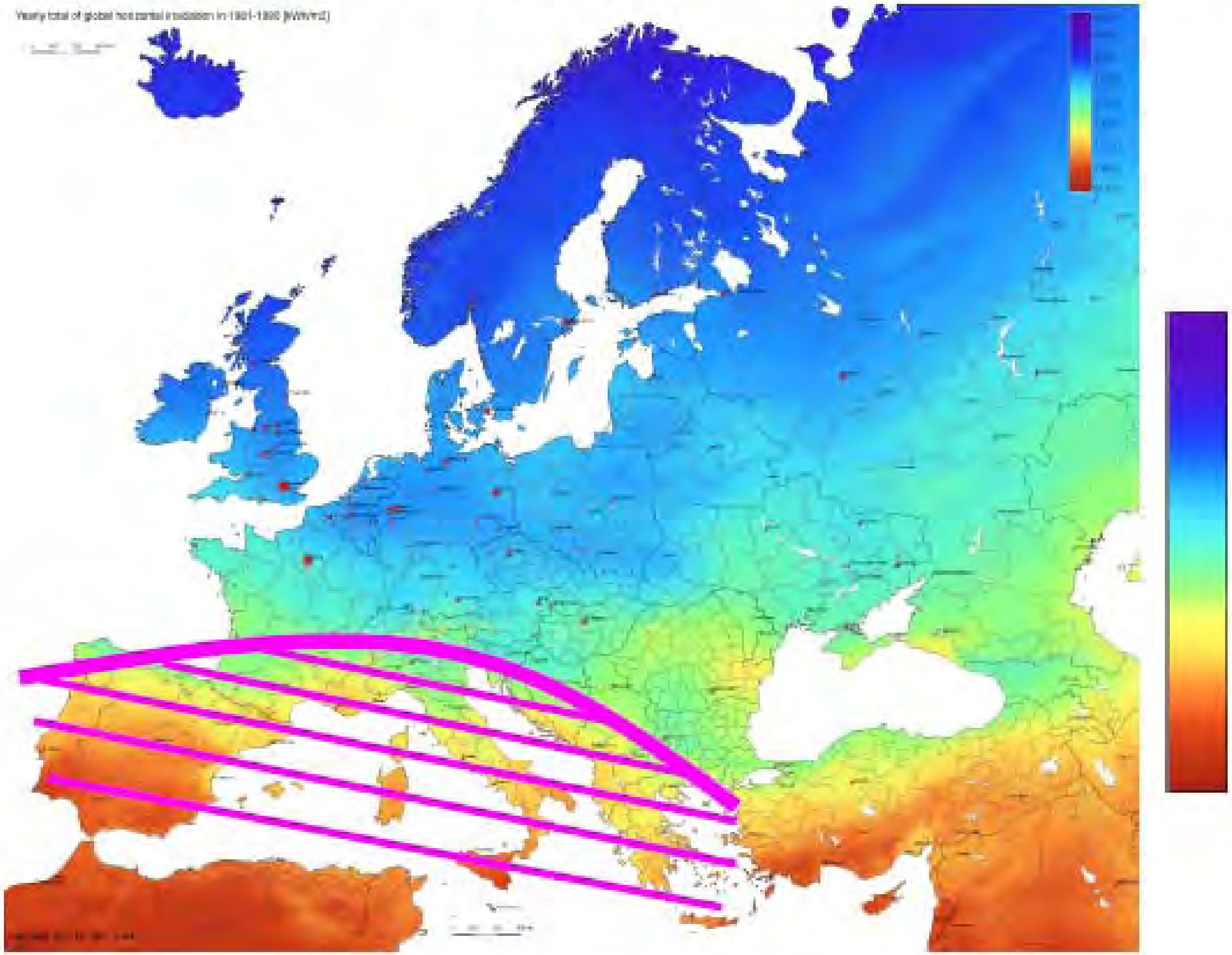


irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.50
1000	0.30
1400	0.21
1800	0.17

