Smartgrids and Microgrids

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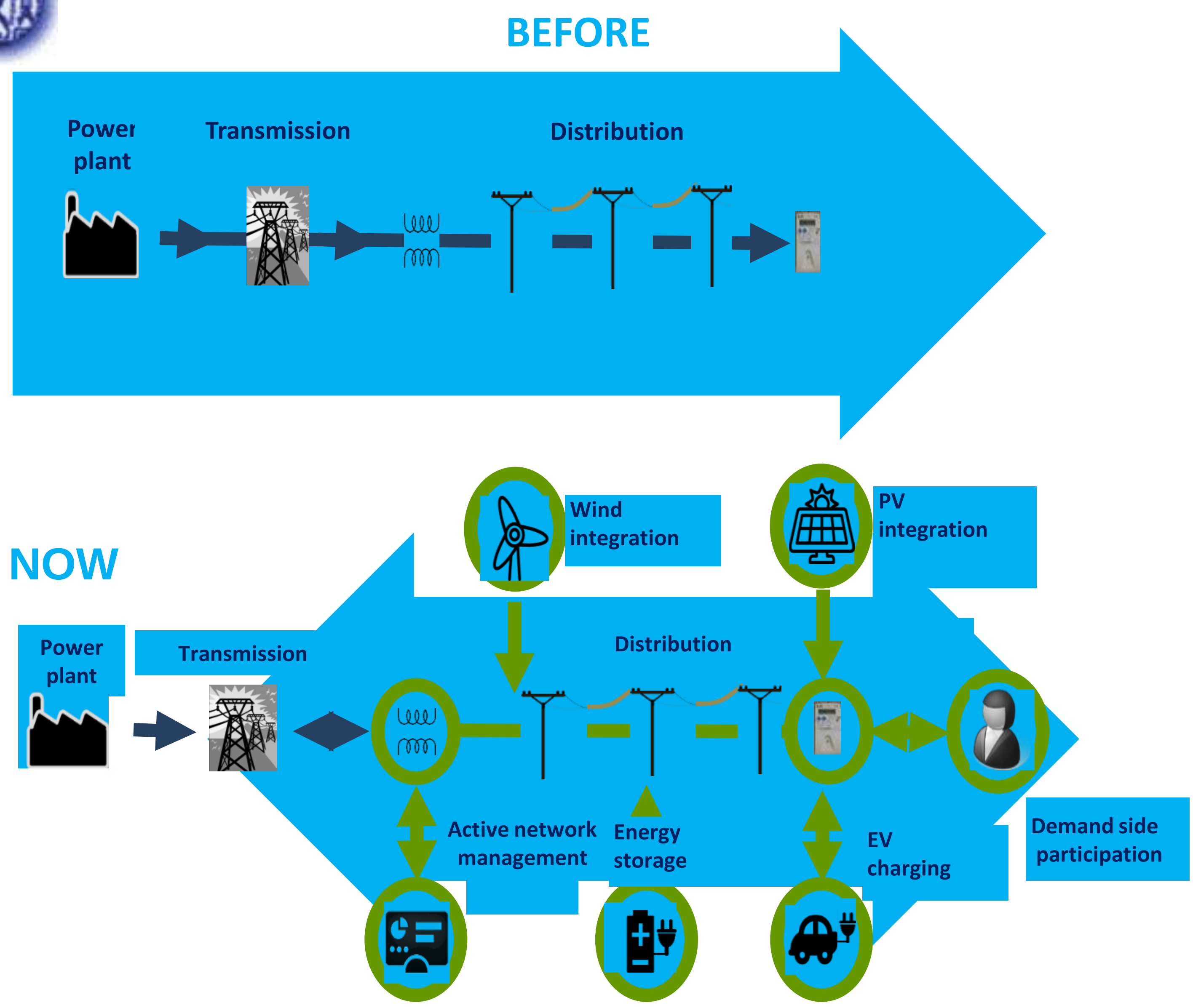
The EU TP SmartGrids Vision (2006)

European Smartgrids Technology Platform: Vision and Strategy for Europe’s Electricity Networks of the Future, EUR 22040



DSOs are key enablers for a successful energy transition . They must act as neutral market facilitators and guarantee distribution system stability, power quality, technical efficiency and cost effectiveness in the future evolution of energy networks towards a smarter grid concept.

The challenge of flexibility

With the empowerment of the customer and the growth of renewable energy sources and demand response, the role of flexibility increases . The activation of flexibility services will influence grid operation and balancing of the electricity system and should be used efficiently from both a technical and economical point of view.

Efficient use requires a well-coordinated process between TSOs, DSOs and market parties. Coordination between TSOs and DSOs is of utmost importance to avoid system disturbances. Data exchanges between TSOs, DSOs and market parties are important to optimise the value customers can bring to different markets (use of flexibility by BRPs, balancing, congestion management, etc.).

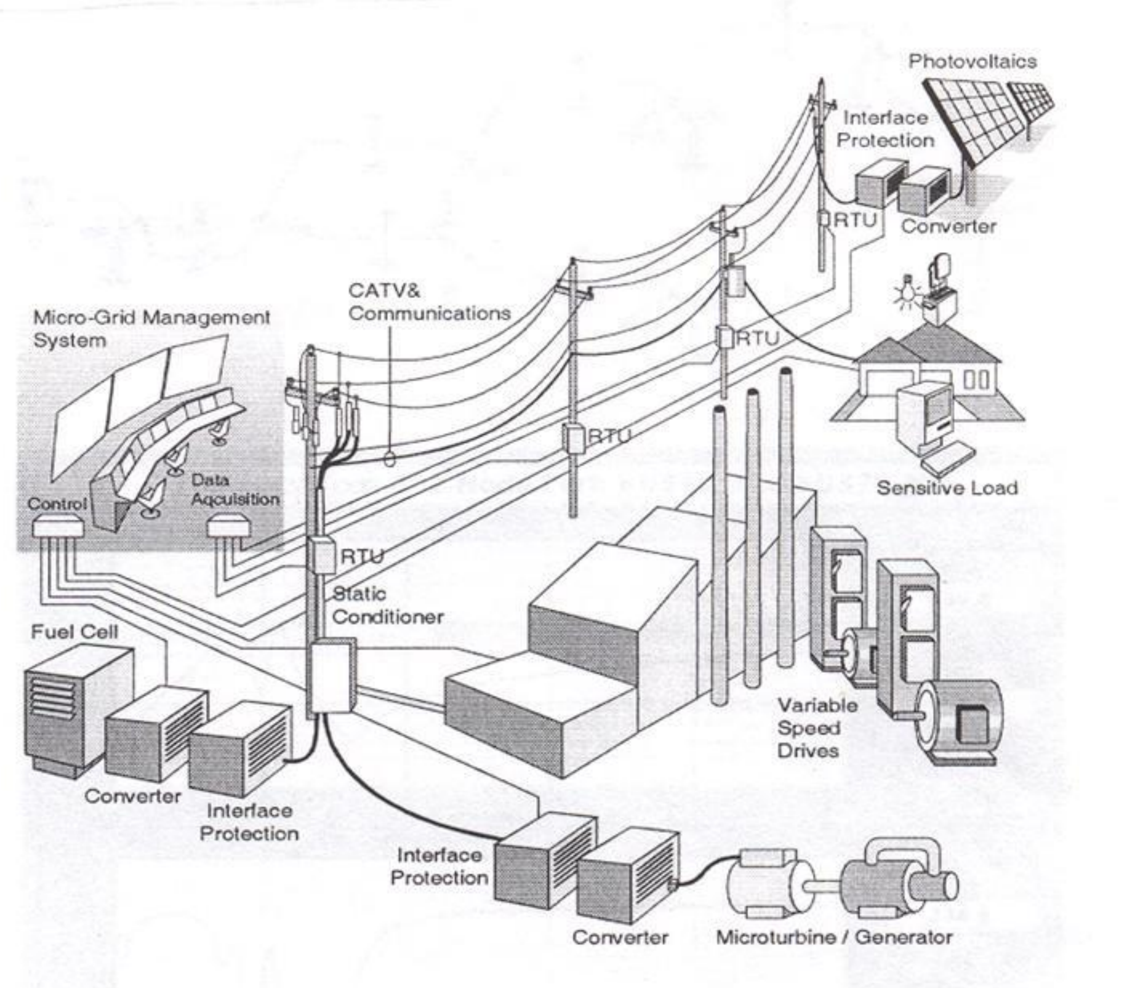
As energy supply becomes increasingly distributed - produced in smaller quantities and closer to customers - the **balancing of demand and supply becomes an increasingly local issue**. To avoid congestion on local grids, DSOs must be able to procure flexibility services delivered locally on the market ; if not, direct contracts with flexibility providers (energy consumers or producers) must be allowed.

