UNIVERSITY OF ZAGREB
FACULTY OF ELECTRICAL ENGINEERING AND COMPUTING

Energy Storage

6. Applications of Energy Storage in Power Systems

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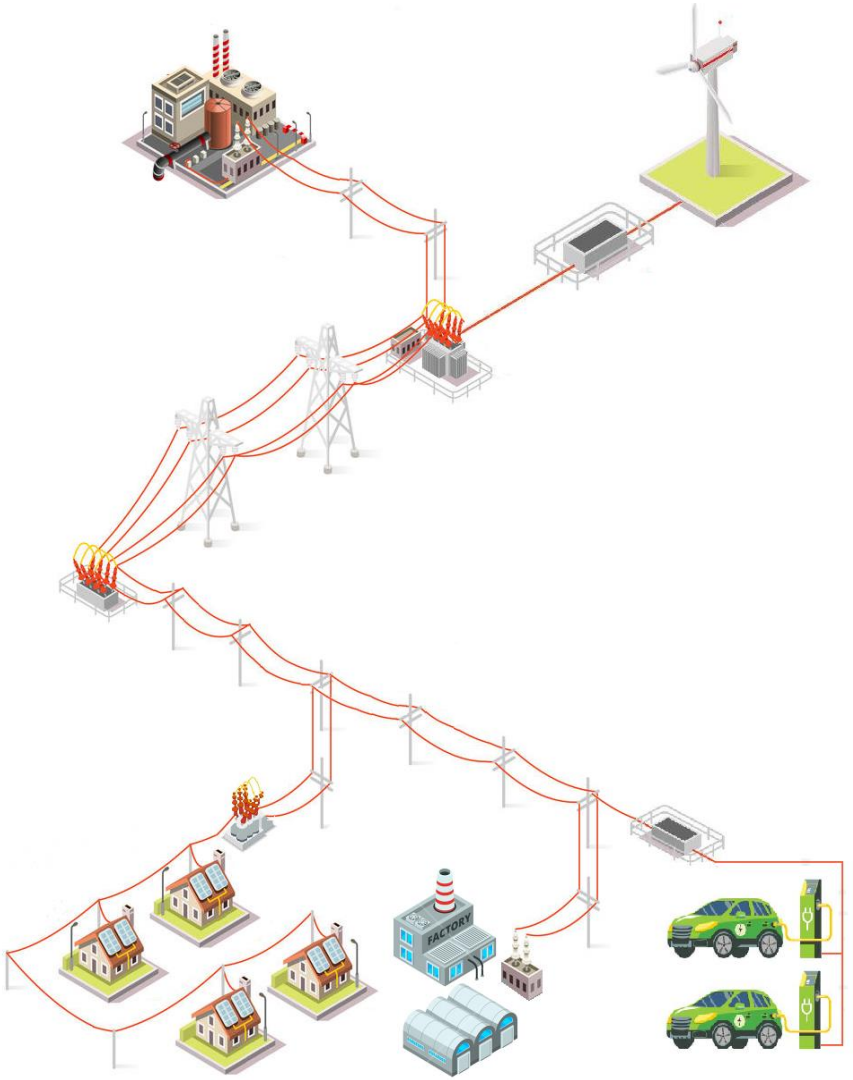
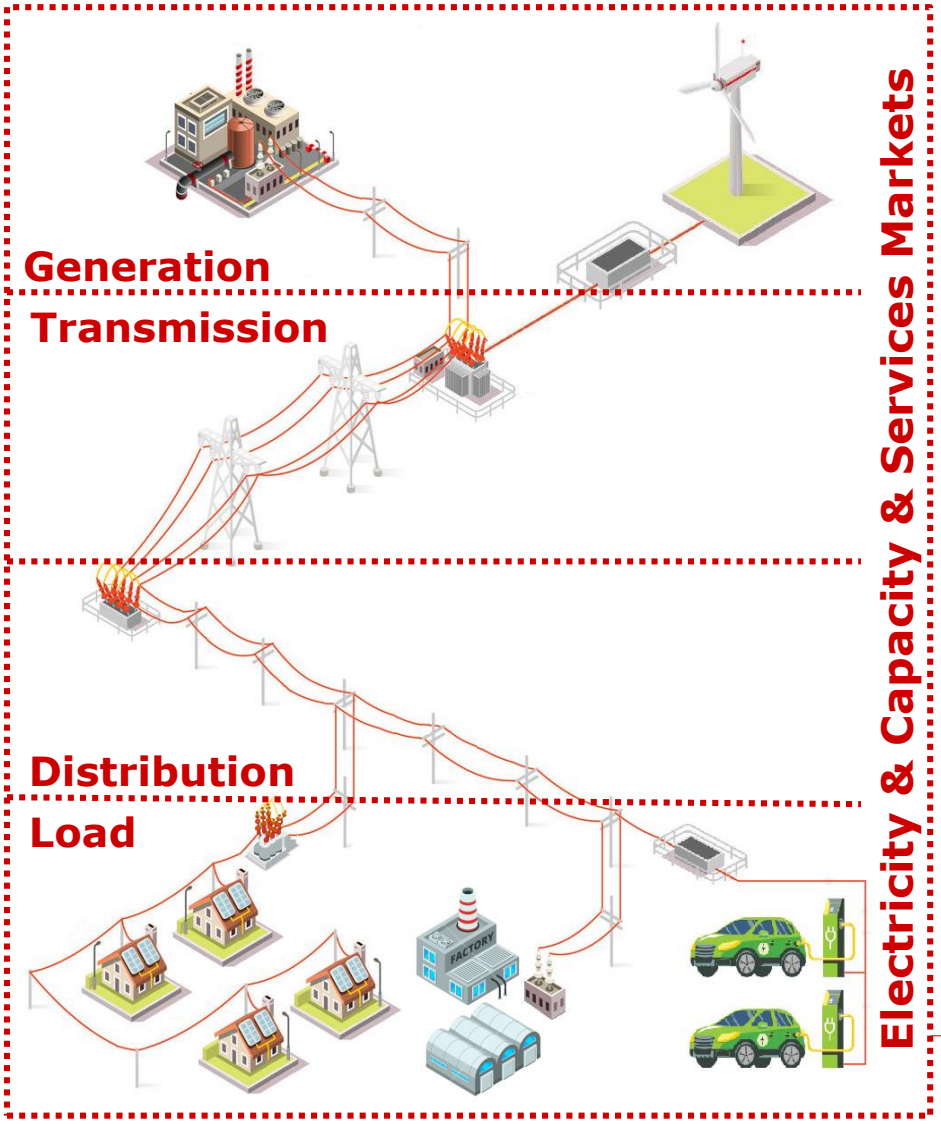
Ivan Pavić, MEE

Power System – Physical Layer



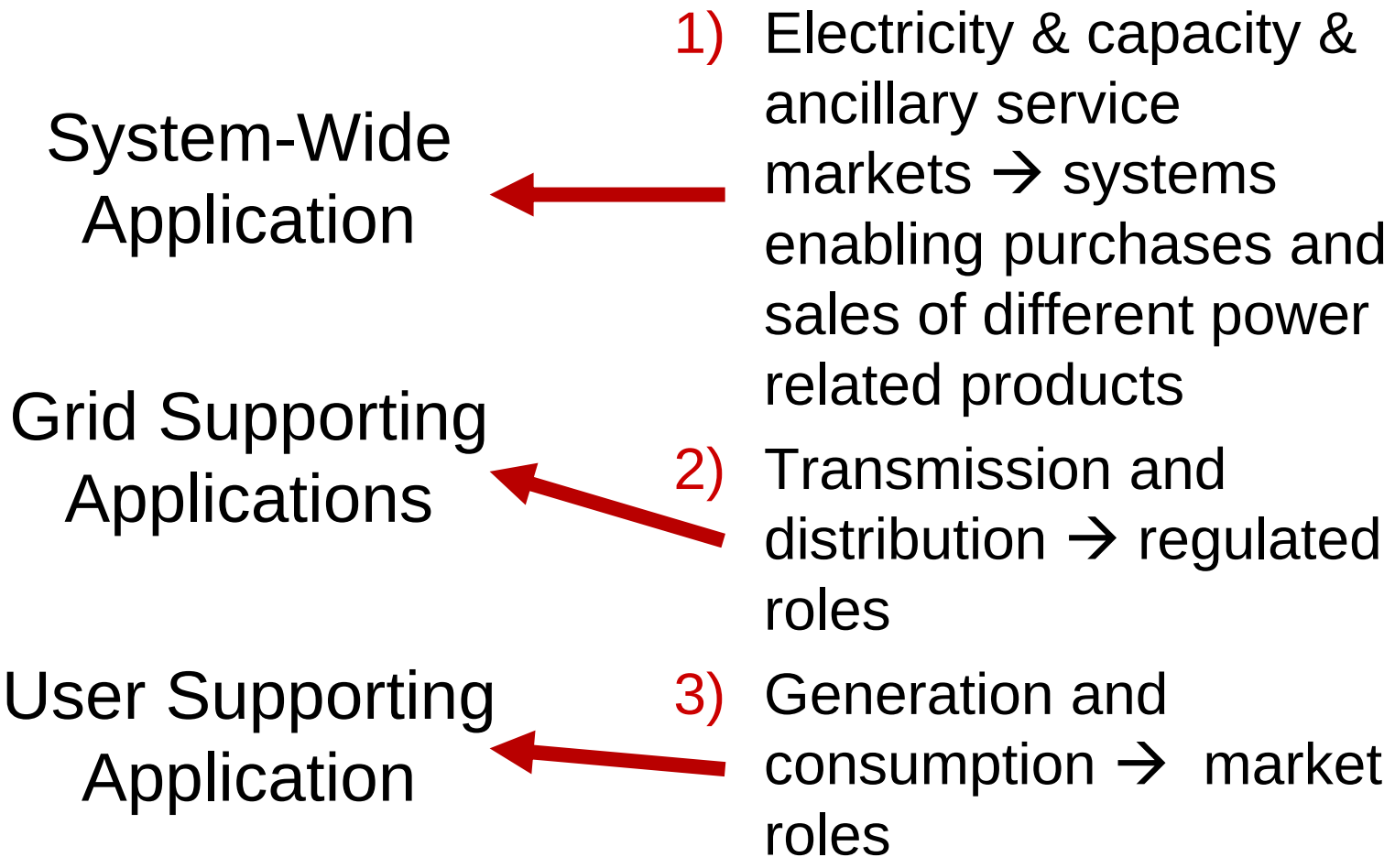
- Electric power system is a network of components deployed to supply, transfer and use electric power:
  - Lines
  - Cables
  - Transformers
  - Generators
  - Loads
  - Secondary equipment