Economics of PV

Grid parity in Europe – 2015

PV module costs 1.0 € /Wp

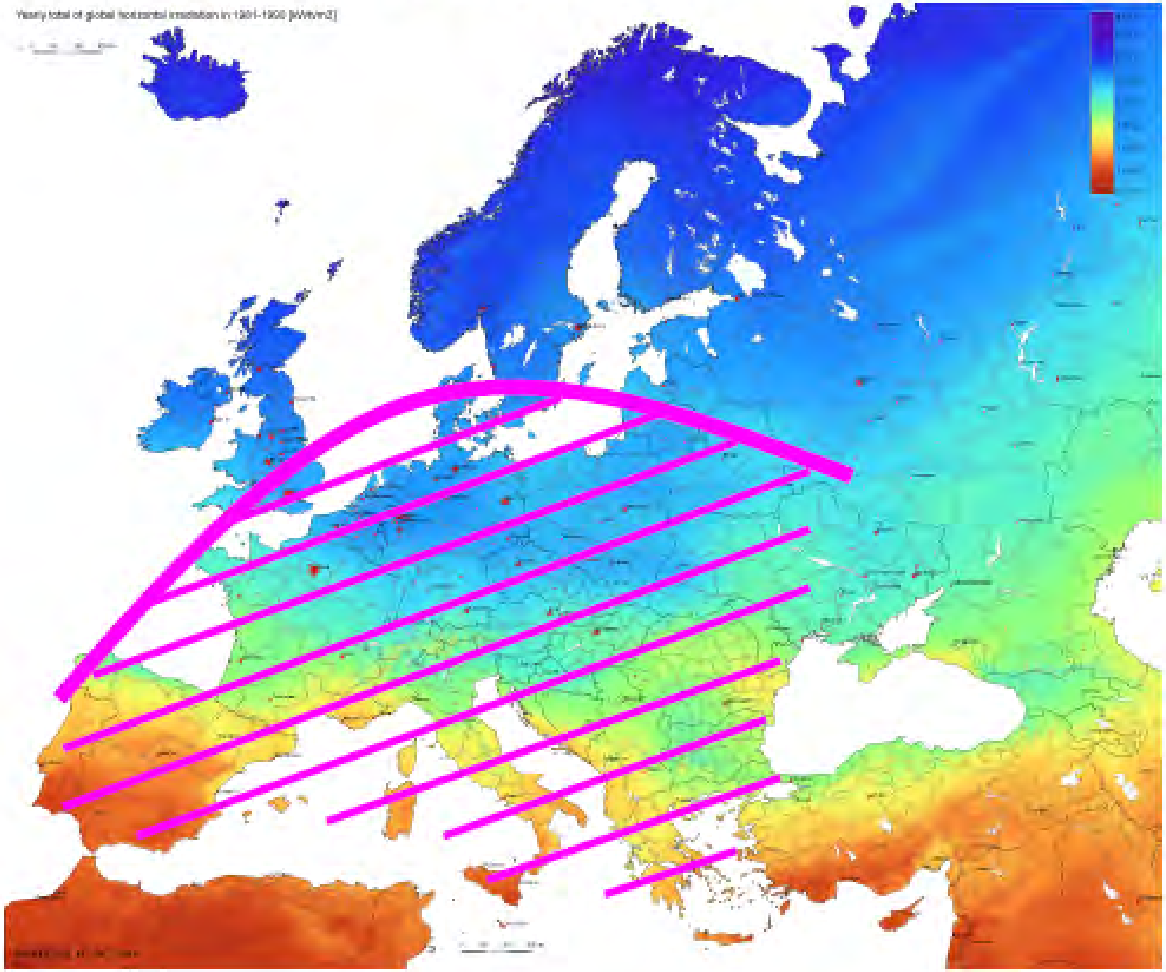


irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.42
1000	0.25
1400	0.18
1800	0.14

Economics of PV

Grid parity in Europe – 2020

PV module costs 0.8 € /Wp

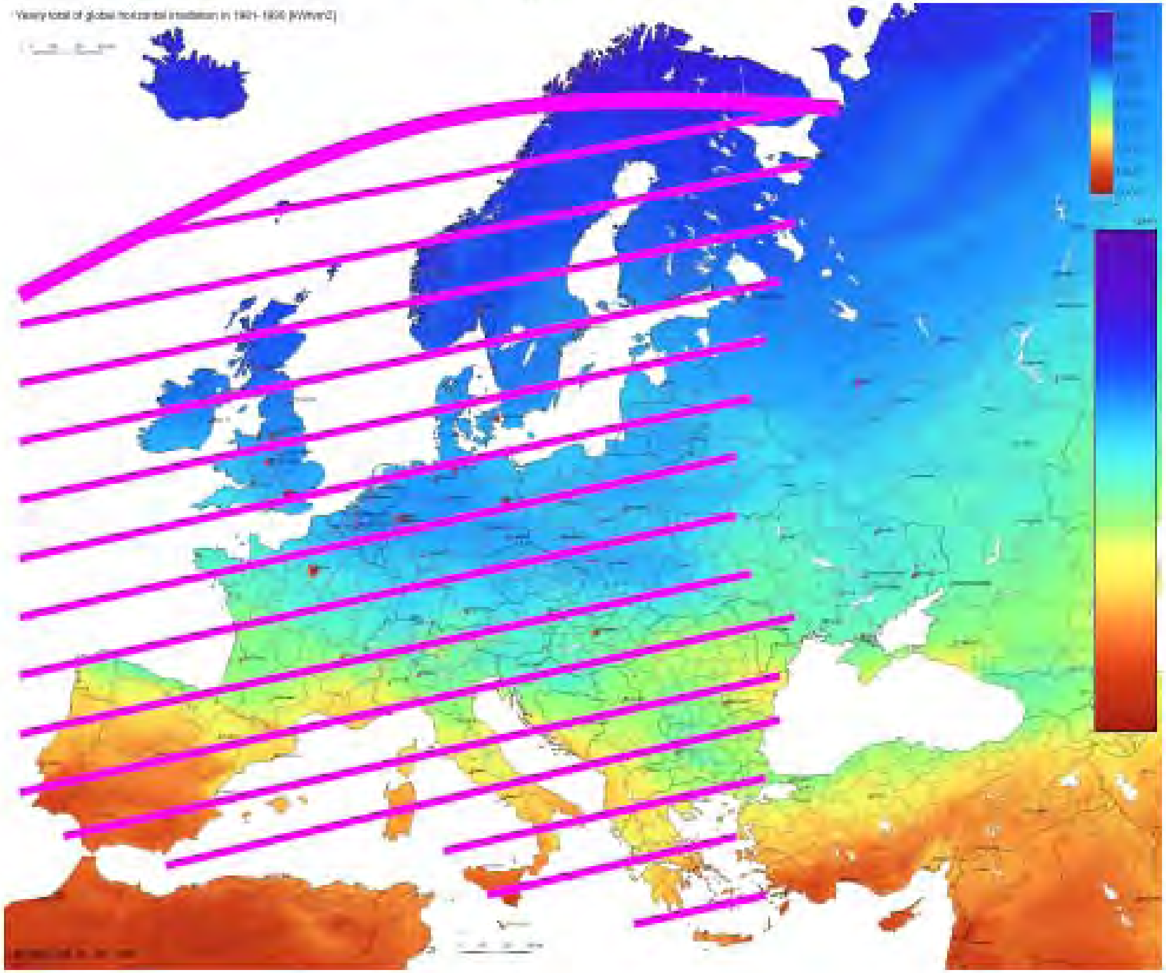


irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.33
1000	0.20
1400	0.14
1800	0.11

