Electricity Supply Systems of the Future

March 23, 2021
16h00 – 17h00

Leonardo ENERGY Webinar Channel
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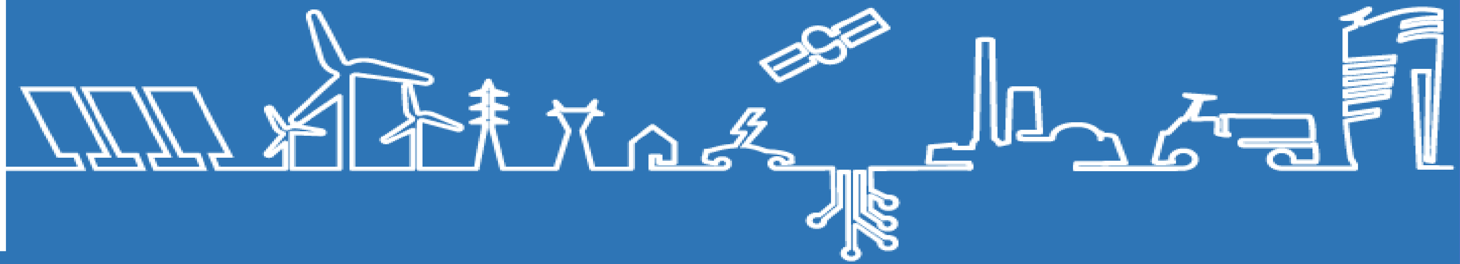
4th Webinar of the Electrification Academy

"A long-term vision of the future network is essential to guide the transition towards a cost-effective, decarbonized, digitalized, reliable and service-oriented power system."

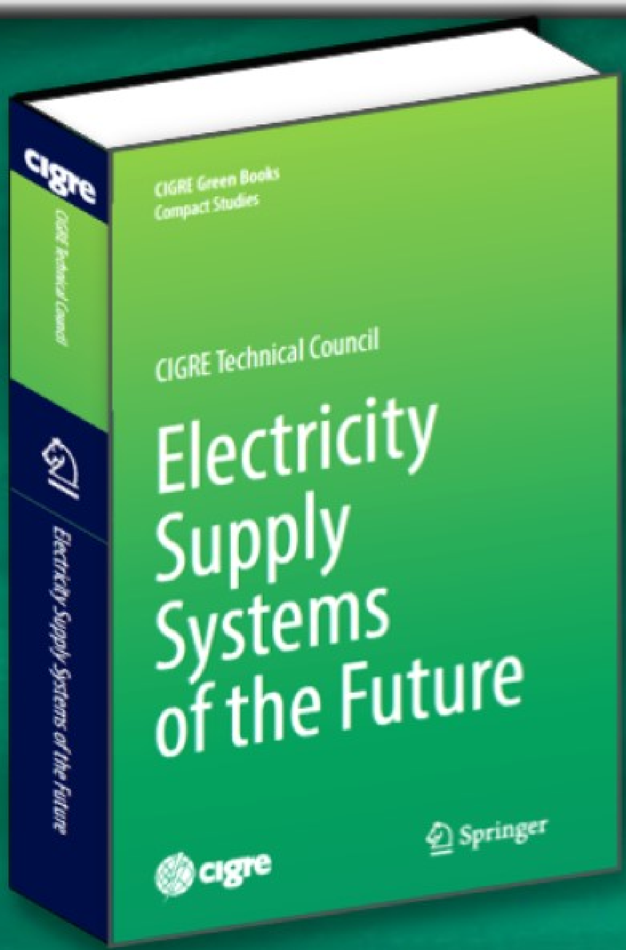
Speakers:
Nikos Hatziargyriou,
Iony Patriota de Siqueira CIGRE

In this webinar, the editors of the Green Book on the "Electricity Supply Systems of the Future" will describe their long journey to summarize the collective knowledge acquired in CIGRE Study Committees. This journey can never be over, as visions become realities or become obsolete and new challenges and developments unavoidably appear. Nevertheless, the Green Book provides CIGRE's unique and unbiased technical views for the current and future state of electricity supply systems. It also shows the value of global collaborative work of numerous experts from industry and academia mobilized within the CIGRE community. CIGRE is the foremost authority for end-to-end power system expertise.



CIGRE Green Book

Electricity Supply Systems of the Future



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cigré

CIGRE - International Council on Large Electric Systems

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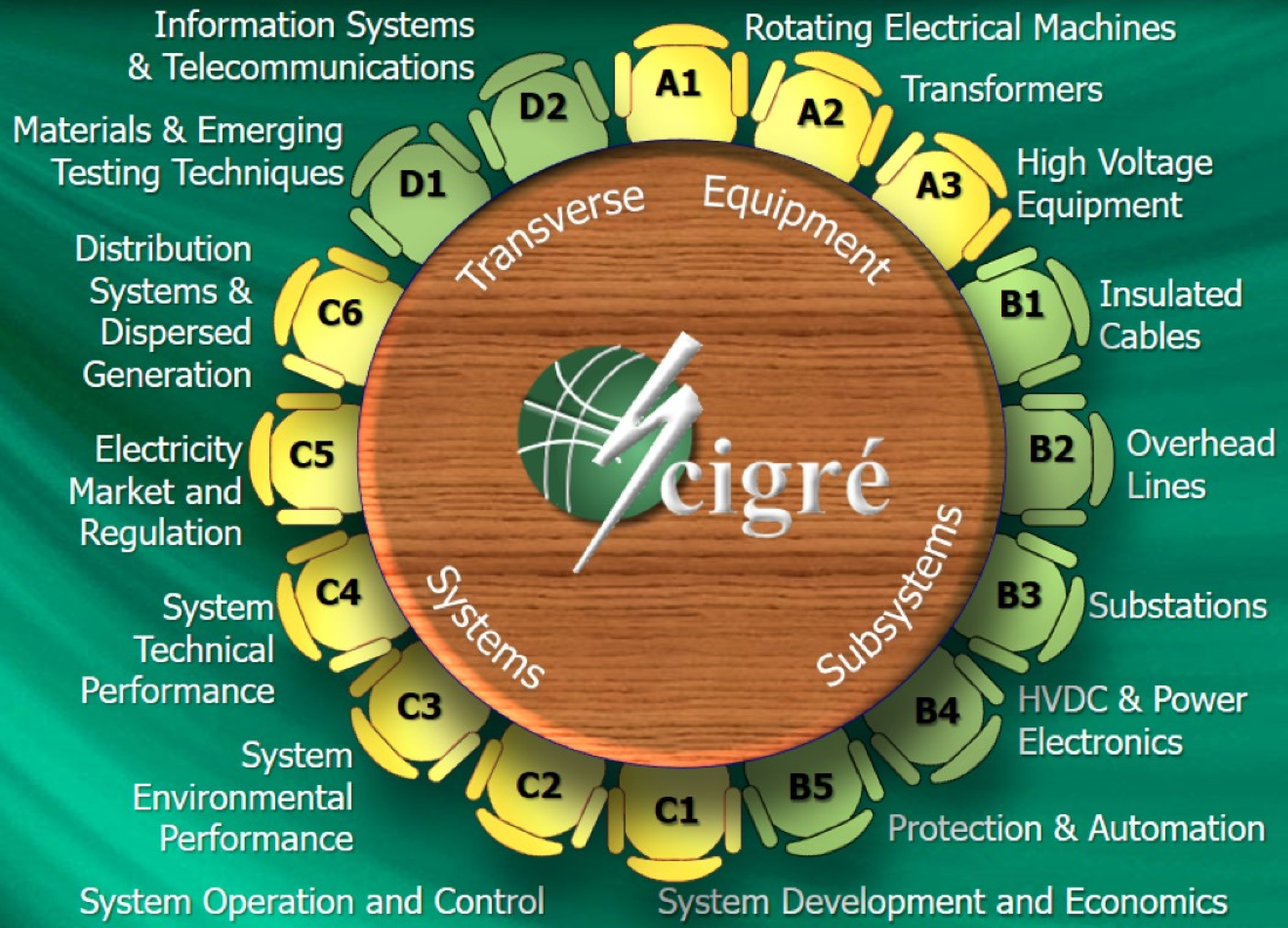
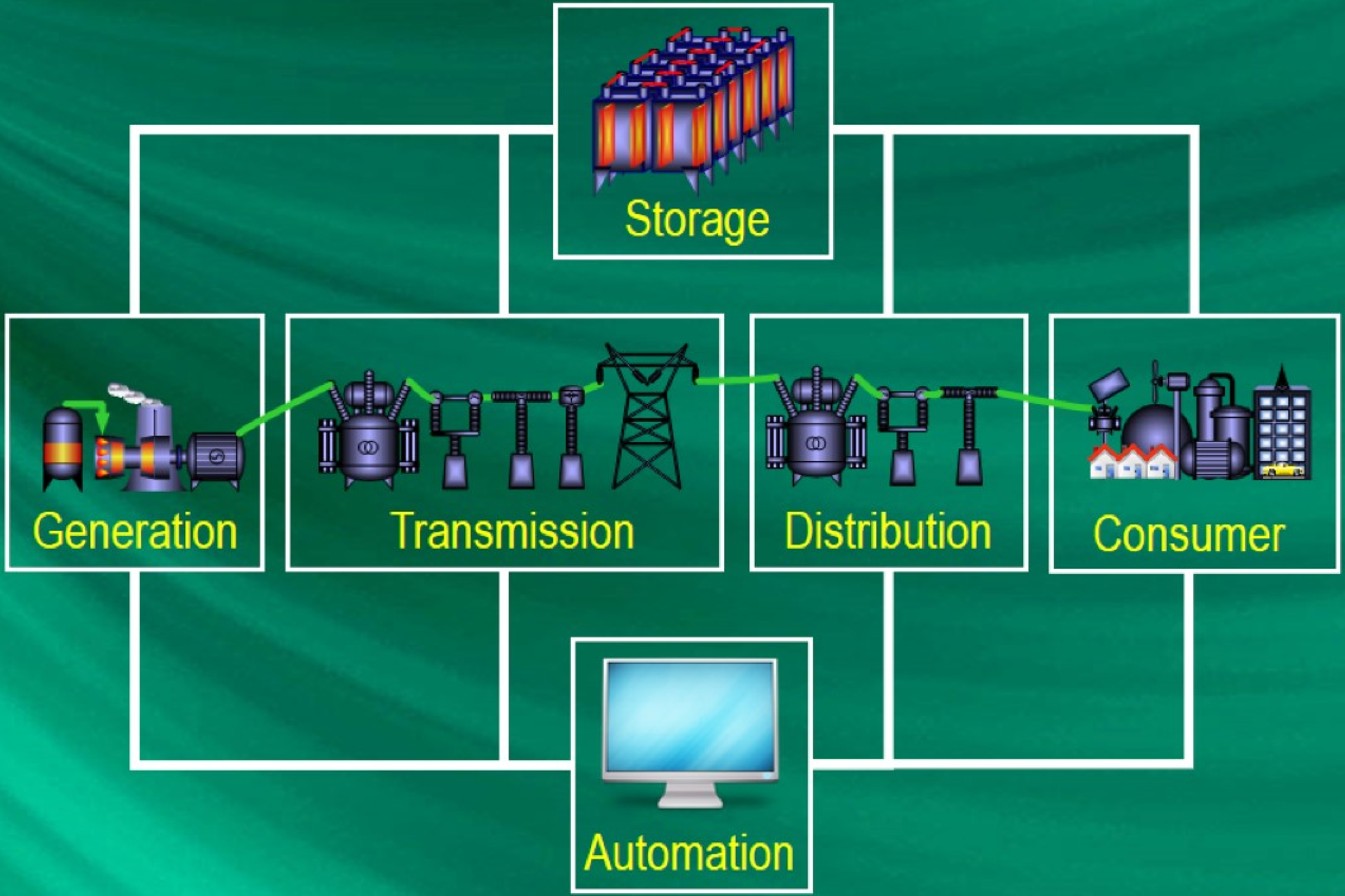


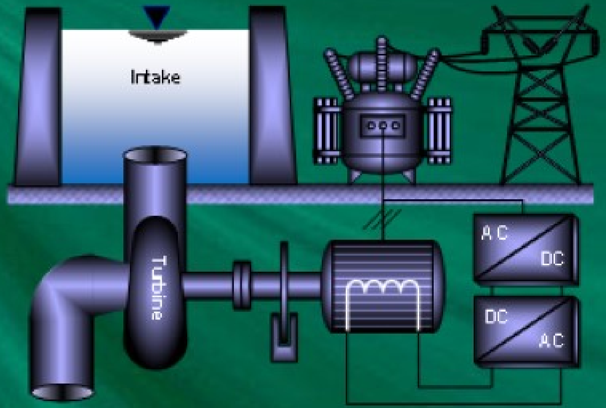
Technological Trends



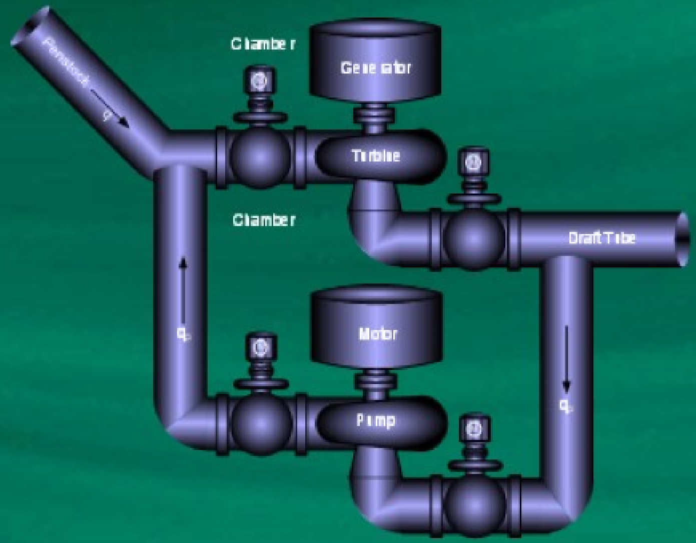
Trends in Generation Systems

- Hydro Power
- Wind Power
- Solar Power
- Sea Power

Trends in Hydro Power

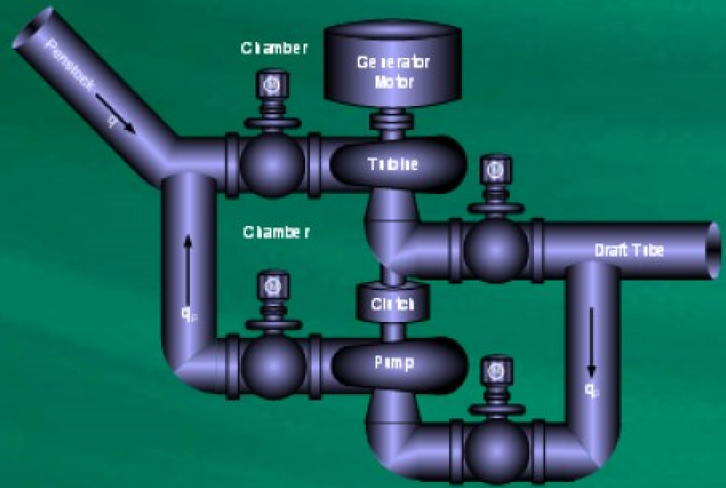


Variable-Speed Hydro Power



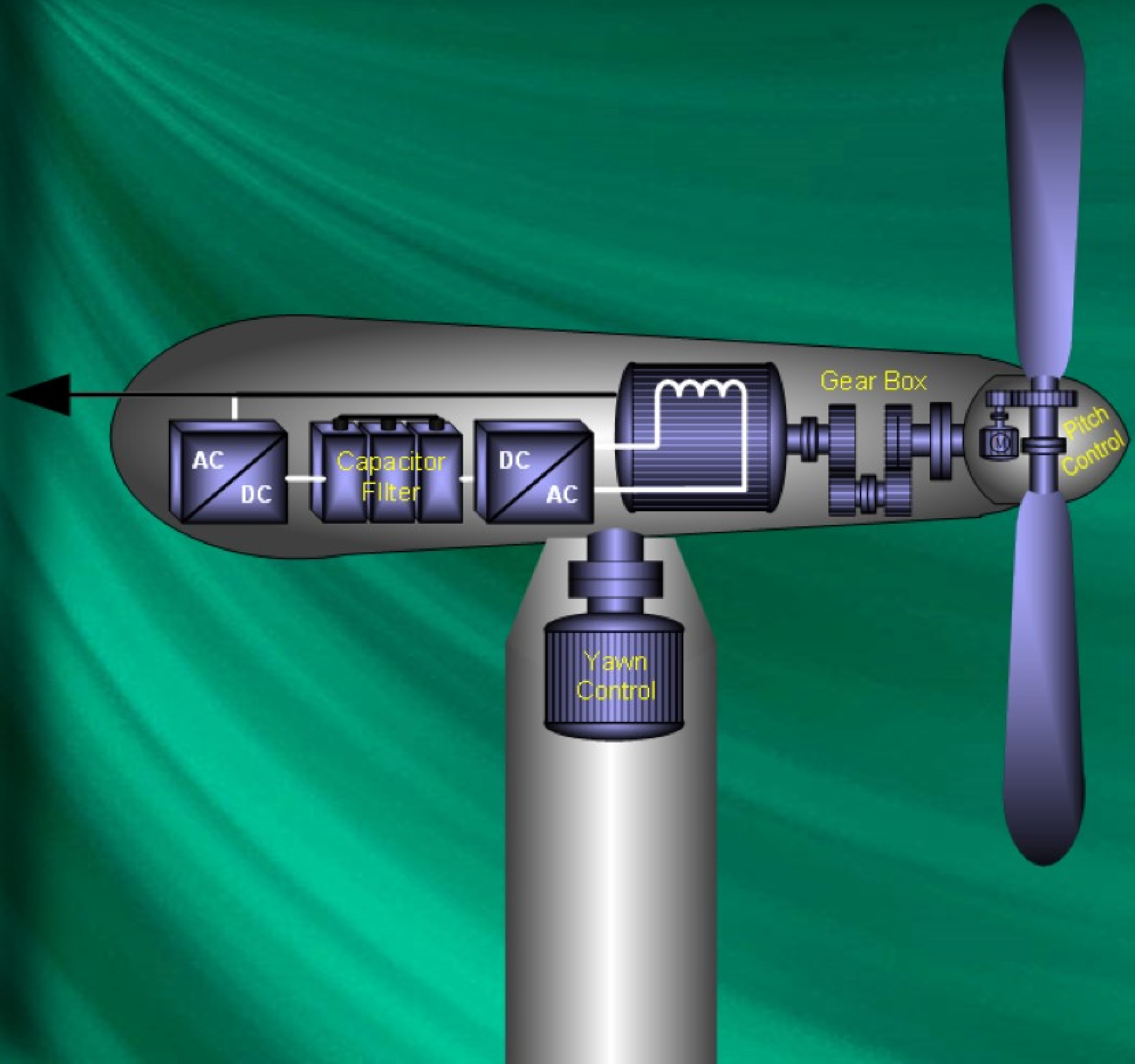
Inversible Short-Circuit Quaternary Pumped-Storage Power Plant

Inversible Binary Pumped-Storage Power Plant



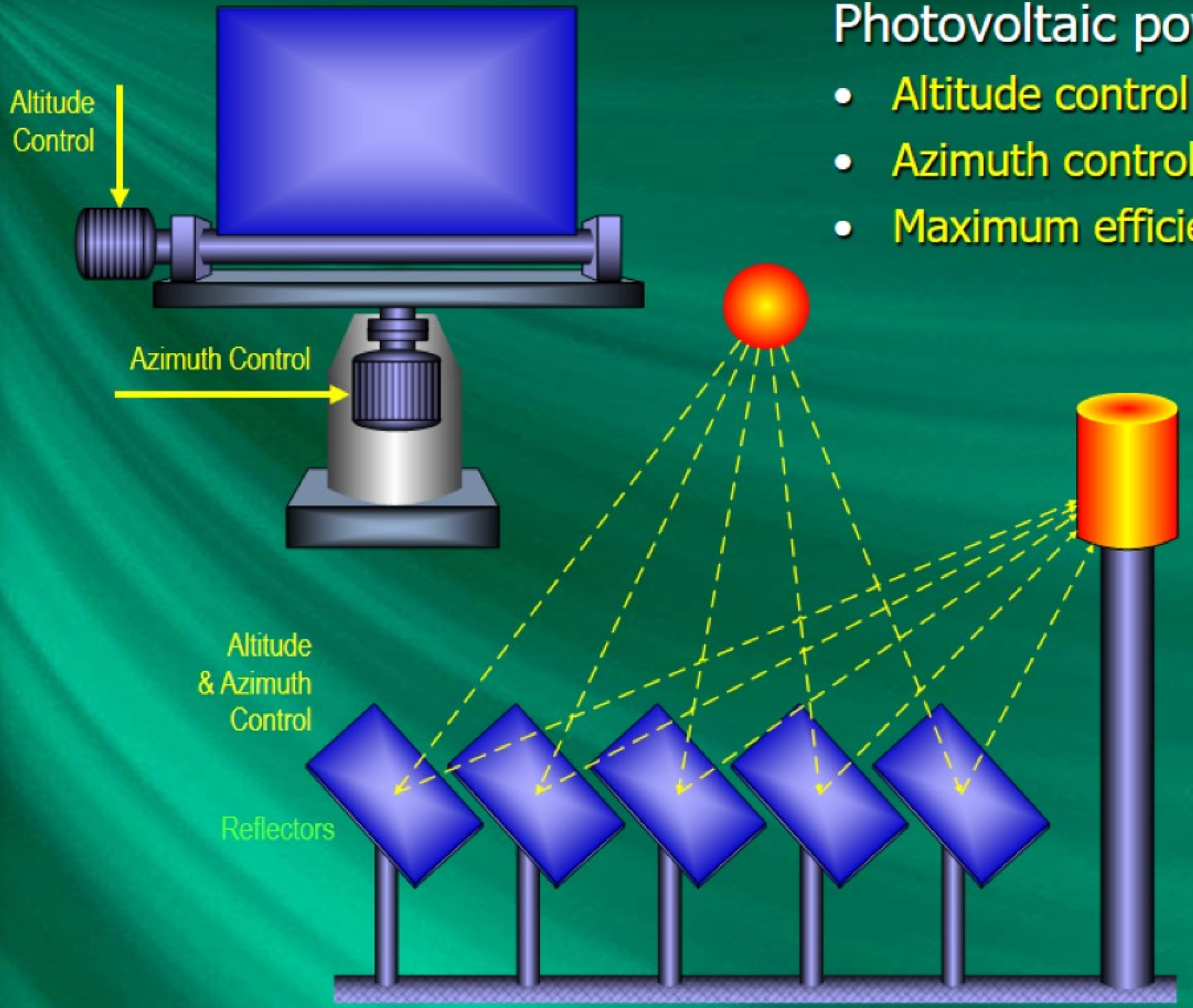
Inversible Short-Circuit Ternary Pumped-Storage Power Plant

Wind Power



- Issues:
  - Variable Speed
  - Intermittency
- Double-Fed Induction Generator
- Real & Reactive Power Control
- Maximum efficiency
- Ancillary Services