Main Components & Roles

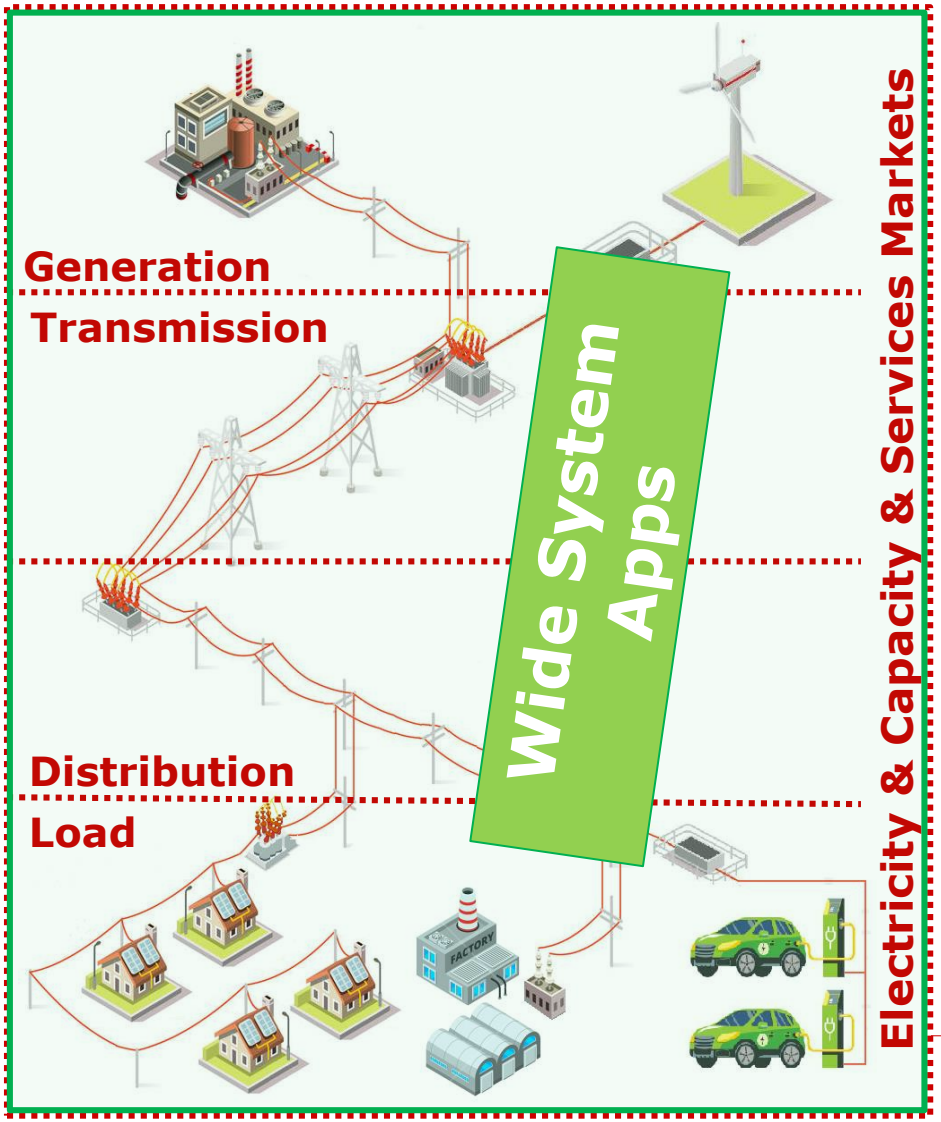


1) Electricity & capacity & ancillary service markets → systems enabling purchases and sales of different power related products
2) Transmission and distribution → regulated roles
3) Generation and consumption → market roles

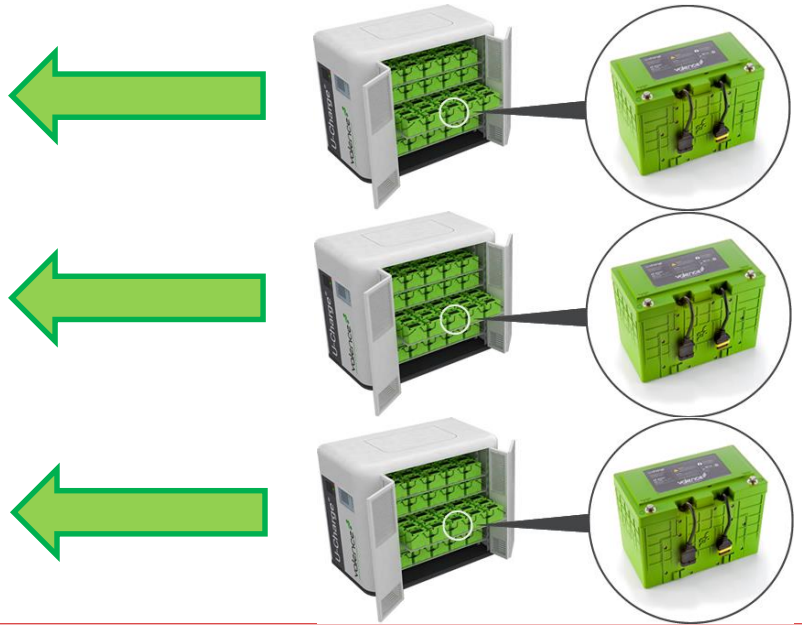
Energy Storage Applications



1. System-Wide Applications



- Location-neutral applications
- Application user is power market/system



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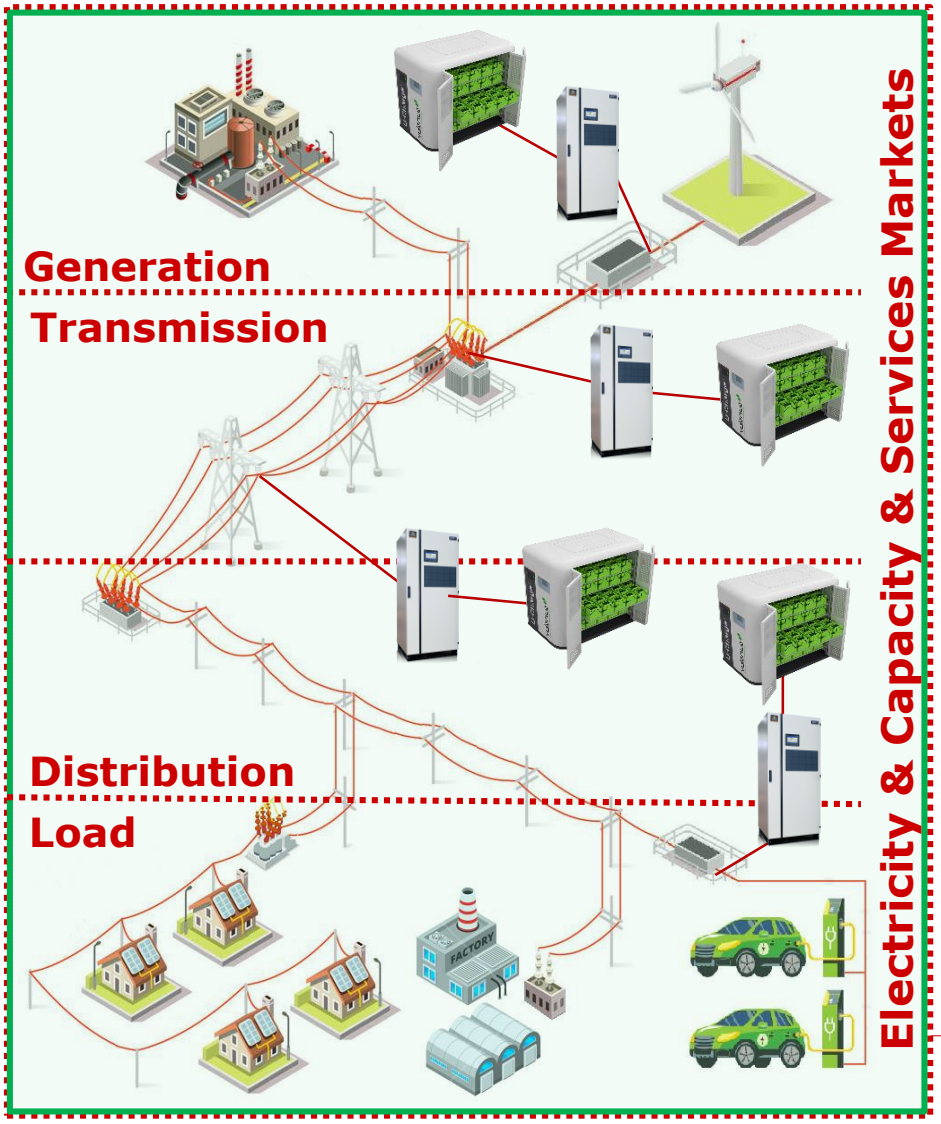
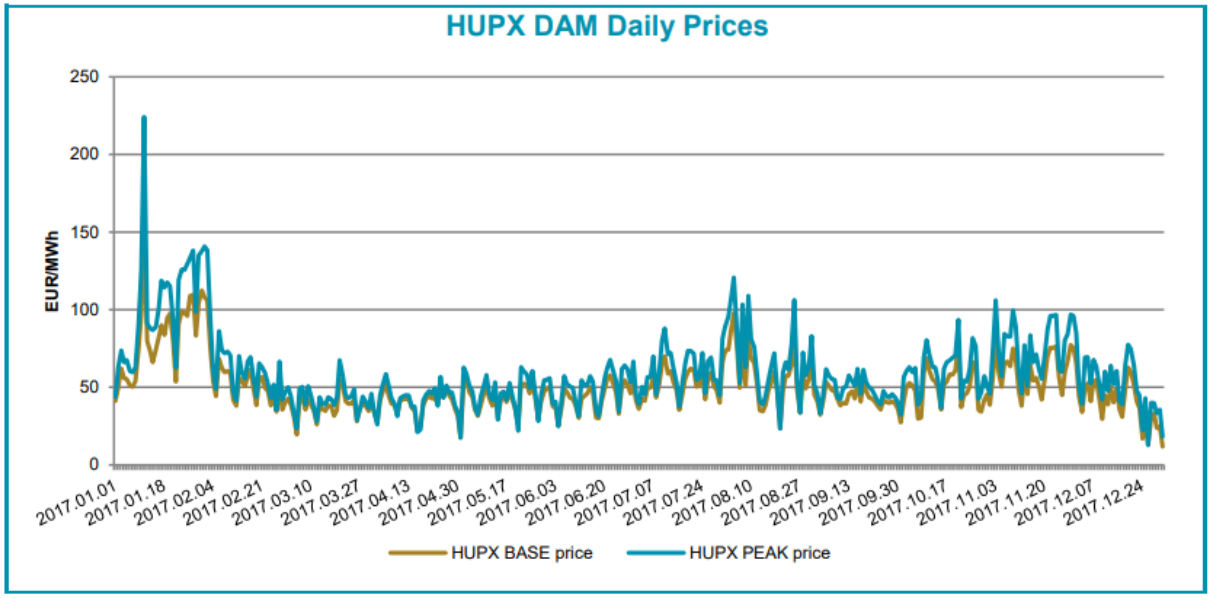


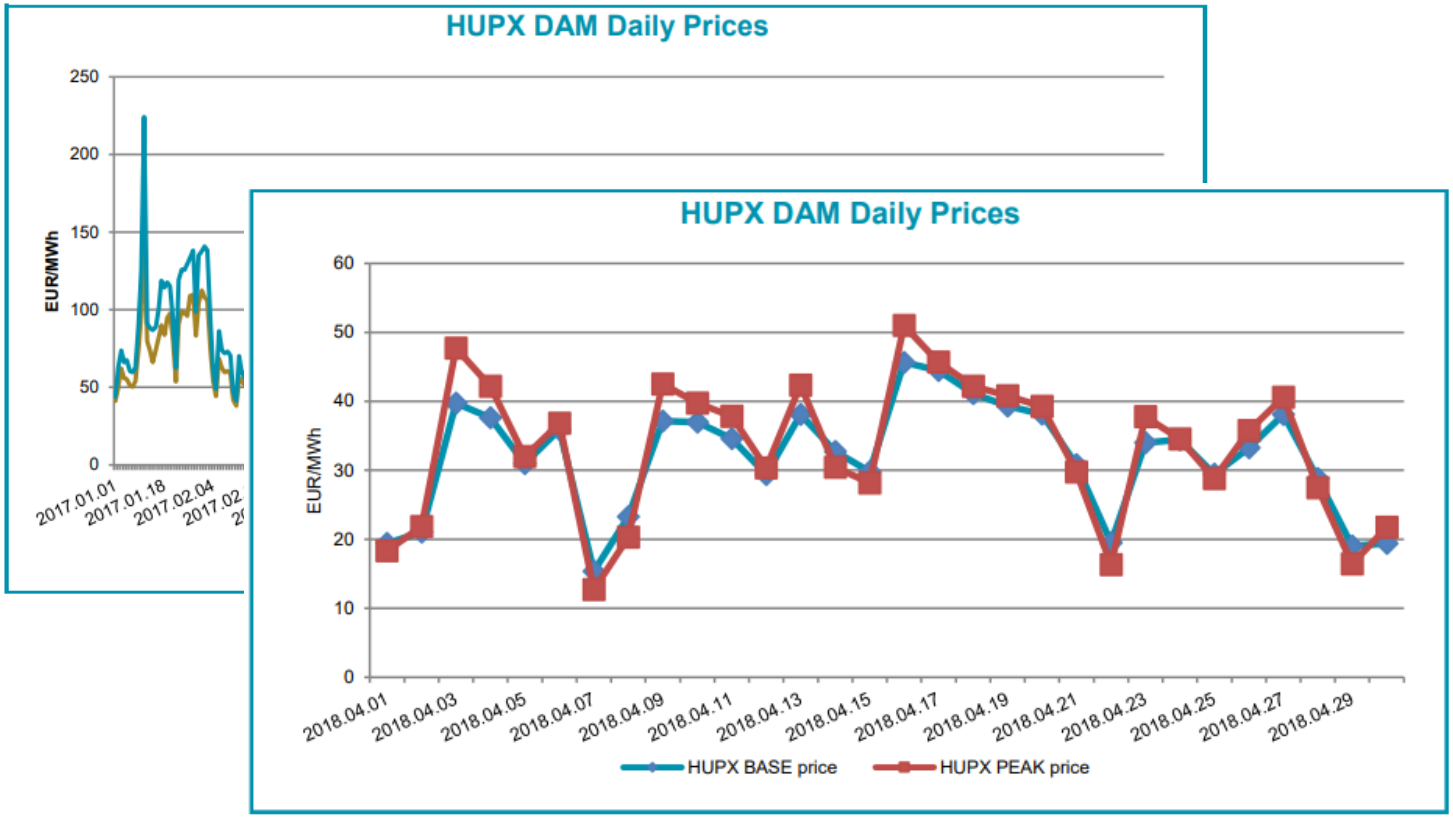
- Electricity Arbitrage
- Power System Adequacy
- Power System Balancing
- Flexiramp
- Footroom
- Balance Group Balancing