Economics of PV

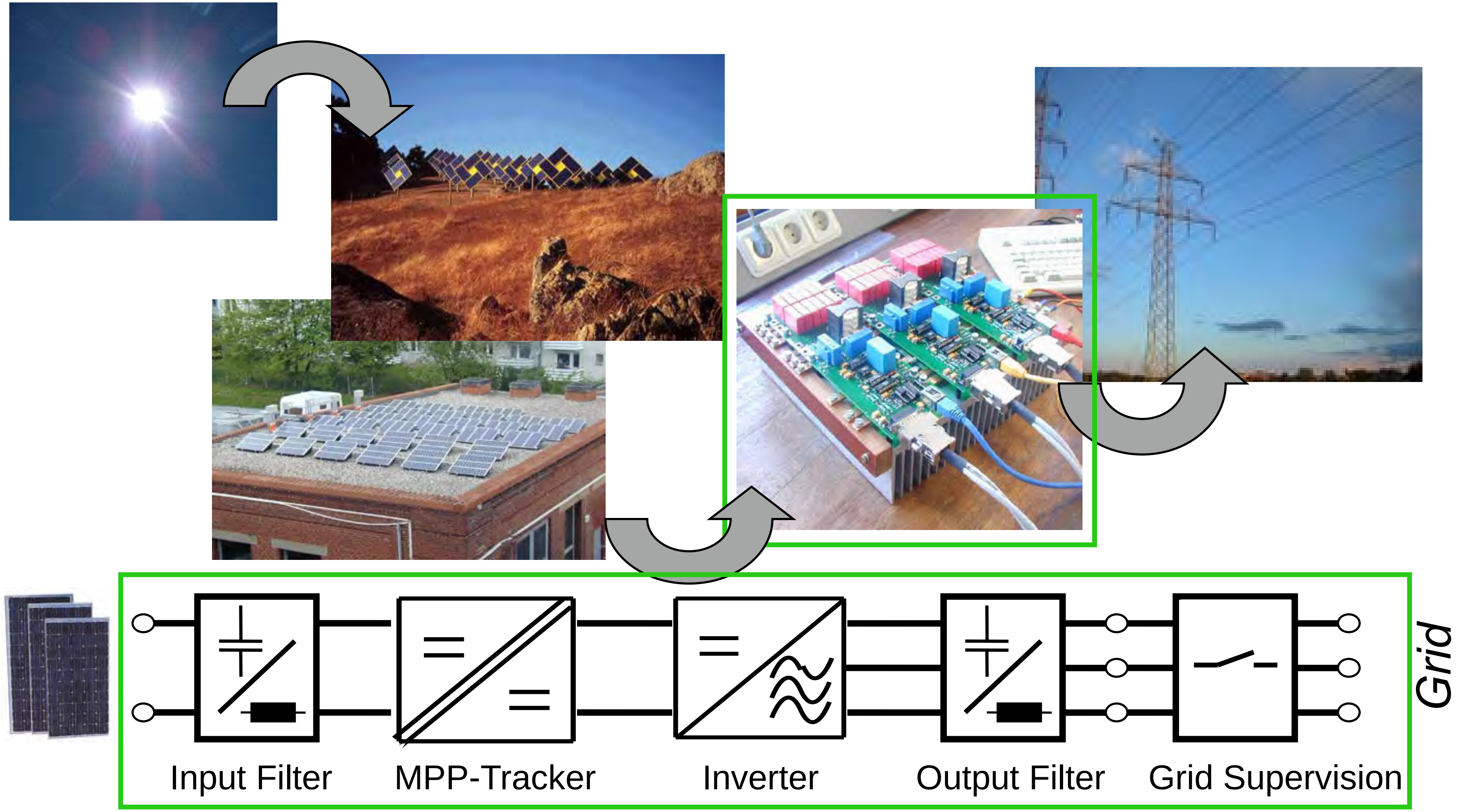
Grid parity in Europe – 2030

PV module costs 0.5 € /Wp



irradiation (kWh/m²·yr)	PV generation cost (€/kWh)
600	0.17
1000	0.10
1400	0.07
1800	0.06

