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Microgrids Integration and the Role of Distribution Systems Operators

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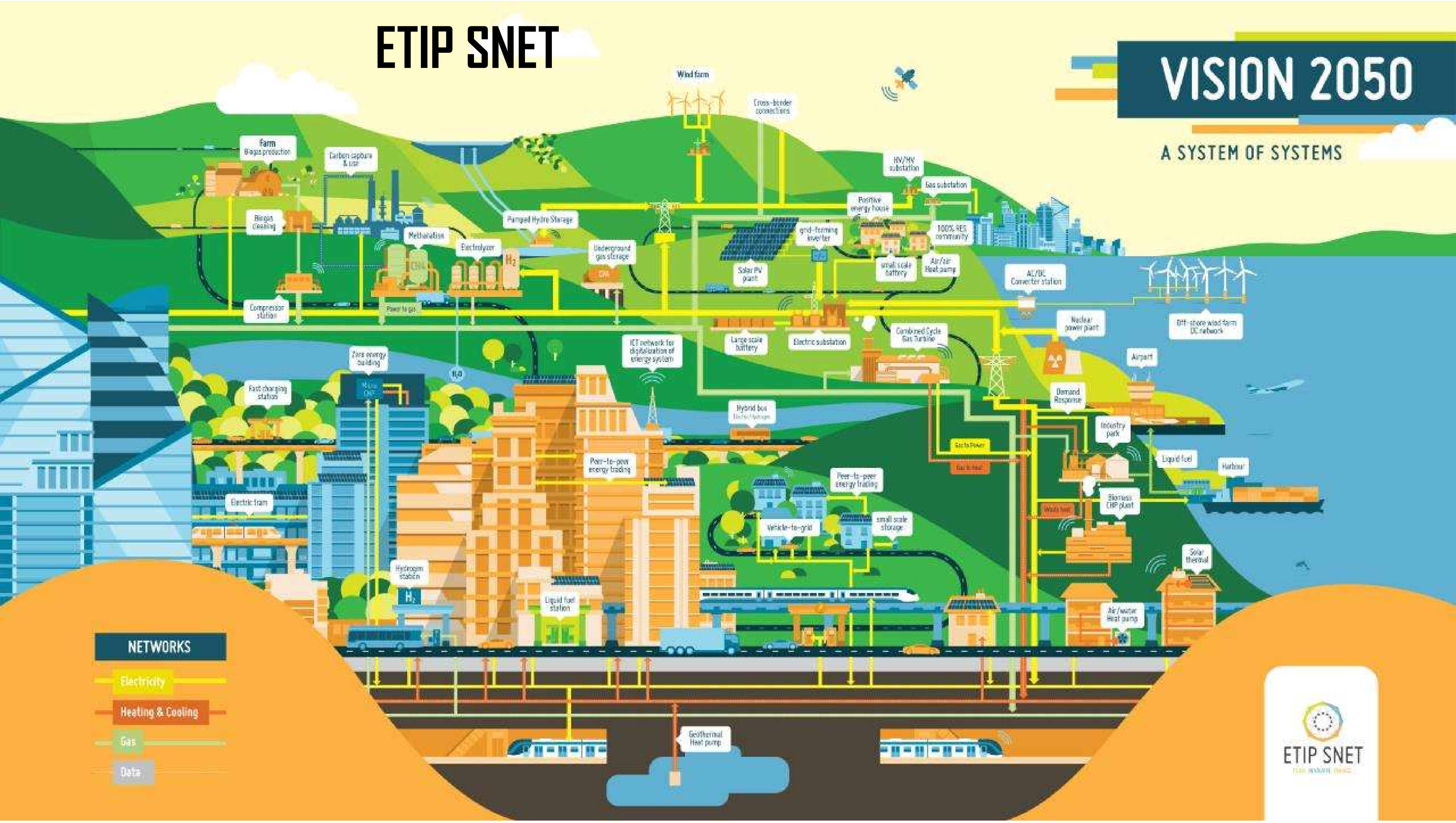
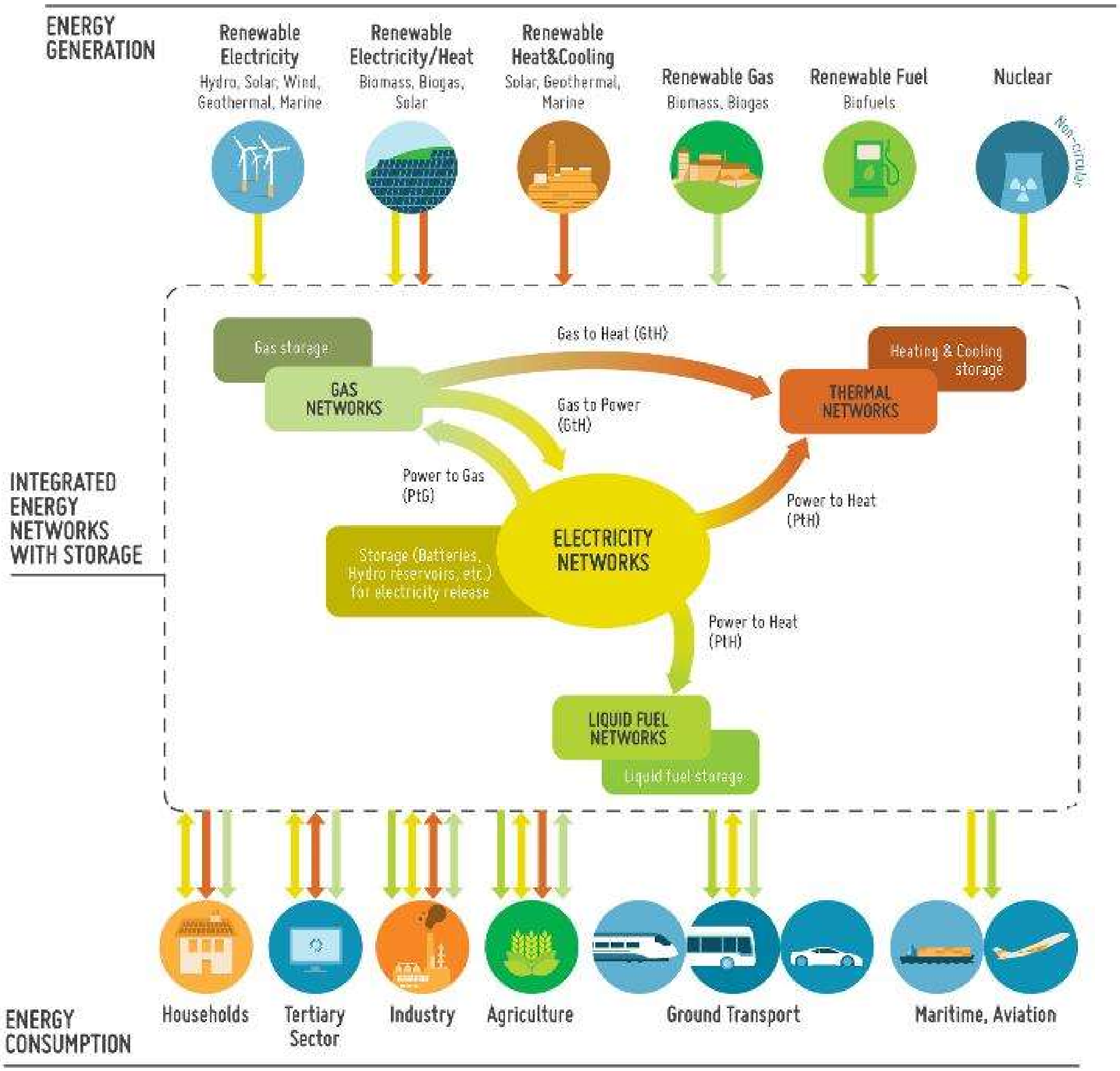
ETIP SNET