Electricity Arbitrage



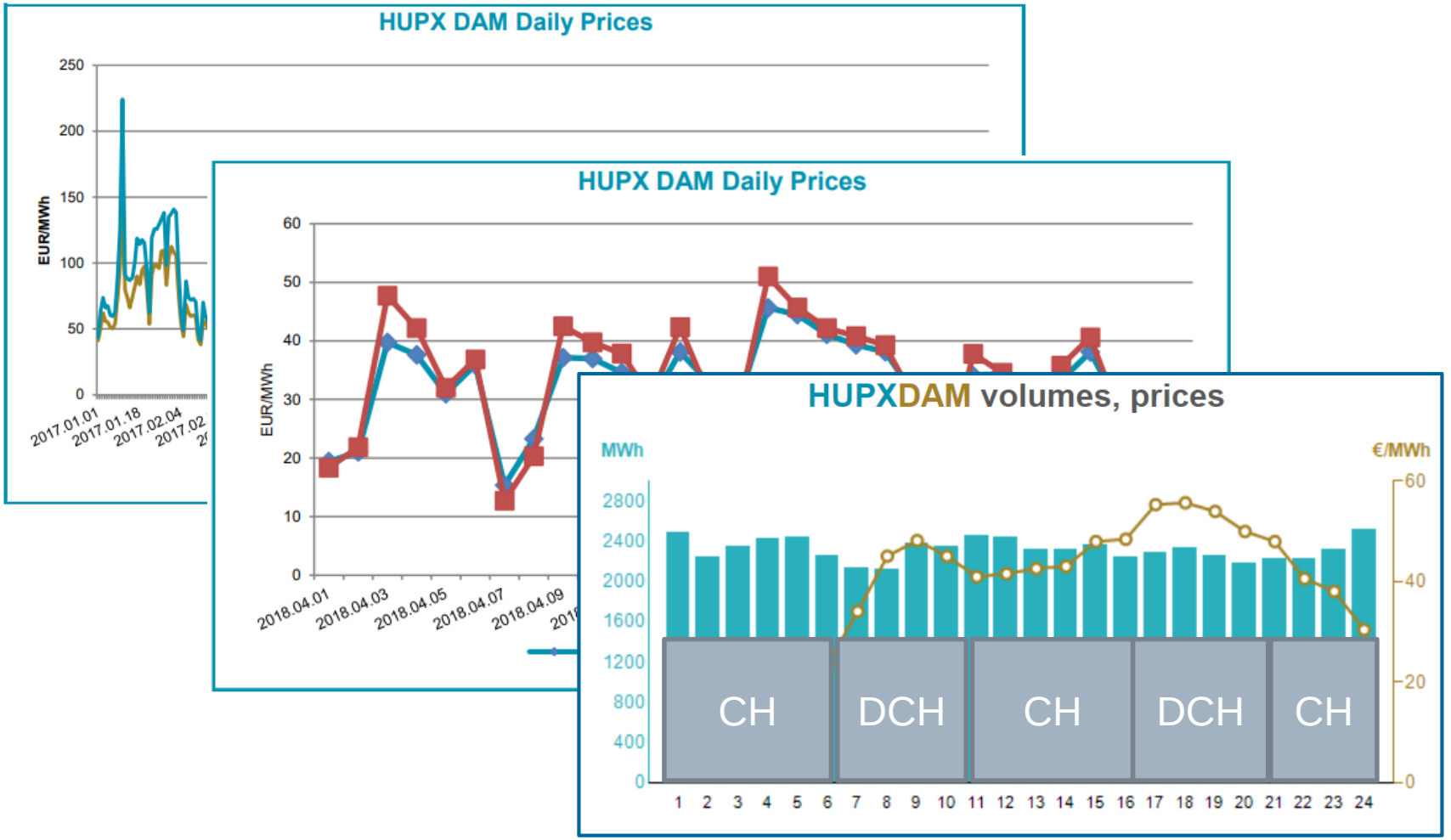
Price on HUPX DAM in 2017

Electricity Arbitrage



Price on HUPX DAM in April 2018

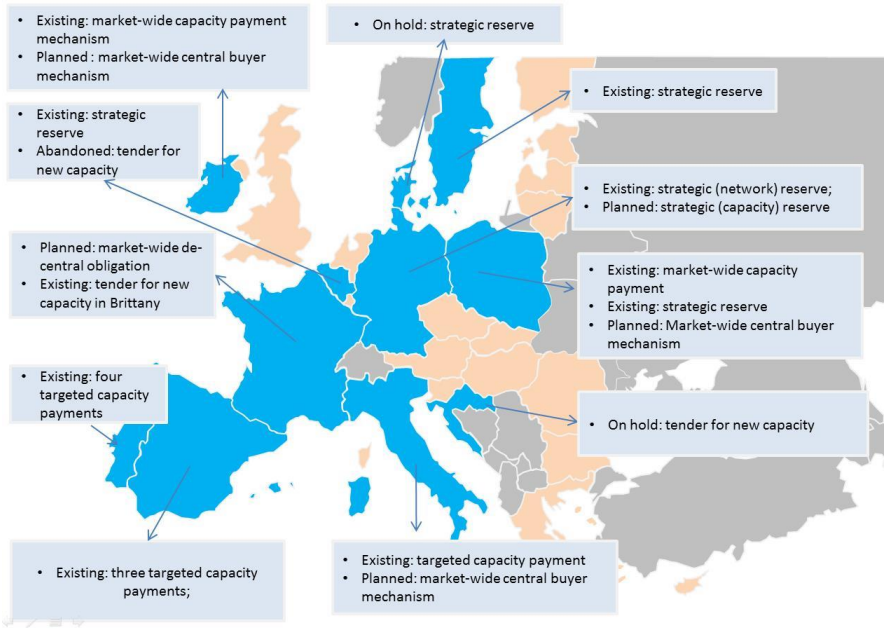
Electricity Arbitrage



Price on HUPX DAM on Dec. 12, 2017

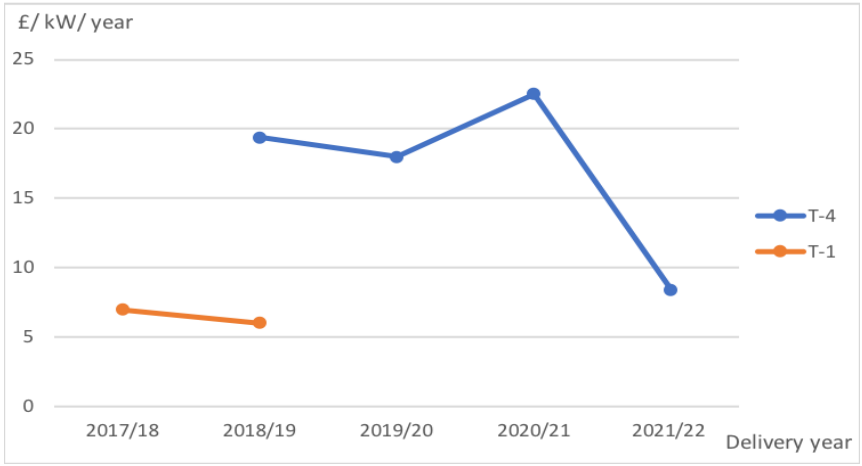
Power System Adequacy

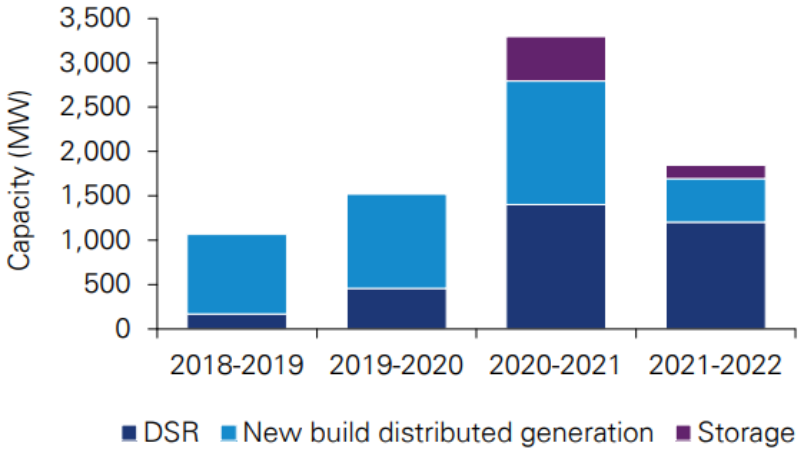
- Capacity Remuneration Mechanisms:
  - Capacity payments
  - Strategic/capacity reserve
  - Capacity market (auction)
  - Capacity obligation
  - Reliability options



Power System Adequacy

UK Capacity Market





everoze

Capacity Market
Duration-limited storage de-rating factors
Dec 2017

Minimum duration	2021/22 **T-4** de-rating factor	2018/19 **T-1** de-rating factor
0.5 hours	17.89%	21.34%
1 hour	36.44%	40.41%
1.5 hours	52.28%	55.95%
2 hours	64.79%	68.05%
2.5 hours	75.47%	77.27%
3 hours	82.03%	82.63%
3.5 hours	85.74%	85.74%
4 hours +	96.11%	96.11%

Typical EFR-sized asset

Typical FFR-sized asset

everoze

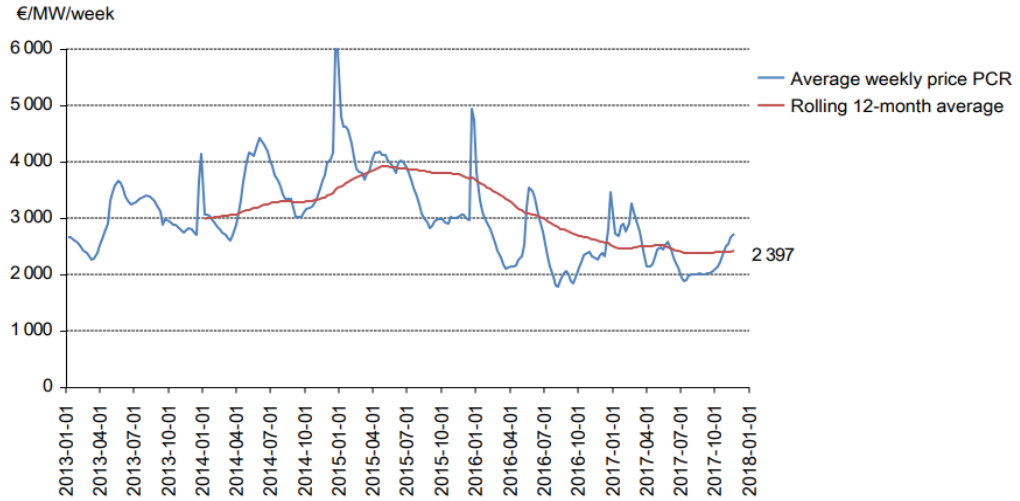
Capacity Market Prequalification
Battery storage key stats
Dec 2017