Microgrids: The Building Blocks of SmartGrids

http://www.microgrids.eu

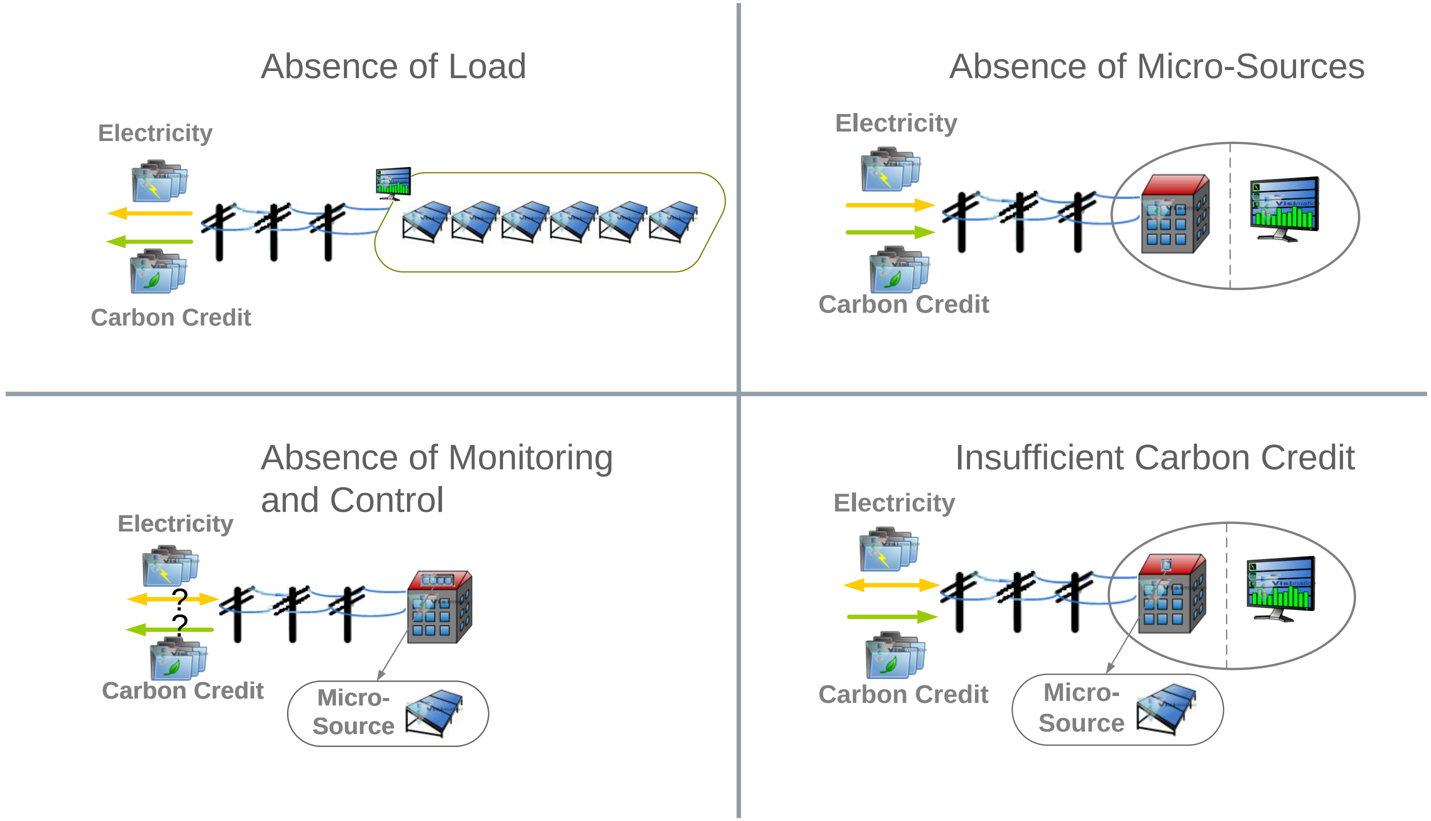
Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded.

(CIGRE WG C6.22)



EU Microgrids (ENK5-CT-2002-00610) and MOREMICROGRIDS (PL019864)

What are not Microgrids



Three essential Microgrid features: local load, local micro-sources, and intelligent control. Different than DG interconnection or Demand Side Integration.

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrids vs. Virtual Power Plants

A **virtual power plant** (VPP) is a cluster of DER which is collectively operated by a central control entity. A VPP can replace a conventional power plant, while providing higher efficiency and more flexibility.

Distinct differences:

- Locality
- Size
- Consumer Focus

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrids vs. Local Energy Communities

EC Electricity Directive COM(2016) 864 final/2

An association, a cooperative, a partnership, a non-profit organisation or other legal entity which is effectively controlled by local shareholders or members, generally value- rather than profit-driven, involved in distributed generation and in performing activities of a distribution system operator, supplier or aggregator at local level, including across borders

Local Energy Communities are based on Microgrids structures

Microgrids ≠ Local Energy Communities

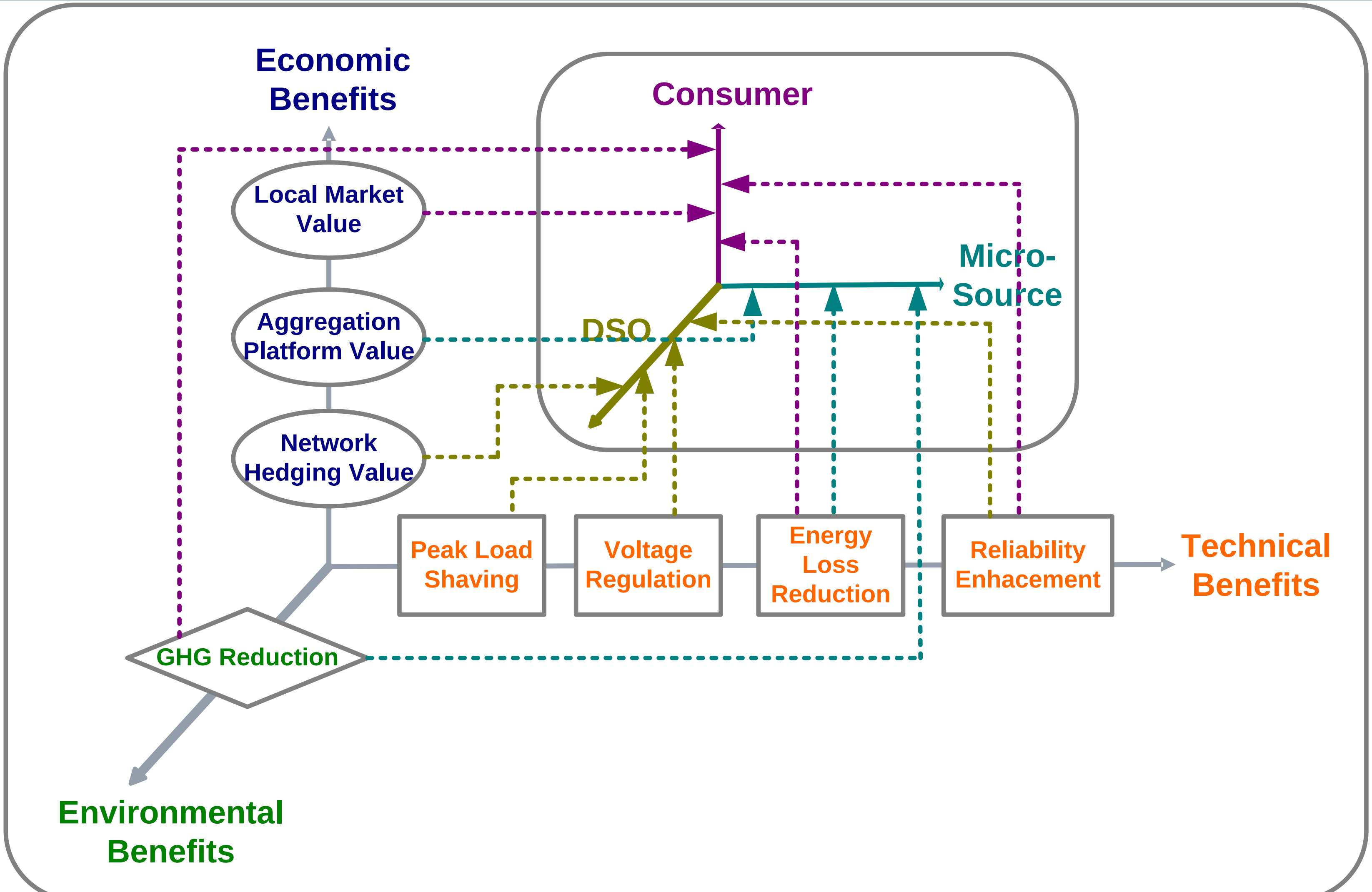
Long Tradition in Europe: in **Germany** over 650 Stadtwerke (local utility companies that provide heat and electricity) , in the **Netherlands**, over 200 local initiatives involved in RE, including over 55 registered cooperatives, in **Denmark** 100s of electricity production (CHP) and community district heating (CDH) systems, 100 wind cooperatives.