VISION 2050

A SYSTEM OF SYSTEMS

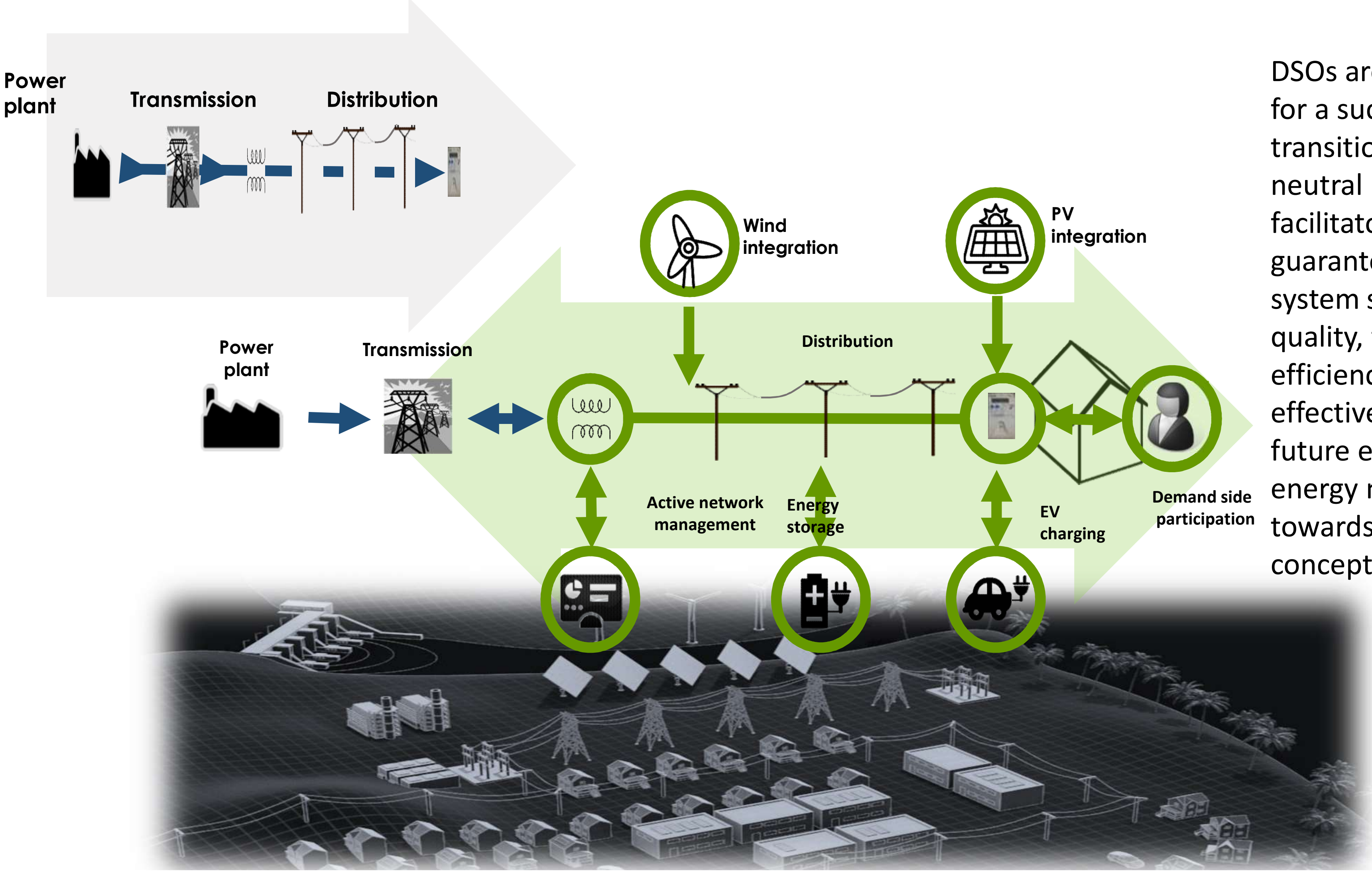


The future integrated energy systems with conversion and storage devices



Electricity network is the backbone of the integrated energy system

Key Role of Operators



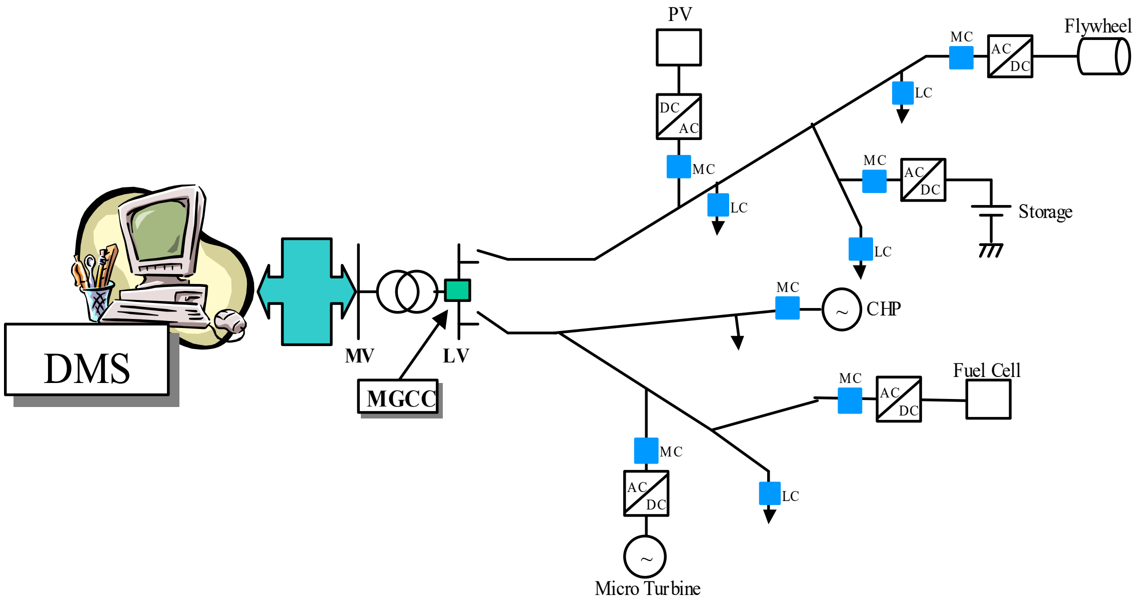
DSOs are key enablers for a successful energy transition . They act as neutral market facilitators and guarantee distribution system stability, power quality, technical efficiency and cost effectiveness in the future evolution of energy networks towards a smarter grid concept.

Definition of Microgrids

http://www.microgrids.eu

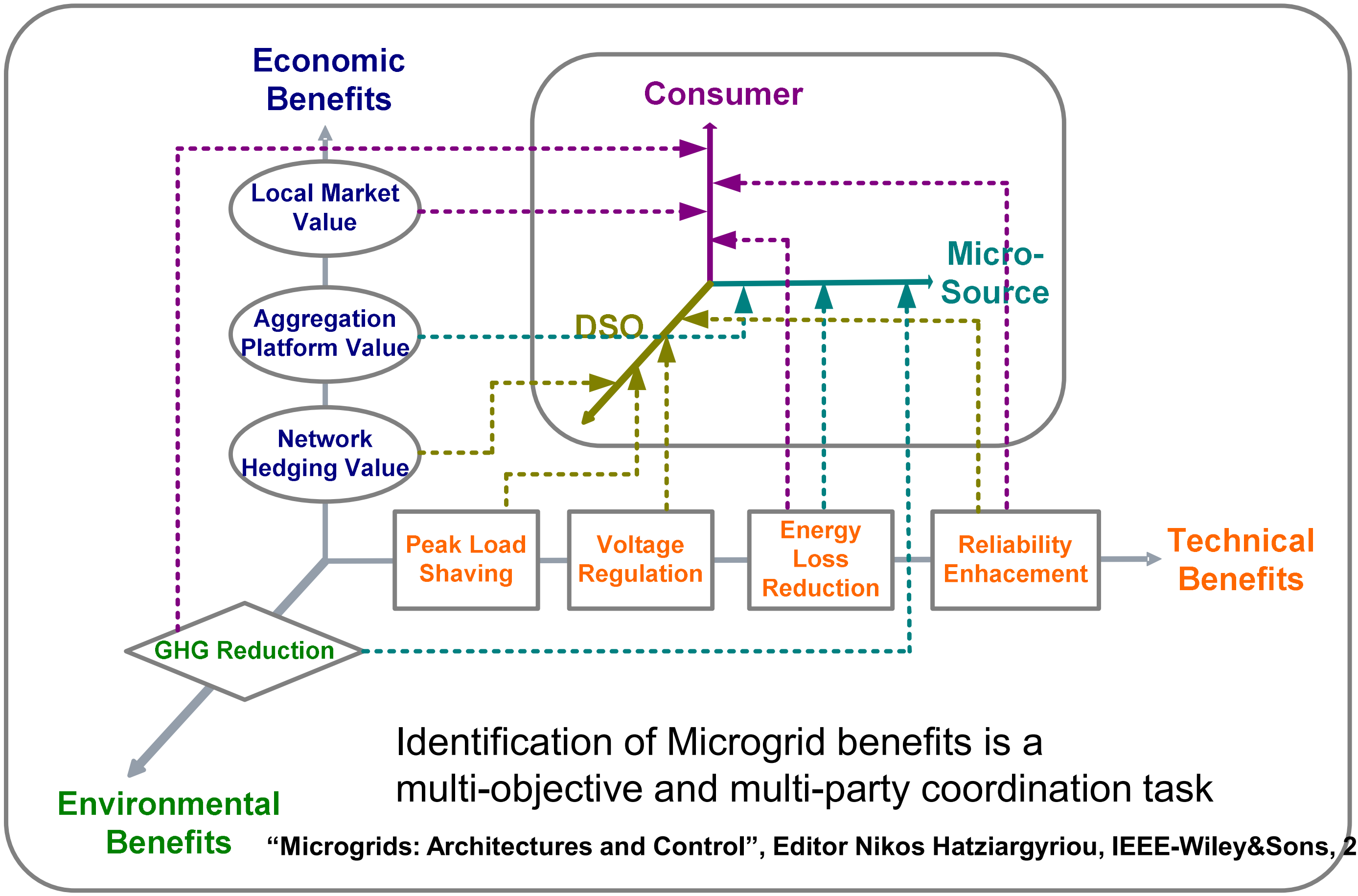
Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way, either while connected to the main power network and/or while islanded.