Solar Power



Photovoltaic power

- Altitude control
- Azimuth control
- Maximum efficiency

Thermosolar power

- Altitude control
- Azimuth control
- Maximum efficiency

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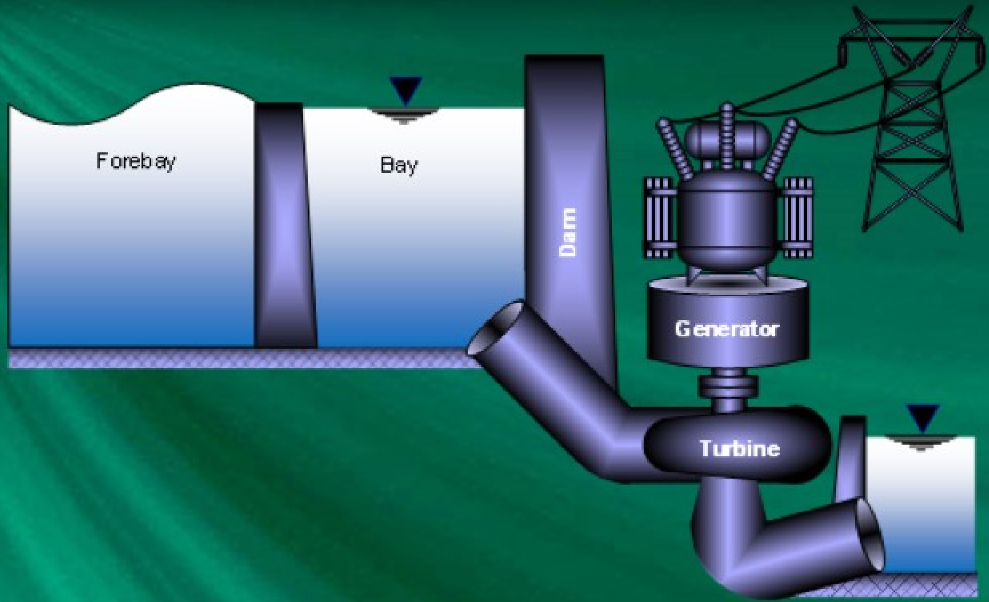
Sea Power

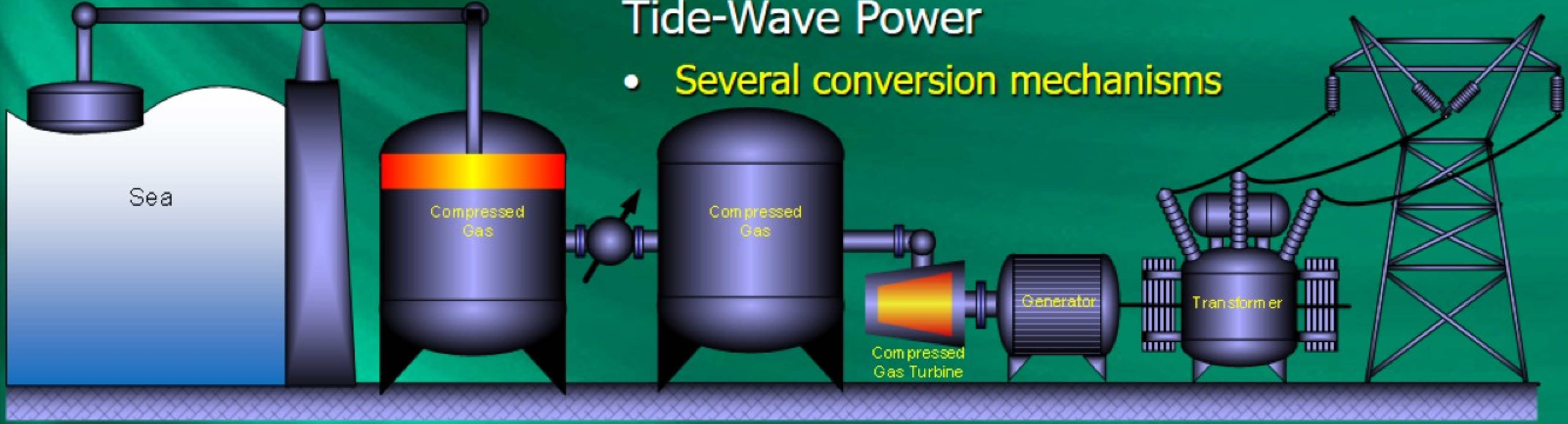


Sea-Wave Power

- Different mechanisms
- More predictable than solar and wind

Tide-Wave Power

- Several conversion mechanisms



Trends in Transmission Systems

- Transformers & Reactors
- Flexible Transmission Systems
- Multi-Terminal Direct Current Transmission
- Direct Current Transformers & Breakers
- Advanced Materials & Transmission Lines

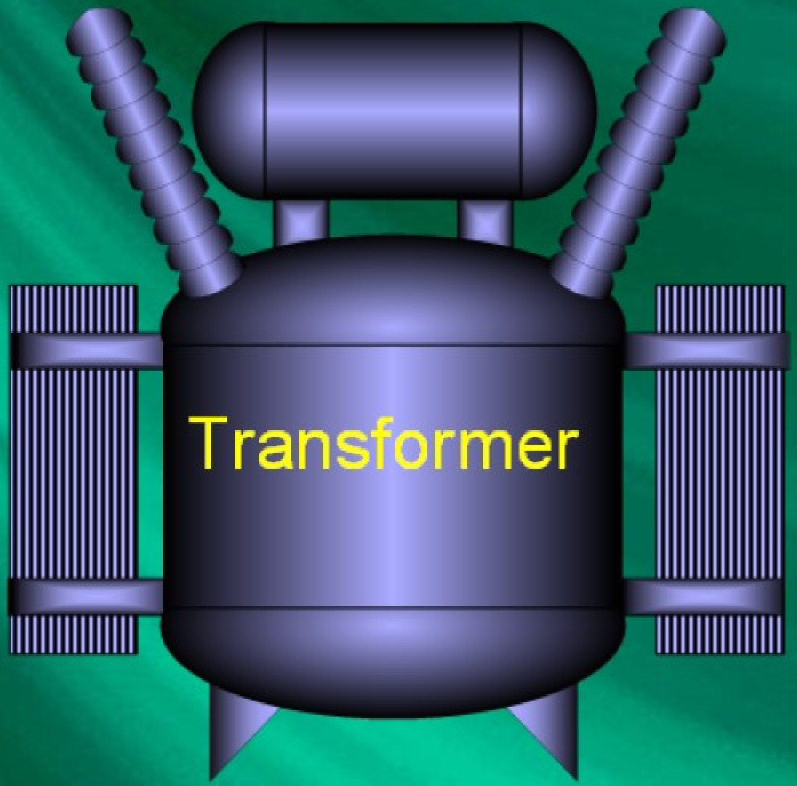
Transformers & Reactors

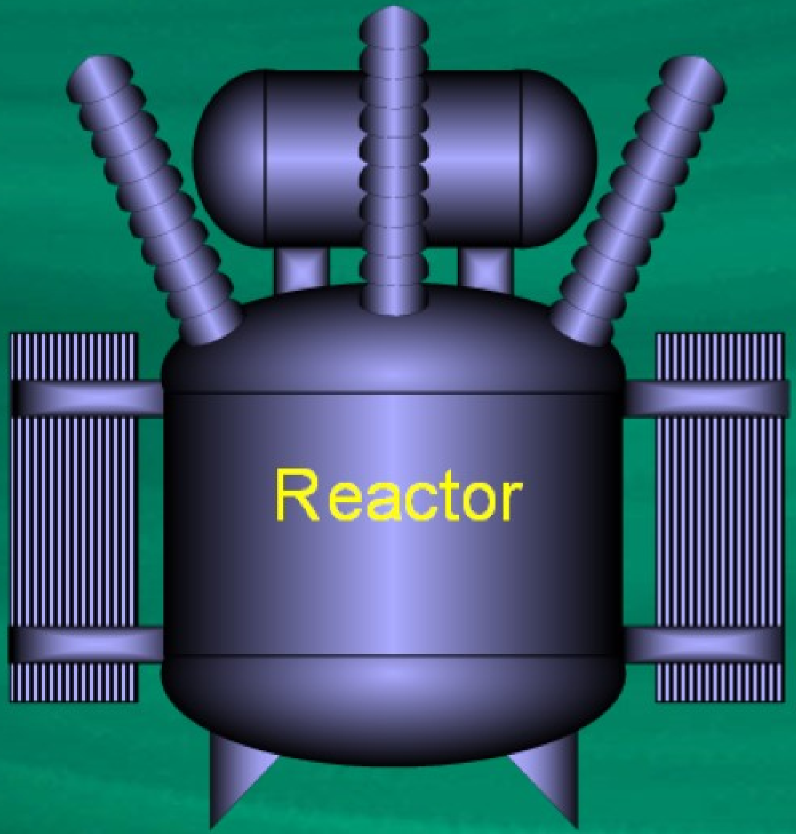
Current Issues

- Environmental restrictions
- Loss of life
- Harmonics from converters

Future Challenges

- New materials
- Design software
- New labs





Flexible Transmission Systems

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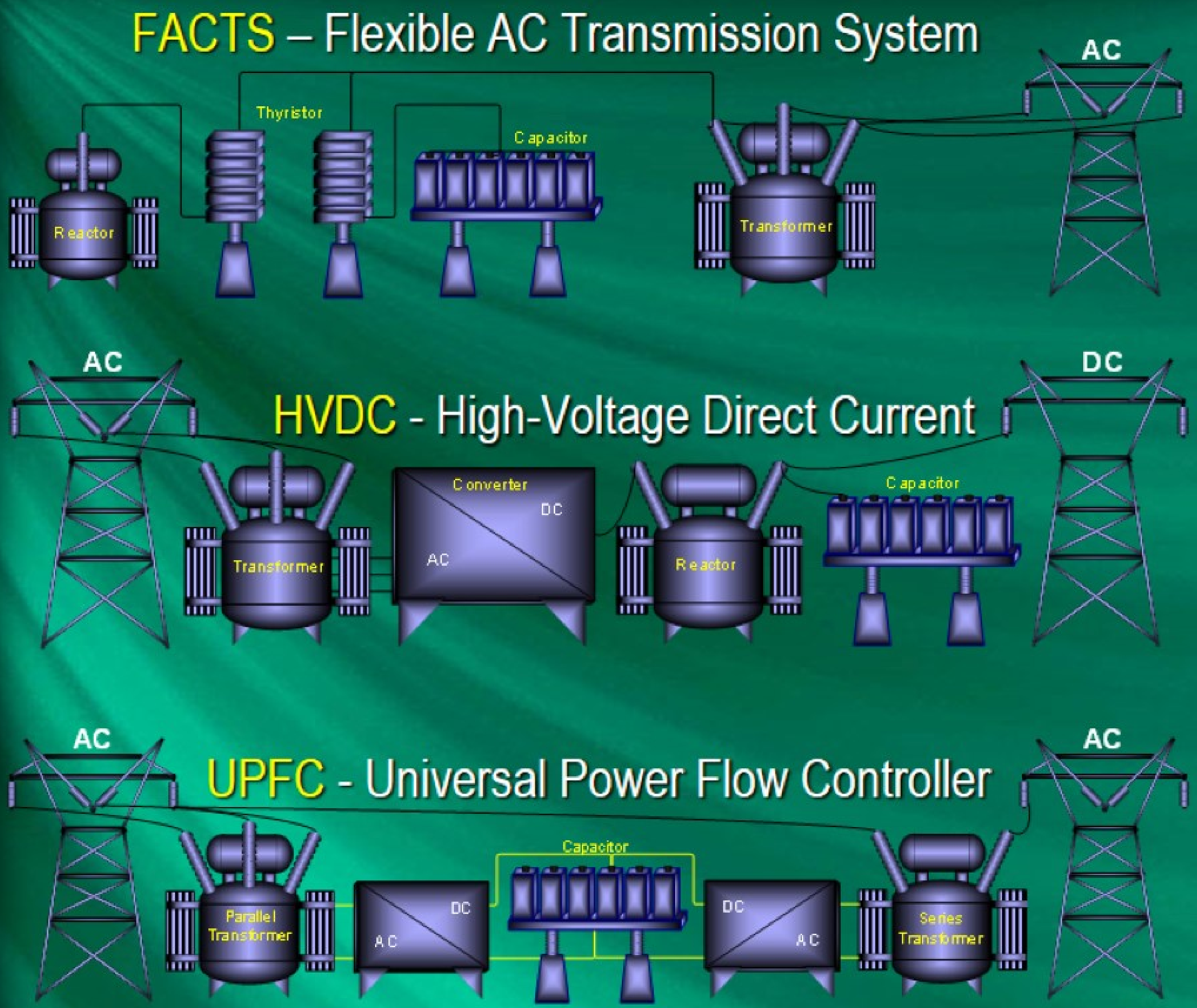
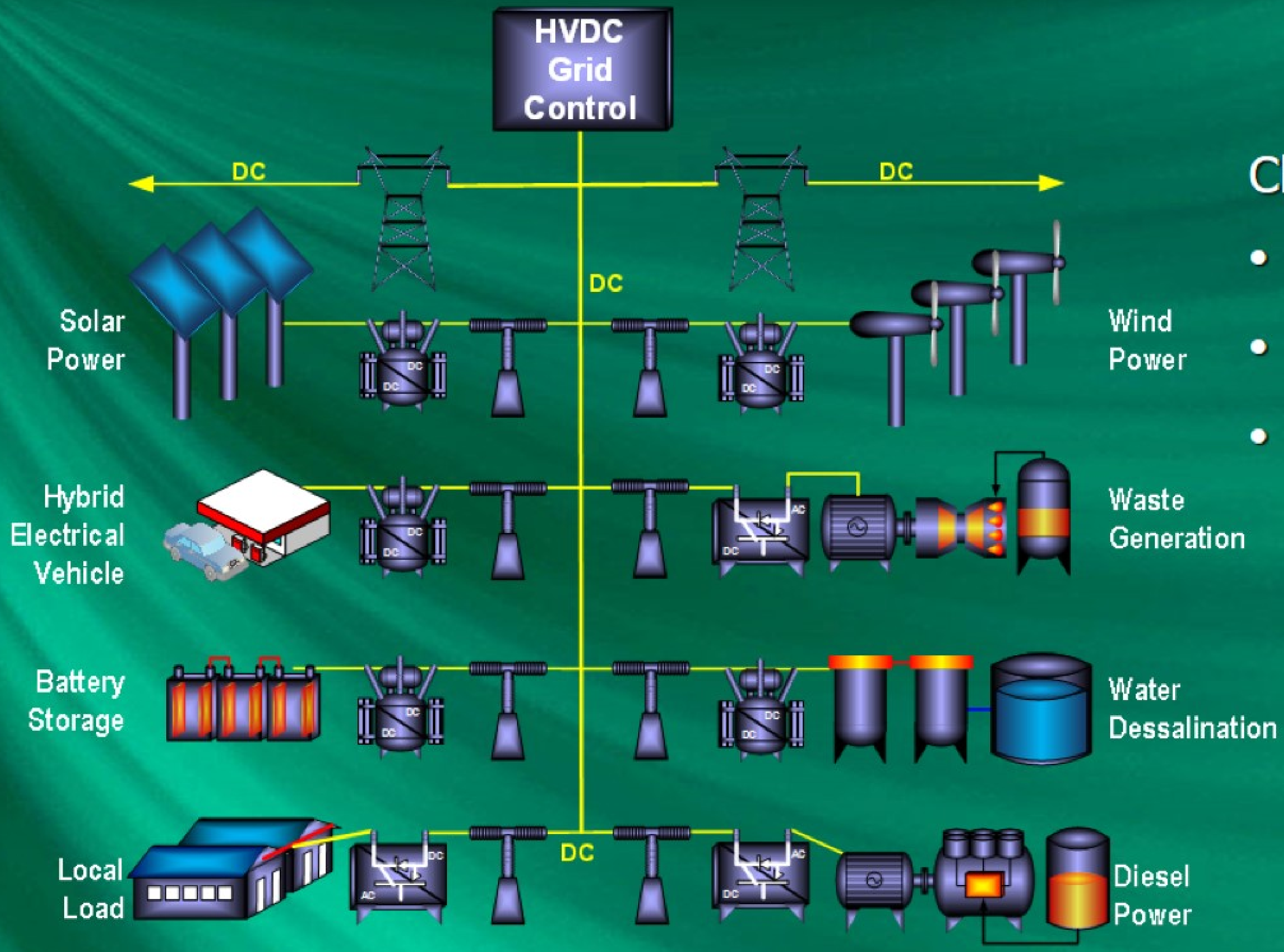


HVDC Advantages

- Maximum efficiency (< copper)
- No stability limits
- Less environment issues
- Fine power control
- Asynchronous connection
- Active x reactive power control

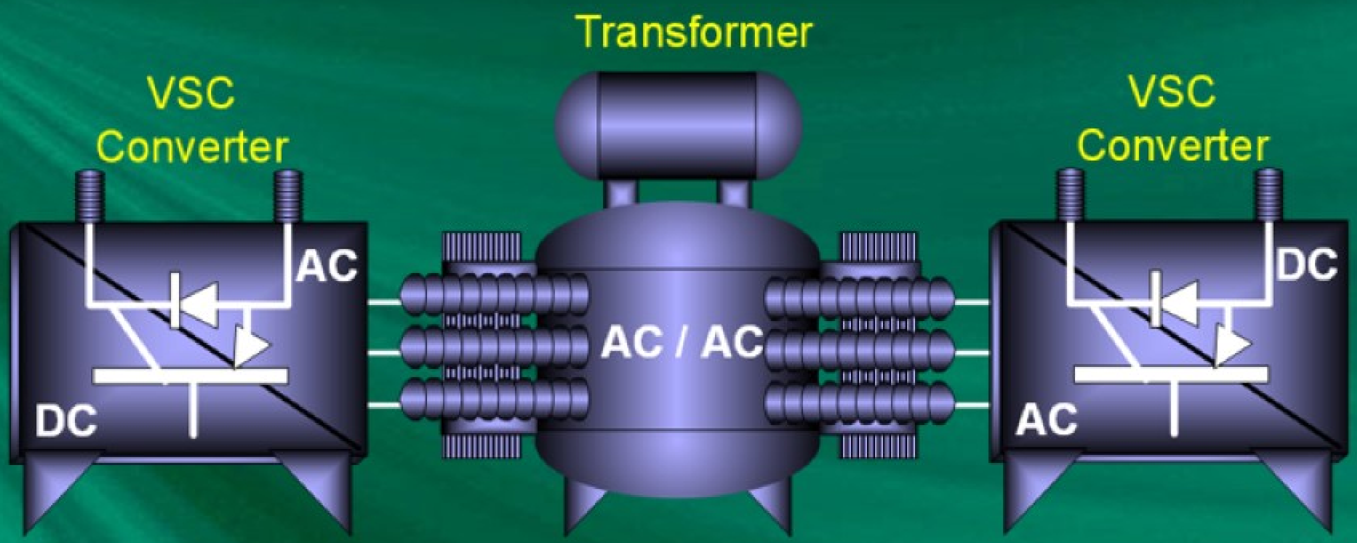
Multi-Terminal HVDC Grid



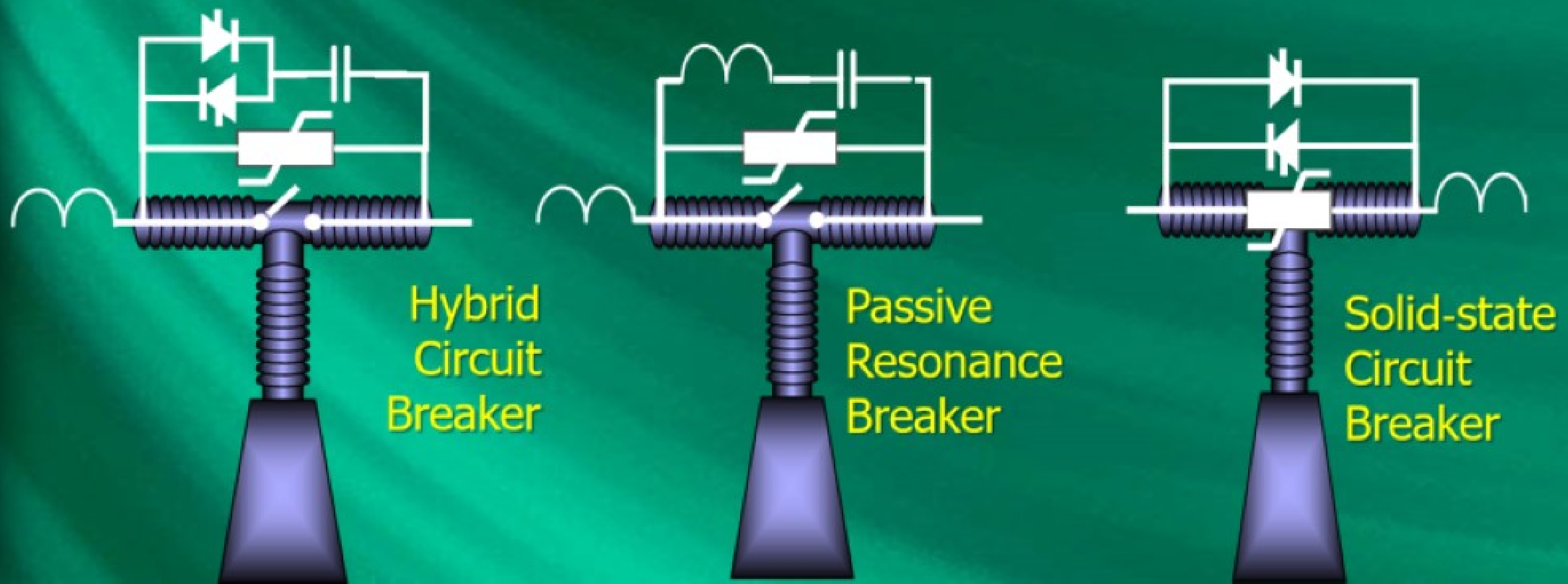
Challenges:

- HVDC Circuit-Breaker
- HVDC Transformer
- Synchronized Control

Direct-Current Transformers & Circuit Breakers



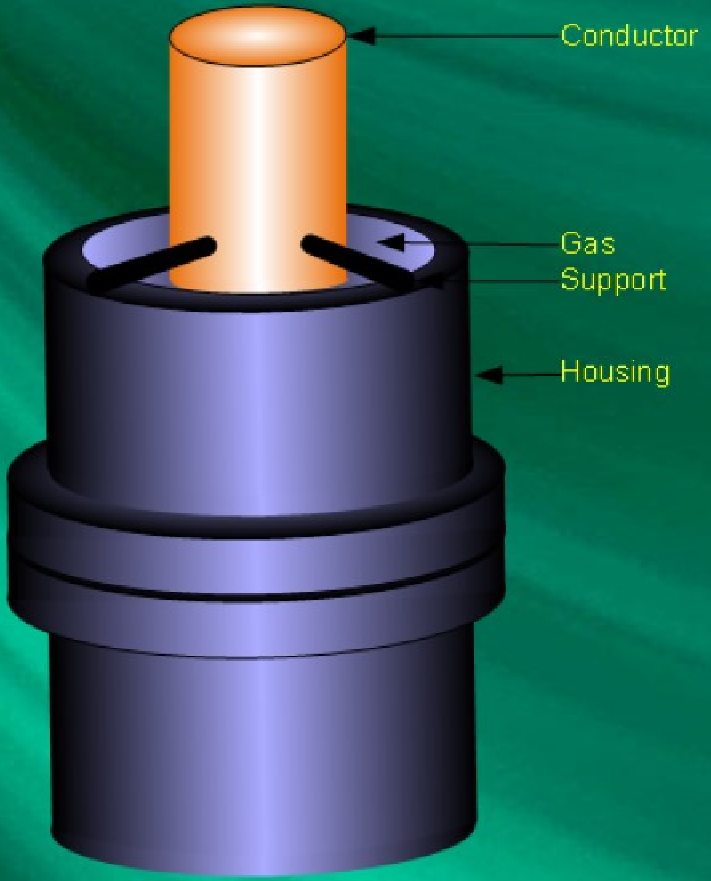
Direct-Current Transformers



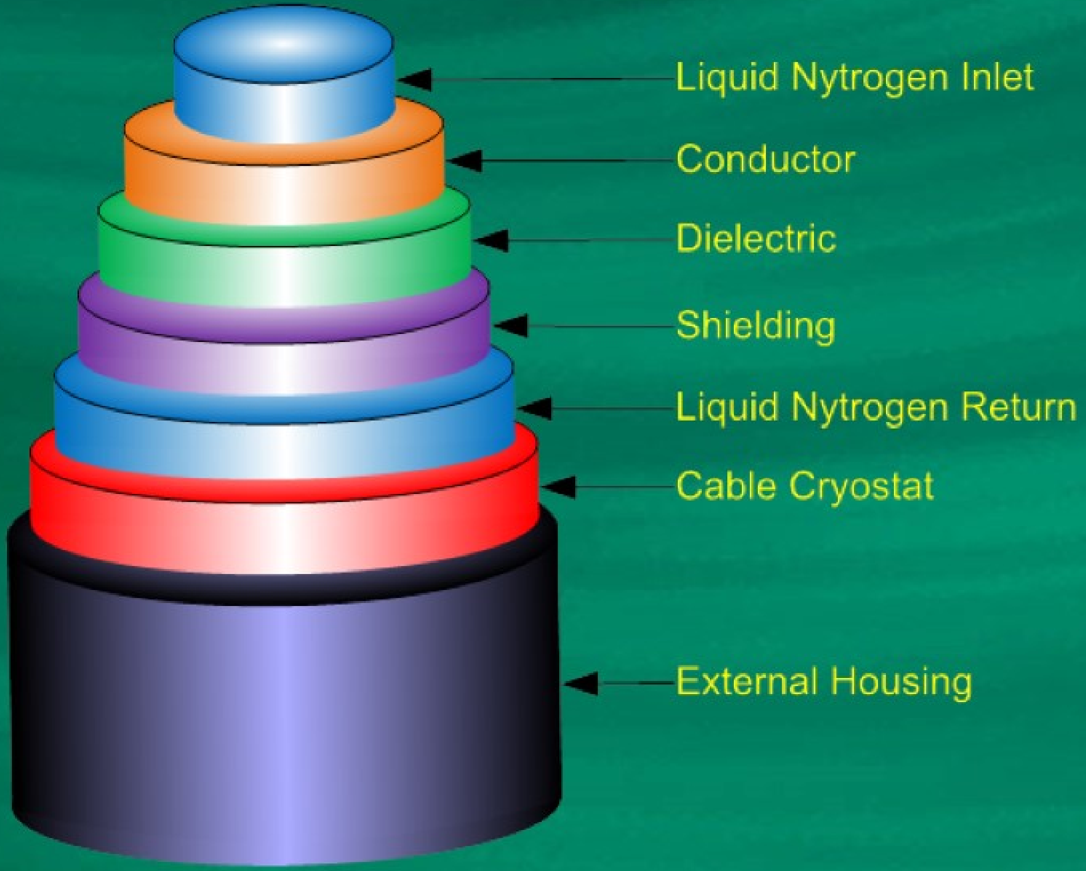
Direct-Current Circuit Breakers

Advanced Materials & Transmission Lines

Gas Insulated Line (GIL)



Superconductor Line

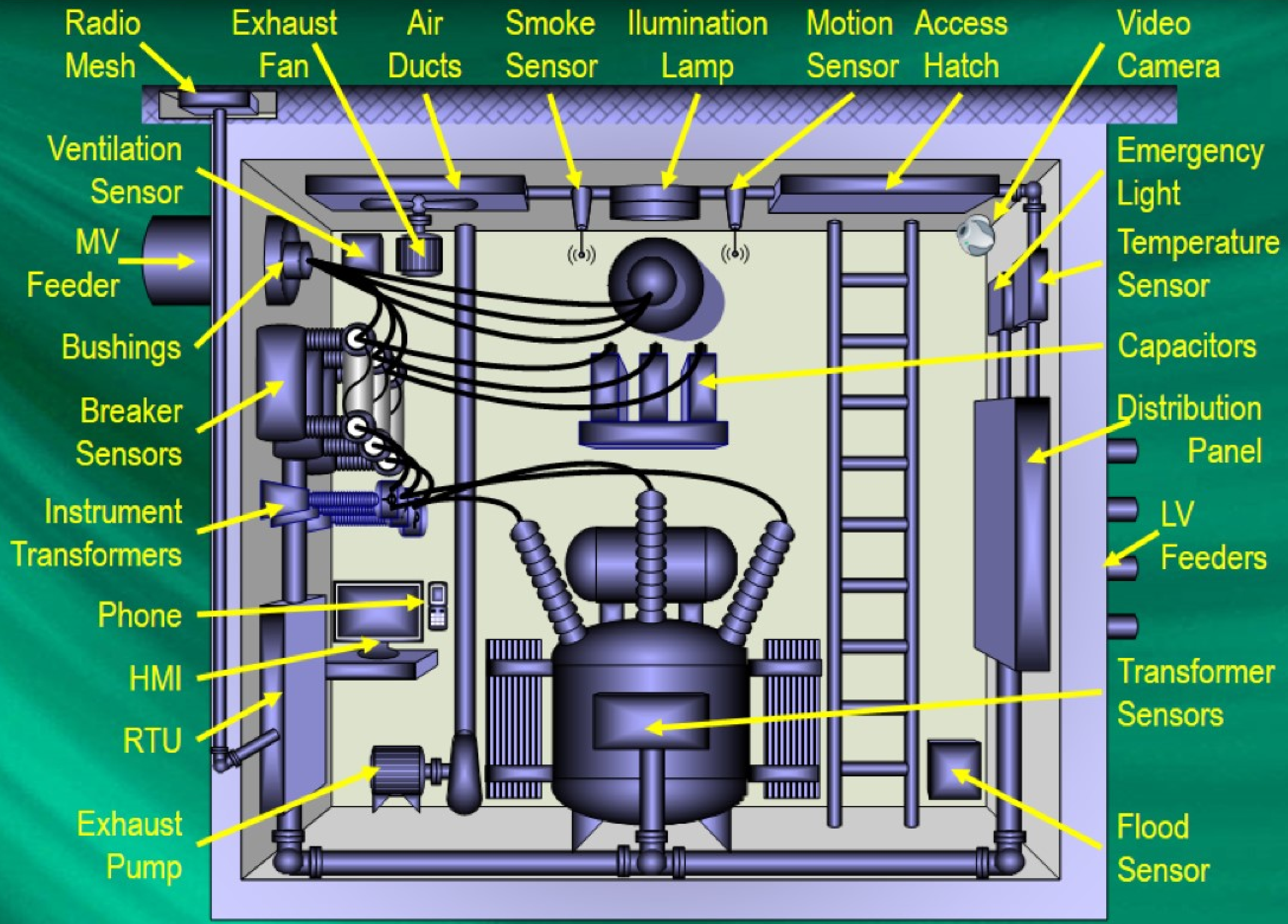


Trends in Distribution Systems

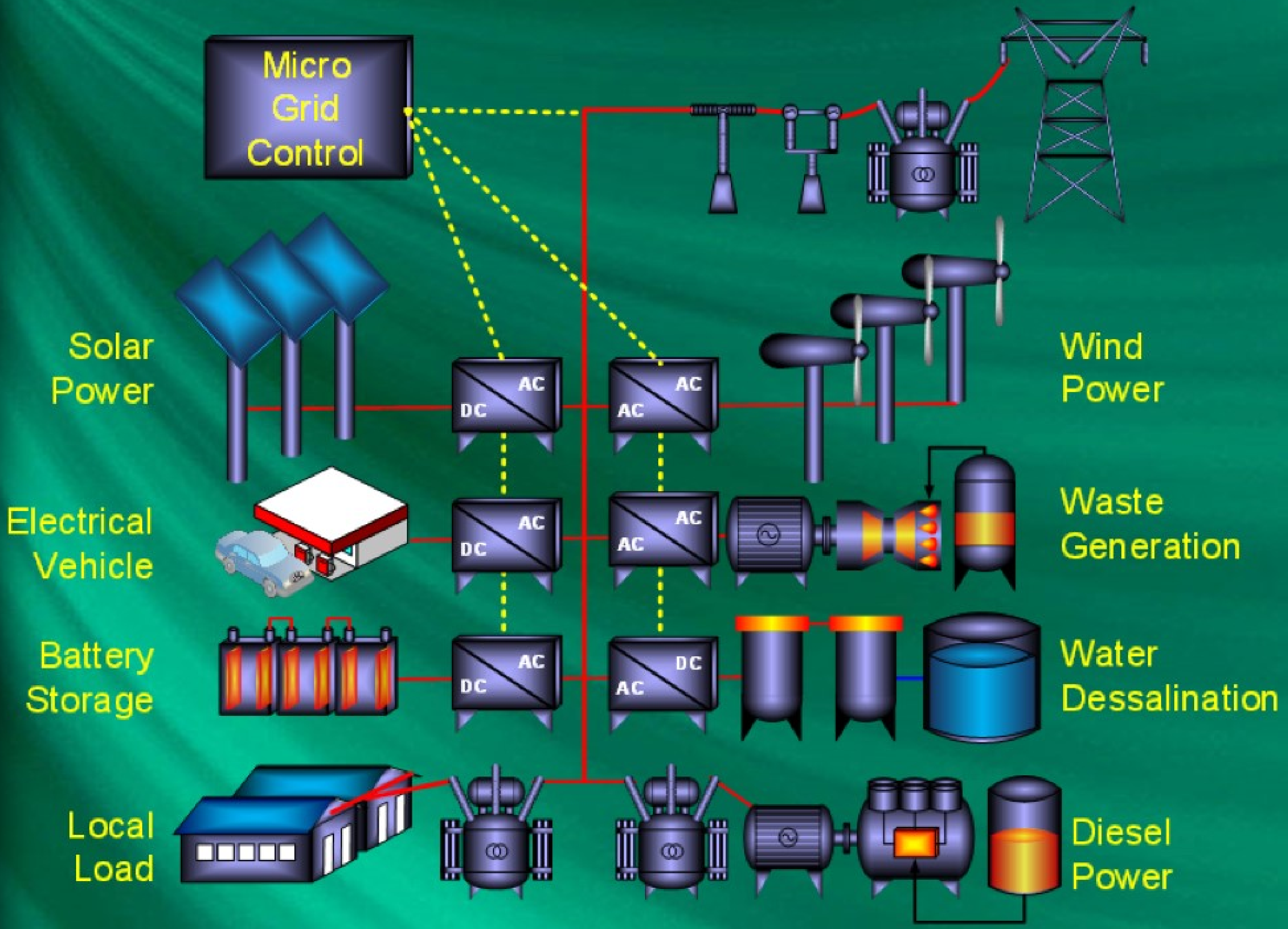
Underground Distribution

Microgrids & Virtual Power Plants

Underground Distribution



Microgrids & Virtual Power Plants



Challenges

- Decreasing short circuit
- Power flow reversal
- Fault Ride Through (FRT)
- Optional off-grid operation
- Market participation

Trends in Energy Storage

- Chemical & Thermal Storage
- Kinetic & Gravitational Storage
- Mechanical Storage

Thermal & Chemical Storage

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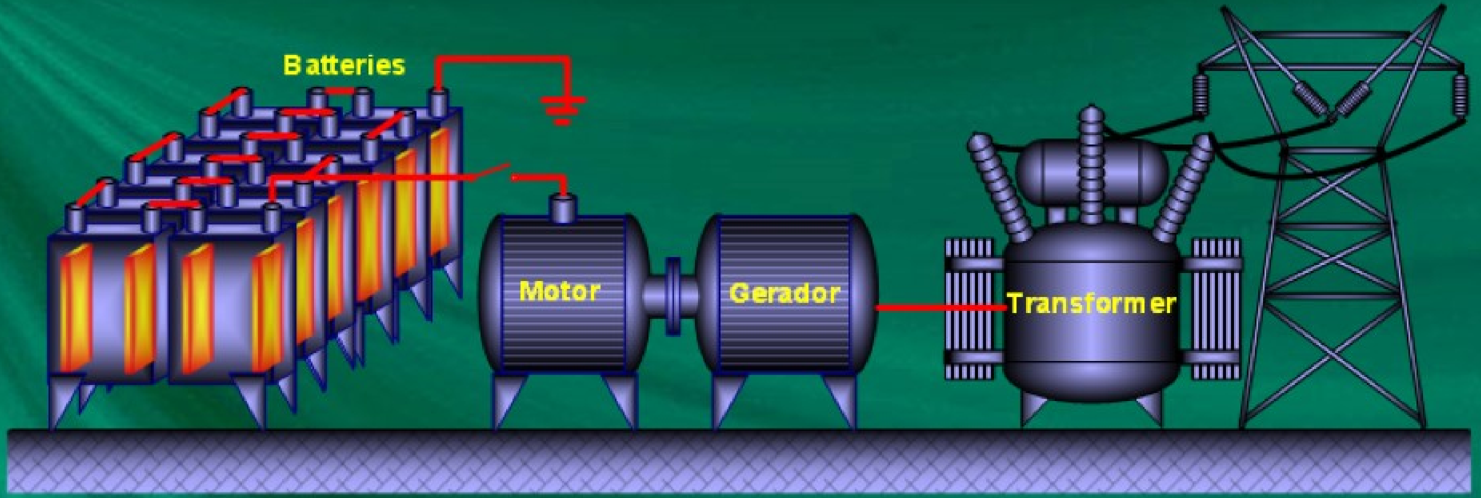
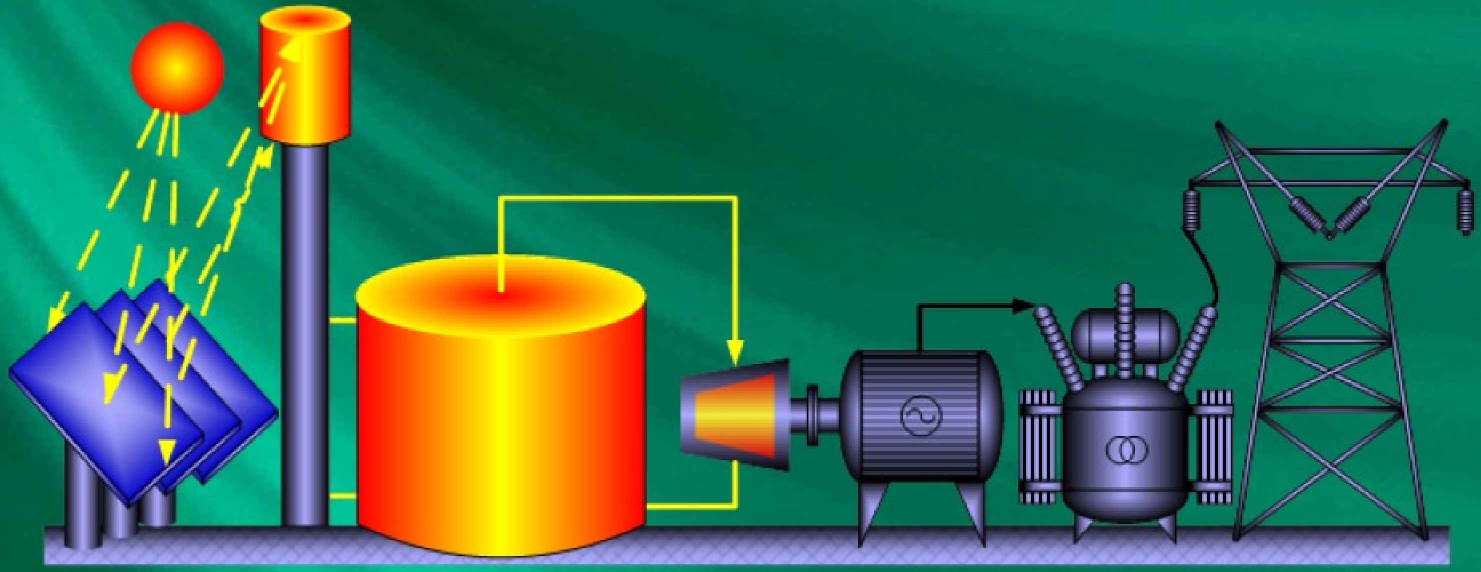