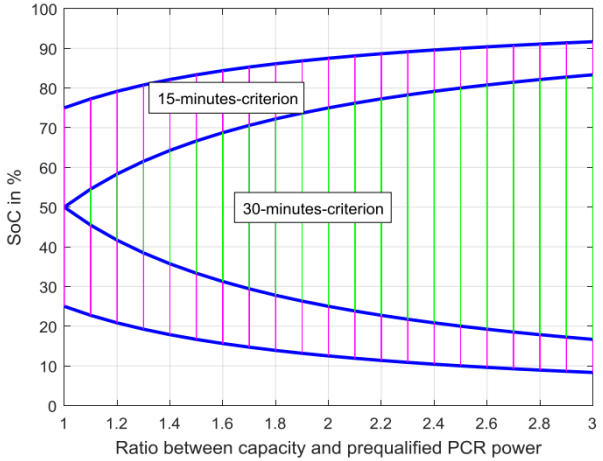
	T-4 auction (delivery in 2021/22)	**T-1 auction** (delivery in 2018/19)
Battery projects applied to prequalify	6.0GW	2.3GW
Battery projects successfully prequalified	4.7GW (78% success rate)	2.0GW (87% success rate)
% that battery storage contributes to total prequalified capacity	5% (of 91.6GW in total)	13% (of 15.6GW in total)

Note: Includes projects that have conditionally prequalified. Figures for total prequalified capacity may include duplicate entries.

Power System Balancing

- Primary, secondary, tertiary reserve
- Regulating power market
- Balancing market/Imbalance settlemenet
- German Reserve Market





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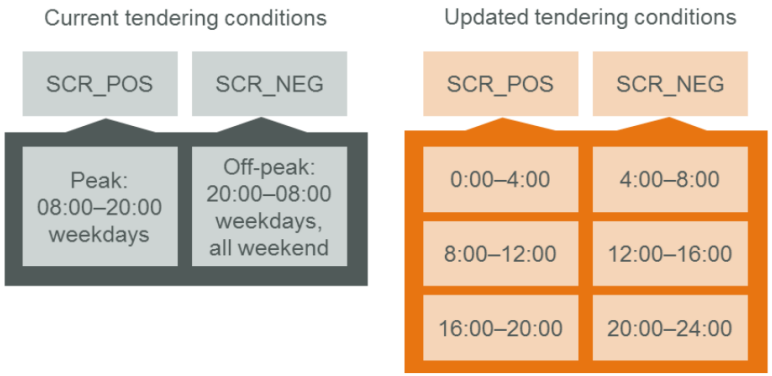
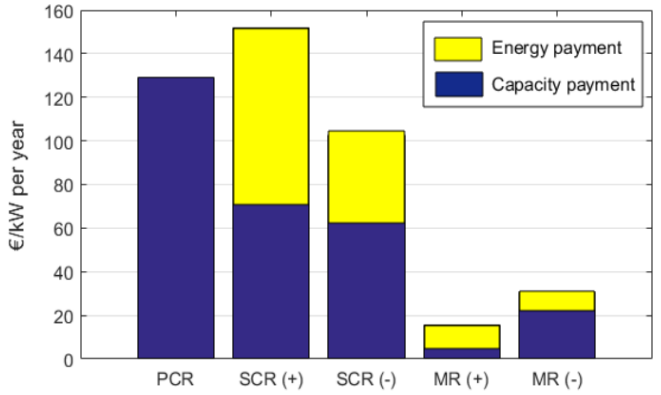




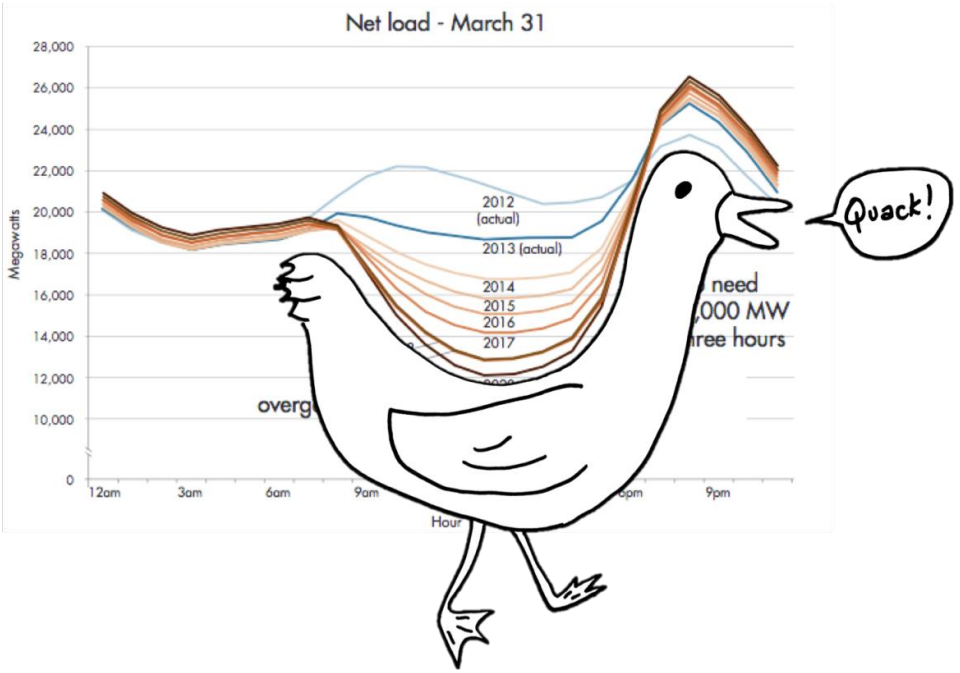
Balance Group Balancing

- Apart from the whole system balancing, each balance responsible party (BRP) should be a member of a balancing group
- BRP – every power system participant: power plants, suppliers, wholesale consumers, traders, system operators…
- Balancing group – group of BRPs sending daily schedules to the TSO for power system balancing

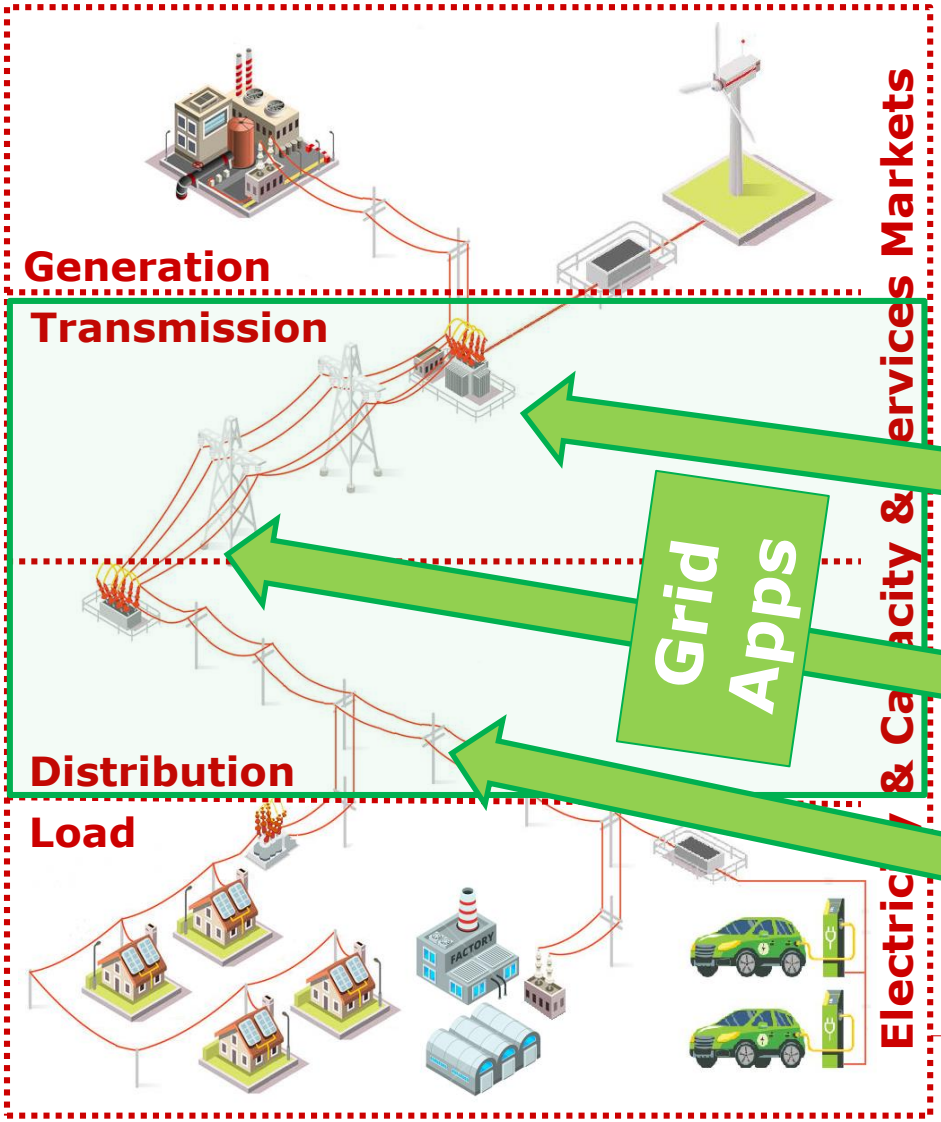
New services

- Demand turn up or Footroom – UK
  - true demand turn up;
  - combined heat and power (CHP);
  - any other type of generation;
  - energy storage (such as batteries); and
  - other technologies, providing they can offer the required flexibility.

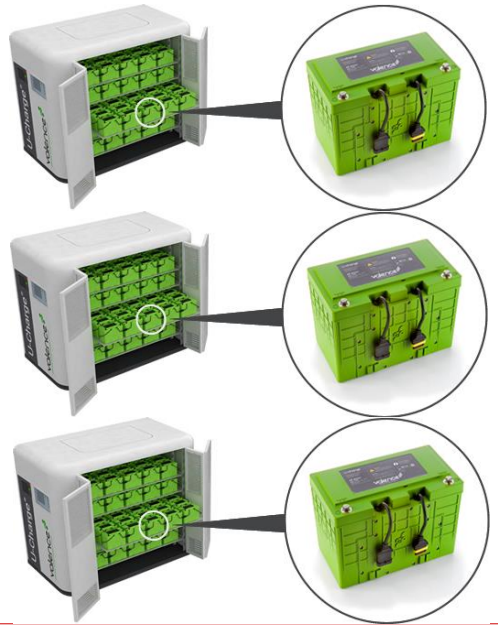
- Flexiramp – CAISO



2. Grid-Supporting Applications



- Applicable oatn specific grid locations
- Application user is the grid (T/D operator)