DER Technical, economic and environmental benefits

- Energy efficiency
- Minimisation of the overall energy consumption
- Improved environmental impact
- Improvement of energy system reliability and resilience
- Network benefits
- Cost efficient electricity infrastructure replacement strategies

Microgrids as the efficient DER integration structures are able to unlock the full benefits of DER

Benefits by Criteria & Stakeholders



"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Who will develop a Microgrid? Who will own and operate it?

- Investments in Microgrids can be done in multiple phases by different stakeholders: DSO, energy supplier, end consumer, etc.
- The operation of the Microgrid will be mainly determined by the ownership and roles of the various stakeholders. Three general models:
  - Integrated Utility or DSO owns and operates the Microgrid. Is there a business case?
  - Prosumers own and operate DER to minimize electricity bills or maximize revenues (Local Energy Community Microgrid)
  - Market Aggregators (ESCOs) maximize the value of the aggregated DER participation in local energy markets.

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Market Participants

- Distributed Energy Resources (DERs): flexible loads and local production units connected to the MV/LV network, part of microgrids,

- Microgrid Aggregator: represents one or multiple microgrids (coordinated DERs) in the market operations

- Market Operator: operates the market (decides the dispatch of conventional units and the bids of the MG Aggregator)

How can the DERs be incorporated in the operation of the system in the most efficient way?

G. Asimakopoulou, N. Hatziargyriou, "Evaluation of Economic Benefits of DER Aggregation", IEEE Trans. STE, 2017

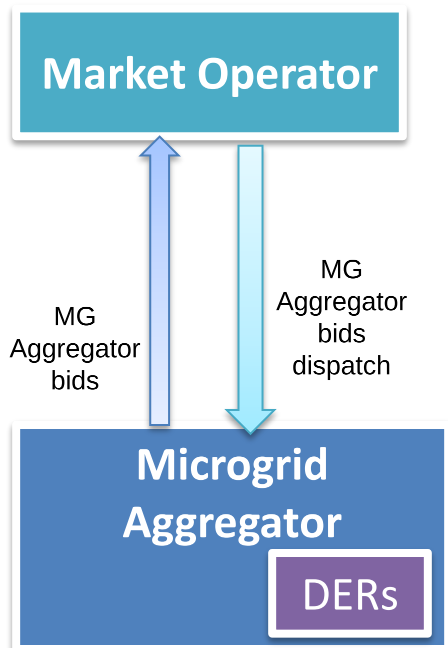
Market Models

Market Operator

- Dispatch of DERs performed by the Market Operator through the market clearing process

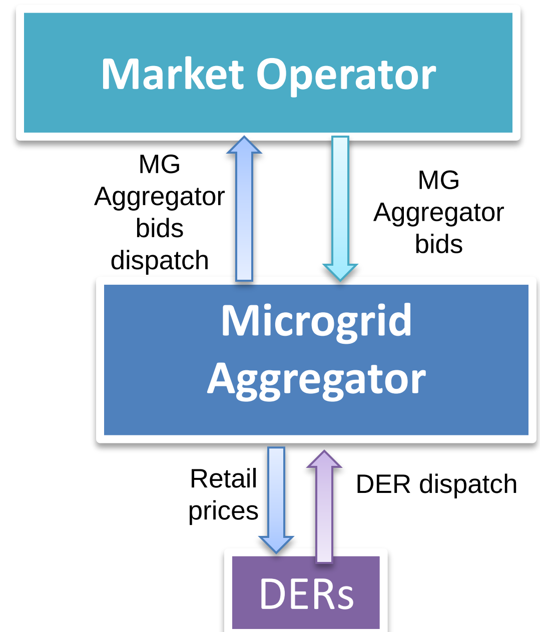
MG Aggregator – Pay-As-Bid (PAB)

- Dispatch of DERs (set-points) by the MG Aggregator)



MG Aggregator – retail prices

- Price signals to DERs
- DERs decide their own dispatch



How can a Microgrid Aggregator interact optimally both with his customers and the wholesale market?

BLPP solution methodology

(Single-level problem)

LEADER: Selects and announces the value of variable x taking into account…

BILEVEL PROBLEM

$$\max_x F(x,y)$$
s.t. $\mathbf{G}(x,y) \le 0$, $\mathbf{H}(x,y)=0$
where:
$$y = \arg\{\min_y f(x,y)\}$$
s.t. $\mathbf{g}(x,y) \le 0$, $\mathbf{h}(x,y)=0$

…the optimal response of the **FOLLOWER**.

KKT →

NON-LINEAR ONE-LEVEL PROBLEM

$$\max_x F(x,y)$$
s.t. $\mathbf{G}(x,y) \le 0$, $\mathbf{H}(x,y)=0$

$$\nabla_y L(x,y,\lambda,\mu) = 0$$
$$0 \le \lambda \perp \mathbf{g}(x,y) \le 0$$
$$\mathbf{h}(x,y)=0$$

Big-M →

Strong Duality Theorem

MIXED-INTEGER LINEAR PROGRAMMING PROBLEM

$$\max_x F(x,y)$$
s.t. $\mathbf{G}(x,y) \le 0$, $\mathbf{H}(x,y)=0$

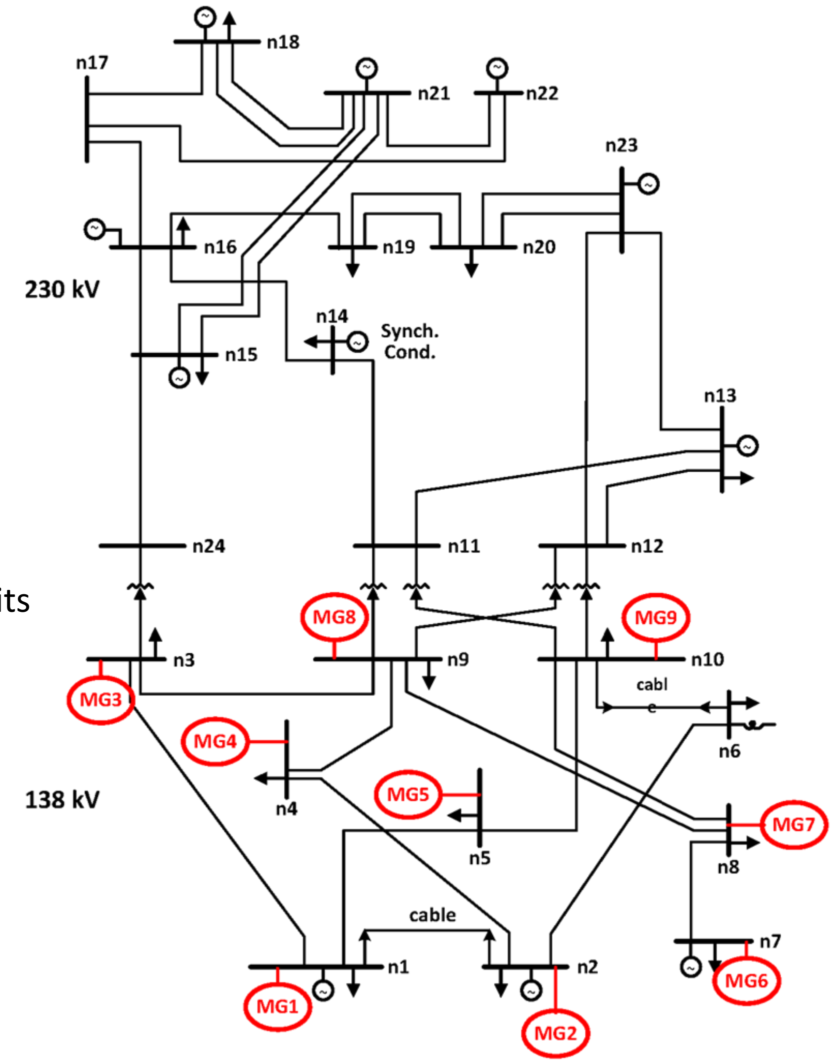
$$\nabla_y L(x,y,\lambda,\mu) = 0$$
$$0 \le \lambda \le M\delta,\ -M(1-\delta) \le \mathbf{g}(x,y) \le 0$$
$$\mathbf{h}(x,y)=0$$