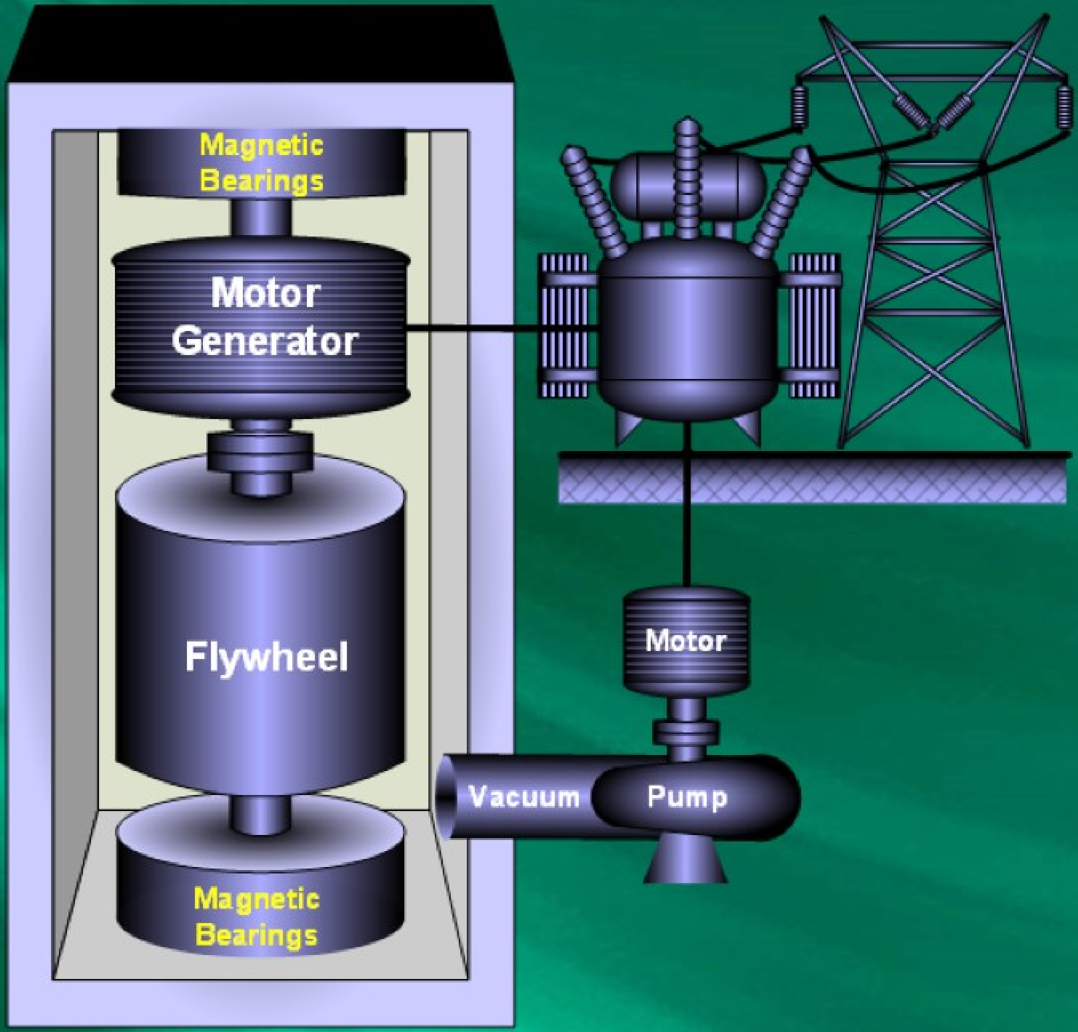
Chemical Storage



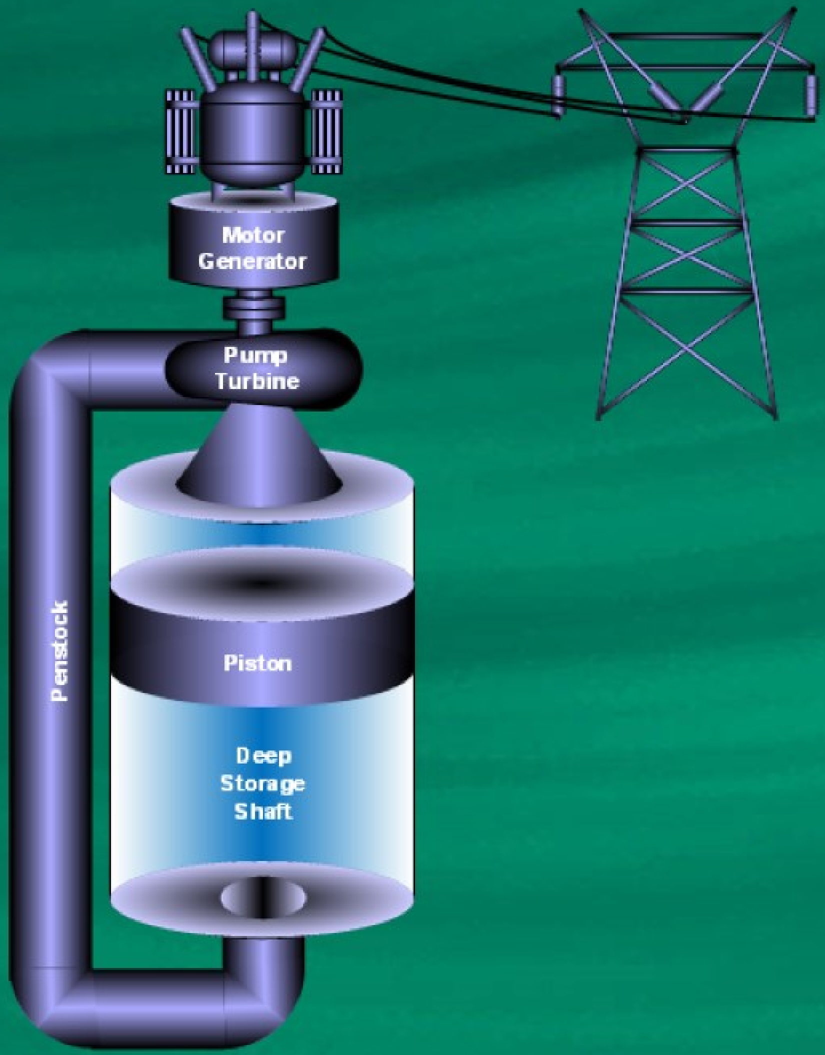
Thermal Storage

Kinetic Storage & Gravitational Storage

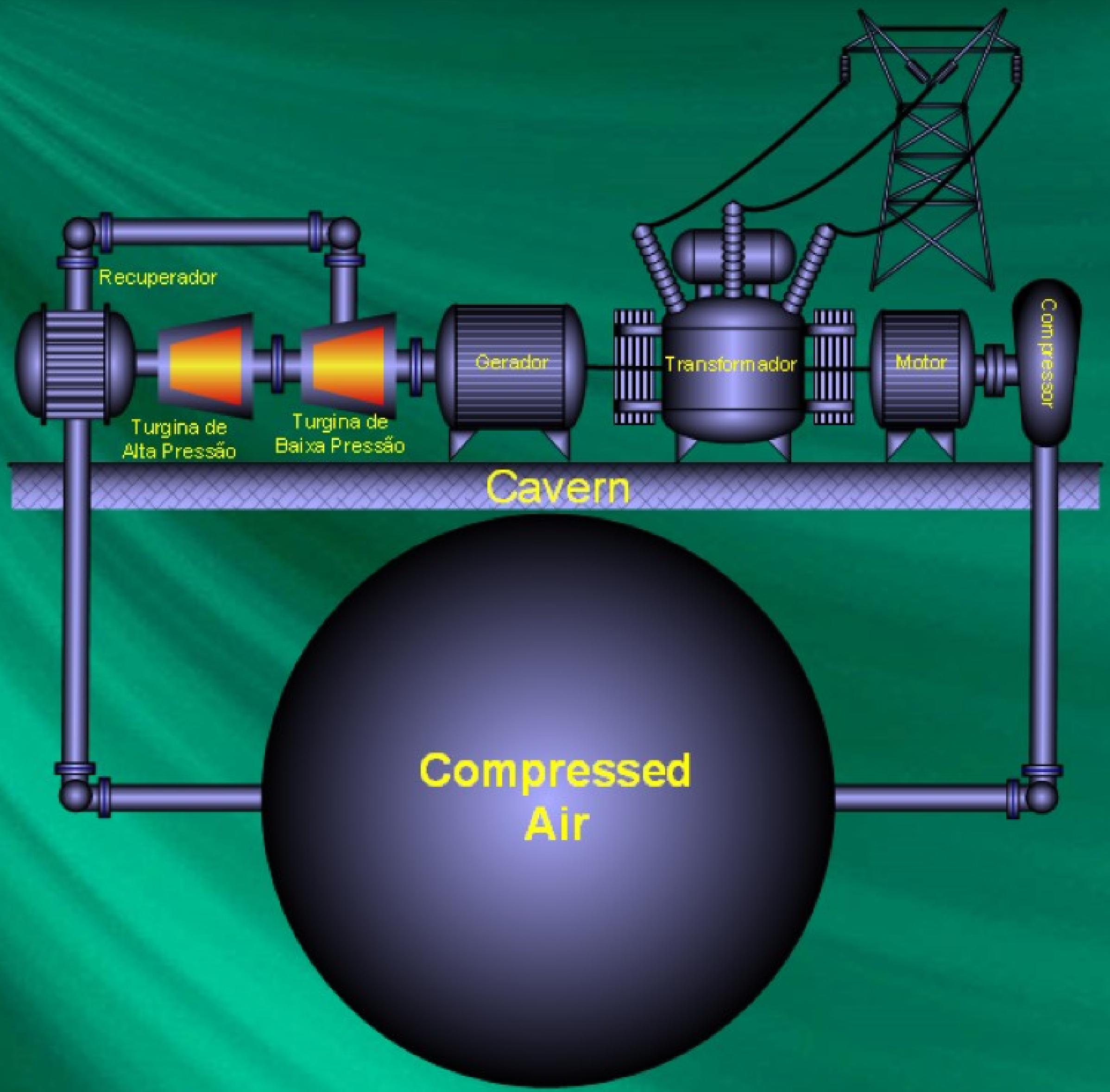
Kinetic Storage



Gravitational Storage



Mechanical Storage



Current Projects:

- Germany: 290 MW
- Alabama: 110 MW
- Iowa: 2700 MW

Trends in Electricity Consumption

Electric Mobility

Residential Automation

Electrical Mobility

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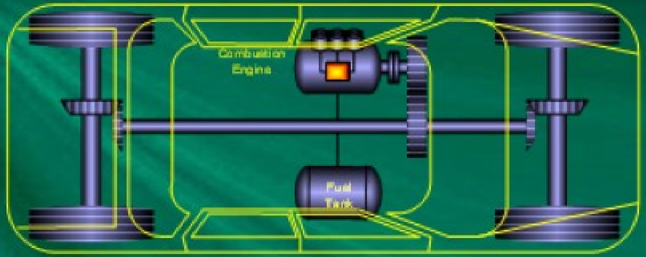
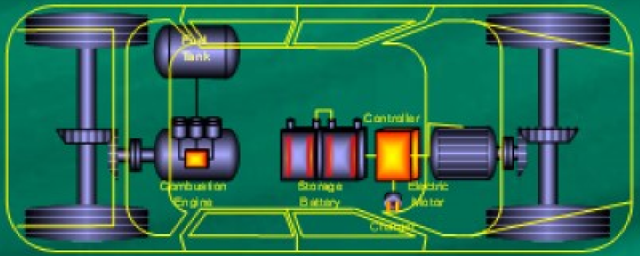
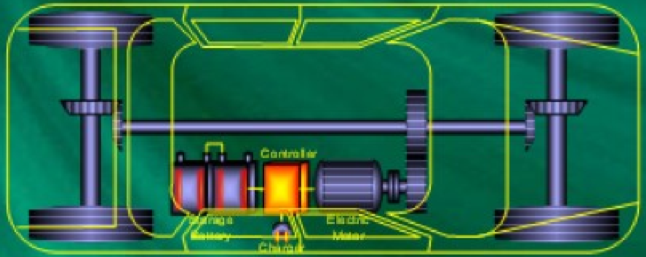


Internal Combustion Engine

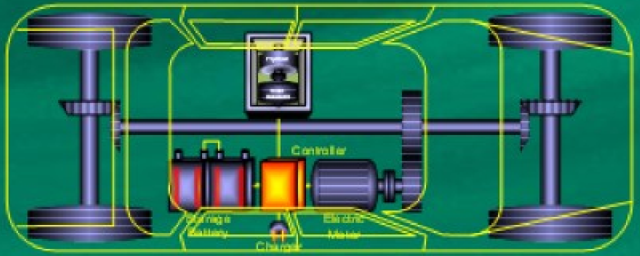
Hybrid Vehicle with Double Traction

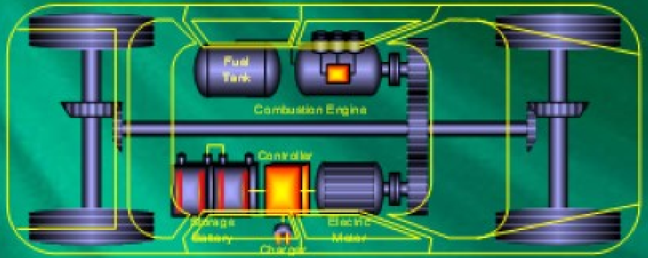




Rechargeable Battery Vehicle

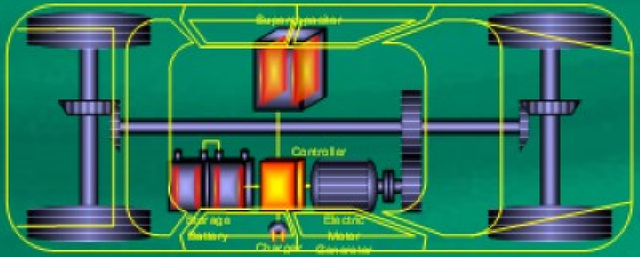
Rechargeable Battery & Flywheel

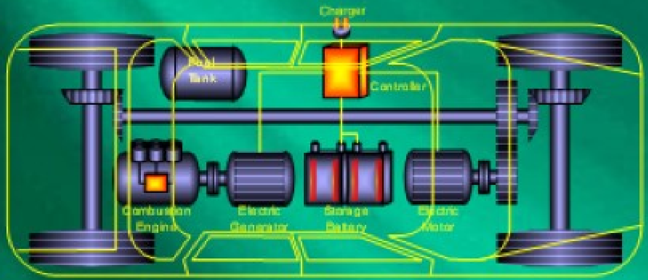




Hybrid Vehicle with Parallel Powerflow

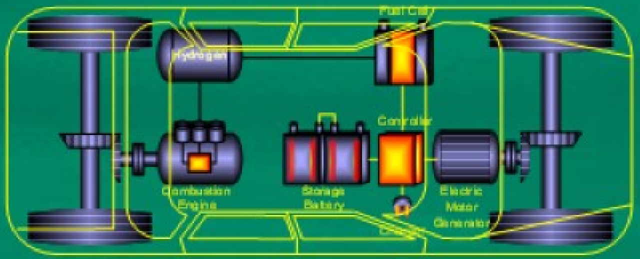
Rechargeable Battery & Supercapcitor



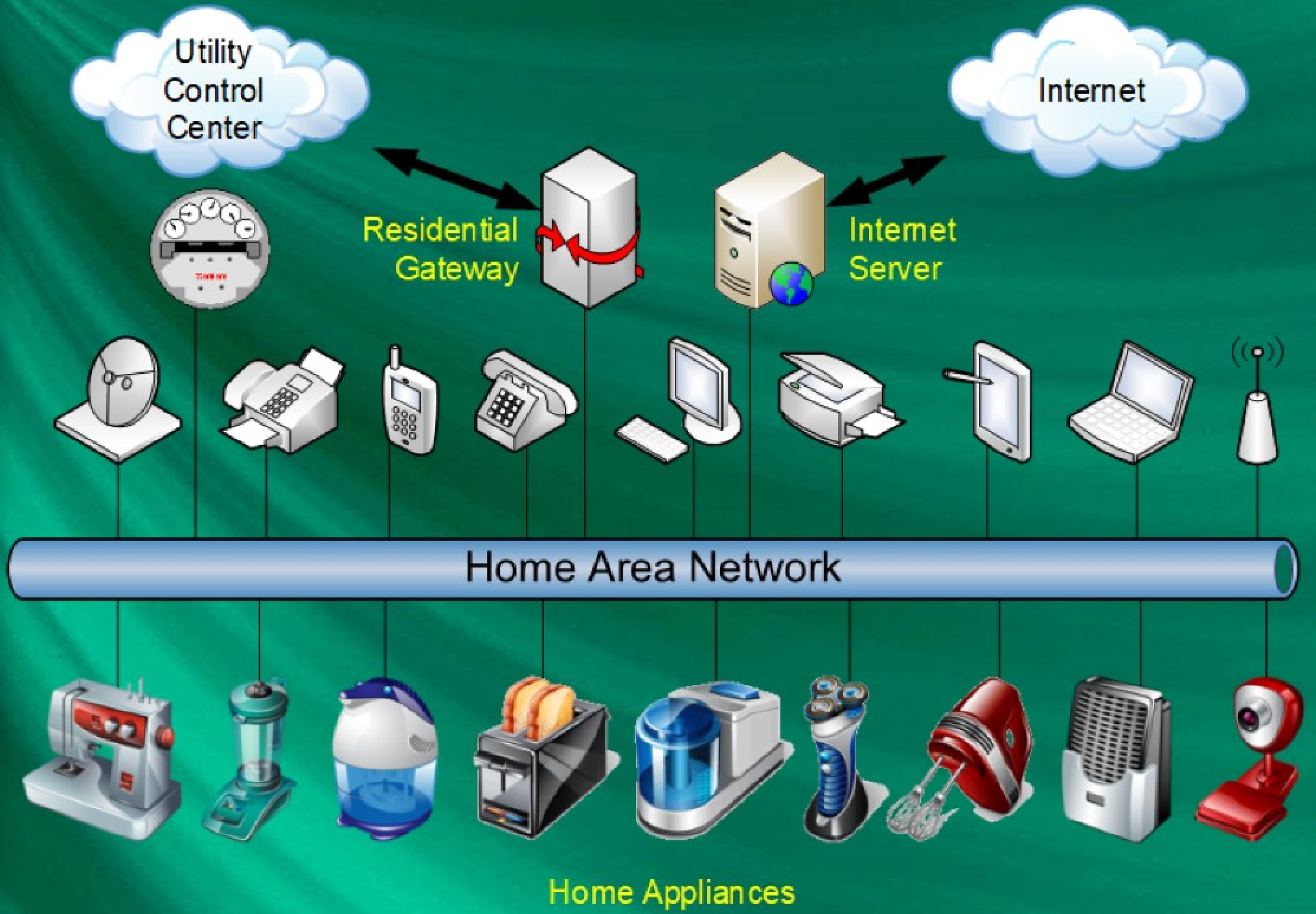


Hybrid Vehicle with Series Powerflow

Hybrid Vehicle with Fuel Cell



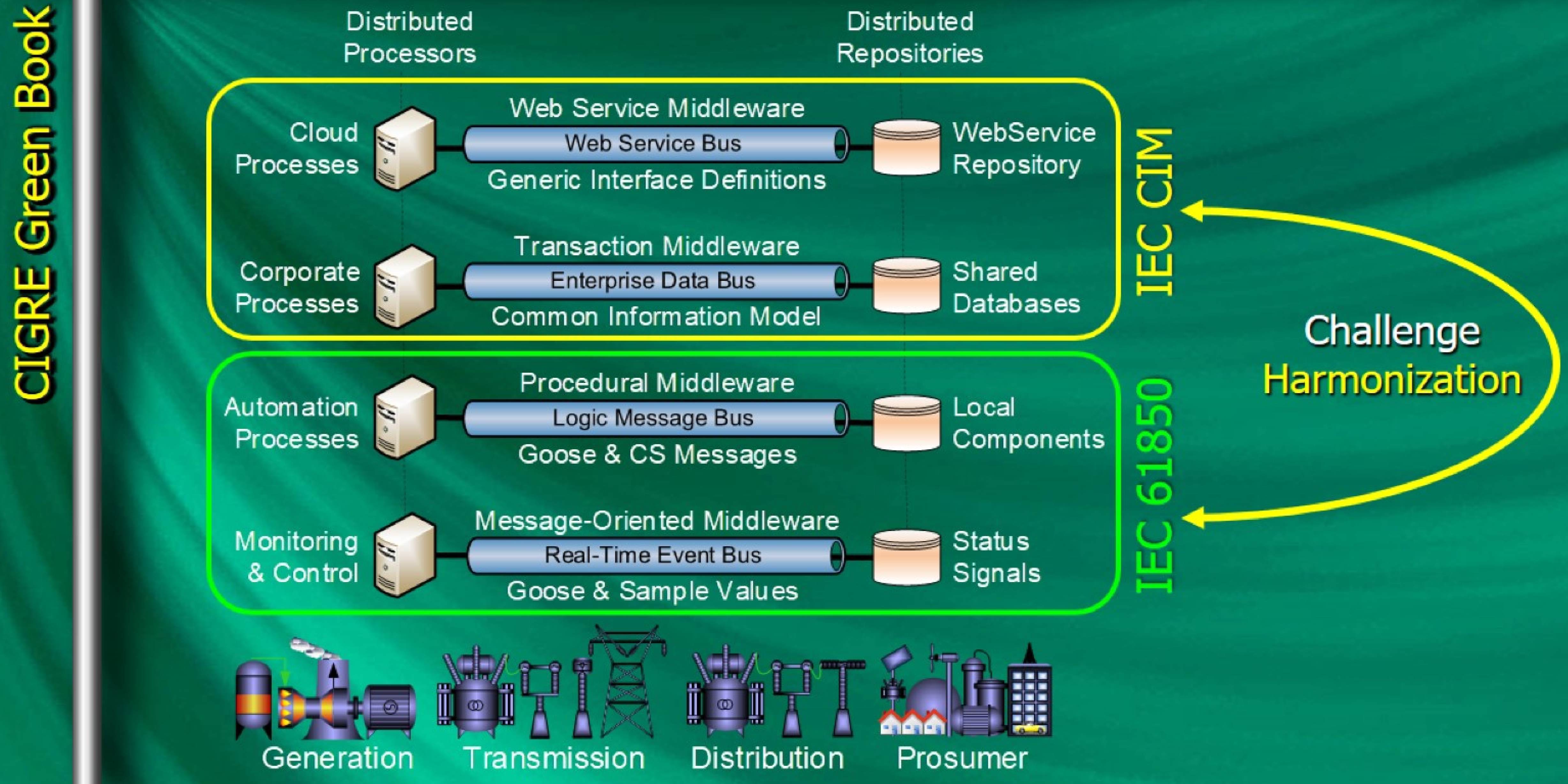
Residential Automation



Trends in Automation

- Telecommunications
- Substation Automation
- Cybersecurity

Trends in Telecommunications



Substation Automation

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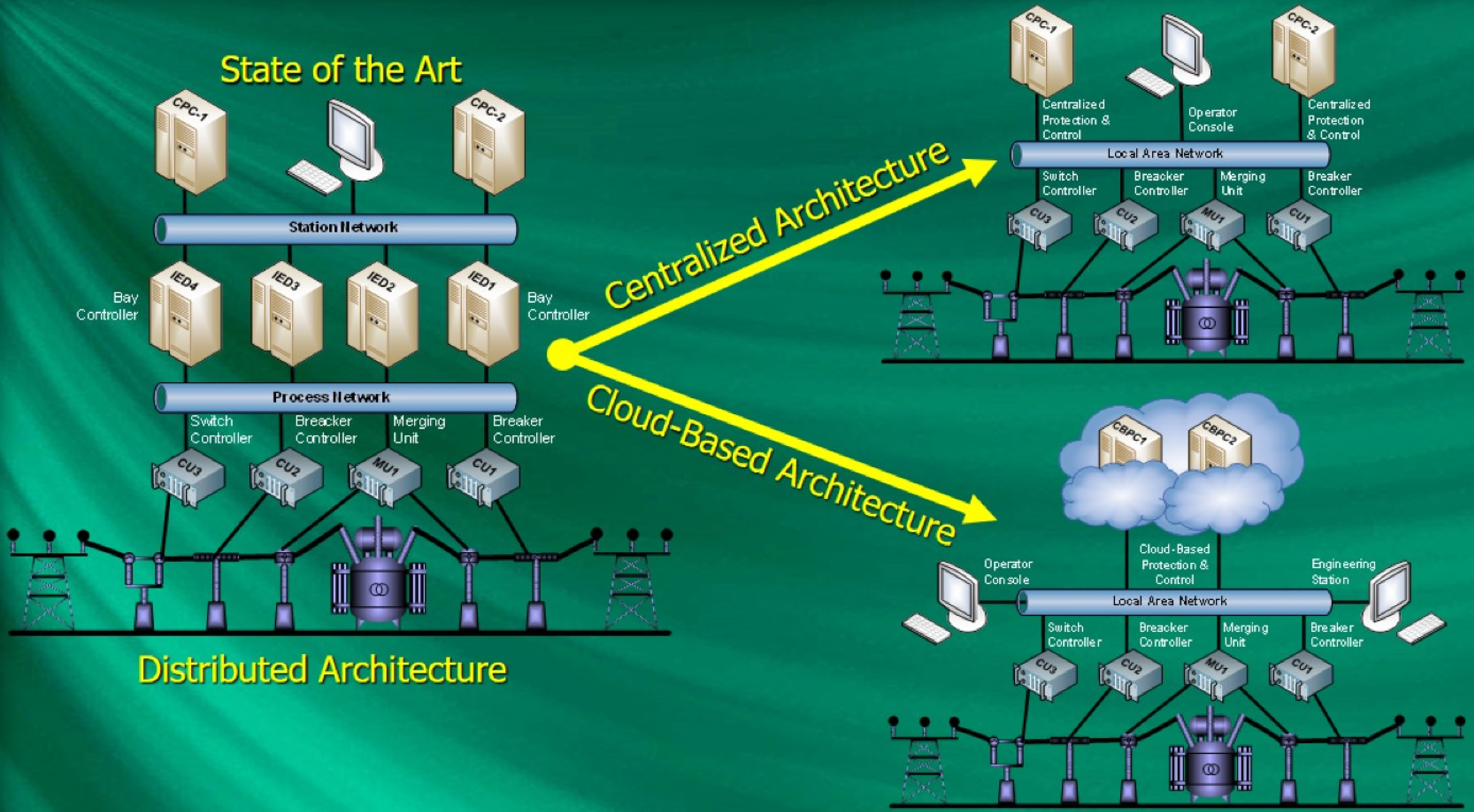
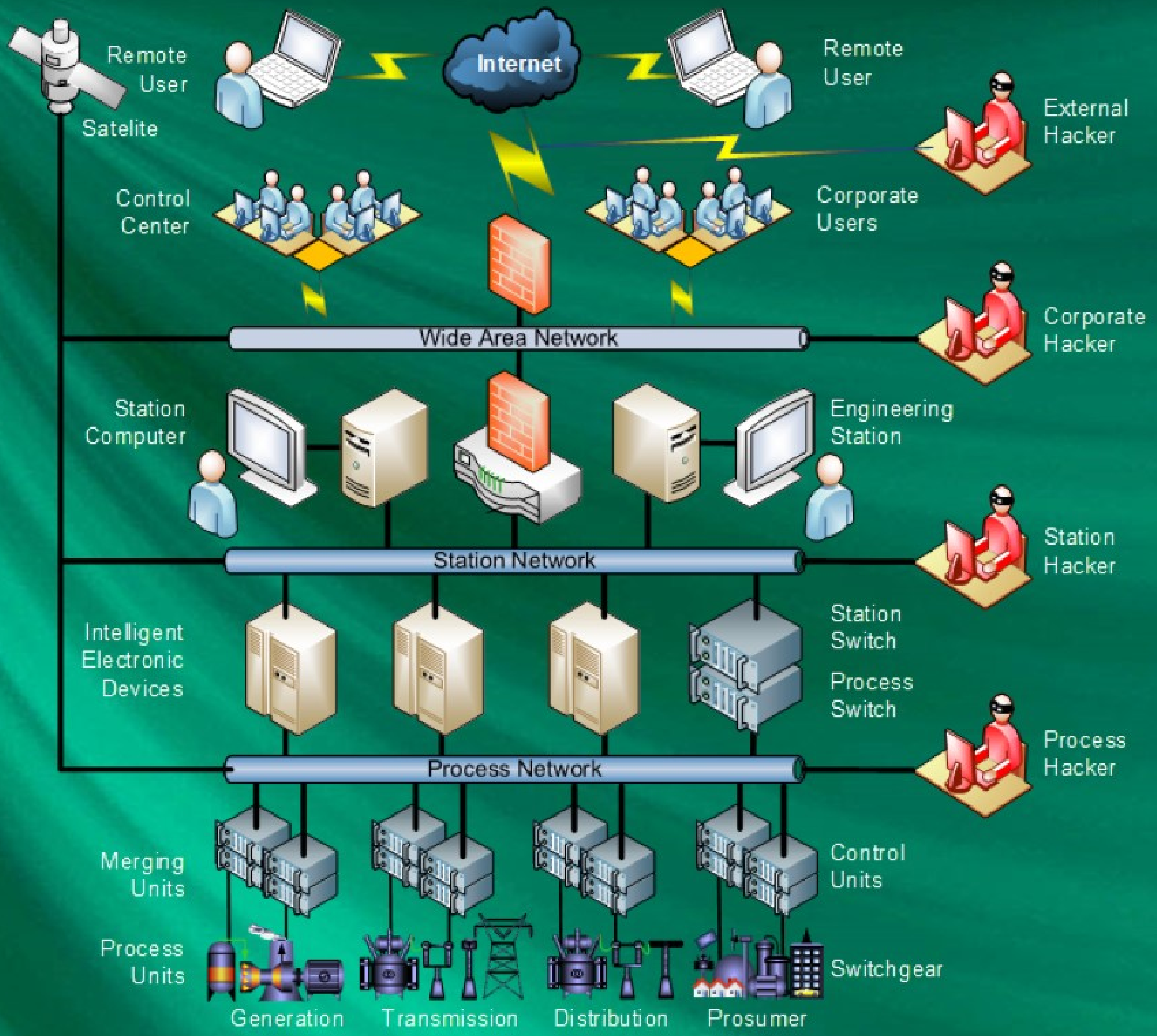