(CIGRE WG C6.22)



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

Benefits by Criteria & Stakeholder



Identification of Microgrid benefits is a multi-objective and multi-party coordination task

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

Microgrids Market Models

- Investments in Microgrids can be done in multiple phases by different stakeholders: end consumers, energy suppliers, DSOs,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. Not possible in current EU regulation
  - 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 run by DSOs or other entities.

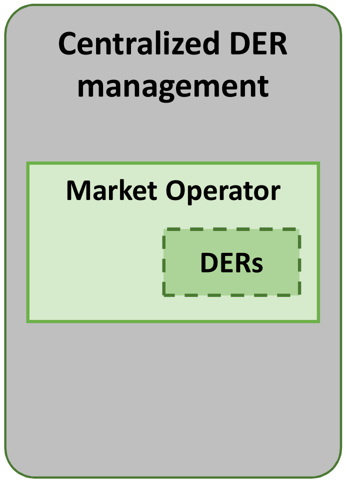
Microgrids ≠ Local Energy Communities

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

DER market models

Centralized model

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



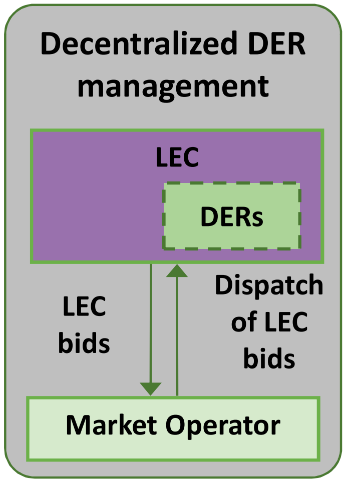
Centralized DER management

Market Operator

DERs

Decentralized model - PAB

- A LEC (value driven) manages DERs (through set-points) and participates in the market procedures



Decentralized DER management

LEC

DERs

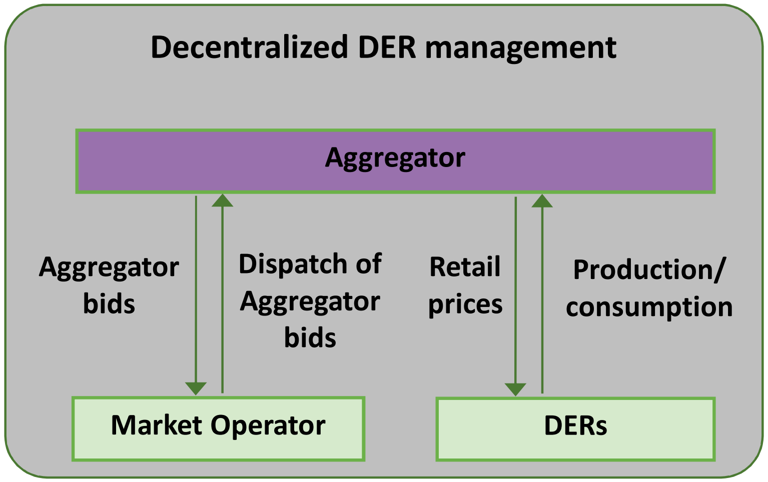
LEC bids

Dispatch of LEC bids

Market Operator

Decentralized model - PAC

- An Aggregator (profit driven) manages DERs (through price signals) and participates in the market procedures
- DERs decide their own dispatch



Decentralized DER management

Aggregator

Aggregator bids

Dispatch of Aggregator bids

Retail prices

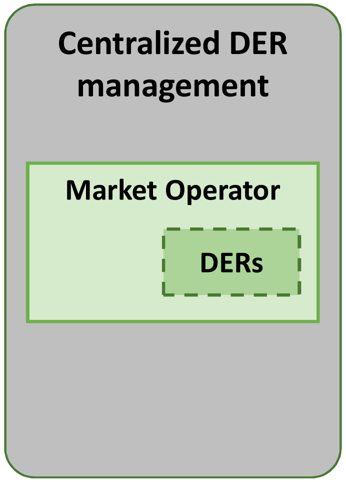
Production/ consumption

Market Operator

DERs

Centralized model

- Central (Global) Market Operator (decides the dispatch):
  - Central Generators connected at the Transmission Level
  - Distributed Energy Resources connected at the Distribution Level
- Distributed Energy Resources (DERs):
  - flexible loads and local production units connected to the MV/LV network
- Objective function: (max) social benefit = revenues from energy sales to flexible customers - central production cost - local production cost (non-flexible customers are charged by known/pre-defined prices, so they are excluded from optimization).
- Decision variables:
  - Dispatch of central generators and DERs (local production, flexible load)
  - Active power flow per line, voltage angle per bus
  - Locational marginal prices
- Constraints:
  - Energy balance per bus
  - Operational limits of central units, local production, flexible loads
  - Transmission line capacity limits
  - Bus voltage angle limits
  - DC load flow equations



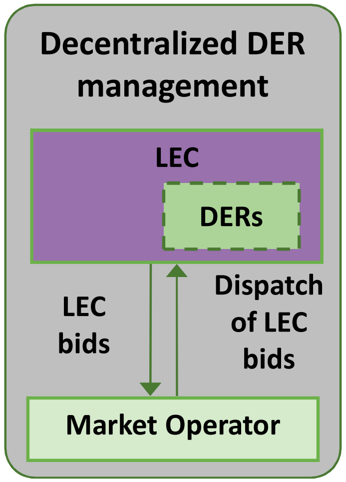
Centralized DER management

Market Operator

DERs

Decentralized model through LEC (Pay-As-Bid) (1/3)

- Local Energy Community:
  - Represents multiple DERs/non-profit (value driven) entity
  - Operates DERs (issues set-points)
  - Submits bids to the Market Operator and receives the dispatch program
- Market Operator:
  - Operates the global market (decides the dispatch of conventional Central Generators and of the bids of the LEC)
- Distributed Energy Resources (DERs):
  - Comprise flexible loads and local production units connected to the MV/LV network,
  - Represented as aggregated units at each MV/LV bus,
  - Receive set-points issued by the LEC.
- BASIC ASSUMPTION: Participation of DERs affect Global Market Prices due to their significant volume (the LEC is not a price-taker)
- Interdependence in decision making + hierarchical structure → Bi-level Programming Problem



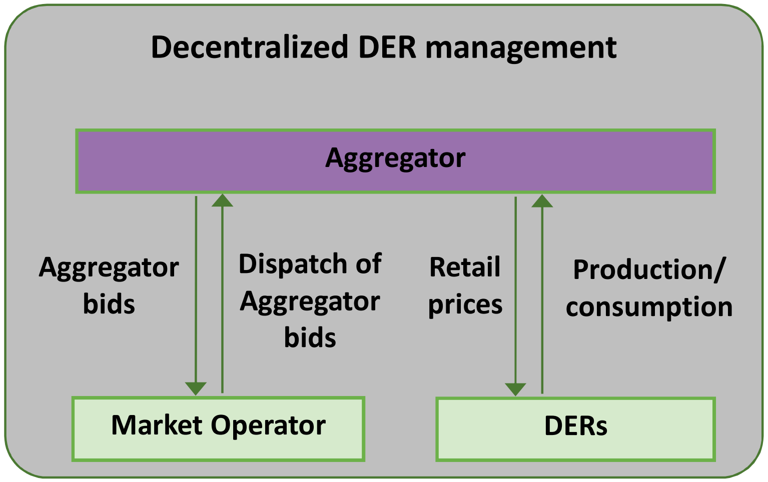
Decentralized model – Pay-As-Bid (2/3)