- GAMS, CPLEX

Study Case

- IEEE 24-bus test system
  - 14 representative dispatch periods (load scenarios)
- Flexible loads (n1, n4, n5, n7, n9, n10):
  - 10 entities
  - Prices: 96.3–247.5€/MWh
  - Quantities: 35.0–53.2MW
- Local production (n1, n2, n3, n4, n8, n10):
  - 10 entities
  - Prices: 30–45€/MWh
  - Quantities: 19.9–60.0MW
- Demand Bids (DB)/Generation Offers (GO) operational limits

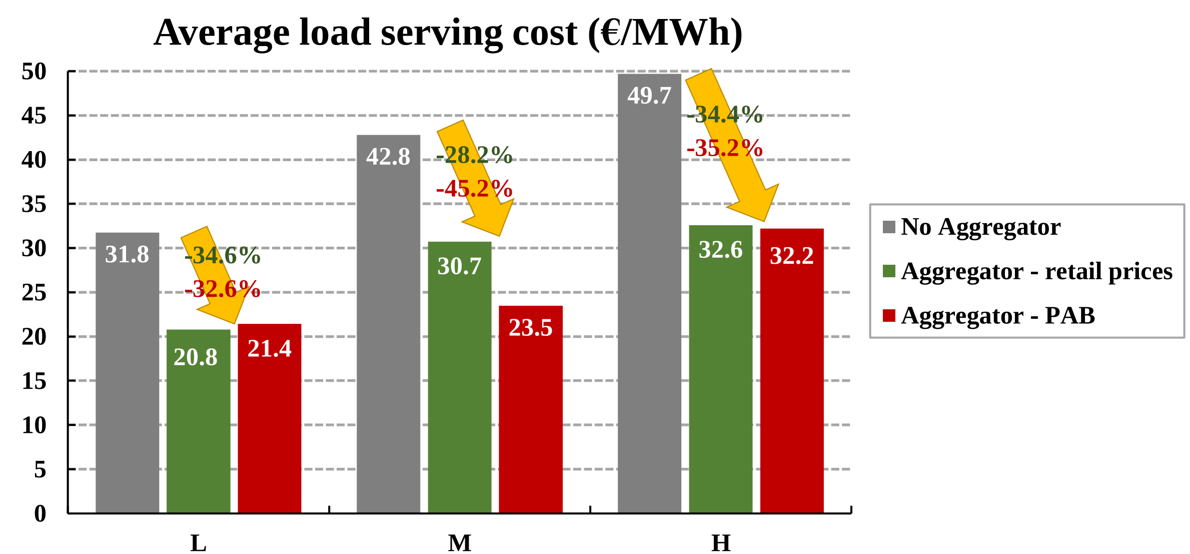
Bus	DB (MW)	GO (MW)
n1	157.6	59.7
n2	95.9	119.3
n3	177.8	90.0
n4	167,2	19.9
n5	147.5	0.0
n6	135.4	0.0
n7	166.1	0.0
n8	169.3	50.0
n9	244.9	0.0
n10	285.7	60.0



Indicative Results

	No MG Aggregator			MG Aggregator – retail prices			MG Aggregator – PAB		
	L	M	H	L	M	H	L	M	H
Conventional production (GWh)	1.7	2.0	2.1	1.6	1.9	2.0	1.7	1.9	2.0
Local production (MWh)	399	163	111	382	155	145	399	215	165
Flexible load (MWh)	373	430	430	209	325	410	346	373	421
Dispatched Generation Offers (MWh)	—	—	—	62	21	23	62	27	24
Dispatched Demand Bids (MWh)	—	—	—	707	1,009	1,105	827	1,003	1,097
MG Aggregator energy balance (MWh)#	—	—	—	-645	-988	-1,082	-765	-976	-1,073
Average conventional production cost (€/MWh)	16.7	18.6	19.9	16.3	17.5	18.9	16.5	17.0	18.9
MG Aggregator cost (thousands €)	—	—	—	8.7	-3.9	-23.5	2.9	-28.8	-65.3

 # Positive balance indicates energy injection. Negative balance signifies energy absorption.



G. Asimakopoulou, N. Hatziargyriou, "Evaluation of Economic Benefits of DER Aggregation", IEEE Trans. STE, 2017

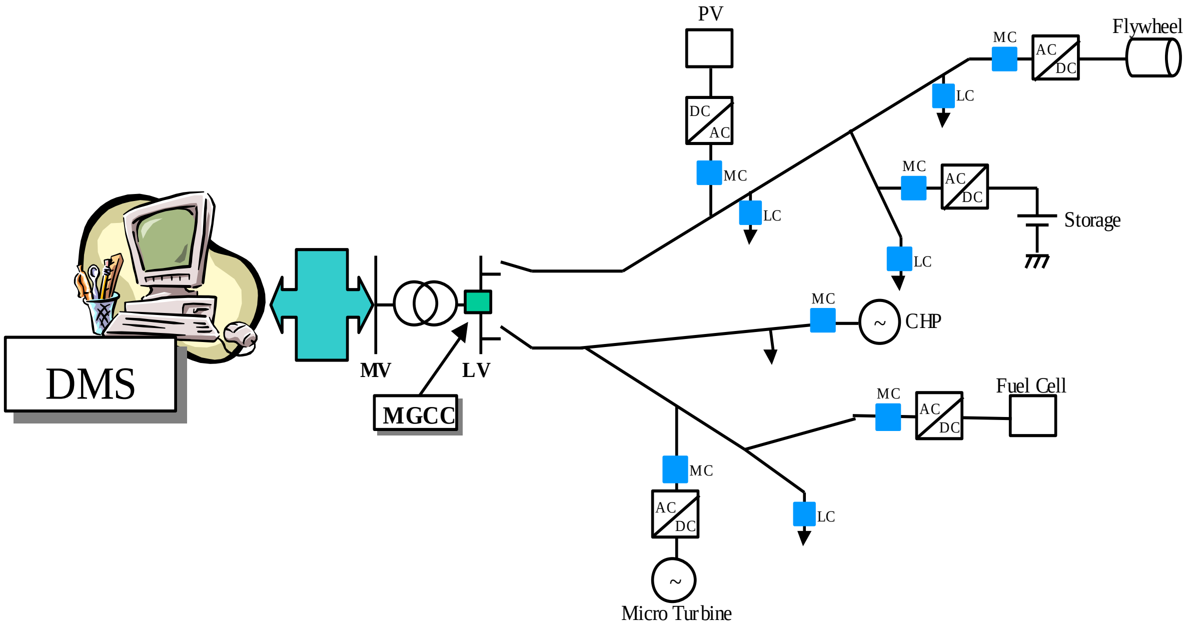
Technical Challenges

- Small size (challenging management)
- Use of different generation technologies (prime movers)
- Presence of power electronic interfaces
- Relatively large imbalances between load and generation to be managed (significant load participation required, need for new technologies, review of the boundaries of microgrids)
- Specific network characteristics (strong interaction between active and reactive power, control and market implications)
- Protection and Safety / static switch
- Communication requirements

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Hierarchical Control

MicroGrid Central Controller (MGCC) promotes technical and economical operation, interface with loads and micro sources and DMS; provides set points or supervises LC and MC; MC and LC Controllers: interfaces to control interruptible loads and DGs



Centralized vs. Decentralized Control

"Micrograms: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

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Centralized & Decentralized Control