Cybersecurity



Challenges

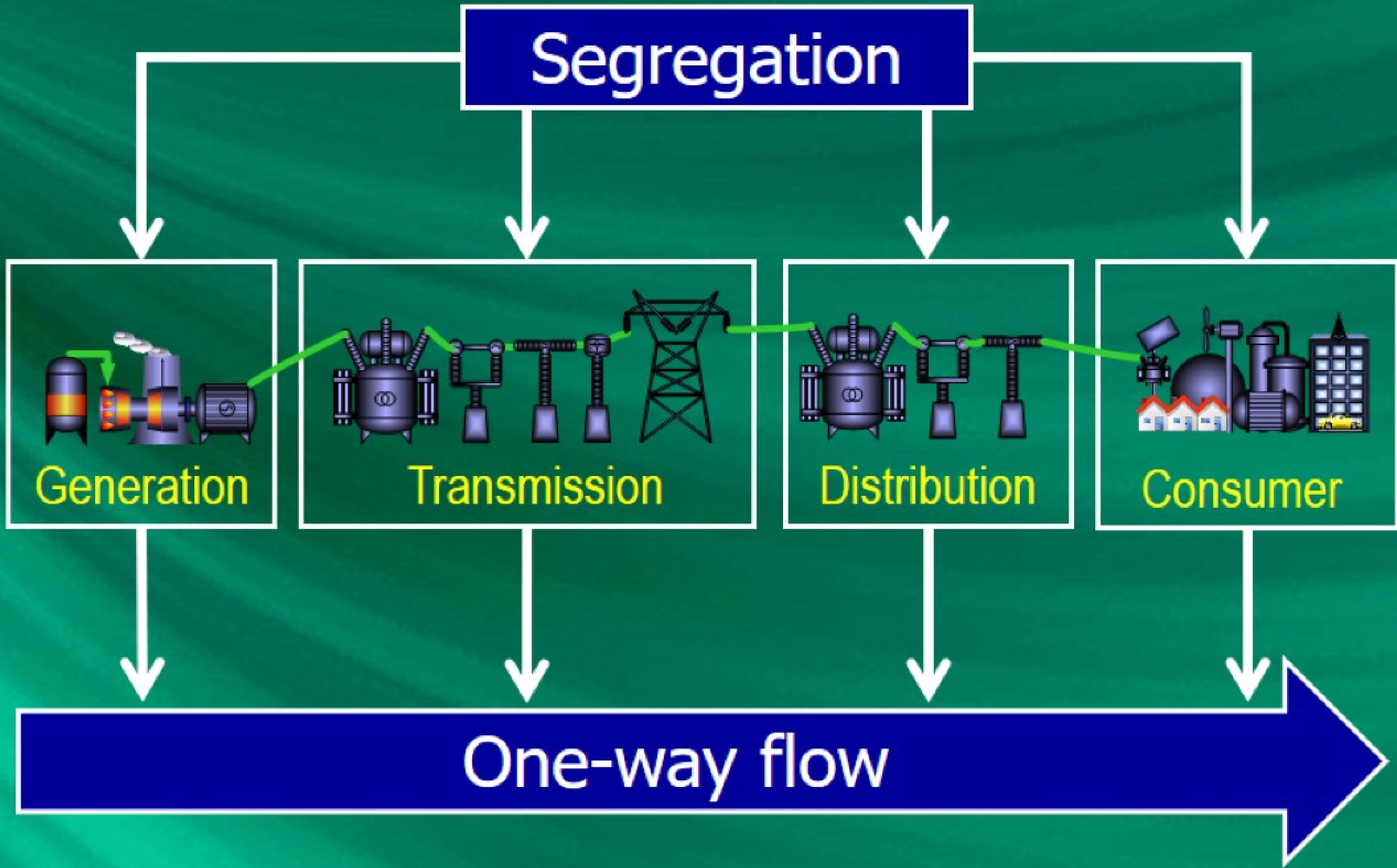
- Large attack surface
- Huge amount of hackers
- High impact of attack
- Complex wide-area solution

Conclusions

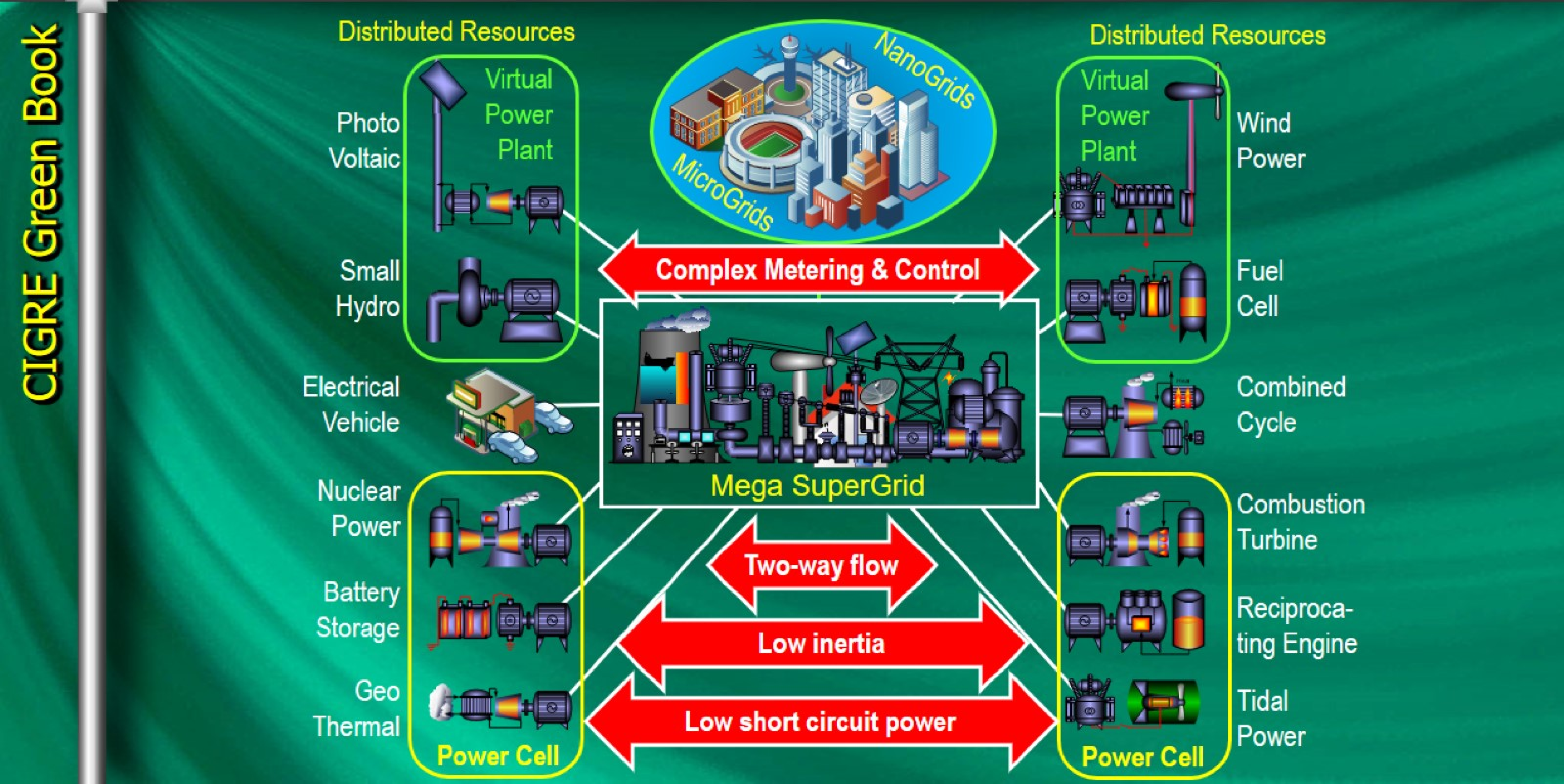
Future Electrical Grid

Educational Challenges

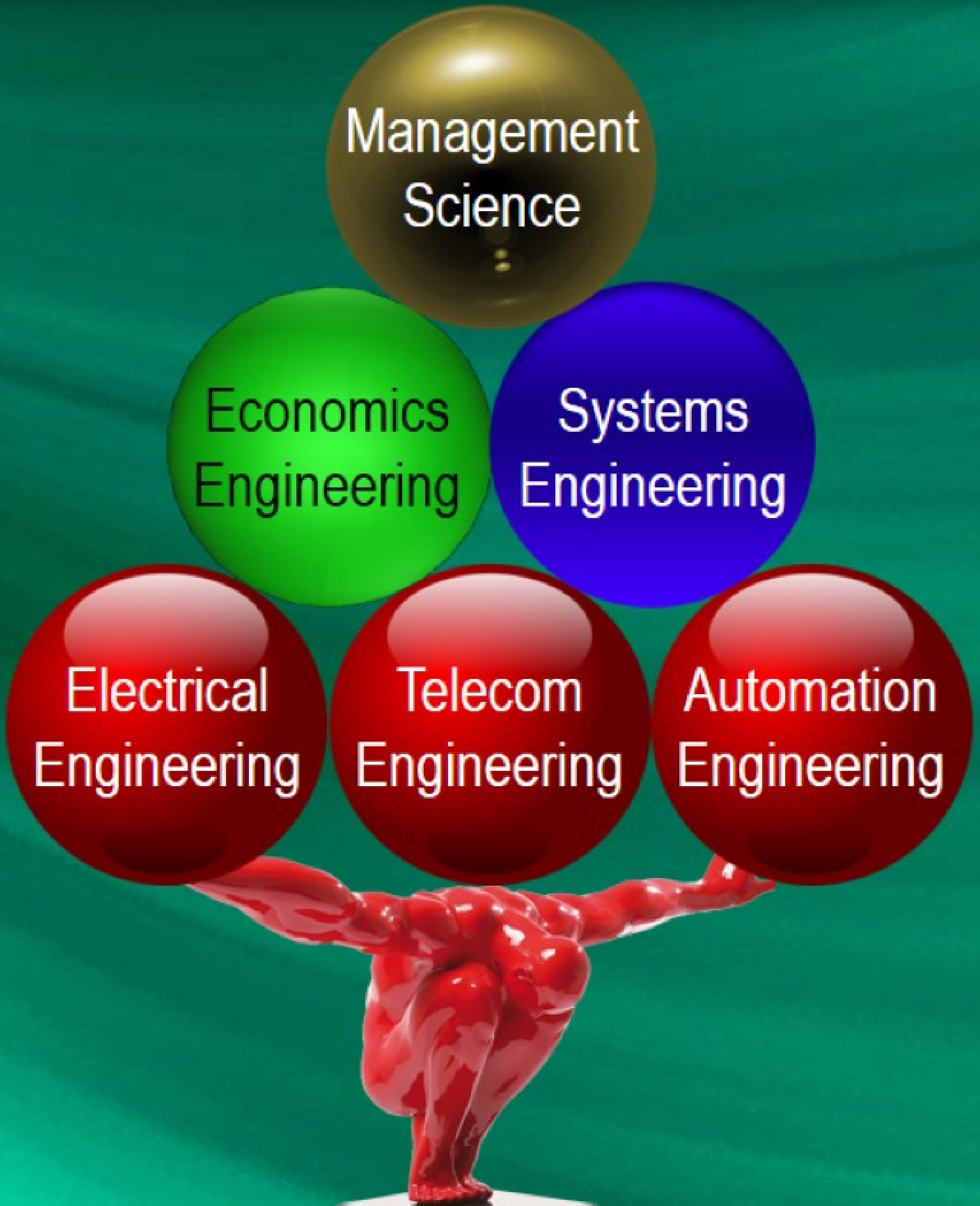
Current Electrical Network

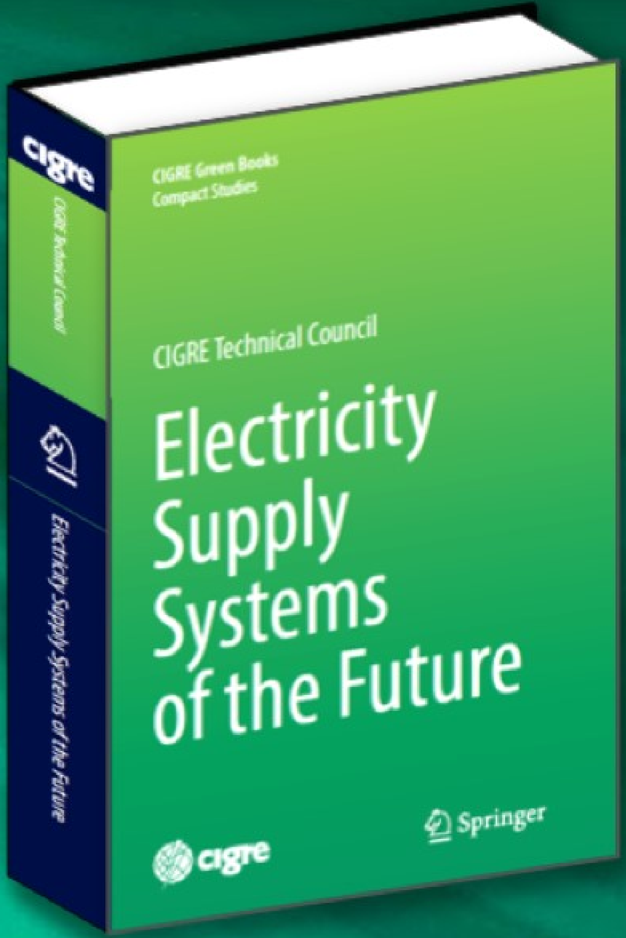


Future Electrical Network



Educational Challenges





Thanks!

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Electricity Supply Systems of the Future
Part II

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24 March 2021

TABLE OF CONTENTS

Acknowledgement: this tutorial is based on the CIGRE Green Book "Electricity Supply Systems of the Future", of CIGRE Technical Council, Editors Nikos Hatziargyriou & Iony Patriota de Siqueira

POWER SYSTEM DEVELOPMENT AND ECONOMICS

SC C1

Konstantin Staschus Chongqing Kang Antonio Iliceto
Ronald Marais Keith Bell Phil Southwell
Yury Tsimberg

Overview of system planning methods

Generation planning

- **Generation planning with uncertainties and through multiple regions or subsystems**

  Equivalent load duration curve based on convolution of load and unit outage distributions, is not effective for strongly correlated unit availabilities, such as for solar and wind generation within a region subject to the same weather. state of the art chronological simulations. Common optimization models involving **uncertainties** include chance constraints models, risk-based models, robust models and stochastic models. Uncertainties impose a huge computational burden on problem solving.

- ***Generation planning with competitive or market frameworks***

Rather than minimizing costs, a generation company **maximizes profits** and system load and emissions constraints are replaced by **contractual values**. The price at which the company sells the energy to different kinds of customers for different products (e.g. energy, capacity, different kinds of reserves), at different times and in different market areas, is in principle not regulated, but depends on competition. **Price forecasting** for all different kinds of energy, capacity and reserve products becomes a major determinant of generation and storage investment decisions.

- ***Generation planning with flexible demand and monetization of reliability and externalities***

The gradual introduction of flexibility in demand and the monetization of environmental and safety externalities lead to formulations, where costs, reliability, environmental externalities like CO_2 emissions, and even safety, become **parts of the objective of planning**. This imposes very explicit tradeoffs among them and needs to monetize them. Shorter-term planning which does take multiple criteria into account, often leaves tradeoffs to politicians rather than to planners. Requirements for very sophisticated price forecasting for hours with sufficient adequacy and also with insufficient adequacy. **Value of lost load** (VOLL) is used to describe the per kWh cost of a blackout, which varies between customers, time of day or season, and the usage of electricity.

Overview of system planning methods

Transmission planning

Traditionally, objective to avoid **equipment overloads** in any contingency scenario. Security analysis based on AC power flows with a nodal representation of system generation and of loads. A master program tries out different additions or reinforcements of equipment to automate the process of finding least cost reinforcements of the system which satisfy all security constraints.

- With higher **penetration of renewables** with limited capacity factors, cases with equipment overloads become harder to identify.
- Equipment overloads might be cheaper to remedy by **demand response** than by reinforcements.
- International electricity trade and renewables make economic **benefits from exchanges** between different areas or countries become economically more important than avoidance of equipment overloads.

Transmission planning has evolved into a **value-based** assessment, similar as generation planning. For large networks with several scenarios, analyses via **security-constrained economic dispatch** with DC network approximations and traditional AC security simulations. Analyses of the **expected nodal price differences** are used to determine the **value** of additional transmission infrastructure between different pairs of nodes. AC power flow and dynamic studies complement these economic analyses to indicate technical requirements for new investments. The value estimates from the nodal price studies and the importance of technically required reinforcements are compared to costs of additional infrastructure. Where benefit/cost ratios are large enough in majority of scenarios, infrastructure investments are proposed.

In Europe chronological stochastic simulations are performed over Europe’s wholesale market bidding zones, to arrive at **expected bidding zone price differences** which are translated into values for additional transmission capacity between each pair of neighboring bidding zones.

Overview of system planning methods

Distribution planning

Distribution planning follows similar development as transmission planning. In practice, LV and MV distribution networks are significantly less meshed than transmission networks, **simplified decision rules** often governed distribution system reinforcement (e.g. assumption of peak load and simultaneity factors per household or type of commerce, combined with standard size steps for conductors, breakers, transformers etc.).

Tools to analyze MV + LV distribution networks through combinations of reinforcement options in a master program and evaluating equipment overloads in a subproblem. More advanced approaches evaluate **unserved energy at VOLL** and **trade off costs** of reinforcement, losses and unserved energy, in order to evaluate combinations of reinforcement options, both technically and economically. A master program can then cycle through different reinforcement combinations to find the economically most attractive one, which a subproblem evaluates economically and against equipment overloads. A further step is to model **distributed energy resources** such as batteries, PV, demand response etc., so that network equipment reinforcements can be traded off against local congestion management (called **non-wire alternatives**).

Planning subproblems integration

Transmission and distribution planning now include **economic simulations** of the system of generation, load, storage and networks. Generation and storage investment optimization needs include **network modeling**, since the price a generation unit can achieve depends on the node where it is located. Planning for transmission and distribution systems requires **future generation** capacities. Transmission and distribution planning depend more strongly on each other, as **DER at distribution** constantly increases. This is very complicated, modeling would **ideally integrate** distribution, transmission, storage, demand flexibility and generation at all voltage levels, with millions of decision makers with different perspectives and of decision variables. Even for today's powerful computers and algorithms, this is too large to handle. Given the different decisions for which **different market parties** are responsible (customer vs. network operator vs. generation investor), is full integration of modeling necessary?

Research and Innovation Needs

Gaps between State-of-the-Art Planning Methods and New Societal and Grid Requirements as well as New Technologies

- Active distribution and Big Data
- Modelling of DC, storage, new operations and control tools
- Climate protection, environmental constraints and multi-criteria tradeoffs
- Sector coupling
- Stakeholder and citizen engagement
- Planning, regulation and economics in energy markets with shifting roles of environmental and reliability constraints