Grid Connection of Photovoltaic Systems



Input Filter

MPP-Tracker

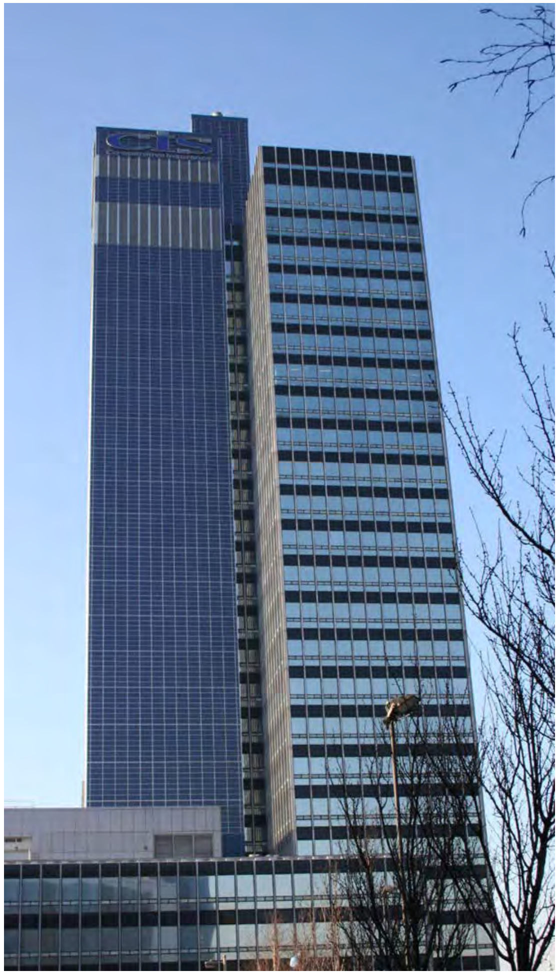
Inverter

Output Filter

Grid Supervision

Grid

Façade-integrated PV installation

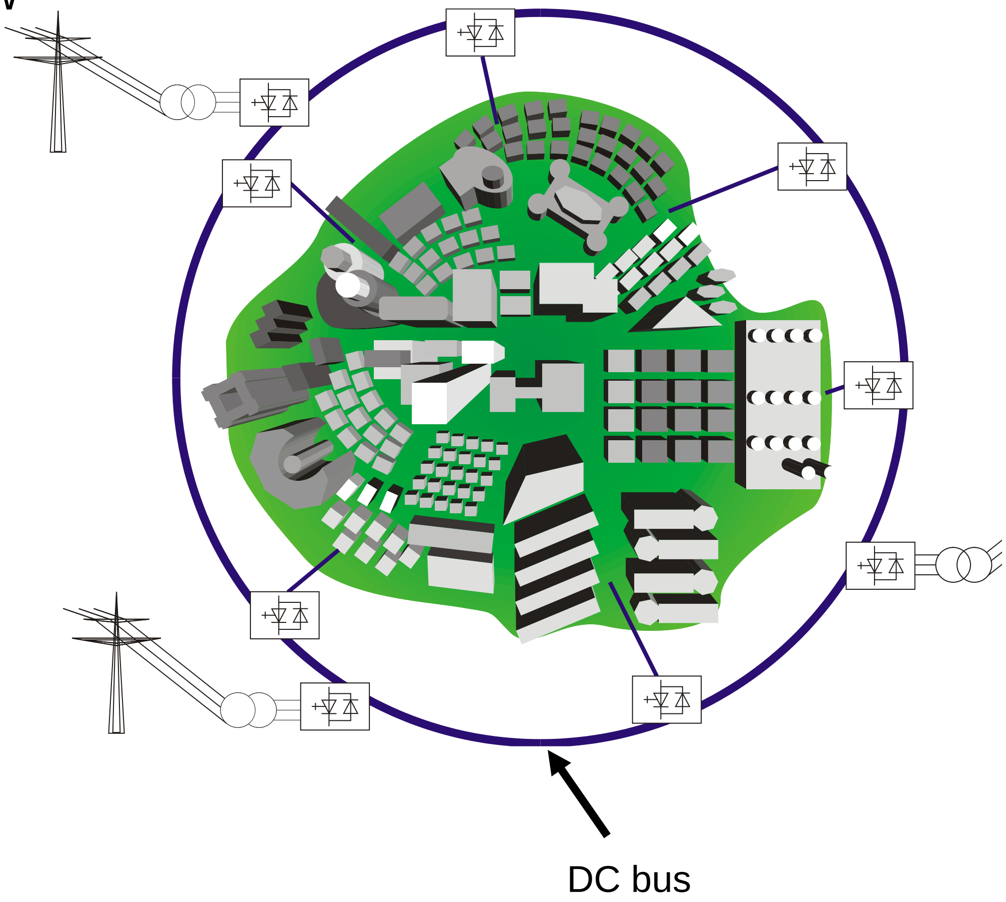


Source: Skyscrapernews

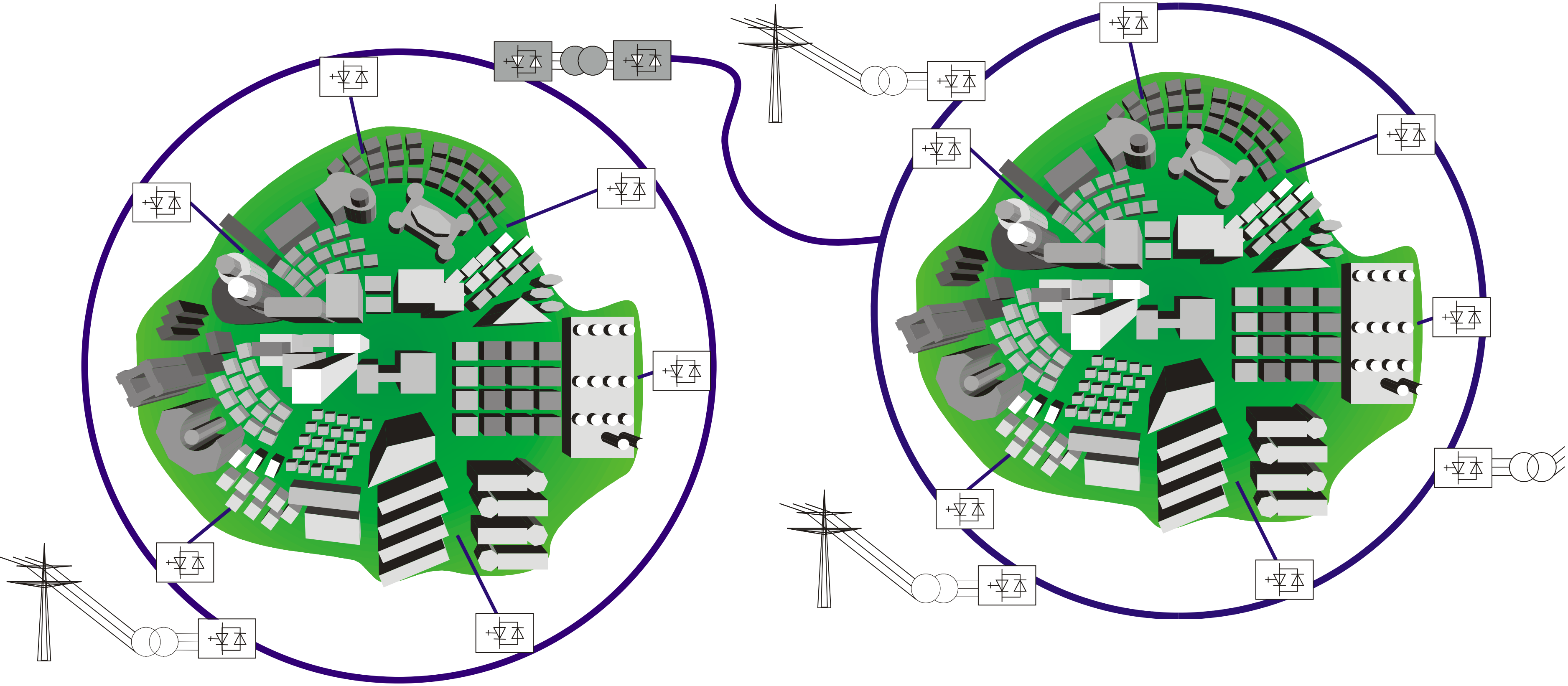
- Building of the Co-operative Insurance Society (CIS) in Manchester
- Height 122 m
- 5,000 poly-crystalline modules are currently installed with 3,200 m^2 solar modules
- Overall installed power is 391 kW
- 180,000 kWh are expected as energy production