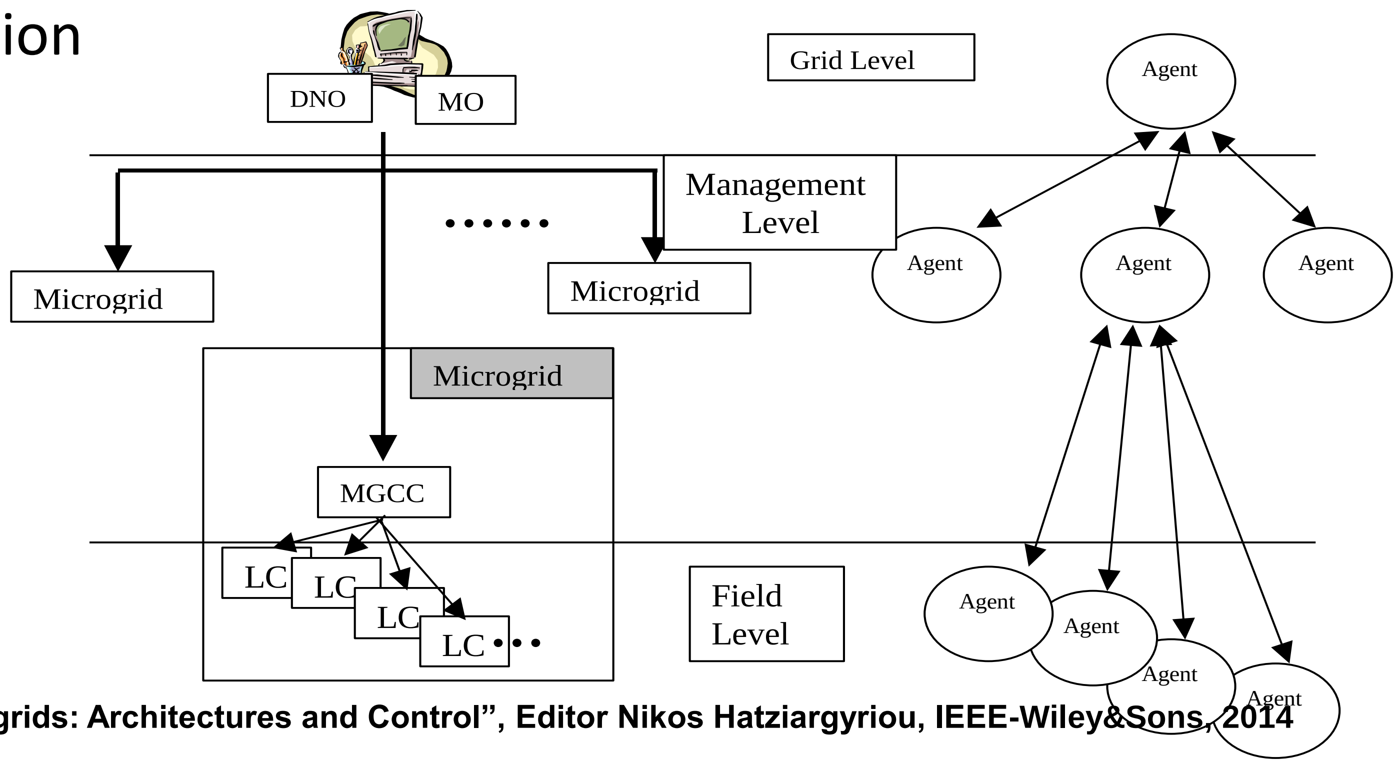
- **The main distinction is where decisions are taken**
- **Centralized Control implies that a Central Processing Unit collects all the measurement and decides next actions.**
- **Decentralized Control implies that advanced controllers are installed at each node forming a distributed control system.**
- **Choice of approach depends on DG ownership, scale, 'plug and play', etc.**

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Decentralized Control - MultiAgent Systems

- Autonomous Local Controllers
- Distributed Intelligence
- Reduced communication needs
- Open Architecture, Plug n’ Play operation

- FIPA organization
- Java Based Platforms
- Agent Communication Language



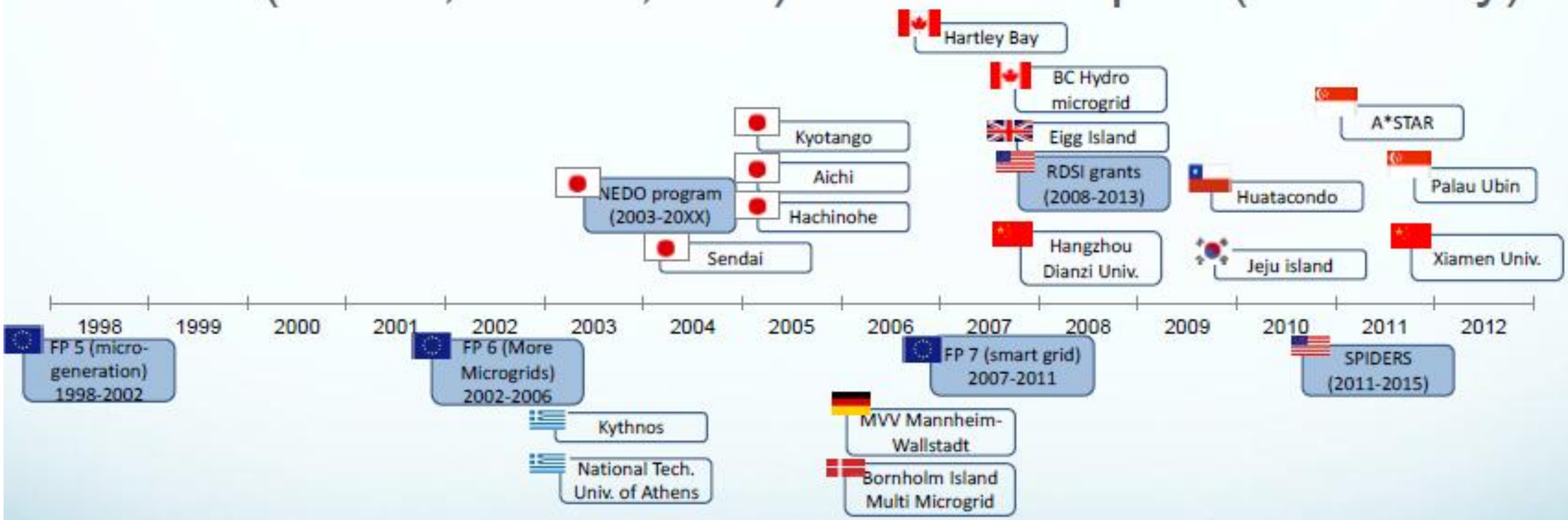
“Microgrids: Architectures and Control”, Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Microgrid Research

ENERGY FOUNDATION
能源基金会

EU → Japan → US (RDSI, SPIDERS)

→ Asia (China, Korea, etc.) → US & Japan (resiliency)



RDSI = Renewable and Distributed System Integration
SPIDERS = Smart Power Infrastructure Demonstration for Energy Reliability and Security

EU MICROGRIDS Project (FP5)

“Large Scale Integration of Micro-Generation to Low Voltage Grids”,
PROJECT N° : NNE5-2001-00463 (2003-2005)