POWER SYSTEM OPERATION AND CONTROL

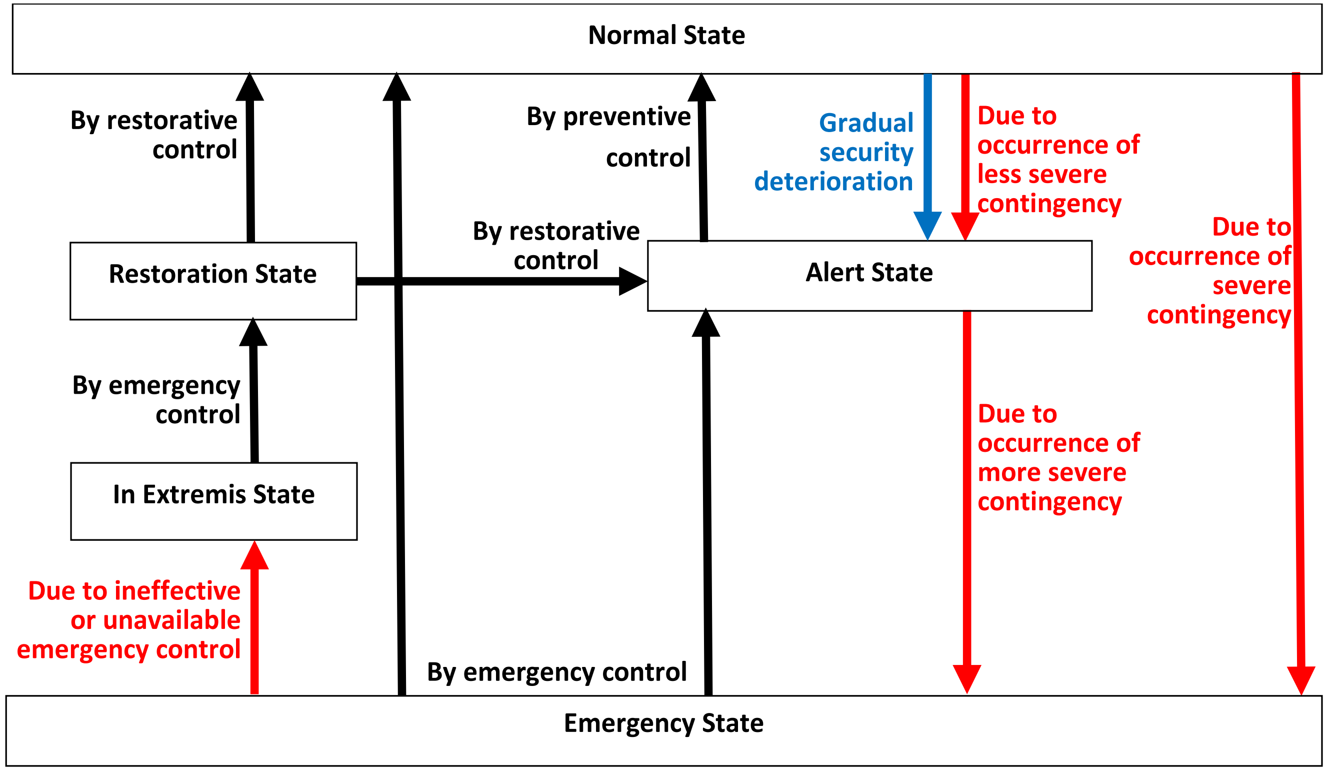
SC C2

Susana Almeida de Graaff

Vinay Sewdien

Greece

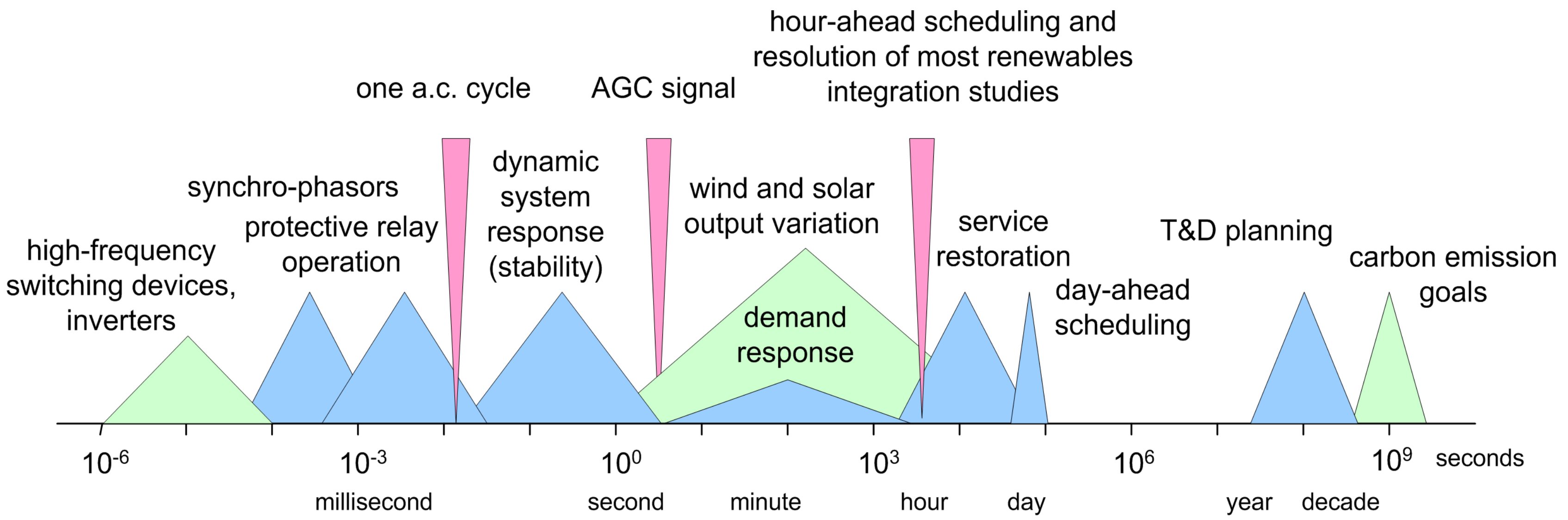
Five Operating Power System States



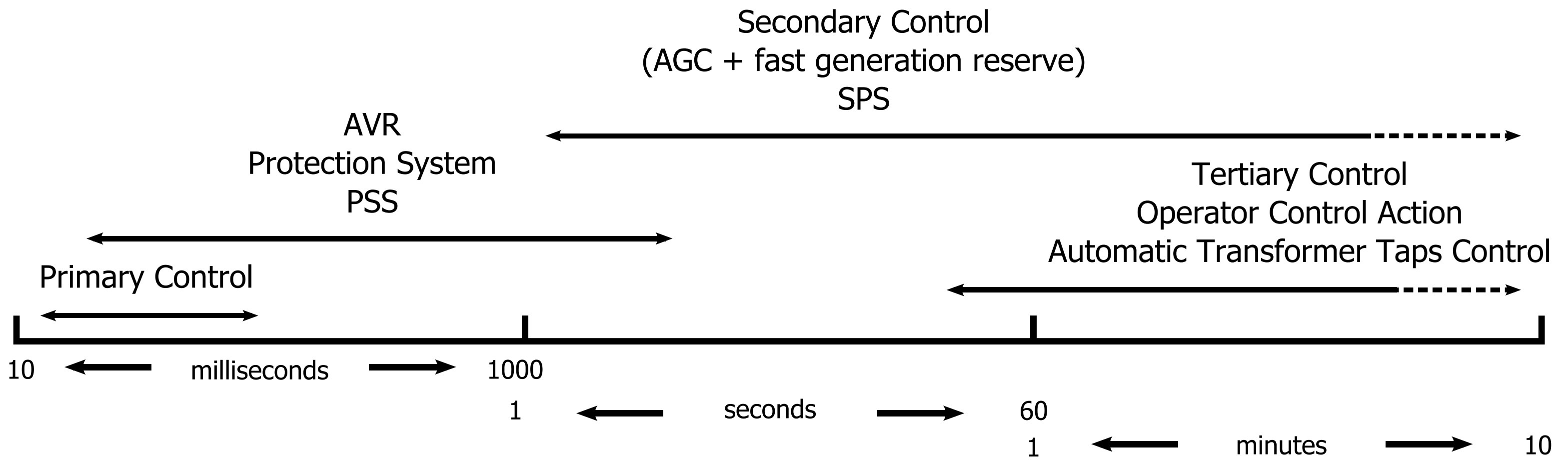
Operating State	EC satisfied?	IC satisfied?	SC satisfied?
Normal	✓	✓	✓
Alert	✓	✓	×
Emergency	✓	×	×
In extremis	×	×	×
Restorative	×	✓	×

EC = Equality Constraints, load-generation balance
IC = Inequality Constraints, operating limits of elements
SC = Security Constraints, security in case of contingencies, available reserves and system robustness

System Operation Timeframes



Timescales of types of control

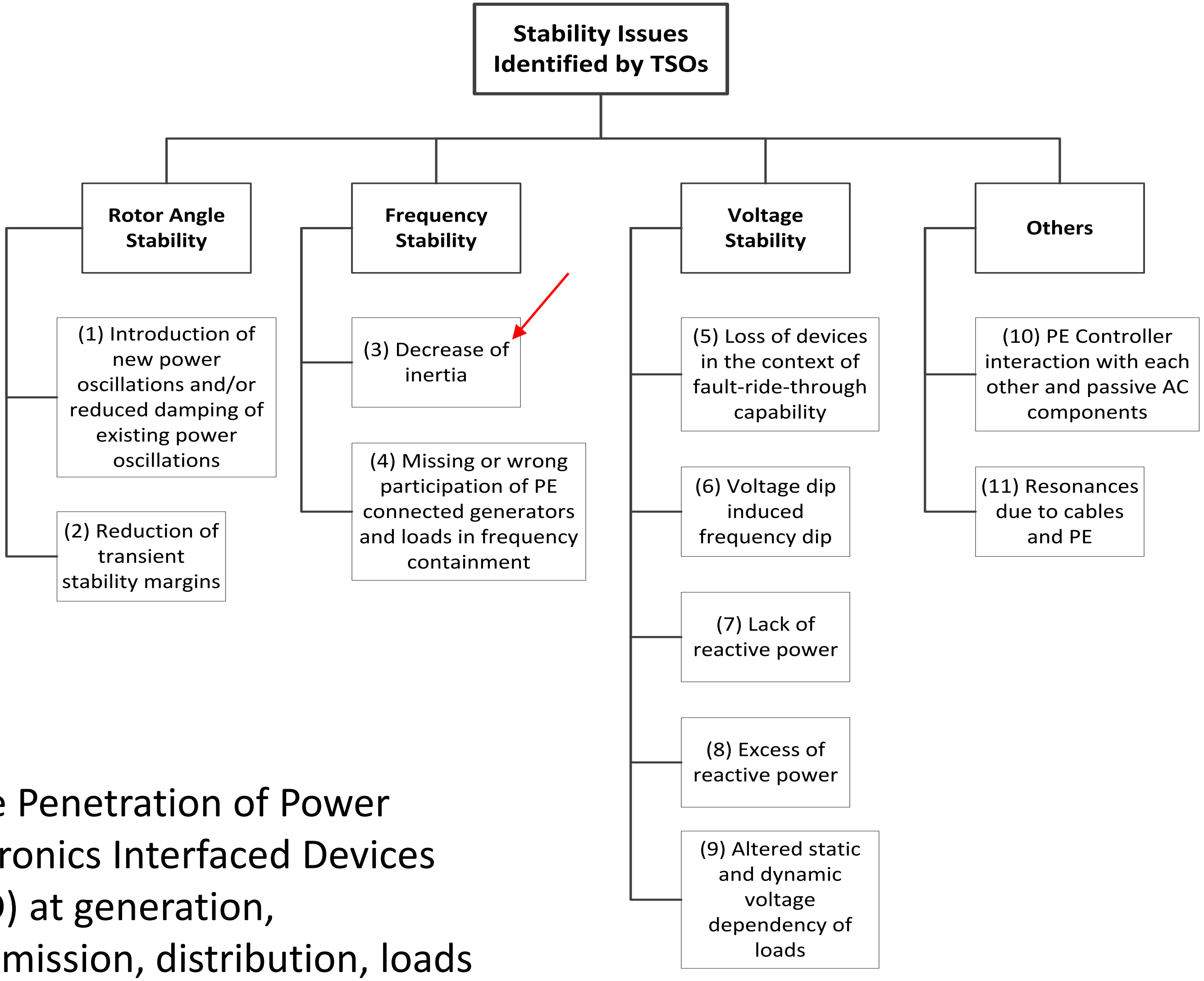


Long Term (2-5 years)
long term contract, strategic management of generation
Medium Term (1 mo-2 years)
maintenance scheduling
Short Term (1-4 weeks)
short-term adequacy forecast, operational reserves
Very short term (1h-1 week)
Coordinated capacity calculation, for day ahead and intra-day, security analysis

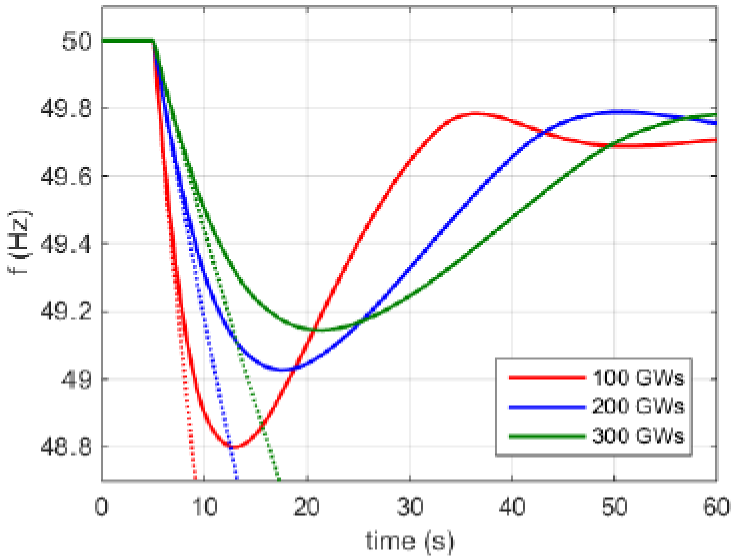
Real Time Operation (up to 1h
Load frequency and voltage control, emergency control, restoration

Stepping into the future of System Operations

System Stability



Large Penetration of Power Electronics Interfaced Devices (PEID) at generation, transmission, distribution, loads



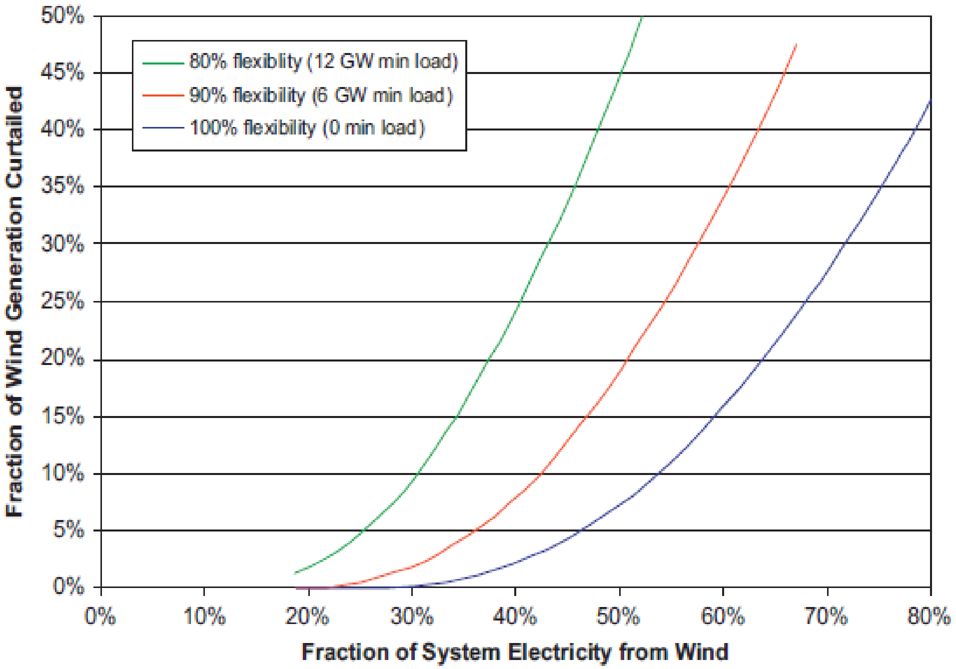
The effect of the amount of inertia (energy stored in rotating masses) on the behaviour of frequency after the loss of generation with (solid) and without (dotted) FCR, i.e. primary control and load reaction

Requirement for new services

- Synchronous Inertial Response (+synchronous condensers)
- Fast Frequency Response
- Dynamic Reactive Response (angular stability)
- Ramping Margins (1/3/8 hour)
- Fast Post-Fault Active Power Recovery (mitigate high ROCOF)

Increased Flexibility

ERCOT Study



Ramping limit, power capacity, energy capacity

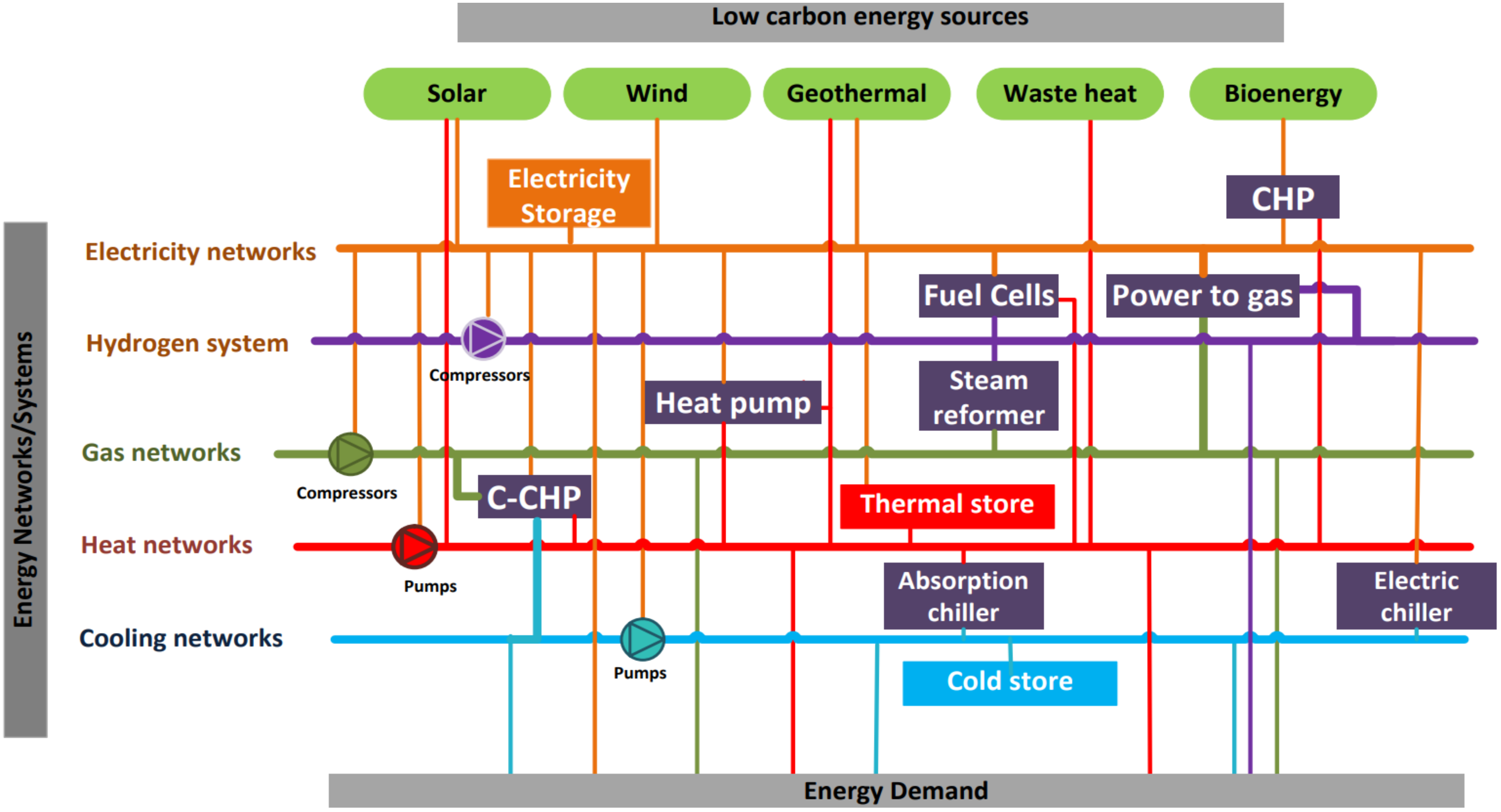
Increased controllability

PEID to enhance system operations and network stability, such as synthetic inertia, grid forming controls, supported system restoration, active and reactive power control, power oscillation damping, etc.

Enhanced Cooperation and Coordination

TSO-DSO Cooperation and Coordination	TSO-TSO Cooperation and Coordination
Management of bidirectional flows	Efficient calculation of interconnection capacity
Increased observability and controllability of DER by increased data exchange between TSO and DSO	Enhanced operational security (e.g. coordinated security analysis, management of critical grid situations)
Provision of ancillary services by DSO connected devices: - Blackstart services - Frequency control - Voltage control	Guaranteeing transmission adequacy (e.g. coordinated outage planning) and generation adequacy Frequency management (primary reserve distribution between TSOs)
Congestion management at DSO and TSO level	Congestion management at TSO level
Restoration support (top down approach)	Restoration support (top down approach)

Sector Coupling



Energy Conversion between electricity, heat and gas

flexibility, storage

Control Centre Evolution

Modern control centre, 2019 [Courtesy of XM Colombia]

Challenges: inaccurate forecasting, control of large number of gens, new transmission operation criteria, security risks, changing flow patterns, etc.

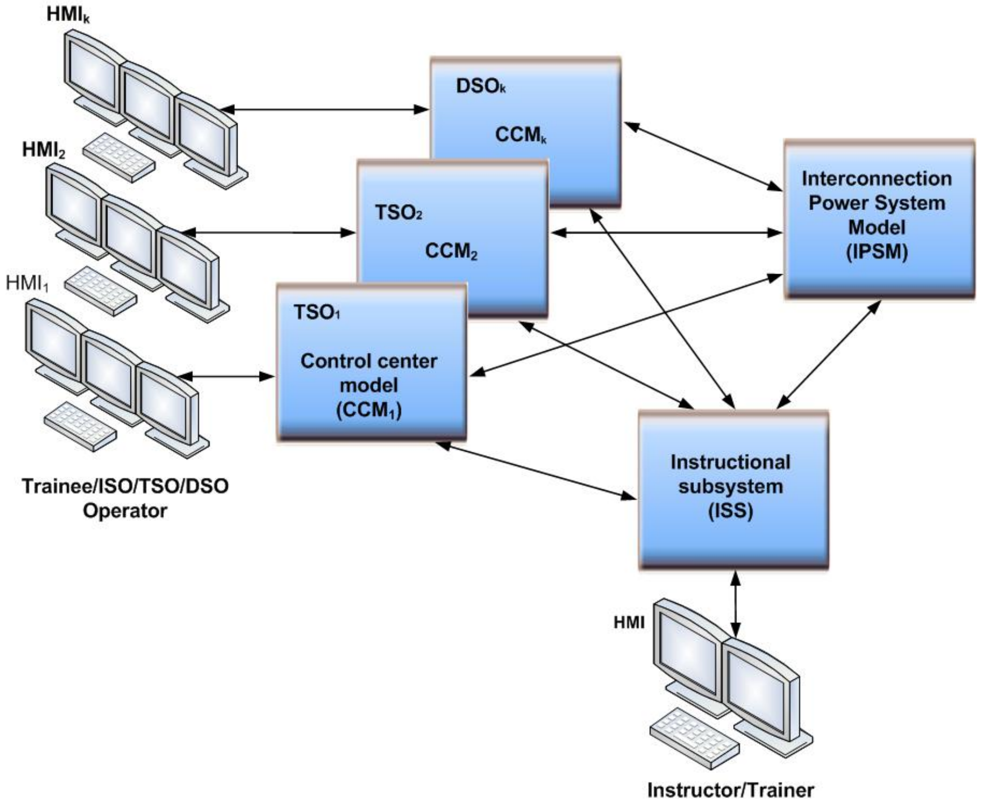
Increased System Observability

Phasor Measurement Units (PMUs) within
Wide Area Monitoring Systems (WAMS) to enhance awareness

Distributed Energy Resource Management Systems

Red Electrica de Espagna (CECRE)

Future Solutions and trends OTS/DTS



Global architecture of the future centralised multi control centre OTS/DTS

MARKETS AND REGULATION

SC C5

Alex Cruickshank **Yannick Phulpin**

Current markets and regulatory approaches

Markets and reliability of supply

- Market balancing and settlement
  - Gross dispatch and settlement

  all energy is traded via the wholesale market and the market operator dispatches and settles all of the energy traded. Each retailer pays the market operator the value of energy purchased

  - Net dispatch and settlement markets

  markets only trade balancing amounts. Participants establish physical contracts for supply between themselves and the grid operator adjusts the generators to balance demand in real time

- Remuneration of capacity in markets

  energy and balancing reserves only

  separate capacity remuneration (withdrawal of thermal resources)

- Ancillary services

  Essential to maintain reliable supply.

  Services incorporated into markets in conjunction with capacity and energy or separately via tenders. Some services purchased through regulatory requirements.

Current markets and regulatory approaches

Distributed Resources

- Increased penetration due to reduced prices, smaller unit sizes (also in customer sites), better control systems, renewable energy subsidies
- Regulation lagged behind and in many countries issues with high penetrations of PV generation, as most of current inverters are not controllable.
- some countries effectively integrated DER using Aggregators or Demand Response Providers and fitting demand response to the relevant market.