DC Power Transmission and Distribution Merge into AC Grids

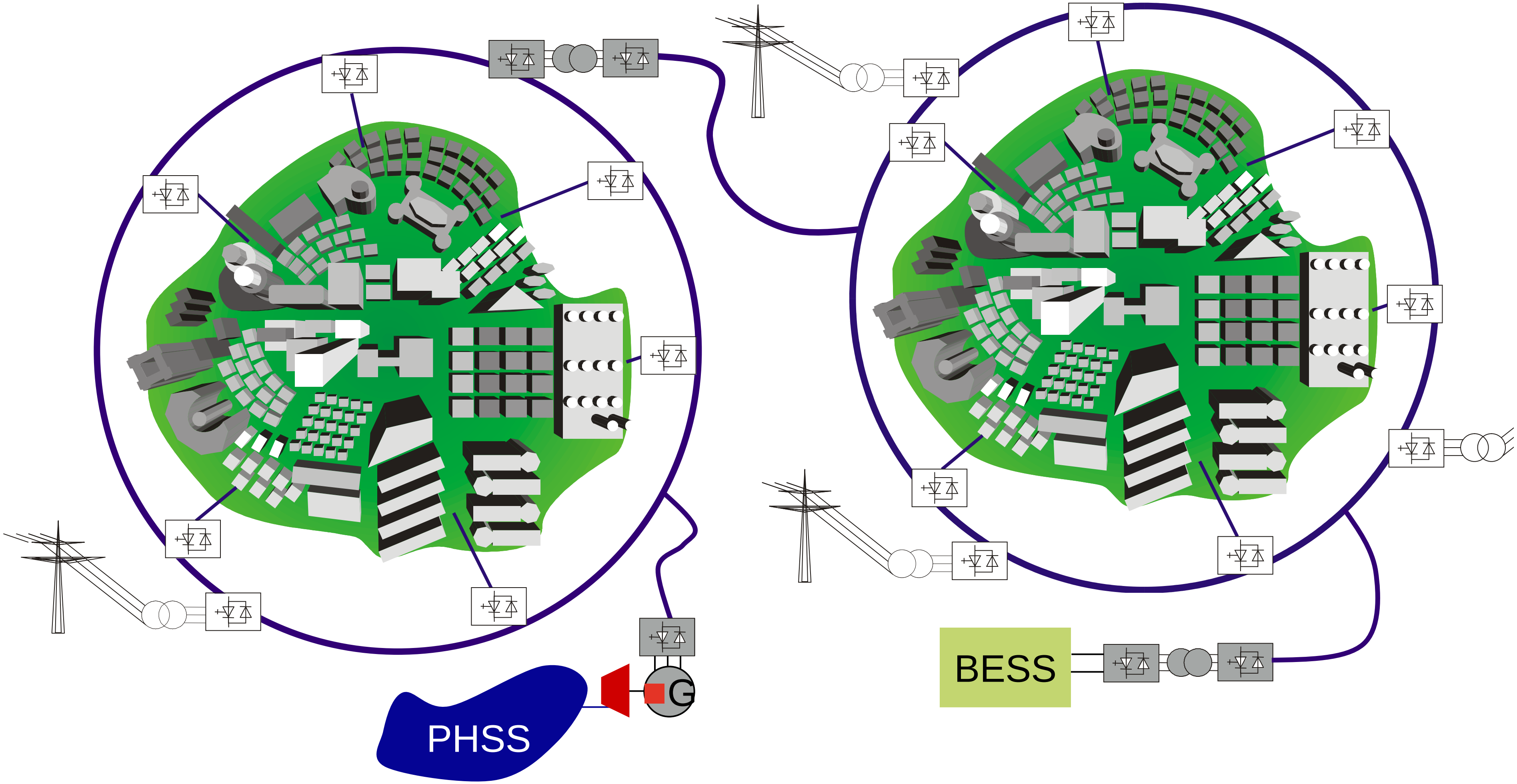
- More stable, high power quality ring bus structure for the city of tomorrow
- Very high reliability, redundancy and self-repairing systems
- Easy connection of decentralized generation and storage systems
- DC cable technology has evolved significantly over the past years
  - Lower losses using DC cables (no overhead lines)
- Reduced losses with HT superconductive cables