- **LEC Market (upper level)**
  - Objective function: (min) net energy procurement cost = imports from central market cost + local production cost - revenues from energy sales to flexible customers – export revenues to central market
  - Decision variables:
    - Dispatch of local generation units and local flexible load
    - Price-quantity pairs of Production Offers and Demand Bids submitted to the Market Operator
  - Constraints:
    - LEC portfolio energy balance (supply of local inflexible load)
    - DERs operational limits
    - Production Offers and Demand Bids validation

Decentralized model – Pay-As-Bid (3/3)

- Market Clearing Problem (lower level)
  - Objective function: (max) social benefit = revenues from energy sales to LEC - conventional production cost - LEC production cost
  - Decision variables
    - Dispatch of central generators
    - Dispatch of LEC Production Offers and LEC Demand Bids
  - Constraints
    - Energy balance per Dispatch Period
    - Operational limits of conventional units
    - LEC Production Offers and LEC Demand Bids operational limits
    - Transmission line capacity limits
    - Bus voltage angle limits
    - DC load flow equations

Decentralized model through Aggregator – Pay-As-Cleared (1/4)



- Aggregator:
  - Represents multiple DERs/profit driven entity
  - Operates a local market by receiving bids from DERs
  - Submits bids to the Market Operator and receives the dispatch program
  - Sends price signals to DERs
- Market Operator:
  - Operates the global market (decides the dispatch of conventional Central Generators and of the bids of the Aggregator)
- Distributed Energy Resources (DERs):
  - Comprise flexible loads and local production units connected to the MV/LV network,
  - Represented as aggregated units at each MV/LV bus,
  - Decide individually the dispatched quantities based on price signals received.
- BASIC ASSUMPTION: Participation of DERs affect Global Market Prices due to their significant volume (the Aggregator is not a price-taker)
- Interdependence in the decision making process + hierarchical structure → Bi-level Programming Problem

Decentralized model – Pay-As-Cleared (2/4)

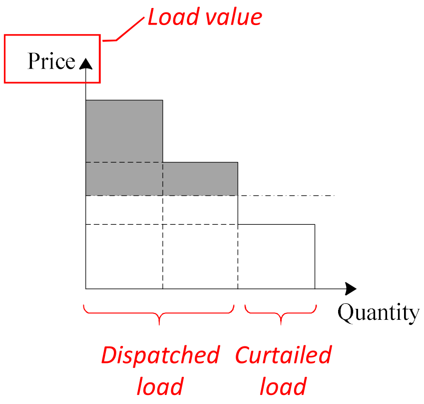
- Aggregator (upper level)
  - Objective function: minimize net energy procurement cost = costs for energy from central market (imports cost) – revenues from selling to central market (export revenues)+ local production cost – revenues from energy sales to flexible customers
  - Decision variables (per Dispatch Period):
    - Retail price for local generation units
    - Retail price for local flexible load
    - Price-quantity pairs of Production Offers and Demand Bids submitted to the Market Operator
  - Constraints:
    - Aggregator portfolio energy balance
    - Production Offers and Demand Bids validation

Decentralized model – Pay-As-Cleared (3/4)

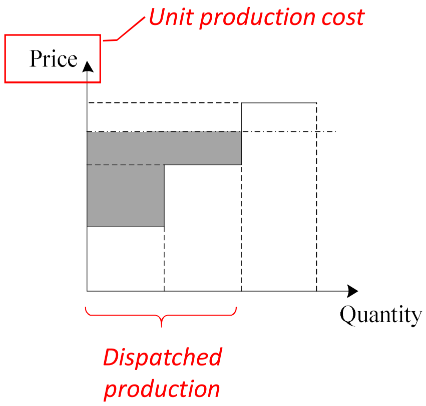
- Market Clearing Problem (lower level)
  - Objective function: social benefit (max) = revenues from energy sales to Aggregator - conventional production cost - Aggregator production cost
  - Decision variables (per Dispatch Period):
    - Dispatch of central generators
    - Dispatch of Aggregator Production Offers and Aggregator Demand Bids
    - Active power flow per line, voltage angle per bus
  - Constraints:
    - Energy balance per bus
    - Operational limits of central units, Aggregator Generation Offers & Aggregator Demand Bids.
    - Transmission line capacity limits
    - Bus voltage angle limits
    - DC load flow equations

Decentralized model – Pay-As-Cleared (4/4)

- DER decision models (lower level)
- Consumers with flexible loads
  - Objective function: consumer's surplus
  - Decision variables: energy demand

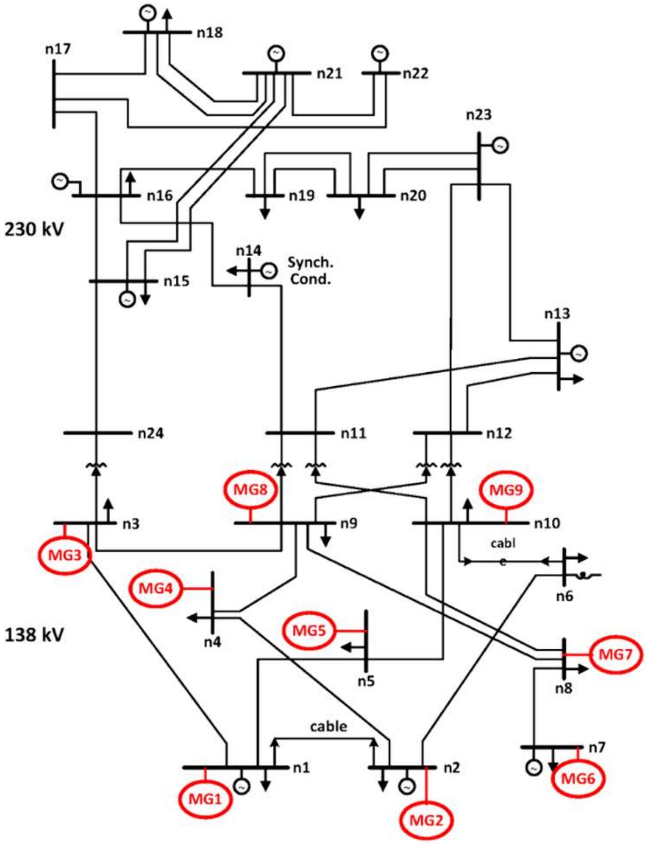


- Local producers
  - Objective function: producer's surplus
  - Decision variables: energy production



Study Case [Modified IEEE 24-bus test system (without hydro units)]

- Flexible loads (n1, n4, n5, n7, n9, n10):
  - 10 entities
  - Prices: 33–82,5€/MWh ⟵ *Sensitivity analysis (-50% + 50%, +150%)*
  - Total capacity: 614MW
- Local production (n1, n2, n3, n4, n8, n10):
  - 10 entities
  - Prices*: 34,6–145€/MWh ⟵ *Sensitivity analysis (-50% + 50%, +150%)*
  - Total capacity: 398,9MW
- *Local production prices are based on the results of the tendering procedure by Regulatory Authority for Energy (RAE Decision 570/2016, PV units) .*
- *Prices are adjusted within the range 34,6-145€/MWh, which is the range of the System Marginal Price of the Greek Interconnected System for the year 2017, as published by the Independent Power Transmission Operator (IPTO).*
- Assumption: one Aggregator/LEC represents all DERs