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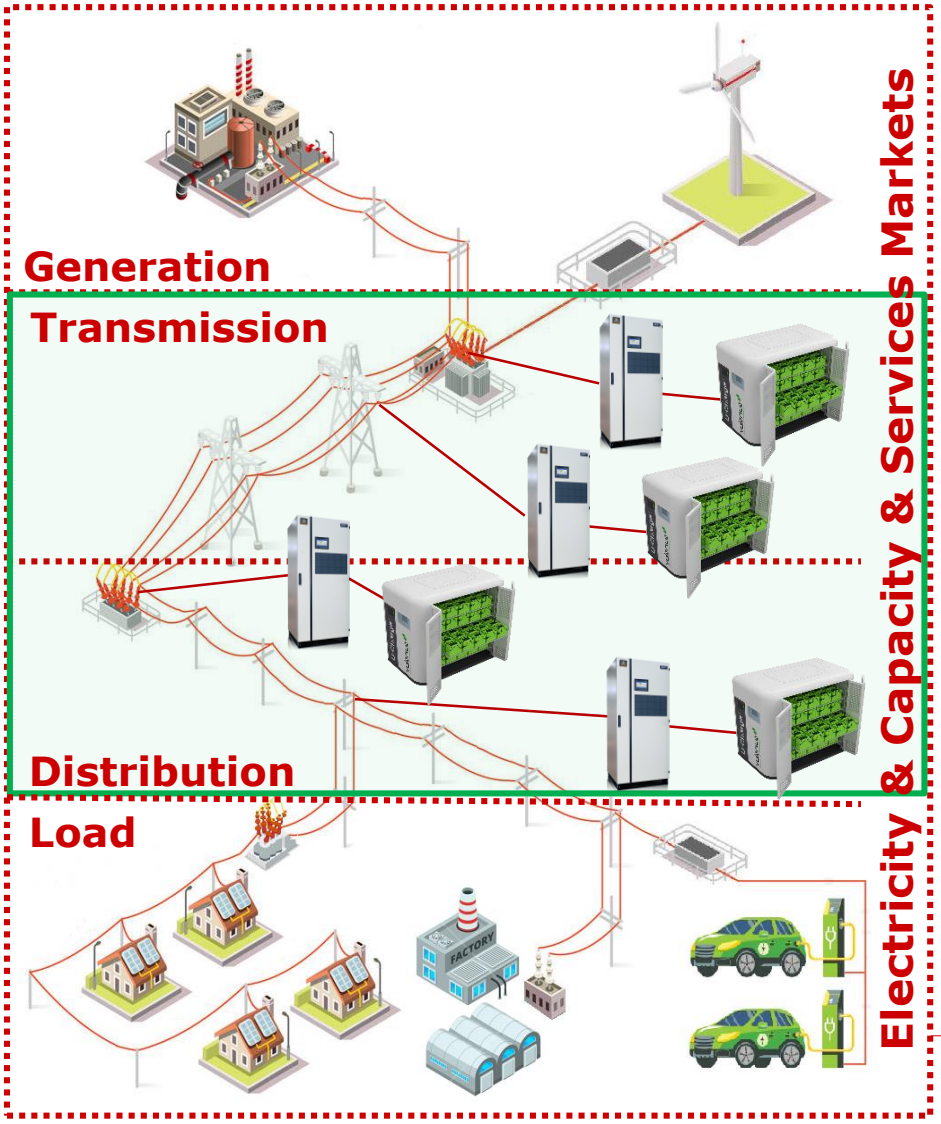
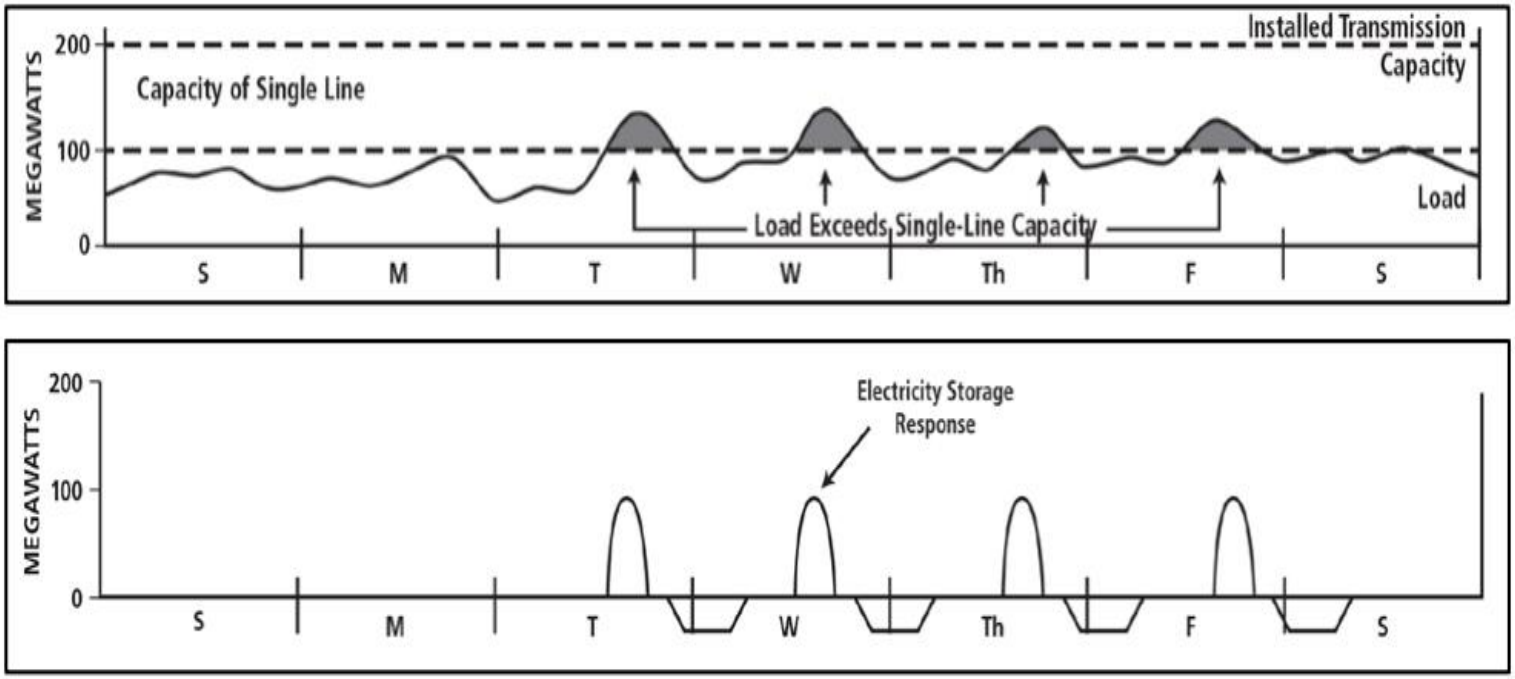


- Congestion Management
- Grid Upgrade Deferral
- Grid Reliablity
- Voltage and Reactive Power Support
- Black start, Island/Open-circuit operation