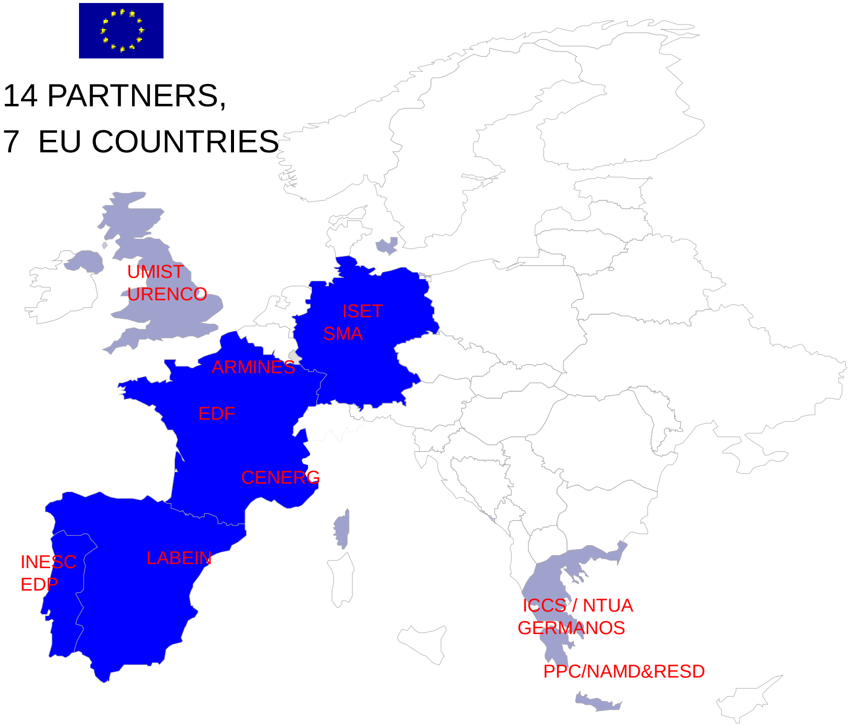
GREAT BRITAIN
- UMIST
- URENCO

PORTUGAL
- EDP
- INESC

SPAIN
- LABEIN

NETHERLANDS
- EMforce

14 PARTNERS,
7 EU COUNTRIES



GREECE
- NTUA
- PPC /NAMD&RESD
- GERMANOS

GERMANY
- SMA
- ISET

FRANCE
- EDF
- Ecole des Mines de Paris/ARMINES
- CENERG

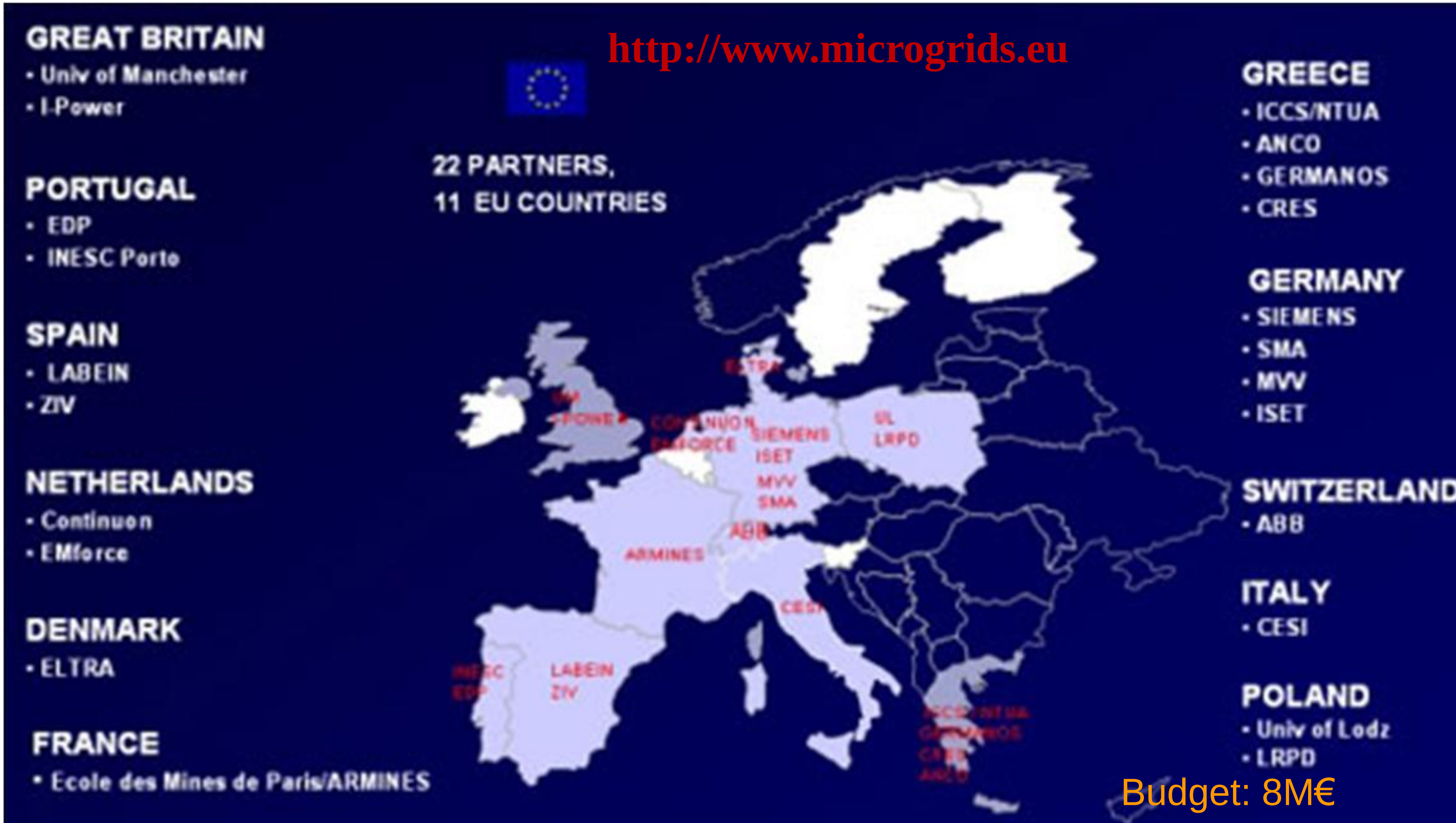
Budget: 4.5M€

http://www.microgrids.eu

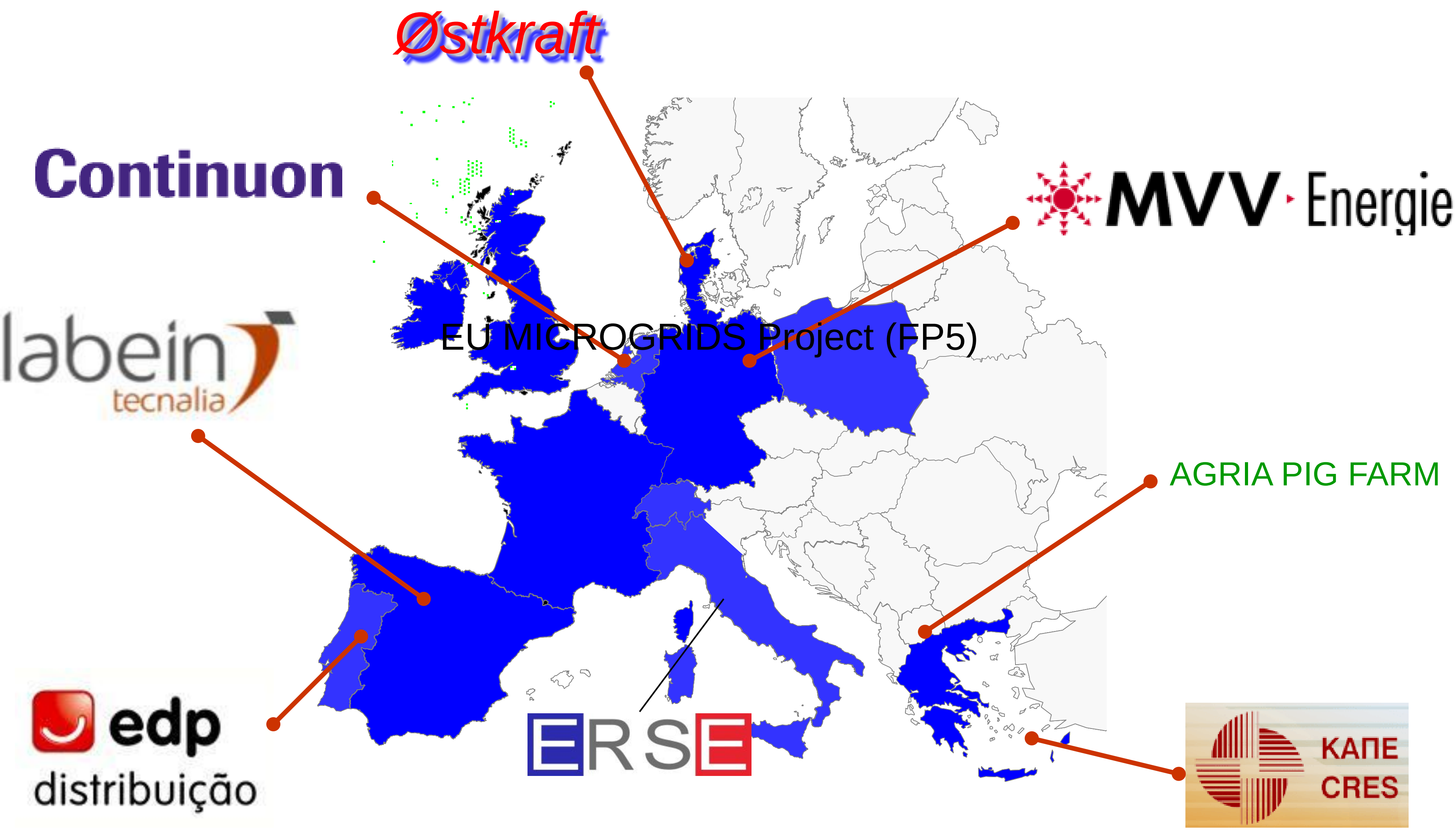
EU MORE MICROGRIDS Project (FP6)

“Advanced Architectures and Control Concepts for more Microgrids”,

Contract : SES6-PL019864 (2006-2009)