One dispatch period (t11), generation bids only

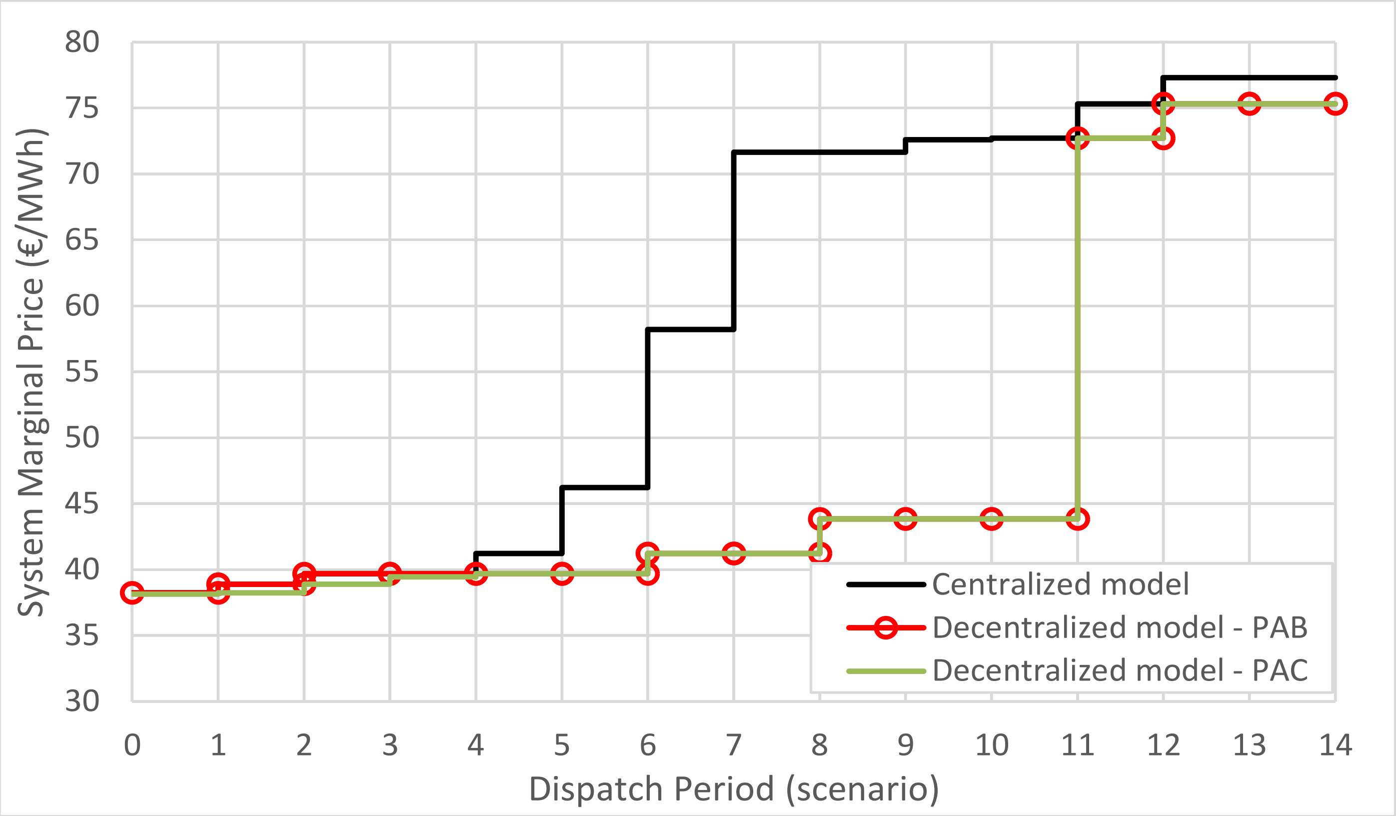
	Centralized management	Decentralized management – Pay-As-Bid	Decentralized management – Pay-As-Cleared
Total load (MWh)	2.364	2.364	2.364
System Load (MWh)	2.364	1.260	1.260
LEC/Aggregator Load (MWh)	–	1.104	1.104
Central units production (MWh)	2.364	2.074	2.074
Local units production (MWh)	0	290	290
Energy absorption by the LEC/Aggregator for covering the load (LB) (MWh)	–	853	853
Energy injection by the LEC/Aggregator (GB) (MWh)	–	39	39
Central units dispatch (MWh)			
u1-u7 (≤38,8€/MWh)	*1.770*	*1.770*	*1.770*
u8-u11 (43,8€/MWh)	*304*	*304*	*304*
u12-u14 (71,6€/MWh)	*150*	*0*	*0*
u15-u17 (72,7€/MWh)	*140*	*0*	*0*
Local generation units dispatch (MWh)			
gb1, gb7 (102,2€/MWh)*	*0*	*60*	*60*
gb2, gb8 (100,4€/MWh)*	*0*	*90*	*90*
gb3, gb9 (98,6€/MWh)*	*0*	*70*	*70*
gb4, gb10 (97€/MWh)*	*0*	*50*	*50*
gb5 (95€/MWh)*	*0*	*20*	*20*
gb6 (104€/MWh)*	*0*	*0*	*0*

** Prices for Basic cost scenario.*

	Centralized management	Decentralized management – Pay-As-Bid	Decentralized management – Pay-As-Cleared
Aggregator/LEC objective function (€)	–	64.457	65.271
Market Operator objective function (€)	- 98.219	-170.512	-169.195
Total production cost (€)	98.219	106.100	106.100
Central units production cost (€)	*98.219*	*77.327*	*77.327*
Local production units cost (€)	*0*	*28.773*	*28.773*
Cost of dispatched LEC/Aggregator production offers (€)	–	389	1.707
Value of dispatched LEC/Aggregator demand bids (€)	–	248.229	248.229
Aggregator/LEC exports revenues (€)	–	1.707	1.707
Aggregator/LEC imports payments (€)	–	37.391	37.391
Central units' revenues (€)	171.801	90.897	90.897
Local production units' revenues (€)	0	28.773	29.587
System load payments (€)	171.801	55.213	55.213
Central units' surplus (€)	73.582	13.570	13.570
Local generation units' surplus (€)	0	0	814
LEC/Aggregator inflexible load charge price (€/MWh)	–	58,40	59,13
LMP (€/MWh)	72,69	43,83	43,83

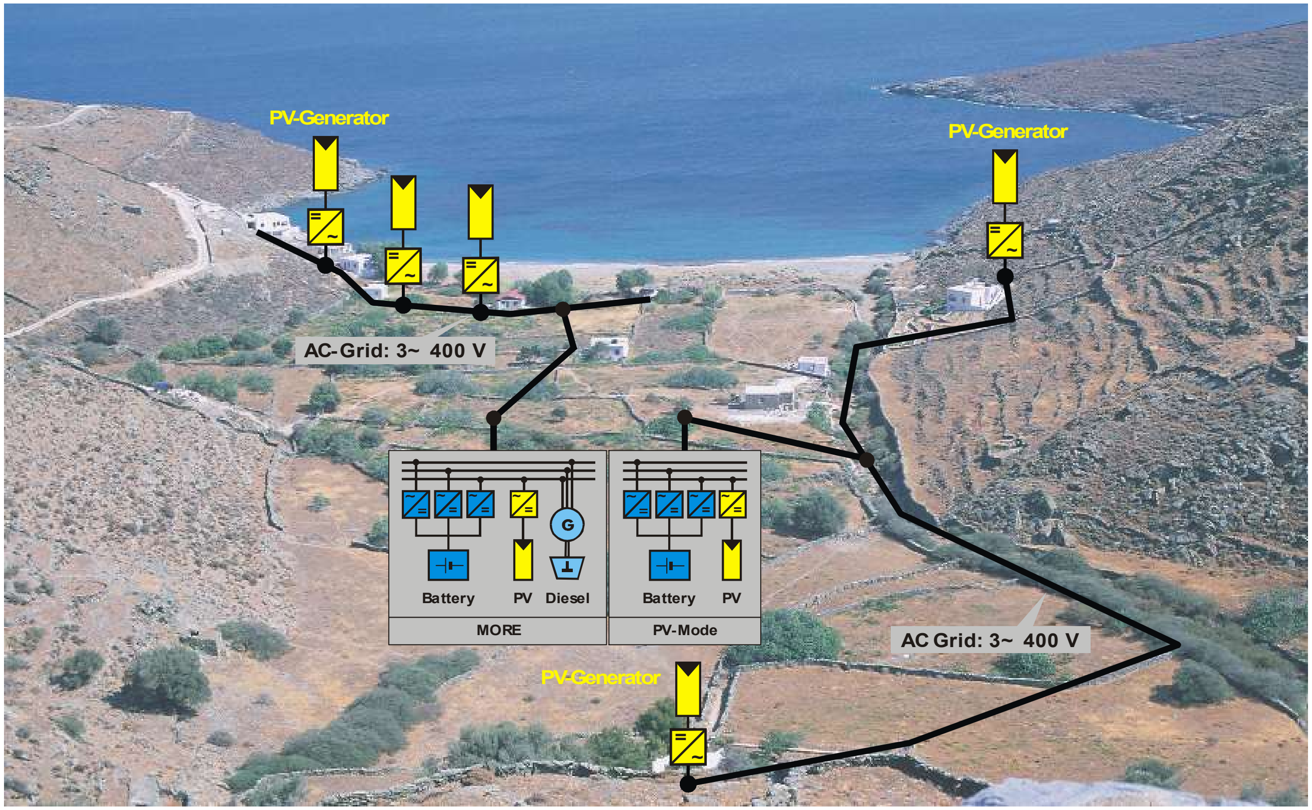
Results – one Dispatch Period, generation bids