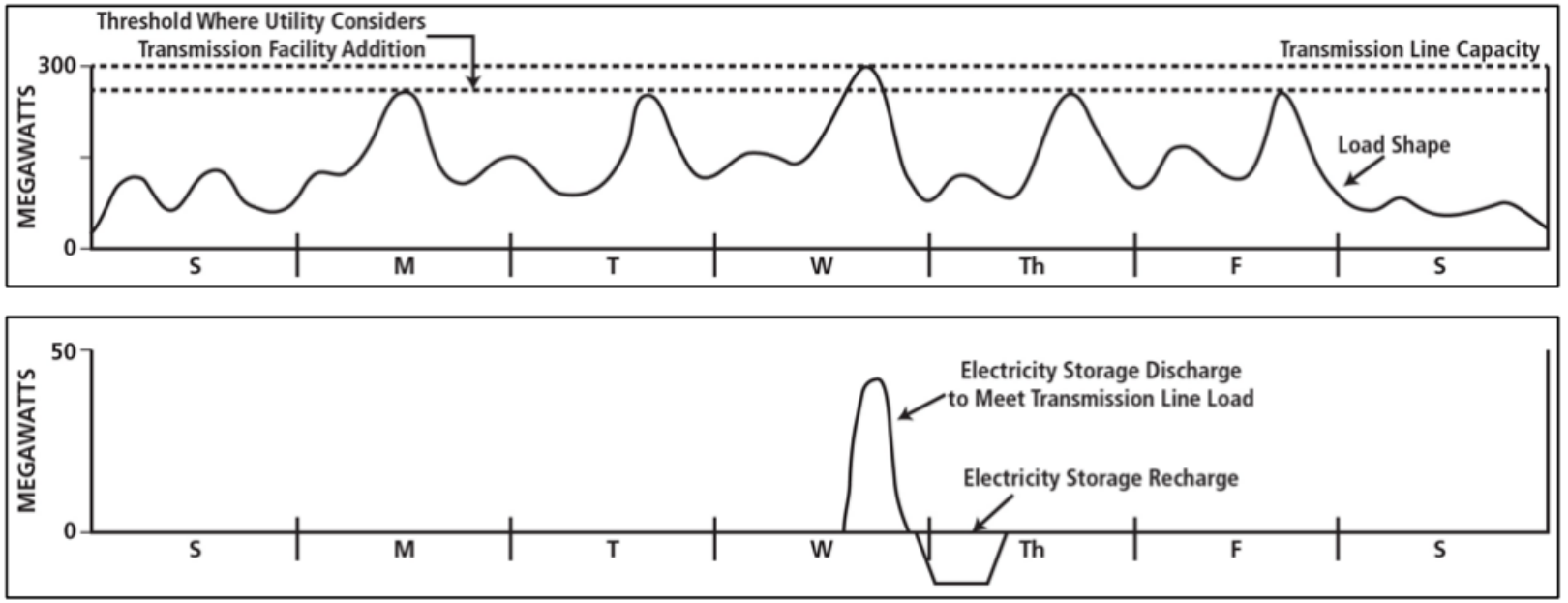
Congestion Management

- Market split-up
- Redispatch measures



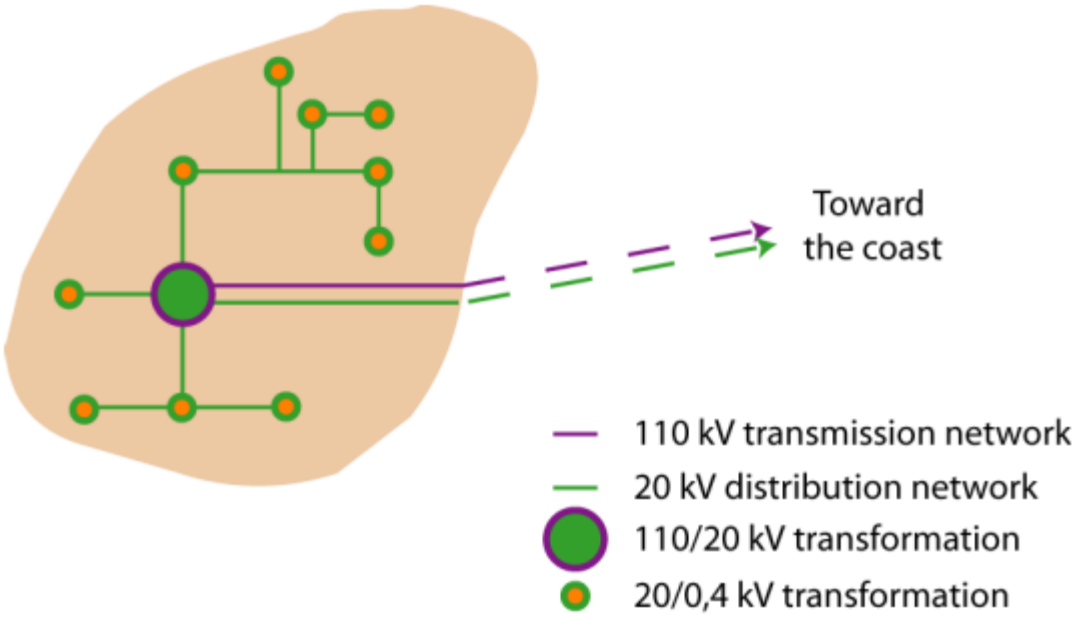
Grid Upgrade Deferral

- Upgrade deferral
- Life cycle proloning



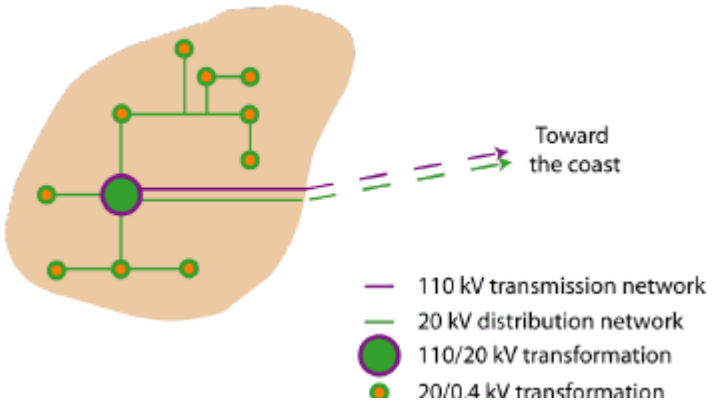
Grid Reliablity

- N-1 criterion

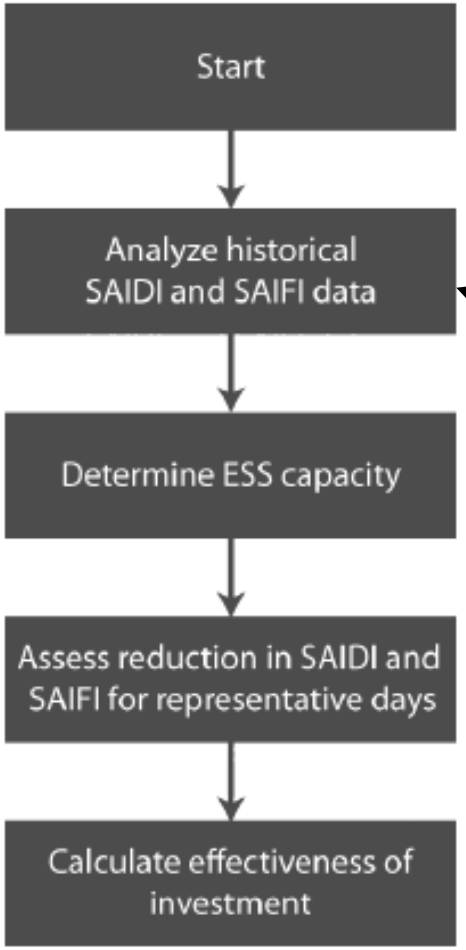


Island Lošinj

- Not obtained the N-1 security criterion
- Submarine cable Crikvenica-Krk out of supply
- Very high investment cost into submarine cables
- If the 110 kV line trips, the island load can only be supplied through distribution network
- It is very risky during the summer time, when load is doubled



Method for ensuring N-1 criterion



- System Average Interruption Frequency Index (SAIFI)
- System Average Interruption Duration Index (SAIDI)

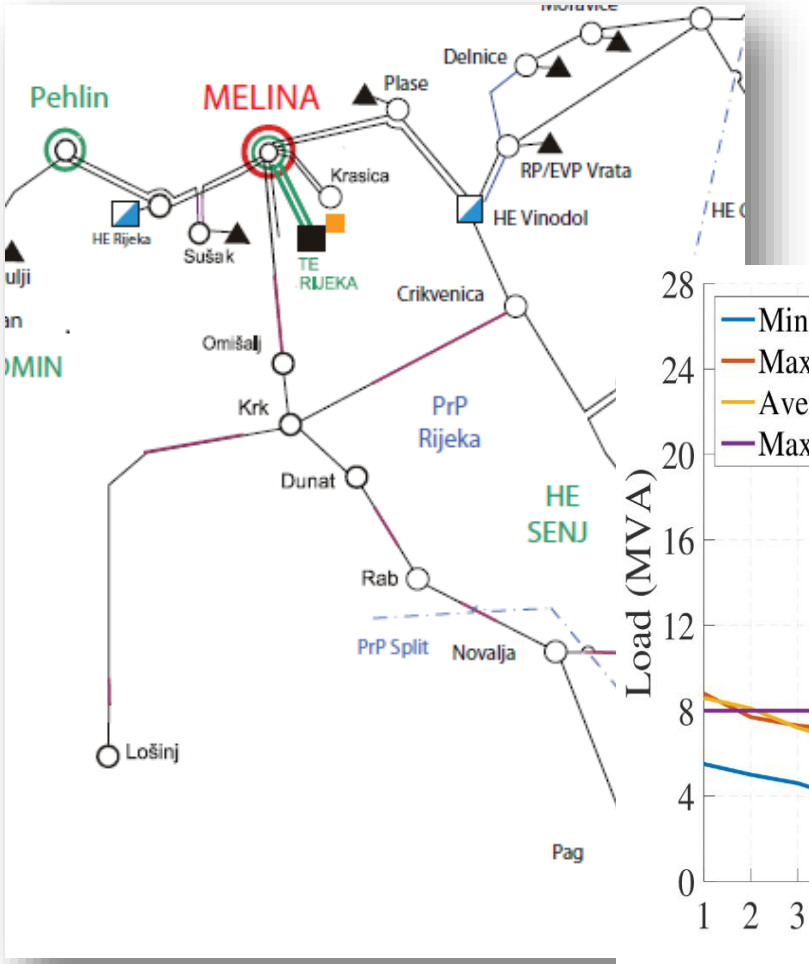
$$SAIFI = \frac{\sum_{i=1}^{I} f_i \cdot C_i}{C_T}$$

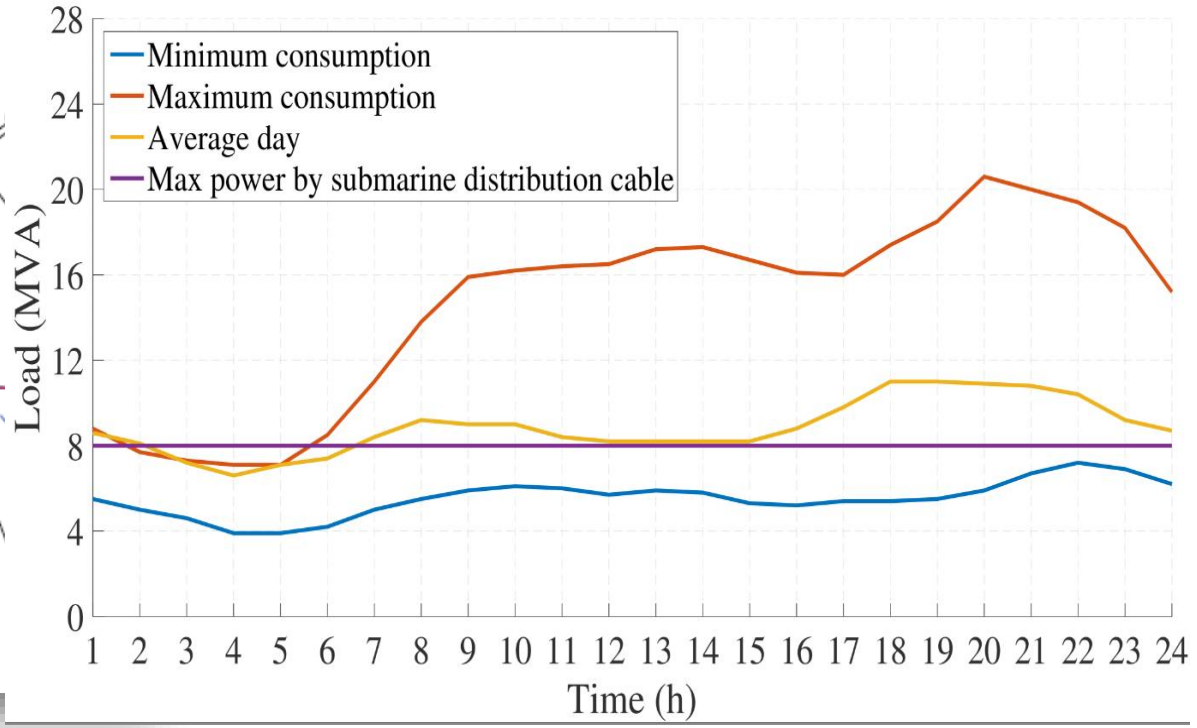
$$SAIDI = \frac{\sum_{i=1}^{I} U_i \cdot C_i}{C_T}$$

where C_i is number of end users at location i, C_T is total number of end users, f_i is total failure rate at location i, and U_i is annual outage time at location i.

„Cost benefit analysis, (CBA)"

Location of Island Lošinj





Investment into ES

- Electrochemical storage: **NaS batteries**
- Energy intensive type
- Two cases:
  - Mini BES – one block: 1.2 MW, 8.6 MWh
  - Maxi BES – seven blocks: 8.4 MW, 60 MWh
- Mini BES – can protect against short interruptions/outages of 110 kW line Krk–Lošinj during low demand
- Maxi BES - contains sufficient capacity for longer transmission line down time and can provide energy for higher load levels

CBA Lošinj

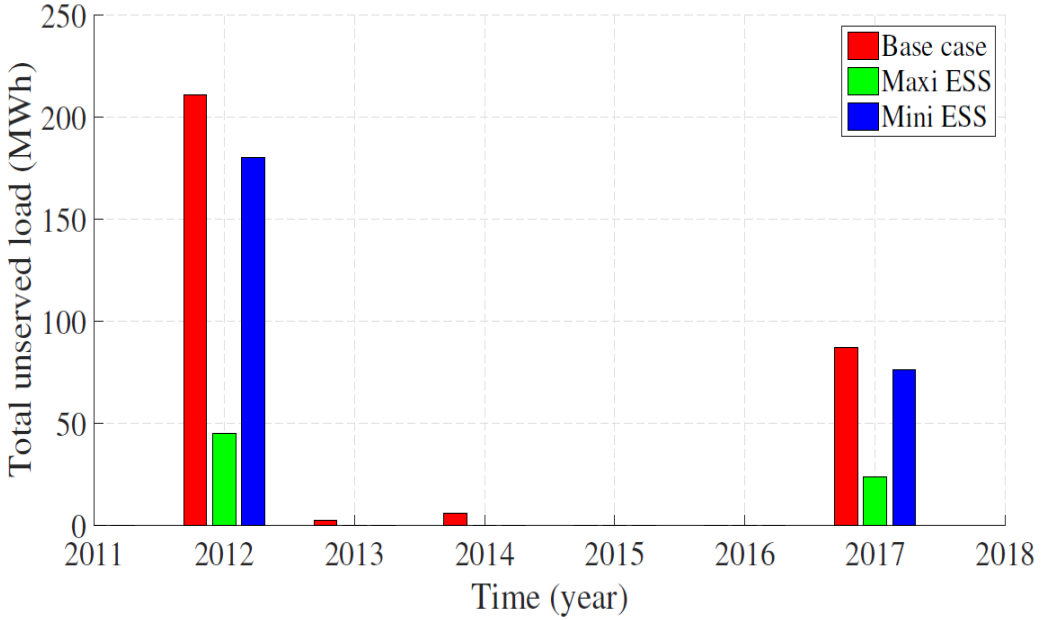
- Assumption of value of lost load to be 10,000 €/MWh
- Base case:
  - Unserved load cost during the period 2011–2017: **3.1 M€**
- Savings:
  - Maxi BES – **2.37 M€**
  - Mini BES – **0.51 M€**
- Investment:
  - New line – 17.77 M€
  - NaS batteries:
    - Mini BES – 3.88 M€
    - Maxi BES – 27.21 M€

SAIDI INDICES

	SAIDI (min)		
Year	Base case	Maxi ESS	Mini ESS
2011	3	0	0
2012	1,209	537	1,159
2013	7	0	0
2014	115	0	0
2015	0	0	0
2016	0	0	0
2017	215	0	190
Overall	1,434	537	1,349