Cellular concept with more decentralized energy production

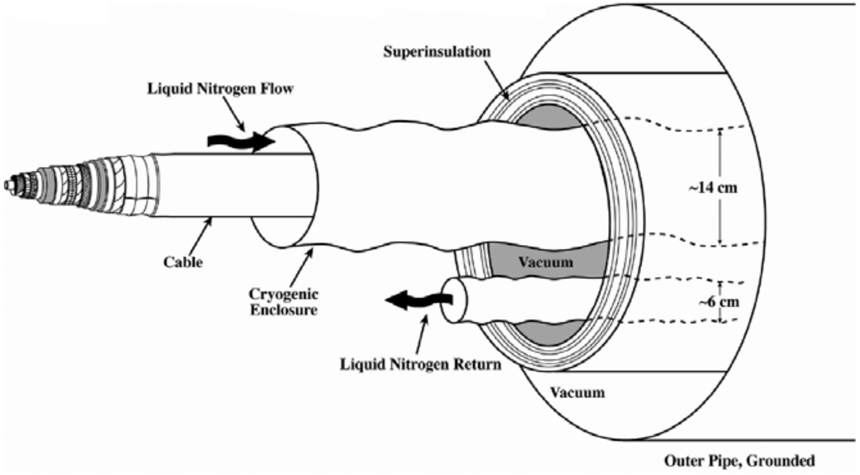


DC Grid and Energy Storage



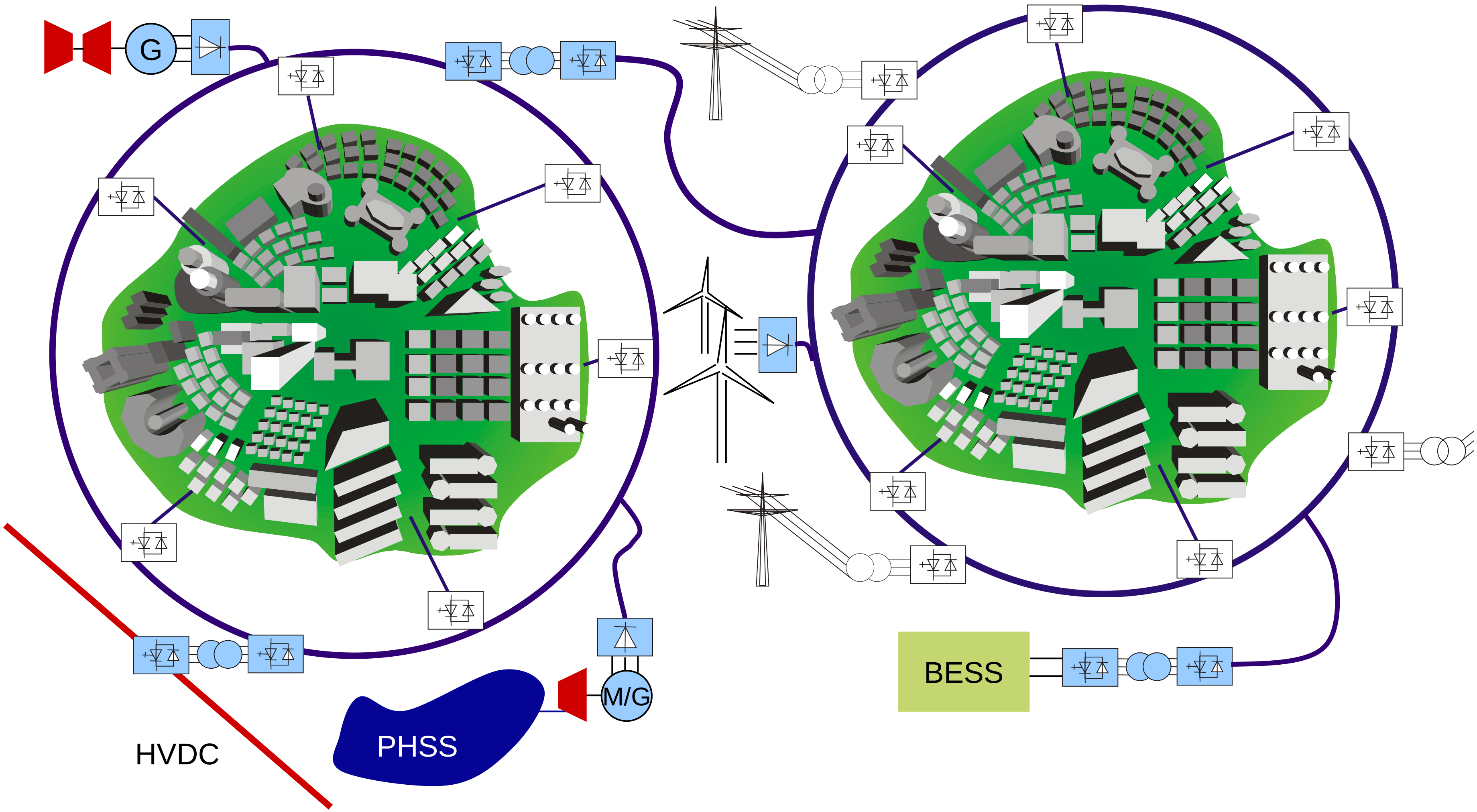
High-Temperature Superconductive Cables

- HTS: Superconducting transition temperature above 77 K (-196 ° C)
  - Boiling point of nitrogen is 77 K
  - Liquid nitrogen allows for simple and inexpensive cooling
- Nearly no transmission losses in HTS cables
- Smaller cable diameter required for similar current rating
- Short-circuit limitation
  - Depending on current density cable changes into a resistive component
  - Current is limited