- Central units are dispatched less in decentralized management (expensive central units are not dispatched).
- As a result, central units' revenues in decentralized management are lower than in centralized model.
- The limited dispatch of central units in the decentralized models results in lower central units' surplus
- Local generation units are dispatched more in decentralized management.
- As a result, local generation units' revenues in decentralized management are higher.
- The total (conventional and local) production cost in the centralized model is lower than in the decentralized models
- However, the total revenues of the generation units are lower in the decentralized models, esp. the revenues of the central units.
- The system marginal price (SMP) is calculated as the dual variable (Lagrange multiplier) of the system energy balance equality constraint. The SMP is the market clearing price, i.e. the uniform price at which the suppliers buy the energy from the system and the price at which the producers sell the energy they inject to the System. These are lower in the decentralized models.
- The local generation units' revenues are higher in the PAC model, compared to the PAB model. In PAB model, dispatched local generation is remunerated at the bid price, in the PAC model at the price of the most expensive local generator dispatched.


System Marginal Price (€/MWh)
80
75
70
65
60
55
50
45
40
35
30
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Dispatch Period (scenario)
Centralized model
Decentralized model - PAB
Decentralized model - PAC

Real World Microgrids Kythnos - 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.

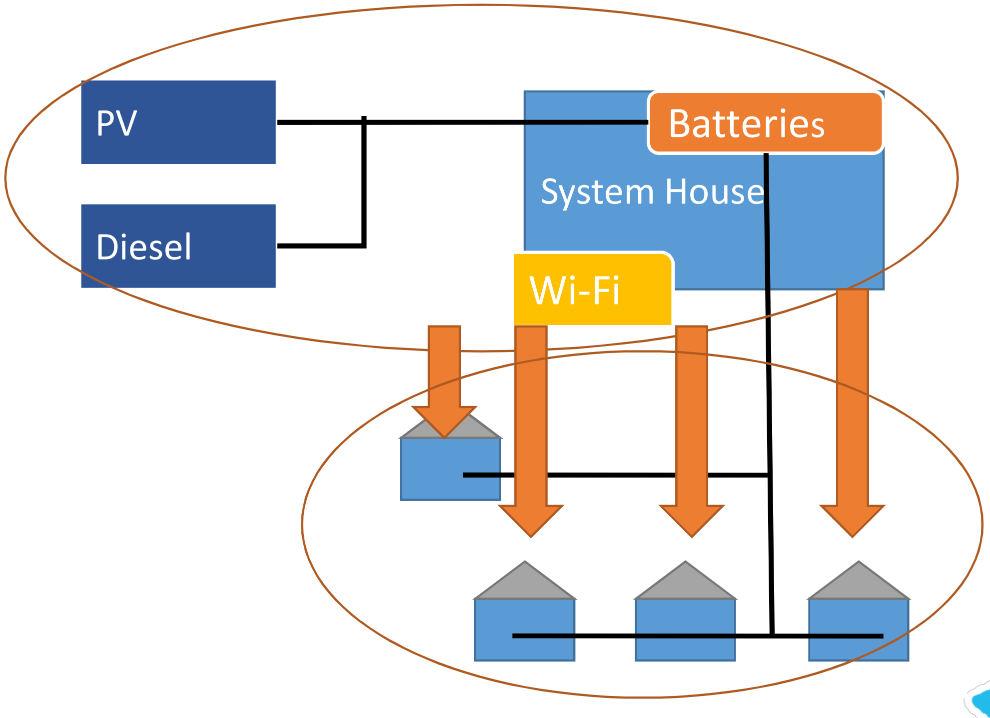
Flexible Loads: 1-2 kW irrigation pumps in each house

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

Decentralized MAS Based Control for Energy Efficiency

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



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

Real World Microgrids Princeton Campus – USA (2006)

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

Source:
C. Marnay

Real World Microgrids Sendai – Japan (2008)

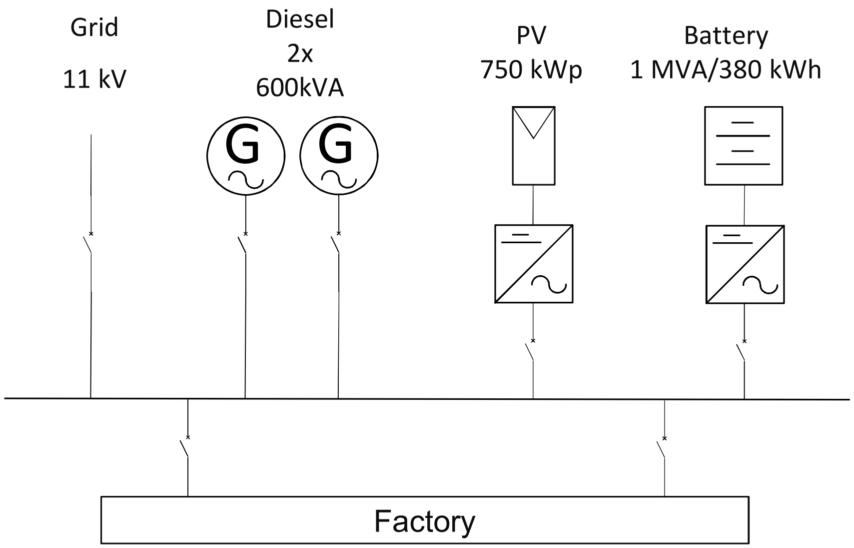
Critical Infrastructure (hospital) : Multiple power quality microgrid – Operation in islanded mode – Resilience in disasters for critical infrastructure

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

Source: NTT

Real World Industrial Microgrid
Johannesburg– S. Africa (2016)

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



Grid
11 kV

Diesel
2x
600kVA

PV
750 kWp

Battery
1 MVA/380 kWh

Factory

Source: ABB

Real World Utility Microgrid, Borrego Springs - 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, San Diego Gas&Electric (SDG&E)

Conclusions

- Microgrids is a fast growing activity in USA, China, Japan, Europe, etc. and 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 Islands, etc), Retailers and Aggregators (Local Energy Markets), Environmental Protection, Social Welfare…
- The operation of local markets (LEC or via Aggregator) versus central markets lowers consumer costs. Although higher dispatch of more expensive local production units in decentralized management results in increased total production cost, the total revenues of the producers decrease, i.e. the producers' surplus decreases and as a result consumers pay less, due to reduced LMPs.

Thank you for your attention!

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Back Up Slides

Centralized model – Problem formulation

local production cost

revenues from energy sales to flexible customers

$$\min_{Q_{u,s,t},Q_{gb,s,t},Q_{db,s,t},\delta_{n,t}} \pi_t \left(\boxed{\sum_{u,s,t} P_{u,s} Q_{u,s,t}} + \boxed{\sum_{gb,s,t} \overline{P}_{gb,s,t} Q_{gb,s,t}} - \boxed{\sum_{db,s,t} \overline{P}_{db,s,t} Q_{db,s,t}} \right)$$

central production cost

$$\left.\begin{aligned} 0 \le Q_{u,s,t} &\le \overline{Q}_{u,s}, \forall u,s,t \\ 0 \le Q_{gb,s,t} &\le \overline{Q}_{gb,s,t}, \forall gb,s,t \\ 0 \le Q_{db,s,t} &\le \overline{Q}_{db,s,t}, \forall db,s,t \end{aligned}\right\}$$

Operational limits of central units, local production, flexible loads

$$\sum_{u\in\mathcal{U}_{n,s}} Q_{u,s,t} - L_{n,t} + \sum_{gb\in\mathcal{GB}_{n},s} Q_{gb,s,t} - \sum_{db\in\mathcal{DB}_{n},s} Q_{db,s,t} = \sum_{l\in L_n} f_{l,t}, \forall n,t$$