Island Lošinj

- Total unserved load 2011-2017



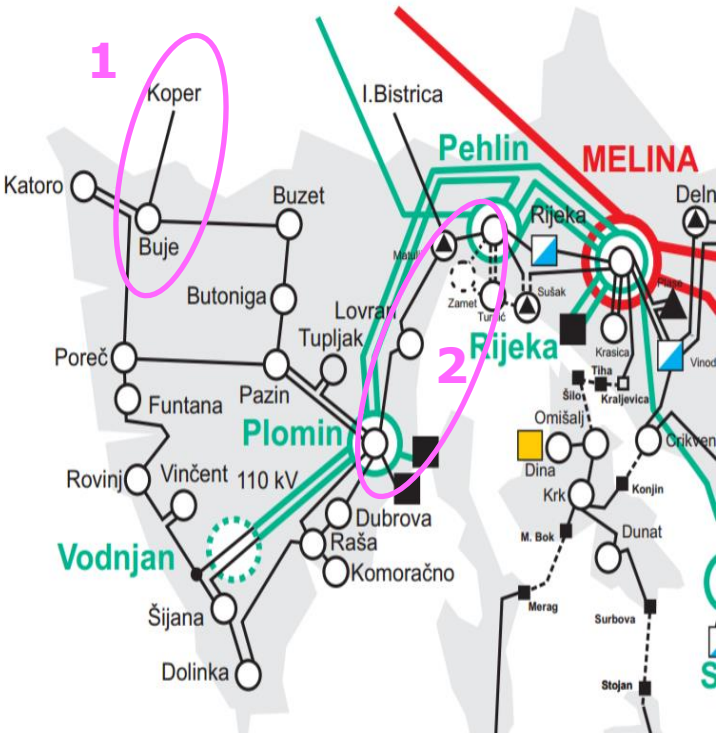
	SAIFI (-)		
Year	Base case	Maxi ESS	Mini ESS
2011	1	0	0
2012	10	1	3
2013	1	0	0
2014	3	0	0
2015	0	0	0
2016	0	0	0
2017	3	0	1
Overall	18	1	4

Istra – case study

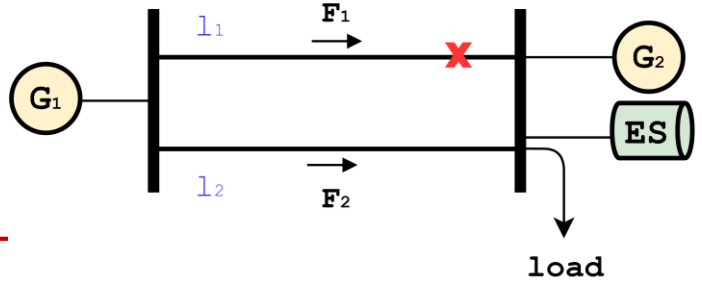
- An isolated part of the Croatian power system
- Total installed power generation capacity in Istria is 300 MW
- Increasing of load up to 230 MW, especially during the summer season
- All simulations performed in the PSSE software

Istra – case study

- Production: TE Plomin
  - TEP 1 (max 105 MW)
  - TEP 2 (max 210 MW)
- Scenarios:
  - Line 2x220 kV:
    - Plomin-TS Pehlin-TS Melina - **MAIN**
  - Line 110 kV
    - Buje-Kopar – **AUXILIARY 1**
  - Line 110 kV
    - Plomin-TS Lovran-TS Matulji-TS Pehlin - **AUXILIARY 2**

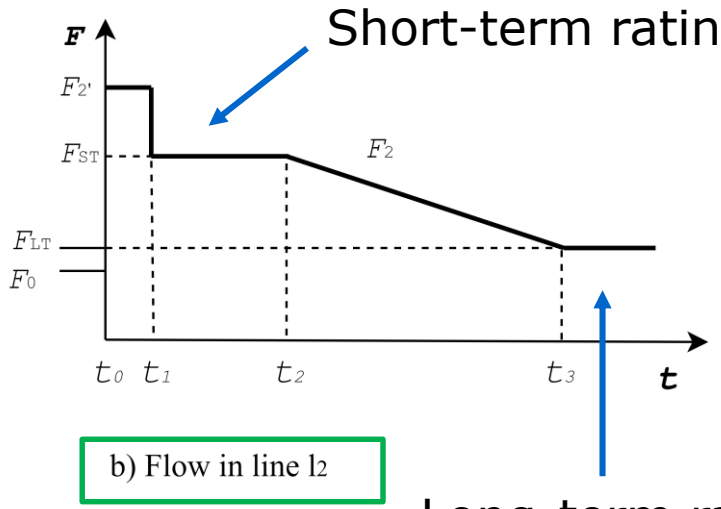


Method - Istra

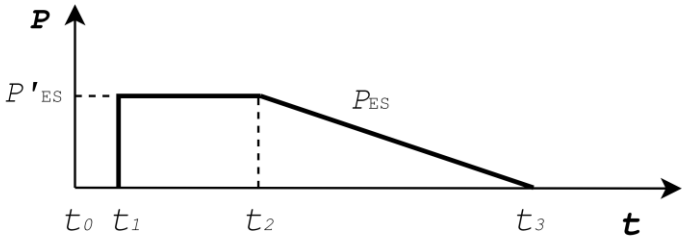


a) Two-bus system

- Two cases:
  - Injection of power
  - Evacuation of power
- Generator G1 less expensive
- When the contingency has occurred, power flow through line l2 increases to the line's short-term rating
- ES starts to inject power until t2, while the generators units start ramping
- After t3 power flow through line reache Its long-term rating



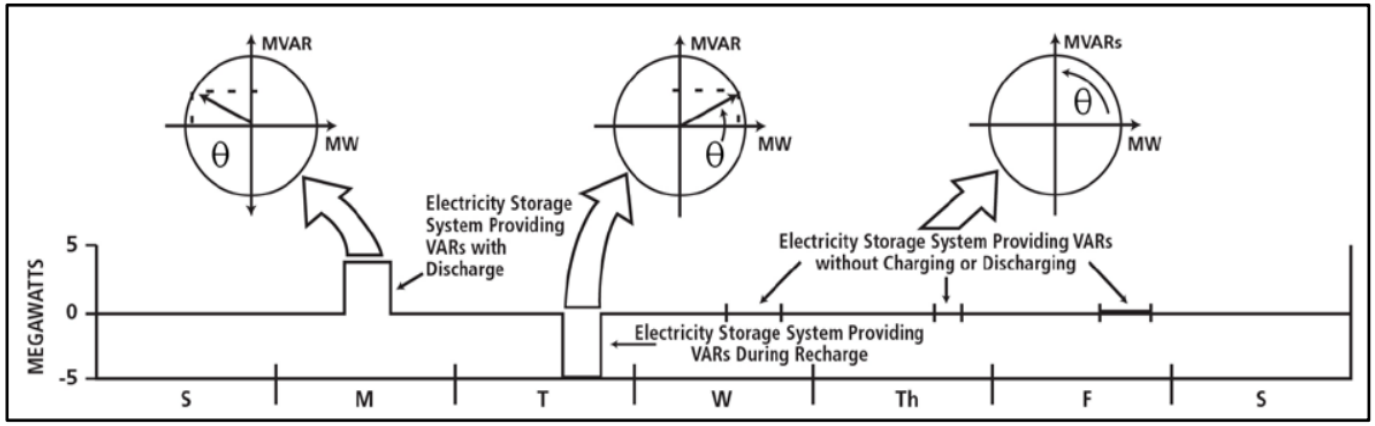
b) Flow in line l2



c) Power injection by ES

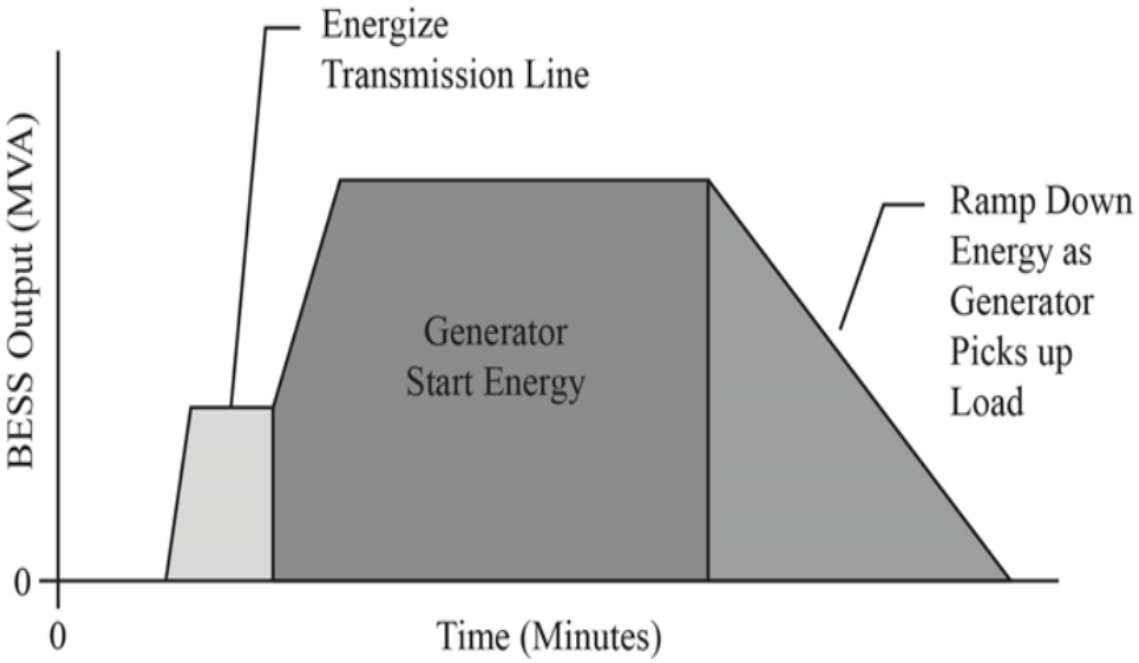
Voltage and Reactive Power Support

- Conventional way:
  - Reactive elements
  - Dynamic compensators
  - FACTS:
    - SVC
    - STATCOM
- New way:
  - STATCOM-ES

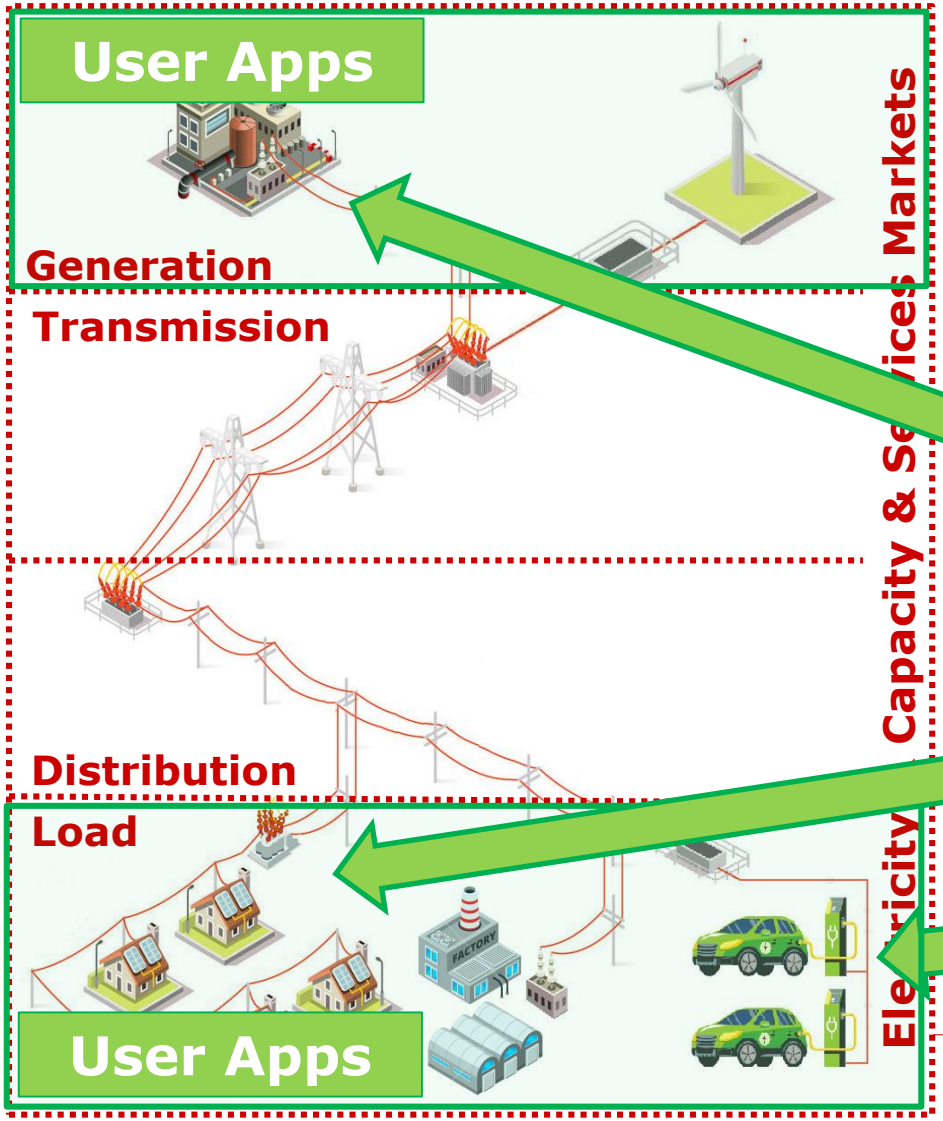


Black start, Island/Open-circuit operation

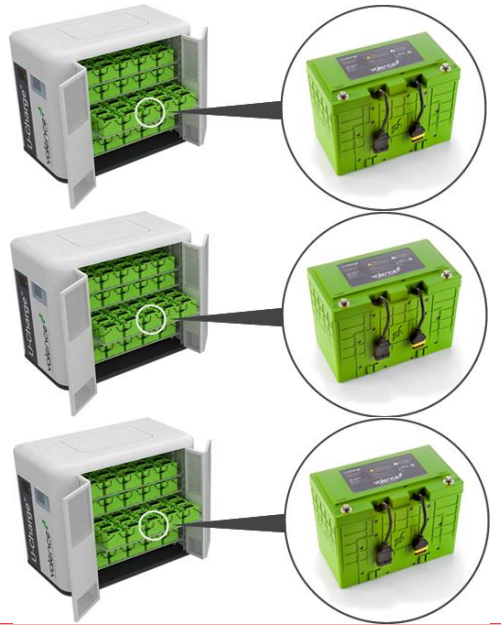
- Black start
- Island operation
- Open-circuit operation