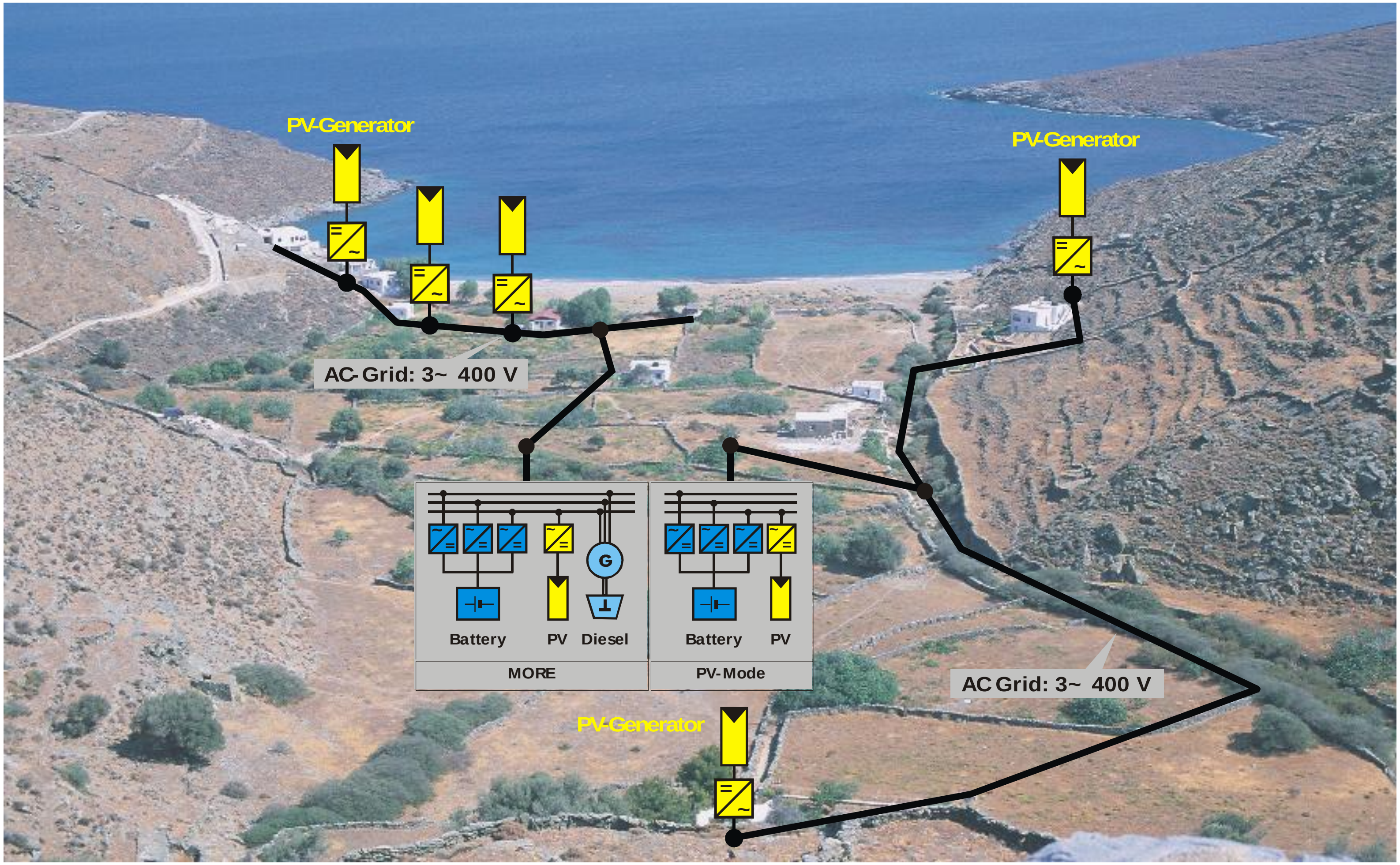
EU Microgrids Pilots



“Microgrids: Architectures and Control”, Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Kythnos Microgrid - Greece (2004)

Autonomous operation: Distributed energy resources (PV, diesel, storage) – Flexible loads (pumps) – Intelligent control (agents, communication – Energy efficiency



"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

Typical House (Kythnos)

Advanced Sunny Island inverters, to deal with islanded mode control
Intelligent Load Controllers

Settlement of 12 houses

Generation:
5 PV units connected via standard grid-tied inverters.
A 9 kVA diesel genset (for back-up).

Storage: Battery (60 Volt, 52 kWh) through 3 bi-directional inverters operating in parallel.

Flexible Loads: 1-2 kW irrigation pumps in each house

"Microgrids: Architectures and Control", Editor Nikos Hatziargyriou, IEEE-Wiley&Sons, 2014

The Kythnos System House

Goals of the Experiment

Software

- Java/Jade implementation
- CIM based ontology

Hardware

- Embedded Controller
- Measurements
- Communication
- Control via PLC

Technical

- Implement Distributed Control
- Test in real Environment

Electrical

- Increase energy efficiency
- Manage Non Critical Loads

Intelligent Load Controllers

In each house an ILC is installed:

- Windows CE 5.0
- Intel® XscaleTM PXA255
- 64MB of RAM
- 32MB FLASH Memory
- Java VM
- Jade LEAP

Outside System House

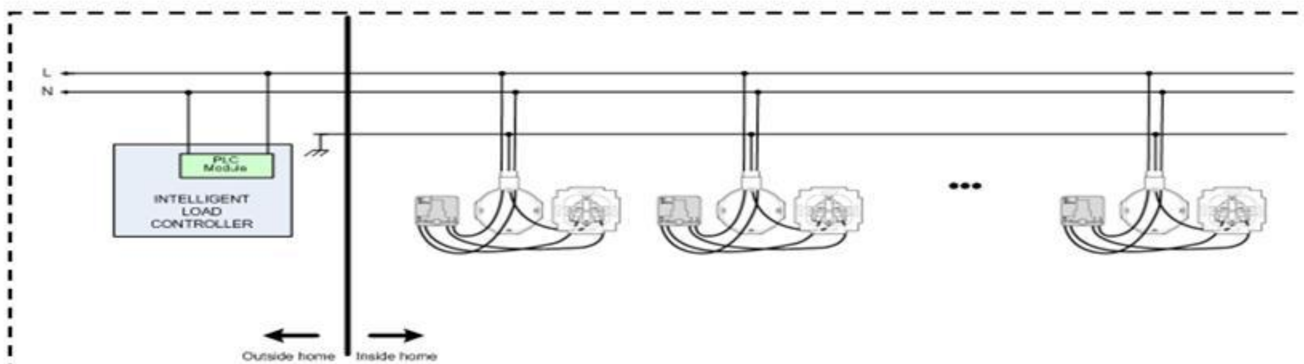
House 11

House 7

Inside System House

House 5

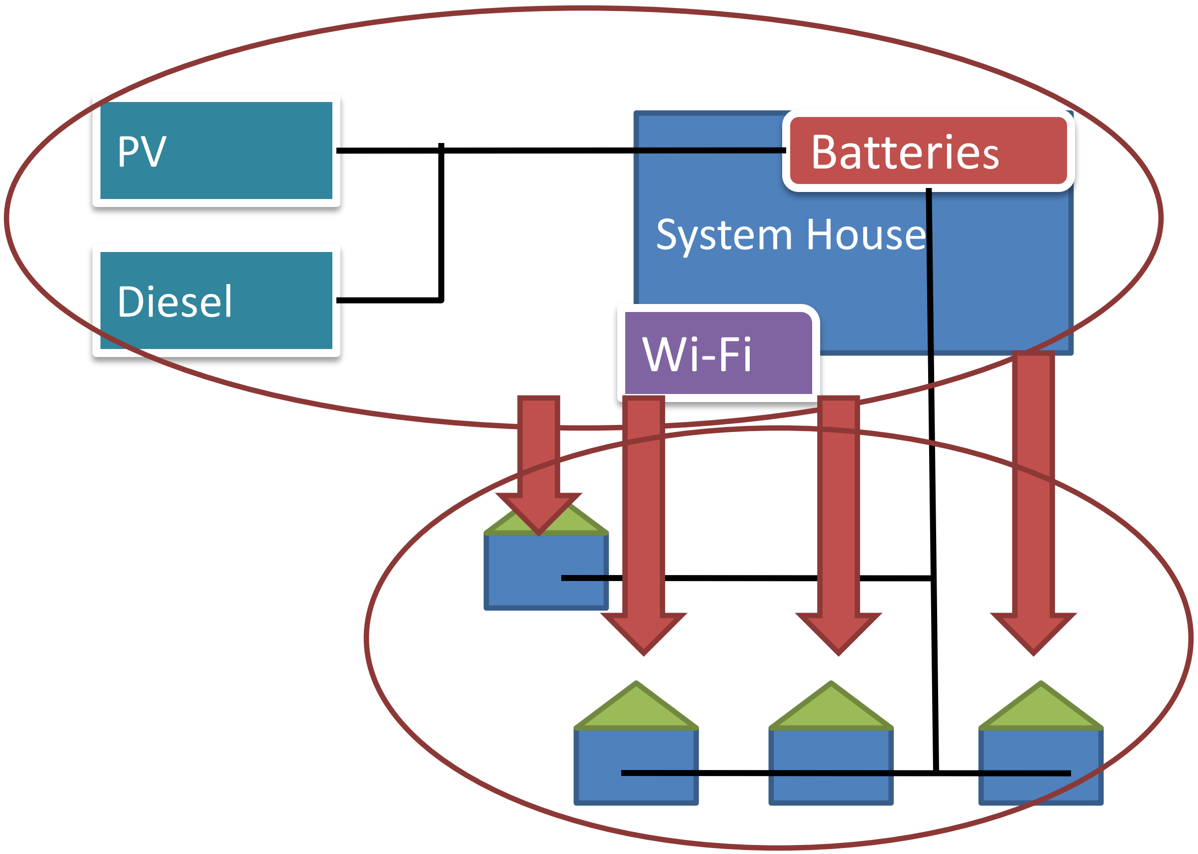
House 4



Decentralized MAS Based Control for Energy Efficiency (Kythnos)