Market Distortions

- Price Caps

Markets need to allow prices to range from values that cause unnecessary generation to withdraw to value that will cost investments in generation

- Subsidies

Impact of subsidies on investments in other competitive assets

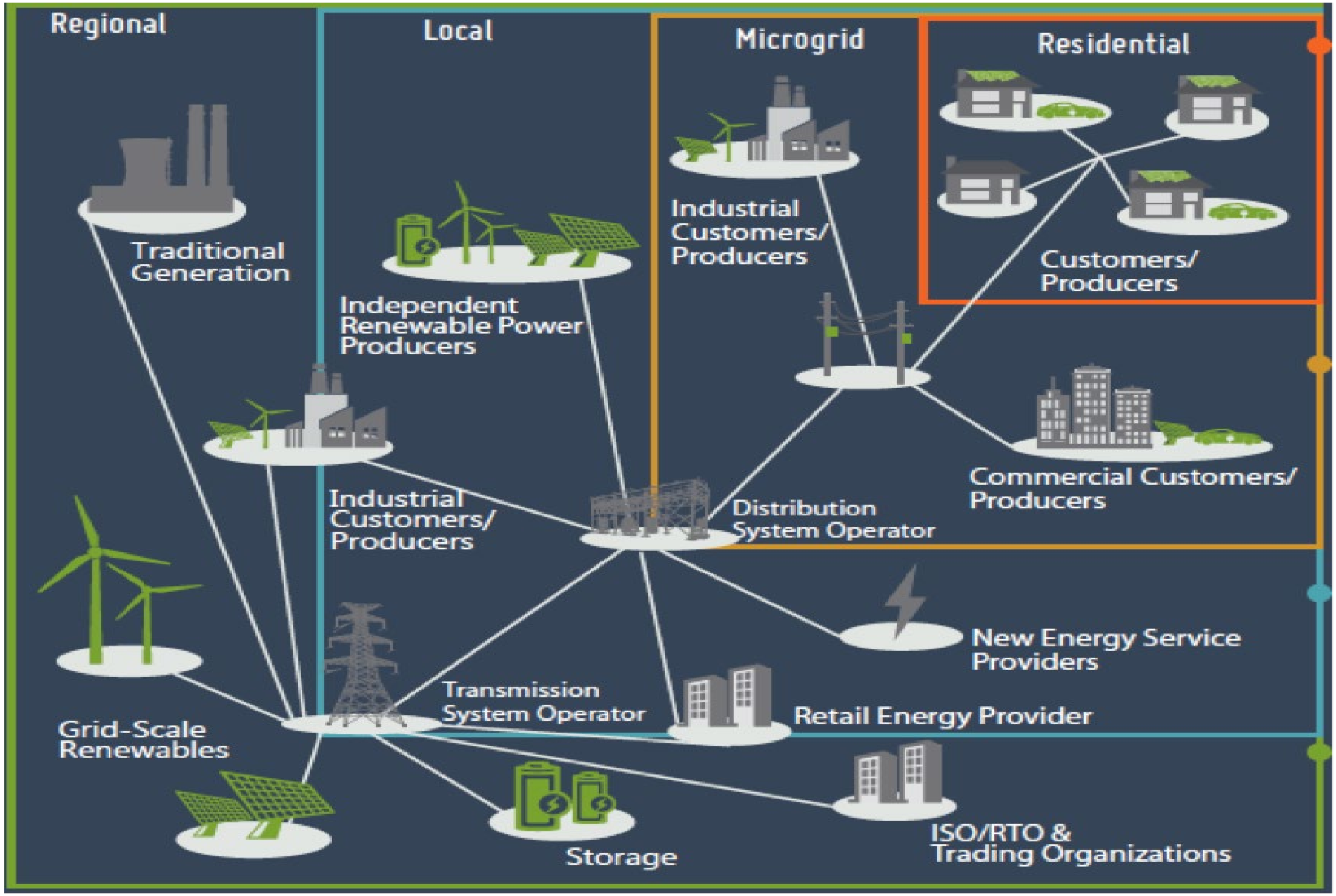
Future Scenarios and their market and regulatory requirements

Option 1 - A highly connected grid incorporating renewables at all levels

- The grid has supply side and demand side;
- Pricing of DER is competitive but not necessarily cheaper; and
- Large scale supplies are still needed for industry and large commercial operations.
- TSO-DSO operations mainly provide a two-way market and allow efficient prices at all levels
- Global interconnections (UHVDC) between continents and regions
  - Common pricing across regions with interconnected AC grid
  - Harmonized (or aligned) regulatory frameworks and pricing mechanisms at the international level
  - At the wholesale level, competitive dispatch (competitive markets permitting) of all energy sources of supply, providing efficient outcomes in terms of pricing.
  - Full reserve sharing and larger grid to absorb intermittent supplies, better reliability
  - At the retail level, efficient tariffs based on efficient wholesale prices allow customers to efficient invest in local DER and to make efficient decisions on its use.
  - The mechanisms for centralized supply will require efficient exchanges for capacity and energy to be in place and for the settlement of those exchanges to be linked in real time so that the true value of energy is known across the entire system.

Future Scenarios and their market and regulatory requirements

Figure 4 A model for a highly centralised approach



In the **Transactive Energy** model, the Transmission System Operator TSO) manages the **larger grid**, while distribution system operators (DSO) manage the **local grid**, which may include micro-grids, power producers and various types of customers. The **network operators** provide and manage **information flows** between all participants in the grid, including Market Operators, TSOs and DSOs, and retailers if their operations are separated from DSOs.

The operator systems provide load and effective local price at each level and site connection point and **customers** can choose to buy, sell or store their energy based on dynamic prices and forecasts.

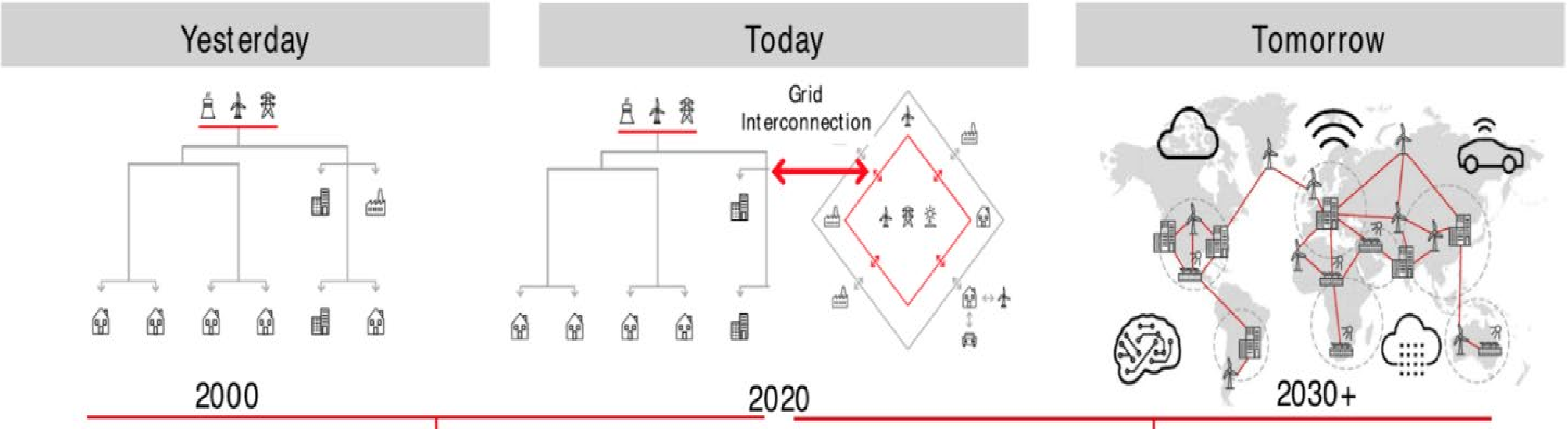
Future Scenarios and their market and regulatory requirements

Option 2 - Loosely connected microgrids

The option where the future grid comprises many loosely connected microgrids is predicated on an extension of current developments where:

- The price and DER availability have increased so that central supplies are needed less and small-scale gas, PV generation, co-generation and local wind power provide most of the supply;
- Local microgrids develop at the town/community scale using their own range of energy sources and site-based DER to meet the local demand;
- A local operator manages the exchange in value and the operation of the grid at the local level; and
- Local markets exchange energy and capacity, not to balance their local grids but purely to optimize the value of grids.
- This approach could allow for long-term supply arrangements between the local grids, but the supplies between grids are managed as if they were generators or load on the edge of the local grid and not essential to the management of the local grid.

The Future of the Grid



Factors:

- Global warming – ecological threats
- Stimulated, regional introduction of renewables
- Exponential reduction of photovoltaics & battery storage costs
- Consumer to Prosumer development
- Digitalization trend
- Interconnection technology development

Factors:

- Full scale deployment of renewables across all regions
- Increased share of energy by wire
- Massive introduction of grid connected Electrical Vehicles
- Utilities adopting to changing environment
- Fully flexible power exchange with related data transfer («Internet of Energy»)
- Artificial Intelligence enabling complex autonomous processes

The future of the grid

DISTRIBUTED ENRGY RESOURCES AND ACTIVE DISTRIBUTION SYSTEMS

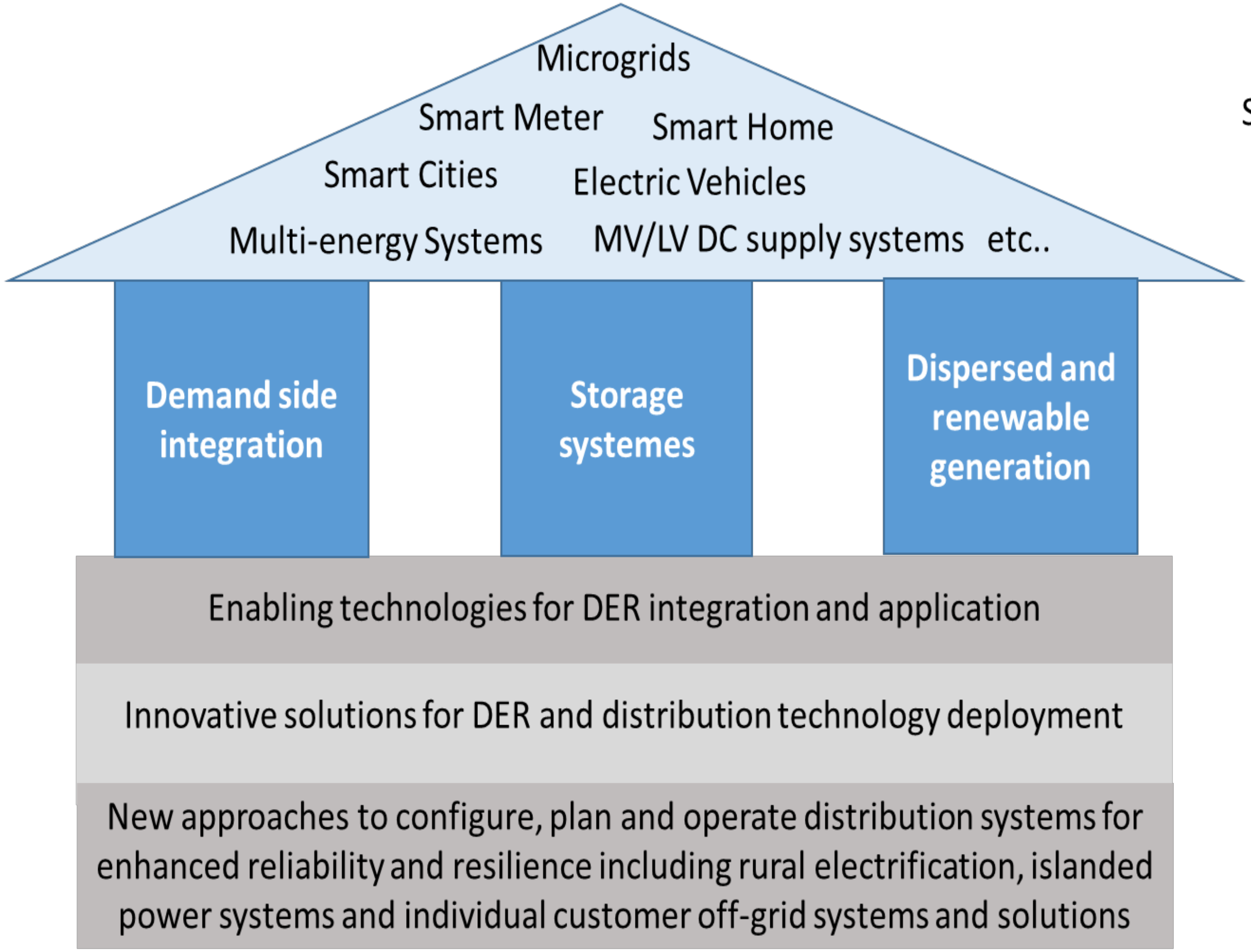
SC C6

Christine Schwaegerl **Geza Joos**

Nikos Hatziargyriou

Greece

Scope of DER and active distribution system technologies



The rooftop:
Segments, technologies and applications of interest

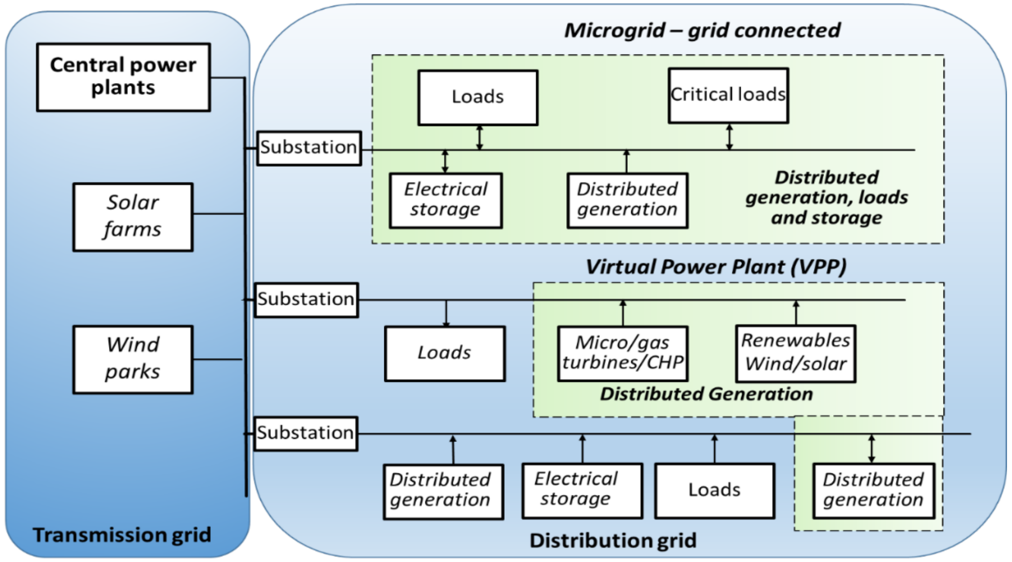
The pillars:
DER in distribution systems

The base:
Areas of attention

Drivers

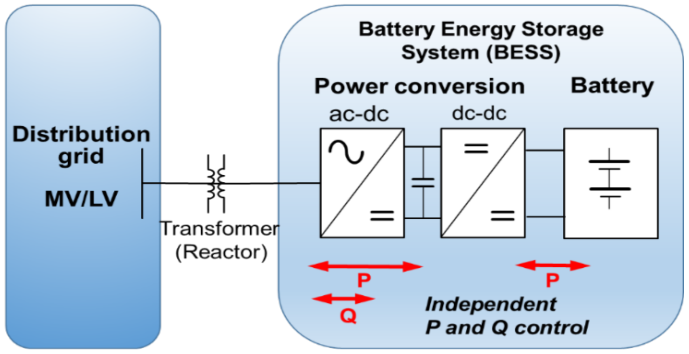
- International and national policies that encourage lower carbon generation, the use of renewable energy sources (RES) and more efficient energy use (energy efficiency)
- Integration of RES and other distributed generation (DG) into distribution grids
- Increased customer participation,
- Progress in technology (technology push) including ICT
- Need for investment in end-of-life asset renewal
- Necessity to handle grid congestion using market and incentive based approaches
- Evolution of market design and regulatory mechanisms to manage the grid transformation
- Environmental compliance and sustainability of newly built and existing infrastructure
- Need to address the energy needs of people with no access to electricity

Technologies for DER deployment

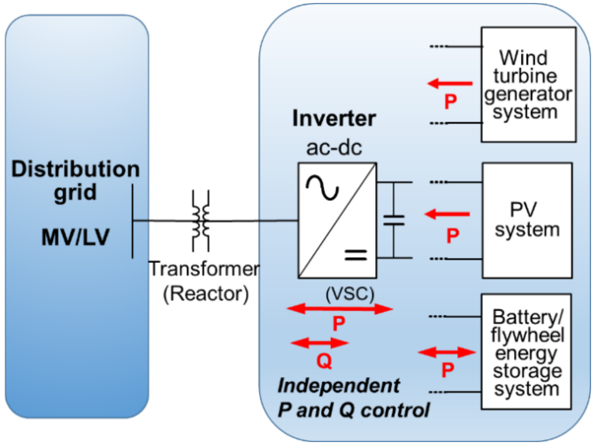


DER deployment at distribution and transmission systems

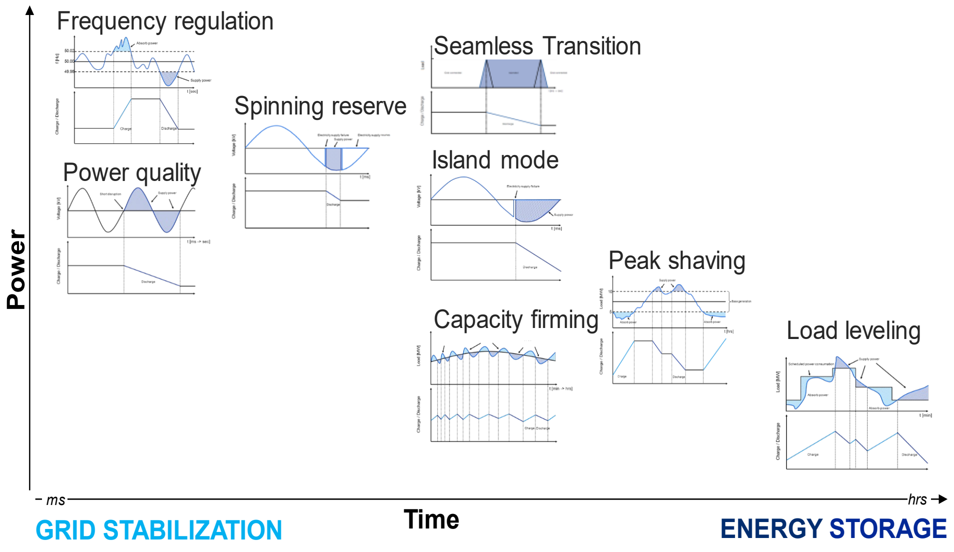
Enabling Technologies in support of DER



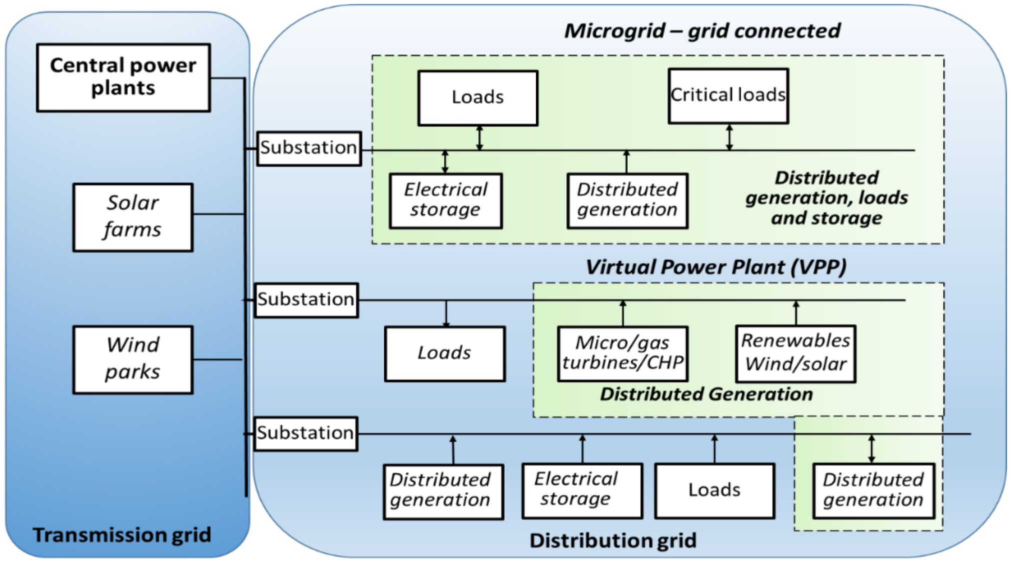
Battery Energy Storage System (BESS) topology and structure



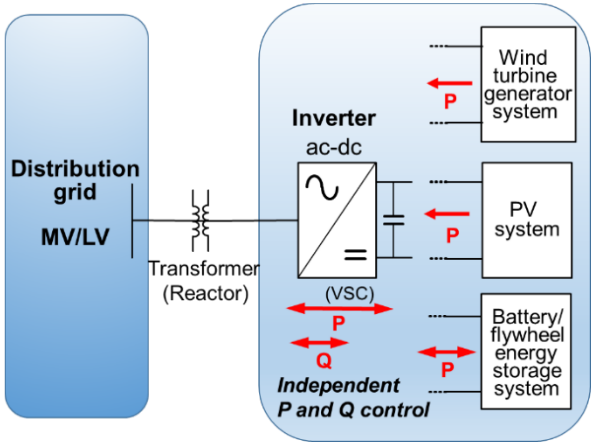
Power electronic inverter-based DER grid interfaces, Inverter based 4-quadrant operation



Technologies for DER deployment

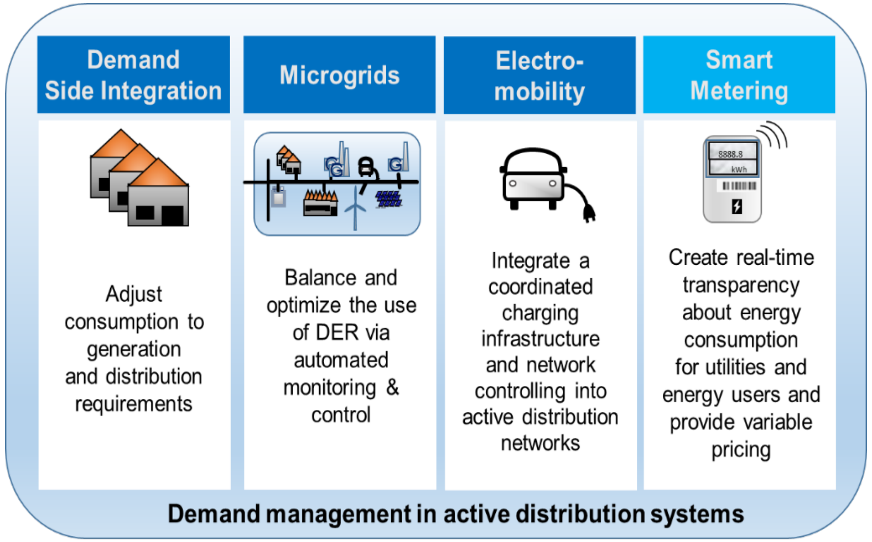


DER deployment at distribution and transmission systems

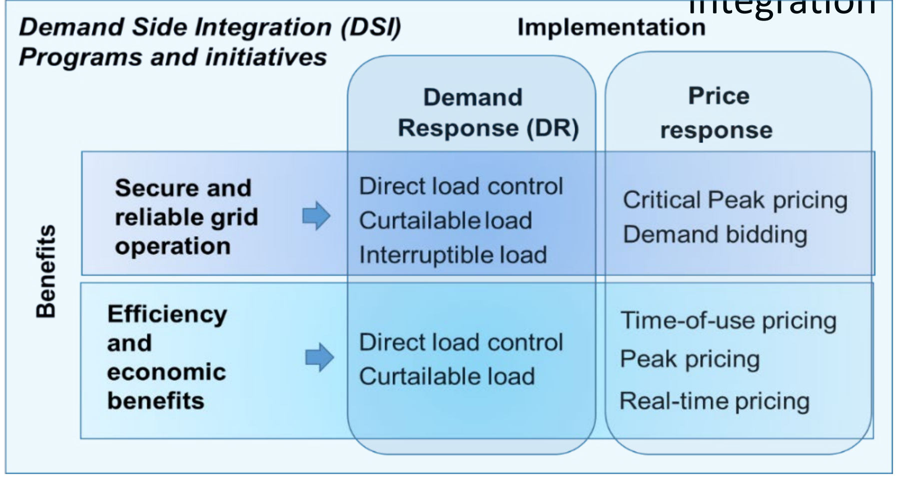


Power electronic inverter-based DER grid interfaces, Inverter based 4-quadrant operation