3. User-Supporting Applications



- Applicable on grid user's location (behind-the-meter)
- Application user is a grid user (generator/load)



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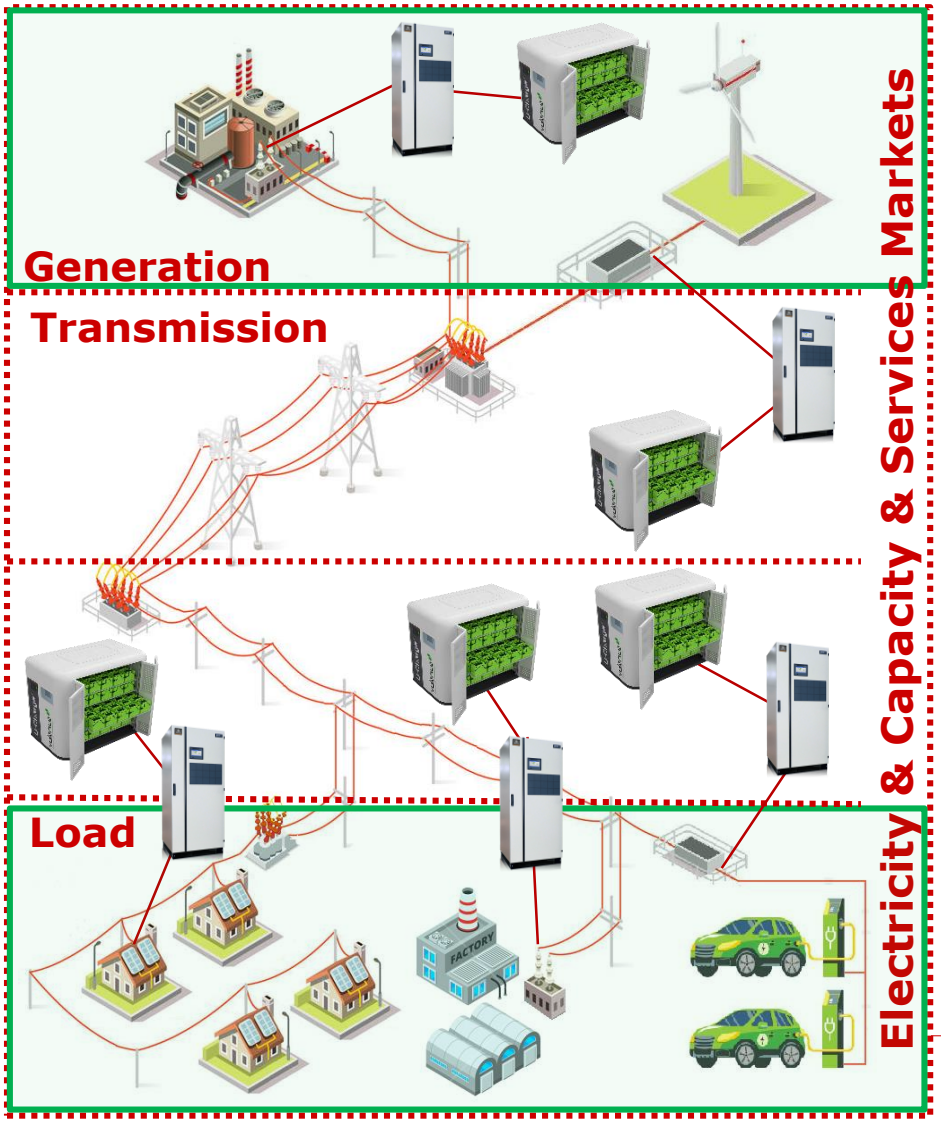


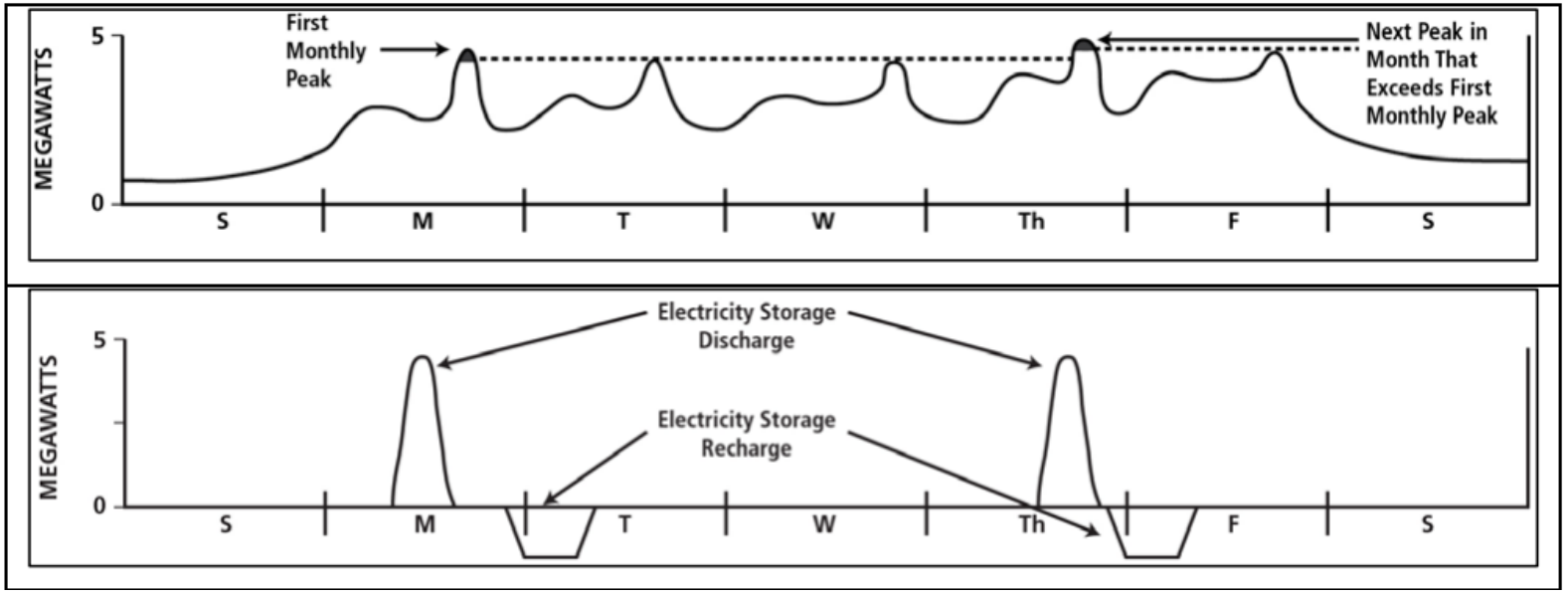
- New Connection Demand Management
- Operation-wise Demand Management
- Retail Arbitrage
- Power Supply (Voltage) Quality
- Power Supply Reliabiltiy (Back-up)

T&D Tariffs

Consumers		Tarifni model		Tariff elements					
				Real Energy			Real Peak Power	Excessive reactive power	Measuring point charge
				One T	High T	Low T			
				[kn/kWh]	[kn/kWh]	[kn/kWh]	[kn/kW]	[kn/kvarh]	[kn/mo]
				Tariff items					
				1	2	3	4	5	6
Economy consumers	High voltage	White	1	-	-	-	-	-	-
	Middle voltage	White	2	–	0,12	0,06	15,00	0,15	66,00
	Low voltage	Blue	3	0,22	–	–	–	0,15	41,30
		White	4	–	0,24	0,12	–	0,15	41,30
		Red	5	–	0,20	0,10	30,00	0,15	41,30
		Yellow	6	0,17	–	–	–	–	14,70
Houshold s	Low voltage	Blue	7	0,22	–	–	–	–	10,00
		White	8	–	0,24	0,12	–	–	10,00
		Red	9	–	0,20	0,10	30,00	–	41,30
		Black	10	0,13	–	–	–	–	5,80

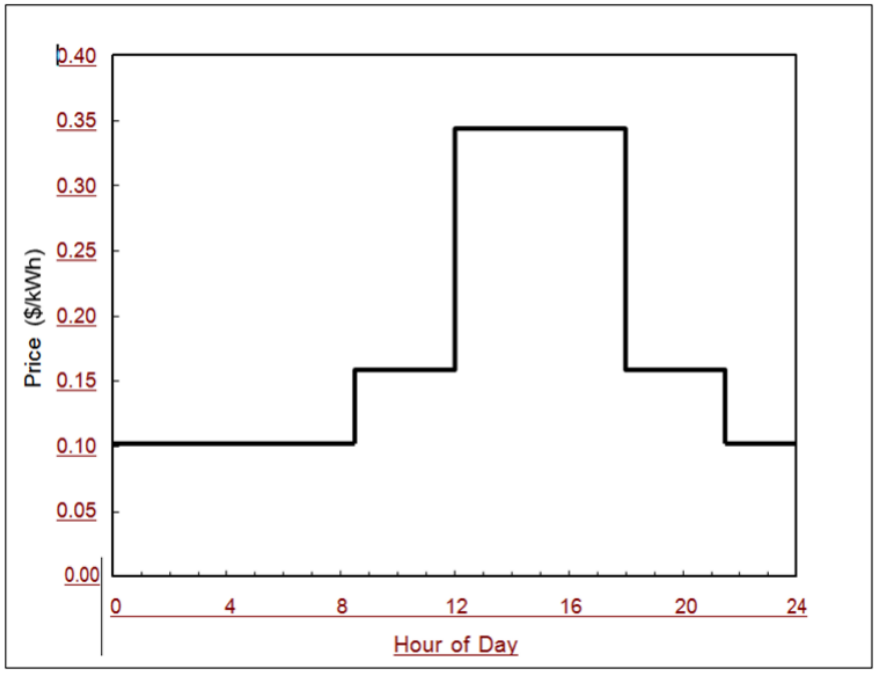
Demand Management

- Highest 15-min demand in peak periods



Retail Arbitrage

- Electricity prices
- Real energy tariffs



Power Supply (Voltage) Quality

- Sensitive loads
  - Variations in voltage magnitude (e.g., short-term spikes or dips, longer term surges, or sags).
  - Variations in the primary 50-hertz (Hz) frequency at which power is delivered.
  - Low power factor (voltage and current excessively out of phase with each other).
  - Harmonics (i.e., the presence of currents or voltages at frequencies other than the primary frequency).
  - Interruptions in service, of any duration, ranging from a fraction of a second to several seconds.

Power Supply (Voltage) Quality