← Energy balance per bus

$$-\overline{f}_l \le f_{l,t} \le \overline{f}_l, \forall l,t$$

← Transmission line capacity limits

$$-\pi \le \delta_{n,t} \le \pi, \forall n \backslash n{:}\, ref., t$$

← Bus voltage angle limits

$$\delta_{n,t} = 0, n{:}\, ref., \forall t$$

← Reference bus voltage angle

$$f_{l,t} = S_b \sum_{n:\, l\in L_n} A_{n,l} B_l \delta_{n,t}, \forall l,t$$

← DC load flow

$$\sum_{l\in L_n} f_{l,t} = S_b \sum_{l:\, A_{n,l}>0} \sum_n A_{n,l} B_l \delta_{n,t} - S_b \sum_{l:\, A_{n,l}<0} \sum_n A_{n,l} B_l \delta_{n,t}, \forall n,t$$

← Incoming energy per bus

LEC decision model (upper level)

local production cost

revenues from energy sales to flexible customers

$$\min_{\substack{\overline{LP}_{n,t},\overline{LQ}_{n,t}\\ \overline{GP}_{n,t},\overline{GQ}_{n,t}}} \sum_{t} \pi_t \left[\boxed{\sum_{n\in\mathcal{N}_A} \lambda_{n,t}\left(LQ_{n,t} - GQ_{n,t}\right)} + \boxed{\sum_{g,s,t} \overline{P}_{g,s,t} Q_{g,s,t}} - \boxed{\sum_{db,s,t} \overline{P}_{db,s,t} Q_{db,s,t}} \right]$$

cost for energy acquired from the grid – revenues from selling energy to the grid

$$\left(LQ_{n,t} - GQ_{n,t}\right) + \sum\nolimits_{gb\in\mathcal{GB}_n,s} Q_{gb,s,t} - \sum\nolimits_{db\in\mathcal{DB}_n,s} Q_{db,s,t} = d_{n,t}, \forall n \in \mathcal{N}_A, t \longleftarrow$$

Energy balance per bus

$$\left.\begin{aligned} 0 \le Q_{gb,s,t} \le \overline{Q}_{gb,s,t}, \forall gb, s, t \\ 0 \le Q_{db,s,t} \le \overline{Q}_{db,s,t}, \forall db, s, t \end{aligned}\right\}$$

DERs operational limits

$$\left.\begin{aligned} GP^{min} \le \overline{GP}_{n,t} \le GP^{max}, \forall n, t \\ 0 \le \overline{LP}_{n,t} \le LP^{max}, \forall n, t \end{aligned}\right\}$$

Administratively defined bounds for prices of LEC bids (validation).

$$\left.\begin{aligned} 0 \le \overline{GQ}_{n,t} \le GQ_n^{max}, \forall n, t \\ 0 \le \overline{LQ}_{n,t} \le LQ_n^{max}, \forall n, t \end{aligned}\right\}$$

Feasible upper limit for quantity of bids based on the composition of the clientele of the LEC per bus.

$$\left.\begin{aligned} -\overline{GQ}_{n,t} M \le \overline{GP}_{n,t} \le \overline{GQ}_{n,t} M, \forall n, t \\ -\overline{GP}_{n,t} M \le \overline{GQ}_{n,t} \le \overline{GP}_{n,t} M, \forall n, t \\ -\overline{LQ}_{n,t} M \le \overline{LP}_{n,t} \le \overline{LQ}_{n,t} M, \forall n, t \\ -\overline{LP}_{n,t} M \le \overline{LQ}_{n,t} \le \overline{LP}_{n,t} M, \forall n, t \end{aligned}\right\}$$

No bid with zero price and non-zero volume is submitted and vice versa (validation).

$$\overline{LQ}_{n,t} > 0 \text{ or } \overline{GQ}_{n,t} > 0, \forall n, t \longleftarrow$$

Each bus is either importing or exporting.

Market Clearing Problem (lower level)

central production cost

cost for compensating the LEC for energy injected into the grid

$$\min_{\substack{Q_{u,s,t},\delta_{n,t}\\ GQ_{n,t},LQ_{n,t}}} \boxed{\sum_{u,s,t} P_{u,s}Q_{u,s,t}} + \sum_{n,t}\left(\boxed{\overline{GP}_{n,t}GQ_{n,t}} - \boxed{\overline{LP}_{n,t}LQ_{n,t}}\right)$$

revenues from energy sales to the LEC for energy absorbed (by the LEC) from the grid

$$\left.\begin{aligned} 0 \le Q_{u,s,t} \le \overline{Q}_{u,s} &: \pi^{min}_{u,s,t}, \pi^{max}_{u,s,t}, \forall u,s,t \\ 0 \le GQ_{n,t} \le \overline{GQ}_{n,t} &: \psi^{min}_{n,t}, \psi^{max}_{n,t}, \forall n,t \\ 0 \le LQ_{n,t} \le \overline{LQ}_{n,t} &: \xi^{min}_{n,t}, \xi^{max}_{n,t}, \forall n,t \end{aligned}\right\}$$

Operational limits of central units, LEC Generation Offers & LEC Demand Bids.

$$\textstyle\sum_{u\in\mathcal{U}_{n,s}} Q_{u,s,t} - D_{n,t} - \left(LQ_{n,t} - GQ_{n,t}\right) = \sum_{l\in L_n} f_{l,t} : \lambda_{n,t}, \forall n,t$$

← *Energy balance per bus*

$$-\bar{f}_l \le f_{l,t} \le \bar{f}_l : \varphi^{min}_{l,t}, \varphi^{max}_{l,t}, \forall l,t$$

← *Transmission line capacity limits*

$$-\pi \le \delta_{n,t} \le \pi : \gamma^{min}_{n,t}, \gamma^{max}_{n,t}, \forall n \backslash n: ref., t$$

← *Bus voltage angle limits*

$$\delta_{n,t} = 0 : \rho_t, n: ref., \forall t$$

← *Reference bus voltage angle*

$$f_{l,t} = S_b \textstyle\sum_{n:\, l\in L_n} A_{n,l}B_l\delta_{n,t}, \forall l,t$$

← *DC load flow*

$$\textstyle\sum_{l\in L_n} f_{l,t} = S_b \sum_{l:\, A_{n,l}>0} \sum_n A_{n,l}B_l\delta_{n,t} - S_b \sum_{l:\, A_{n,l}<0} \sum_n A_{n,l}B_l\delta_{n,t}, \forall n,t$$

← *Incoming energy per bus*

Aggregator decision model (upper level)

local production cost

revenues from energy sales to flexible customers

$$\min_{\substack{PP_t,RP_t\\ \overline{LP}_{n,t},\overline{LQ}_{n,t}\\ \overline{GP}_{n,t},\overline{GQ}_{n,t}}} \sum_t \pi_t \left[\boxed{\sum_{n\in\mathcal{N}_A} \lambda_{n,t}\left(LQ_{n,t}-GQ_{n,t}\right)} + \boxed{\sum_{gb,s,t} PP_t Q_{gb,s,t}} - \boxed{\sum_{db,s,t} RP_t Q_{db,s,t}} \right]$$

cost for energy acquired from the grid – revenues from selling energy to the grid

$$\left(LQ_{n,t}-GQ_{n,t}\right)+\sum\nolimits_{gb\in\mathcal{GB}_{n,s}} Q_{gb,s,t}-\sum\nolimits_{db\in\mathcal{DB}_{n,s}} Q_{db,s,t}=d_{n,t}, \forall n\in\mathcal{N}_A, t$$

← Energy balance per bus

$$\left.\begin{array}{c} 0\le PP_t\le PP^{max}, \forall t \\ 0\le RP_t\le RP^{max}, \forall t \\ GP^{min}\le \overline{GP}_{n,t}\le GP^{max}, \forall n,t \\ 0\le \overline{LP}_{n,t}\le LP^{max}, \forall n,t \end{array}\right\}$$

Administratively defined bounds for prices of bids (validation).

$$\left.\begin{array}{c} 0\le \overline{GQ}_{n,t}\le GQ_n^{max}, \forall n,t \\ 0\le \overline{LQ}_{n,t}\le LQ_n^{max}, \forall n,t \end{array}\right\}$$

Feasible upper limit for quantity of bids based on the composition of the clientele of the Aggregator per bus.

$$\left.\begin{array}{c} -\overline{GQ}_{n,t}M\le \overline{GP}_{n,t}\le \overline{GQ}_{n,t}M, \forall n,t \\ -\overline{GP}_{n,t}M\le \overline{GQ}_{n,t}\le \overline{GP}_{n,t}M, \forall n,t \\ -\overline{LQ}_{n,t}M\le \overline{LP}_{n,t}\le \overline{LQ}_{n,t}M, \forall n,t \\ -\overline{LP}_{n,t}M\le \overline{LQ}_{n,t}\le \overline{LP}_{n,t}M, \forall n,t \end{array}\right\}$$

No bid with zero price and non-zero volume is submitted and vice versa.

$$\overline{LQ}_{n,t}>0 \text{ or } \overline{GQ}_{n,t}>0, \forall n,t$$

← Each bus is either importing or exporting.