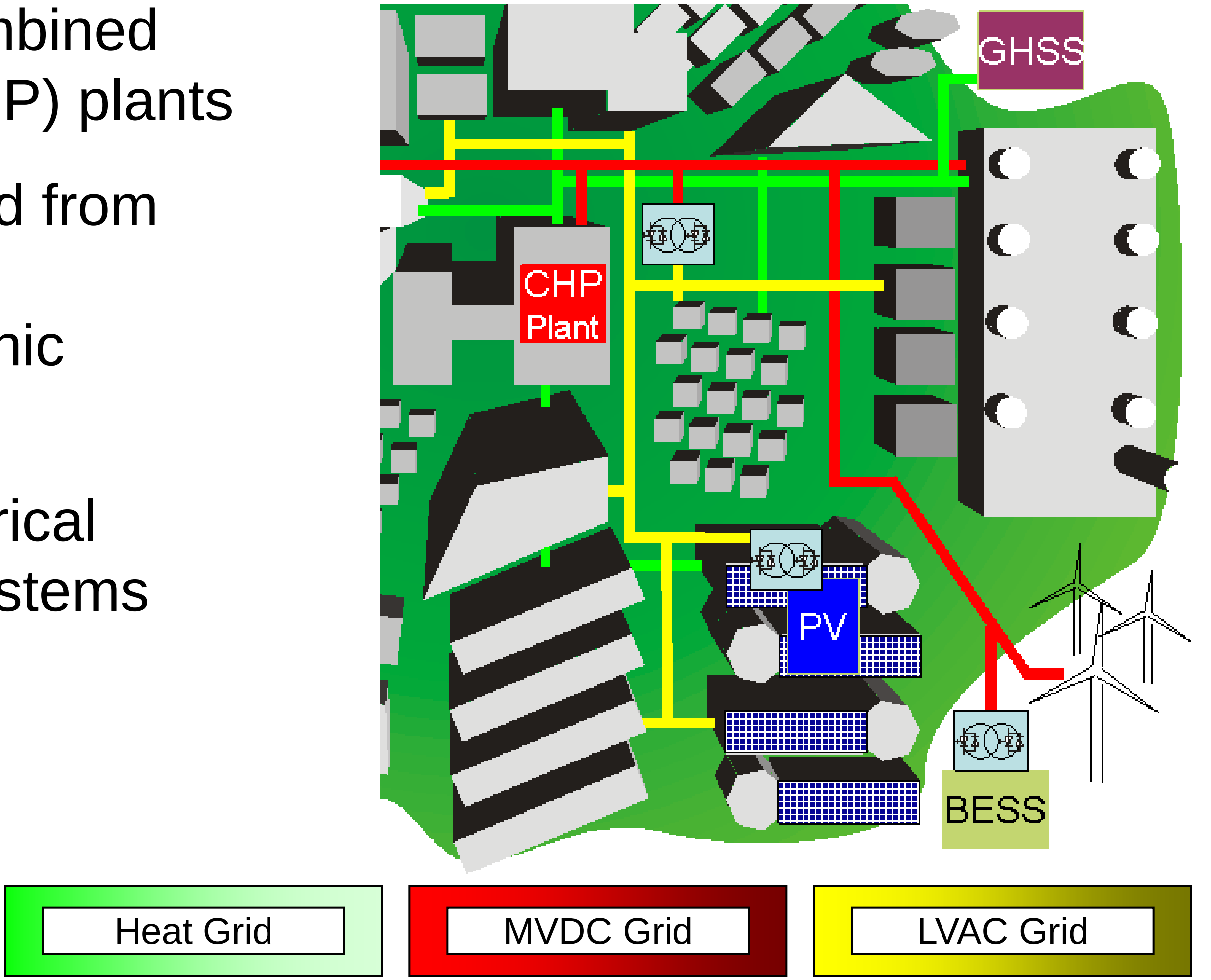
- *Source*: Hassenzahl et al.: A High-Power Superconducting DC Cable. IEEE Transactions on Applied Superconductivity, vol. 19, no. 3, June 2009

DC Power Transmission and Distribution Merge into AC Grids



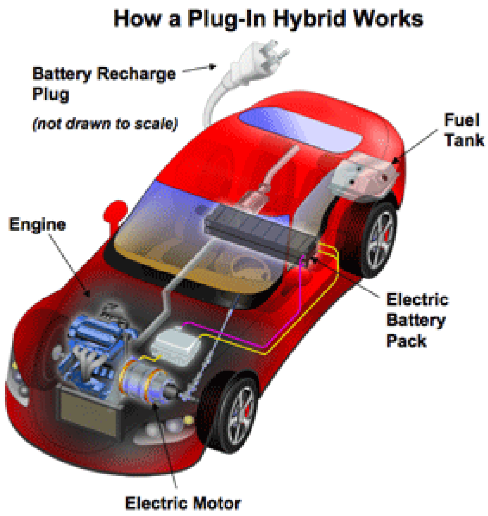
District Level Power Grids

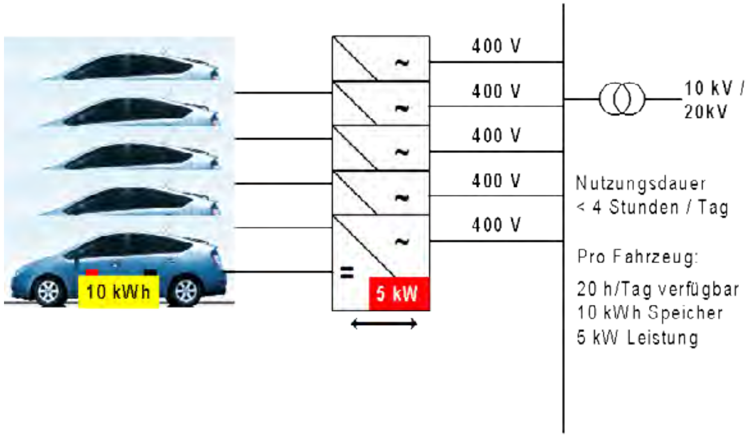
- Megawatt-scale combined heat and power (CHP) plants
- LVAC grid generated from MVDC
  by means of electronic transformers
- Including local electrical and heat storage systems



Plug-in Hybrids and Electric Cars – A Storage System for Power Grids

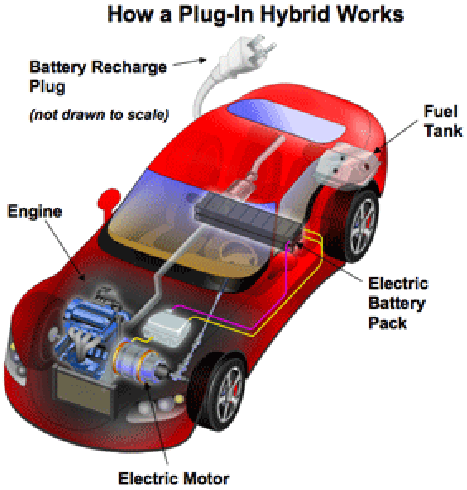
- Electric and hybrid cars will be widely used in the near future
- Possibility of using installed batteries as storage devices
- Advantages on a system level
  - Load leveling of grids is possible
  - Supports the integration of renewable energy sources in future grids