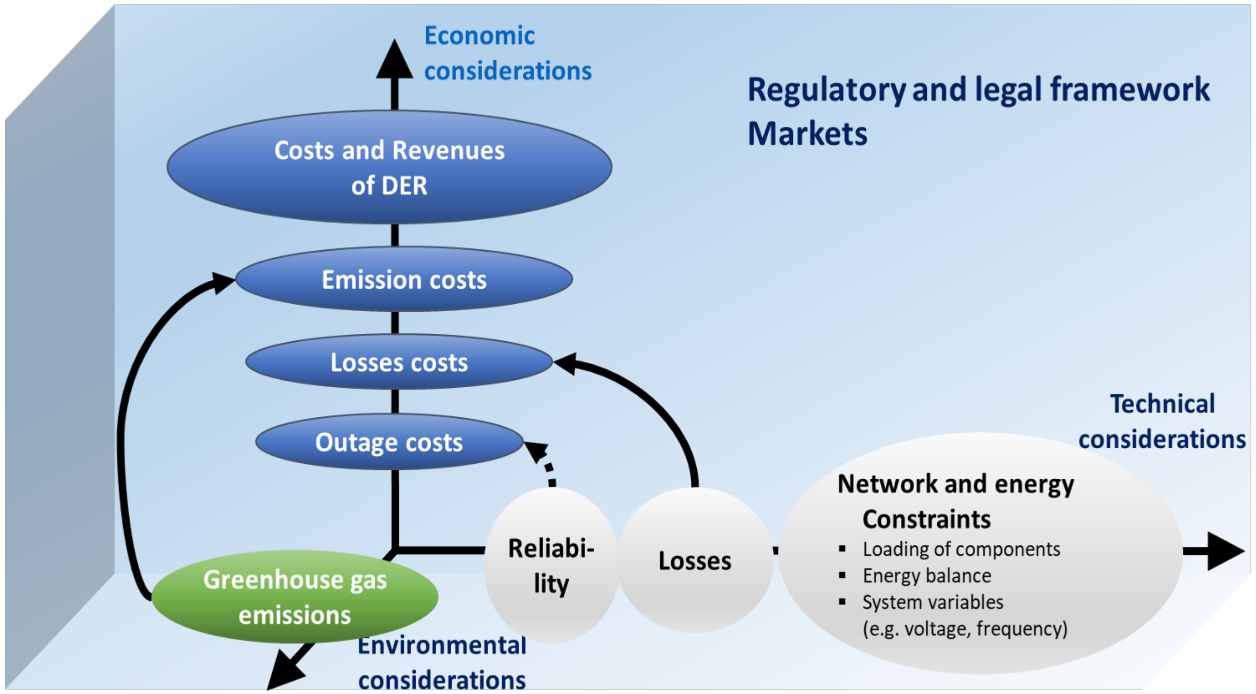
Enabling Technologies in support of DER

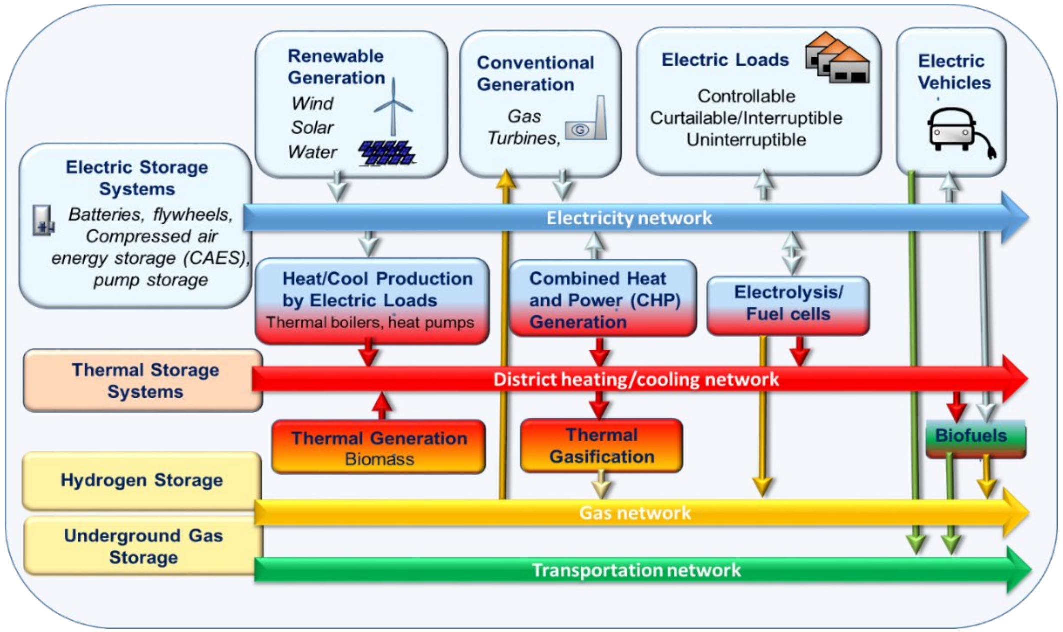


Active distribution systems – demand side integration

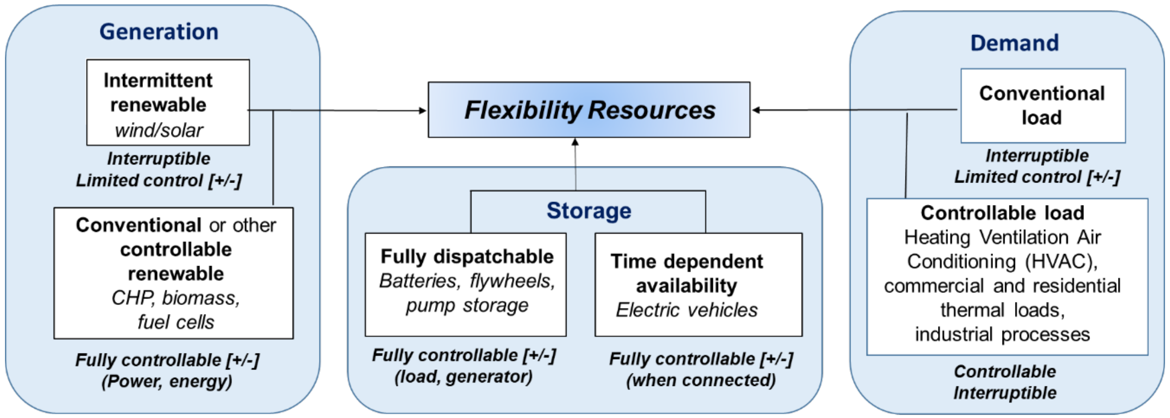


Active Distribution Networks Impacts





Application of multi-energy systems



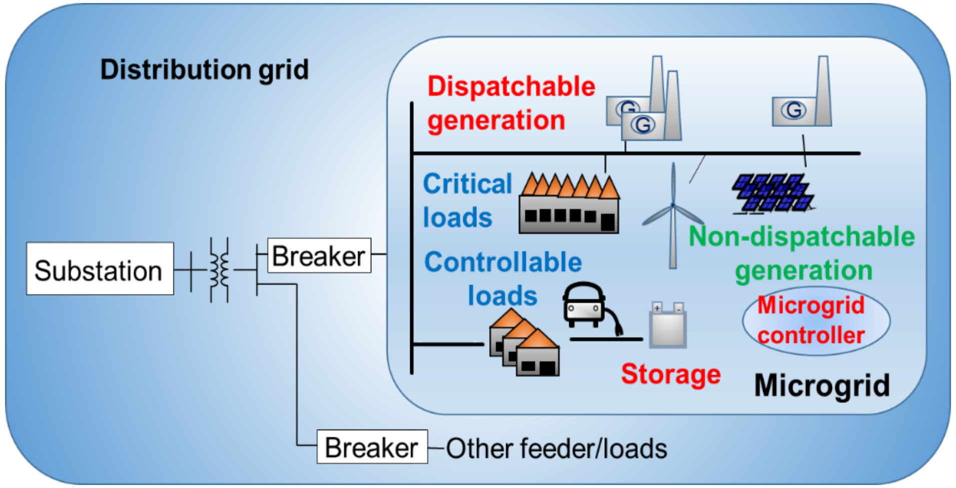
DER providing flexibility

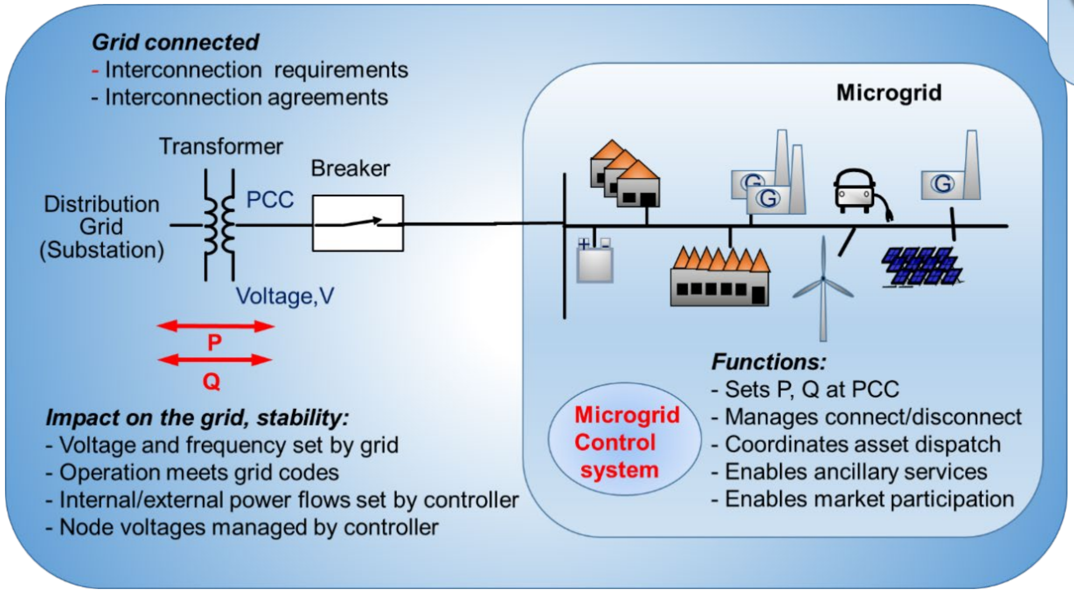
Impacts of electric vehicle (EV) control strategies

	Technical	Economical	Environmental	Social	Regulatory
Benefits of advanced strategies	- Reduce loading of network components - Postpone reinforcements	- Reduce amount of investments - Postpone reinforcements	- Avoid curtail-ment of RES; reduction in greenhouse gas emissions	- Price incentives for prosumers providing V2G services	- New markets and services (i.e. blockchain) allow customer interaction
Drawbacks of inadequate strategies	- Increase loading of network components - Require investments	- Investments in information and communication technologies as well as in new trading structures	- Building new equipment may have impact on environment	- Increasing electricity costs due to higher use of system charges	- New rules required for providing V2G services as prosumers

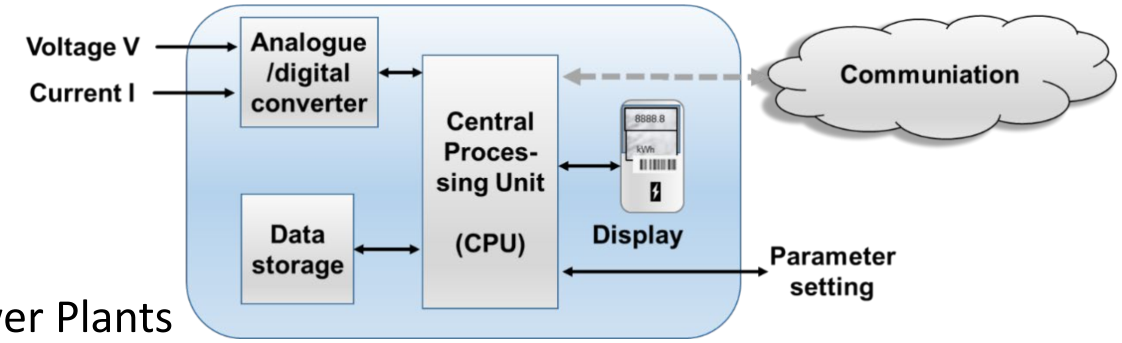
EV charging station – impact of control strategies

Emerging Technologies and Applications

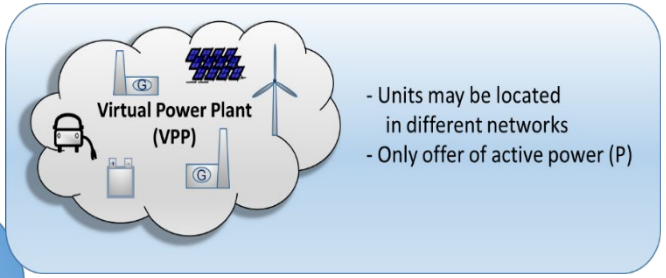




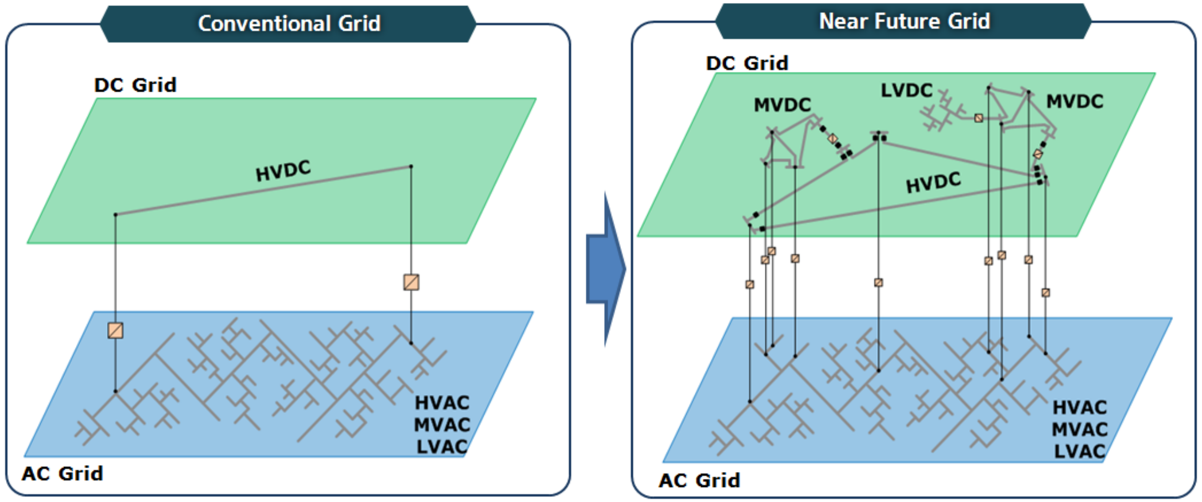
Microgrids and Microgrids Control



Virtual Power Plants

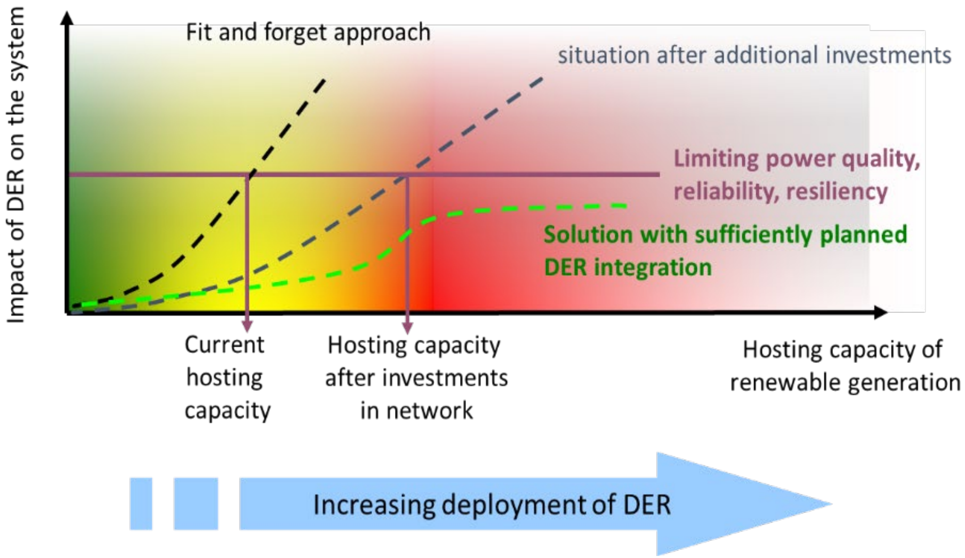


Typical smart meter system,
(measurement intervals 15-30 min
Internet of Things
Cybesecurity Issues



Conventional grid (left) and future grid with parallel DC structure

New Methods and Tools

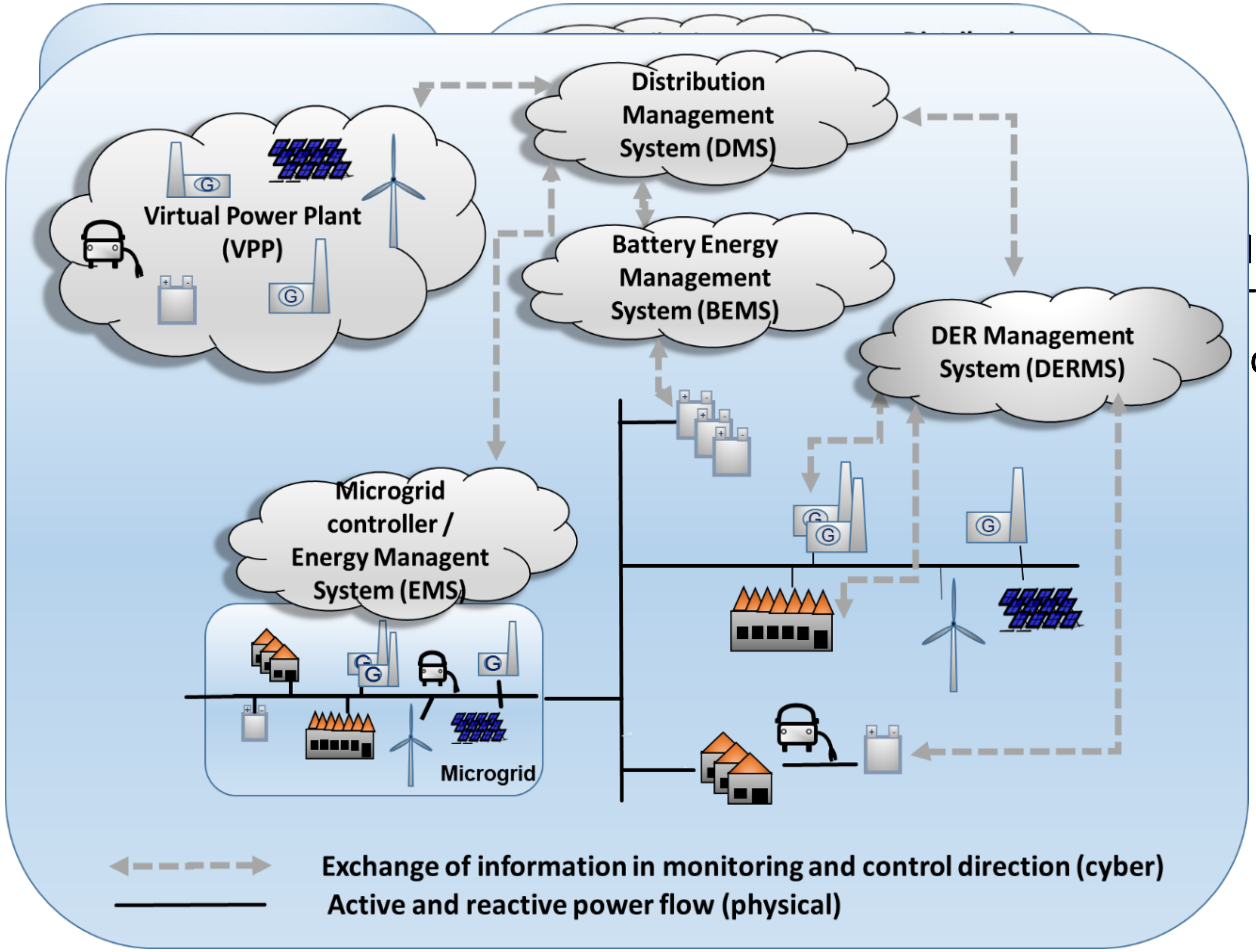


Objectives of Network Planning

DER devices and associated components

DMS/ TSO/ ISO	Level 3	**Higher level functions** Operator interface — Communications/SCADA Grid/market — Optimal dispatch
DERMS control system	Level 2	**Core level functions** Aggregation (grouping, visualisation) Monitoring (measuring, validation) Operation (dispatch, scheduling, control)
DER control system	Level 1	**Lower level functions** Voltage/frequency control — Device specific functions Real/reactive power control

Electric grid – distribution / transmission



DER Aggregation platforms

General Future Directions

Reliability and resilience of regional and local power systems rely on:

- Integrated energy systems, with the electricity systems as the backbone, designed and operated to prevent or minimise the effects of contingencies, with local/regional black-start capabilities activated within a few minutes.
- Risk (weather and other hazards) assessment and mitigation measures, considered in system planning and operation.
- Seamless (strongly automated) operation through fully interoperable and networked sub-systems allowing the coupling of all energy carriers in an optimal, integrated way.
- Peer-to-peer transactions integrated with centrally- and locally-controlled electricity networks, supported by automated local grids together with network operator actions.

Specific issues:

- Integrating increasing amounts of DER into existing distribution systems, and the design of new systems integrating larger shares of renewable resource-based DER;
- Managing existing distribution systems in an increasingly constrained financial environment, thus requiring innovative ideas in order to survive as an industry;
- Creating affordable alternatives to conventional grid solutions for the developing world via the adoption of microgrid and nanogrid technologies;
- Taking cognizance of the disruptive influences of new technology requirements, particularly in transportation systems, such as electric vehicle (EV) charging systems and their potential Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) capabilities.

Thank you for your attention!

CIGRE Greece