Market Clearing problem (lower level)

Central production cost

cost for compensating the LEC for energy injected into the grid

$$\min_{\substack{Q_{u,s,t},\delta_{n,t}\\ GQ_{n,t},LQ_{n,t}}} \boxed{\sum_{u,s,t} P_{u,s}Q_{u,s,t}} + \sum_{n,t}\left(\boxed{\overline{GP}_{n,t}GQ_{n,t}} - \boxed{\overline{LP}_{n,t}LQ_{n,t}}\right)$$

revenues from energy sales to the LEC for energy absorbed (by the LEC) from the grid

$$\left.\begin{aligned} 0 \le Q_{u,s,t} \le \overline{Q}_{u,s}&: \pi_{u,s,t}^{min}, \pi_{u,s,t}^{max}, \forall u,s,t \\ 0 \le GQ_{n,t} \le \overline{GQ}_{n,t}&: \psi_{n,t}^{min}, \psi_{n,t}^{max}, \forall n,t \\ 0 \le LQ_{n,t} \le \overline{LQ}_{n,t}&: \xi_{n,t}^{min}, \xi_{n,t}^{max}, \forall n,t \end{aligned}\right\}$$

Operational limits of central units, LEC Generation Offers & LEC Demand Bids.

$$\textstyle\sum_{u\in\mathcal{U}_{n},s} Q_{u,s,t} - D_{n,t} - \left(LQ_{n,t} - GQ_{n,t}\right) = \sum_{l\in L_n} f_{l,t} : \lambda_{n,t}, \forall n,t$$

← *Energy balance per bus*

$$-\bar{f}_l \le f_{l,t} \le \bar{f}_l : \varphi_{l,t}^{min}, \varphi_{l,t}^{max}, \forall l,t$$

← *Transmission line capacity limits*

$$-\pi \le \delta_{n,t} \le \pi : \gamma_{n,t}^{min}, \gamma_{n,t}^{max}, \forall n \backslash n : ref., t$$

← *Bus voltage angle limits*

$$\delta_{n,t} = 0 : \rho_t, n : ref., \forall t$$

← *Reference bus voltage angle*

$$f_{l,t} = S_b \textstyle\sum_{n:\, l\in L_n} A_{n,l}B_l\delta_{n,t}, \forall l,t$$

← *DC load flow*

$$\textstyle\sum_{l\in L_n} f_{l,t} = S_b \sum_{l:\, A_{n,l}>0} \sum_n A_{n,l}B_l\delta_{n,t} - S_b \sum_{l:\, A_{n,l}<0} \sum_n A_{n,l}B_l\delta_{n,t}, \forall n,t$$

← *Incoming energy per bus*

One dispatch period (t10), generation bids only, 5 cost scenarios

	Centralized management				Decentralized management – Pay-As-Bid				Decentralized management – Pay-As-Cleared			
	-50%	Basic	+50%	+150%	-50%	Basic	+50%	+150%	-50%	Basic	+50%	+150%
Central units production (MWh)	2.074	2.151	2.151	2.151	1.922	2.074	2.074	2.074	1.922	2.074	2.074	2.151
Local units production (MWh)	77	0	0	0	229	77	77	77	229	77	77	0
Energy absorption by the LEC/Aggregator for covering the load (LB) (MWh)	–	–	–	–	822	928	928	928	822	928	928	1,004
Energy injection by the LEC/Aggregator (GB) (MWh)	–	–	–	–	46	0	0	0	46	0	0	0
Central units dispatch (MWh)												
u1-u7 (≤38,8€/MWh)	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*	*1.770*
u8-u11 (39,7€/MWh)	*152*	*152*	*152*	*152*	*152*	*152*	*152*	*152*	*152*	*152*	*152*	*152*
u8-u11 (43,8€/MWh)	*152*	*152*	*152*	*152*	*0*	*152*	*152*	*152*	*0*	*152*	*152*	*152*
u12-u14 (71,6€/MWh)	*0*	*77*	*77*	*77*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*77*
Local generation units dispatch (MWh)												
gb1, gb7 (102,2€/MWh*)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
gb2, gb8 (100,4€/MWh*)	*0*	*0*	*0*	*0*	*89*	*0*	*0*	*0*	*89*	*0*	*0*	*0*
gb3, gb9 (98,6€/MWh*)	*7*	*0*	*0*	*0*	*70*	*7*	*7*	*7*	*70*	*7*	*7*	*0*
gb4, gb10 (97€/MWh*)	*50*	*0*	*0*	*0*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*0*
gb5 (95€/MWh*)	*20*	*0*	*0*	*0*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*0*
gb6 (104€/MWh*)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*

** Prices for Basic cost scenario.*

One dispatch period (t10), generation bids only, 5 cost scenarios

	Centralized management				Decentralized management – Pay-As-Bid				Decentralized management – Pay-As-Cleared			
	-50%	Basic	+50%	+150%	-50%	Basic	+50%	+150%	-50%	Basic	+50%	+150%
Aggregator/LEC objective function (€)	–	–	–	–	42.060	48.081	51.795	59.224	42.261	48.232	52.021	71.959
Market Operator objective function (€)	81.041	82.835	82.835	82.835	-152.511	-170.749	-170.749	-170.749	-175.159	-200.946	-189.846	-218.504
Total production cost (€)	81.041	82.835	82.835	82.835	82.190	84.756	88.470	95.898	82.190	84.756	88.470	82.835
Central units production cost (€)	77.327	82.835	82.835	82.835	70.904	77.327	77.327	77.327	70.904	77.327	77.327	82.835
Local production units cost (€)	3.714	0	0	0	11.286	7.428	11.143	18.571	11.286	7.428	11.143	0
Cost of dispatched LEC/Aggregator production offers (€)	–	–	–	–	1.832	0	0	0	462	0	0	0
Value of dispatched LEC/Aggregator demand bids (€)	–	–	–	–	225.247	248.076	248.076	248.076	246.524	278.273	267.173	301.339
Aggregator/LEC exports revenues (€)	–	–	–	–	1.832	0	0	0	1.832	0	0	0
Aggregator/LEC imports payments (€)	–	–	–	–	32.606	40.653	40.653	40.653	32.606	40.653	40.653	71.959
Central units' revenues (€)	102.217	154.087	154.087	154.087	76.263	90.897	90.897	90.897	76.263	90.897	90.897	154.087
Local production units' revenues (€)	3.789	0	0	0	11.286	7.428	11.143	18.571	11.487	7.579	11.368	0
System inflexible load payments (€)	106.006	154.087	154.087	154.087	45.489	50.244	50.244	50.244	45.489	50.244	50.244	82.129
Central units' surplus (€)	24.890	71.252	71.252	71.252	5.359	13.570	13.570	13.570	5.359	13.570	13.570	71.252
Local generation units' surplus (€)	75	0	0	0	0	0	0	0	201	150	225	0
LEC/Aggregator inflexible load charge price (€/MWh)	–	–	–	–	41,87	47,87	51,57	58,96	42,07	48,02	51,79	71,64
LMP (€/MWh)	49,29	71,64	71,64	71,64	39,68	43,83	43,83	43,83	39,68	43,83	43,83	71,64
LMP standard deviation (€/MWh)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Results – one Dispatch Period, generation bids only– 5 cost scenarios

- Lower cost of local production (-50%) leads to:

→ higher dispatch of local generation, even at centralized model,

→ identical dispatch of the local resources (due to their low cost, they are dispatched to the highest level in order to minimize the LEC/Aggregator cost)

- Higher cost of local production (+50%) leads to:
  - less local units dispatch → higher dispatch of central generation units → higher LMPs
  - higher total production cost, higher revenues and producer's surplus for both generation units (central and local)
- Very high cost of local production (+150%)leads to:
  - zero dispatch of local production in the PAC model
  - quantitative results in the PAC model identical to the centralized model
- PAB-PAC comparison:
  - Cost scenario +150%: higher dispatch of local production in the PAB model → the compensation scheme in the PAC model (uniform price) deteriorates the cost component of the Aggregator, leading to reduced dispatch in the PAC model