Step 1: The agents embedded in Intelligent Load Controllers identify the status of the environment (available energy)

Step 2: The agents negotiate on how the share the available energy without central coordination



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Auction Algorithm

- In the English Auction the auctioneer seeks to find the market price of a good by initially proposing a price below that of the supposed market value and then gradually raising the price.
- Each time the price is announced, the auctioneer waits to see if any buyers will signal their willingness to pay the proposed price. As soon as one buyer indicates that it will accept the price, the auctioneer issues a new call for bids with an incremented price.
- The auction continues until no buyers are prepared to pay the proposed price, at which point the auction ends. If the last price that was accepted by a buyer exceeds the auctioneer's (privately known) reservation price, the good is sold to that buyer for the agreed price. If the last accepted price is less than the reservation price, the good is not sold

Kythnos - Lessons learnt

- The Kythnos was the first test site where the MAS system was implemented
- Controller with an Embedded processor has been used to host the agents.
- Negotiation algorithms, wireless communication, CIM based ontology etc.
- The architecture is too complex for small systems but offers great scalability.

Princeton Microgrid – USA (2006)

Campus microgrid: Resilience (to super storms) – Combined heat and power – Load shedding capability and control – PV system – Islandable

Source:
C. Marnay

Sendai Microgrid – Japan (2008)

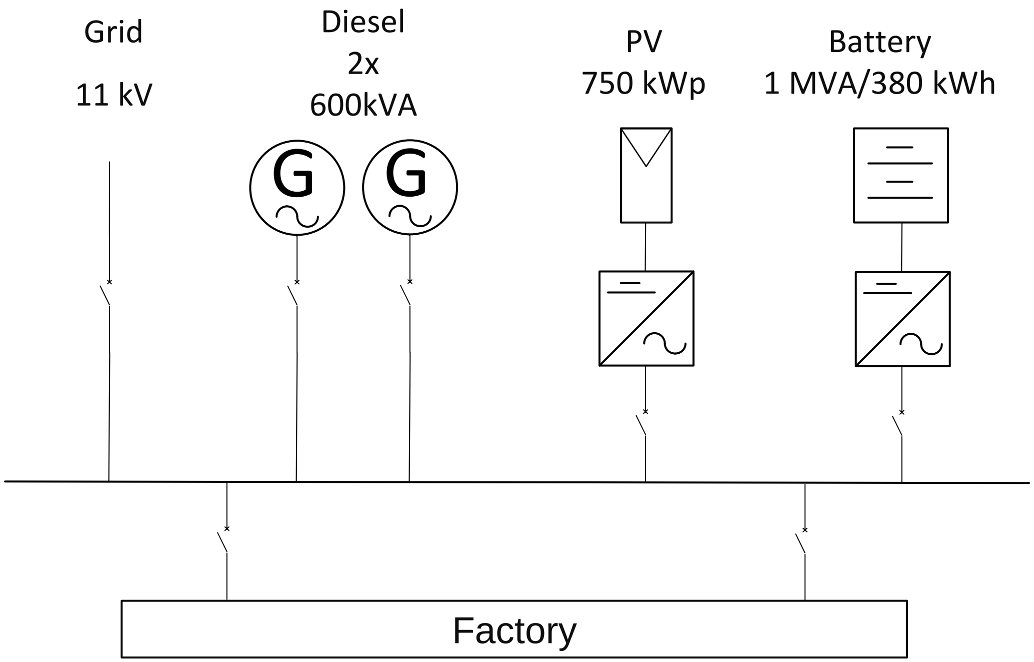
Critical Infrastructure (hospital) : Multiple power quality microgrid – Operation in islanded mode – Resilience in disasters for critical infrastructure

Great East Japan Earthquake (2011): Power was supplied to important loads by microgrid (Utility grid: blackout for 3 days)

Source: NTT

Johannesburg Microgrid– S. Africa (2016)

Industrial microgrid: maximizing renewables - reducing CO2 – seamless transition, grid connection and islanding – energy security – supply reliability



Source: ABB

Borrego Springs Microgrid - USA

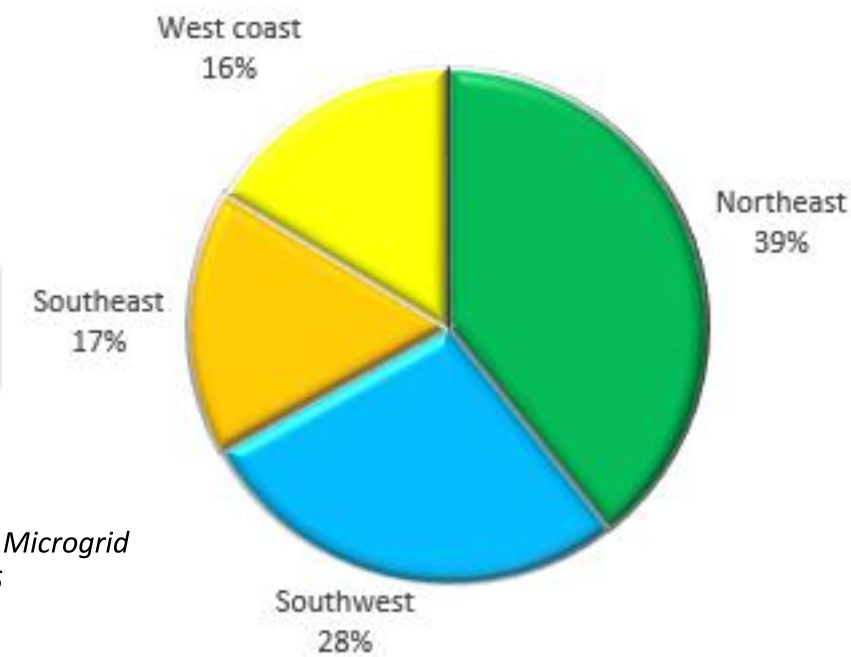
- 10 hour outage to entire community required to perform compliance-driven transmission maintenance and to replace 2 suspect transmission poles
- Utilized Borrego Springs Microgrid to keep all 2800 customers energized during transmission outage
- Base load was fed by the solar facility, using the batteries and distributed generation to “follow the load”
- Customers experienced a brief 10 minute planned outage to reconnect to the transmission grid

Source:
David Geier, SDG&E

Microgrid Installations in USA

- In 2016, 52% of microgrid capacity was military, 27% was data centers
- Seven states dominate: New York, California, Texas, Georgia, Maryland, Alaska and Oklahoma (in descending order)
- Microgrid capacity is estimated to reach 4.3 GW by 2020

Installed microgrid capacity by region



Source: GTM Research, US Microgrid Tracker Q3, 2016

Microgrid Installations in China

- National Renewable Energy Development Plan for 2016-2020
  - Build 100 RES microgrid demonstration areas by 2020, to explore the microgrid technology and business operation mode that suit the RES development.
- 1st Batch of RES Microgrid Demonstration Projects
  - May 2017, NDRC and NEA approved the 1st batch of 28 RES Microgird Demonstration Projects, including 24 grid-connected microgrid and 4 islanded microgrid projects
- Up to the end of 2016
  - 56 Microgrid demonstration projects have been completed, including community/utility Microgrids, campus Microgrids, commercial/industrial Microgrids and remote Microgrids

Source: CEPRI, 2017

Conclusions

- Microgrids: The building Blocks of SmartGrids
- Numerous Technical Challenges, but a lot of active research by Research Centers, Technology Providers, Universities. A number of promising solutions proposed/demonstrated, large number of pilot installations worldwide.
- Fast growing activity in USA, China, Japan, Europe, etc and also in the developing world (remote installations)
- Numerous advantages provided by the effective integration of DER for Network Operation (Local Balancing, Investment Deferral, Resilience and Reliability, Power Quality, Ancillary Services to Transmission, etc), Prosumer Participation (Local Energy Communities, Smart Islannds, etc), Retailers and Aggregators (Local Energy Markets), Environmental Protection, Social Welfare…
- For increased Microgrids development an efficient integration to system planning and operation the active role of DSOs should be encouraged (incentivized).