Plug-in Hybrids and Electric Cars
Some Numbers for Germany

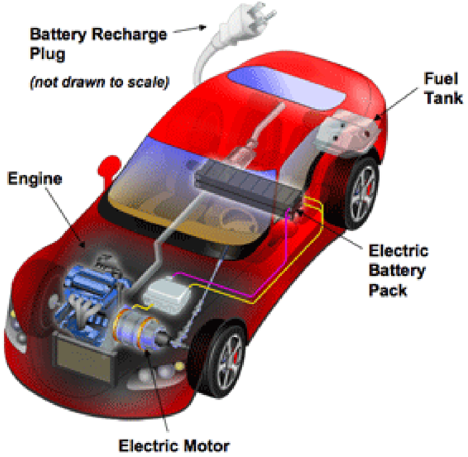
- Operated passenger cars in Germany
  - Approx. 50 Mio.
- Capacity of a typical battery in a vehicle
  - Conventional: 0.912 kWh
  - Hybrid: 1.3 kWh (Toyota Prius)
- Storage capacity in the grid (theoretical)
  - 45.6 GWh (with present vehicles)
  - 65 GWh (with existing technology)
- Comparison with existing storage technology
  - Goldisthal (pumped hydro): 8.5 GWh
  - Huntorf (compressed air): 0.58 GWh
- Huge potential for energy storage is presently unused



Plug-in Hybrids and Electric Cars
Technical Challenges

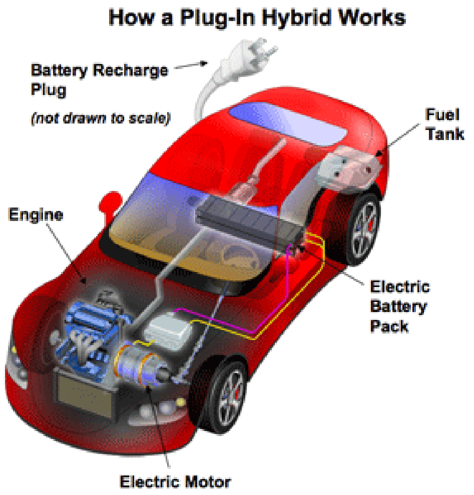
- Further research and development is needed to realize plug-in hybrids on a broad level
- Charge & recharge units need to be developed
  - Within each car
  - Stationary units
- Lifetime of the batteries would be significantly reduced if the complete energy is used
  - Definition of limits (cranking capability, aging etc.)
- Development of optimized charging and discharging strategies
- Grid control with dispersed storage units
  - Investigation on stability and power quality in the grid

How a Plug-In Hybrid Works



Plug-in Hybrids and Electric Cars
Legal Issues and Economics

- Should customers get extra money for supporting the grid (billing)?
- The needed capacitance of the battery could be defined by the requirements of the car or the utility
  - Who will define the design goal?
- Standards are needed to assure a proper functionality not only in Germany but at least all over Europe
- Who is responsible for failures and grid instabilities by private owned storage units?
- If the battery is destroyed will the utility be responsible?



Summary of changes

- From centralized to more decentralized production
- Distribution grids become now active players
- Power Electronics supports smart routing of power
- The network becomes dynamically configured

Need for more decentralized control

to optimize efficiency

Why decentralized control ?

- Too many data to manage to operate with the standard centralized approach
- Better support for Plug and Play concept
- Increased survivability of the system -> minimize single points of failure conditions
- Possibility to better open the market to new players (e.g. Virtual Power Plant)

What is a SMART GRID?

- Many definitions and many different levels of implementation
- Common elements:
  - Two ways flow of energy
  - Two ways flow of information
- First step is the redefinition of the measurement/metering infrastructure:
  - Phasor Measurement Units (PMU)
  - Smart Meters
- Urgent Need for Standards!!!!

A Pathway to smart grid

- Transmission Level
  - Partly already smart
  - Power Electronics (FACTS) can make routing more efficient
- Distribution Level
  - Full deployment of automation
  - First level of involvement of the customers: Peak Shaving
  - Second level of involvement of the customers: Generation (VPP)
  - Third level of involvement: Storage

Standards for Smart Grid

- Automation within the Substations: IEEE 61850 completed and active
- IEC 61970-301 with extension IEC 61968 (in particular part 11) – Common Information Model (CIM)
- Series of IEEE 1547 for Distributed Resources
- NIST Smart Grid Interoperability Framework (released in 2009)

Identified significant Standard gaps!

IEEE P2030 Overall Goals

- **1. Provide guidelines in understanding and defining smart grid interoperability of the electric power system with end-use applications and loads**
- **2. Focus on integration of energy technology and information and communications technology**
- **3. Achieve seamless operation for electric generation, delivery, and end-use benefits to permit two way power flow with communication and control**
- **4. Address interconnection and intra-facing frameworks and strategies with design definitions**
- **5. Expand knowledge in grid architectural designs and operation to promote a more reliable and flexible electric power system**
- **6. Stimulate the development of a Body of IEEE 2030 smart grid standards and or revise current standards applicable to smart grid body of standards.**

Smart Grid Interoperability – IEEE P2030

- Organized in three task forces:
  - TF1 Power Engineering Technology
  - TF2 Information Technologies
  - TF3 Communication Technologies

Conclusions

- The Power Network is supposed to dramatically change in the close future
- Distribution is supposed to be mostly affected
- Many technologies are already mature to support the change
- Still significant uncertainty is present of the definition of the future scenarios (significant role of political pressure)
- Standard are a critical enablers for the change