Aalto University
School of Electrical Engineering

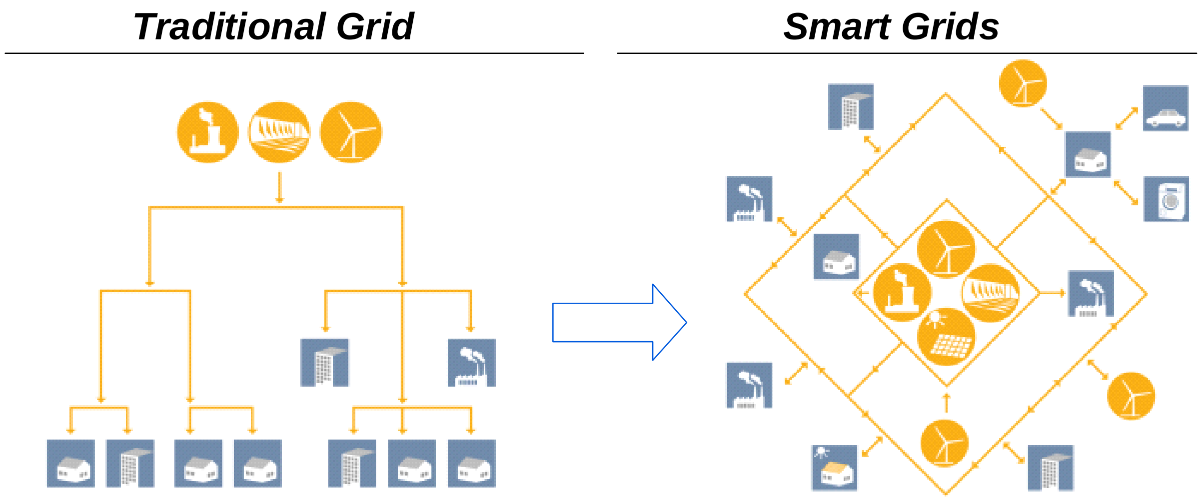
Distributed Control Architectures For Energy Systems

Matti Lehtonen, 26.5.2015

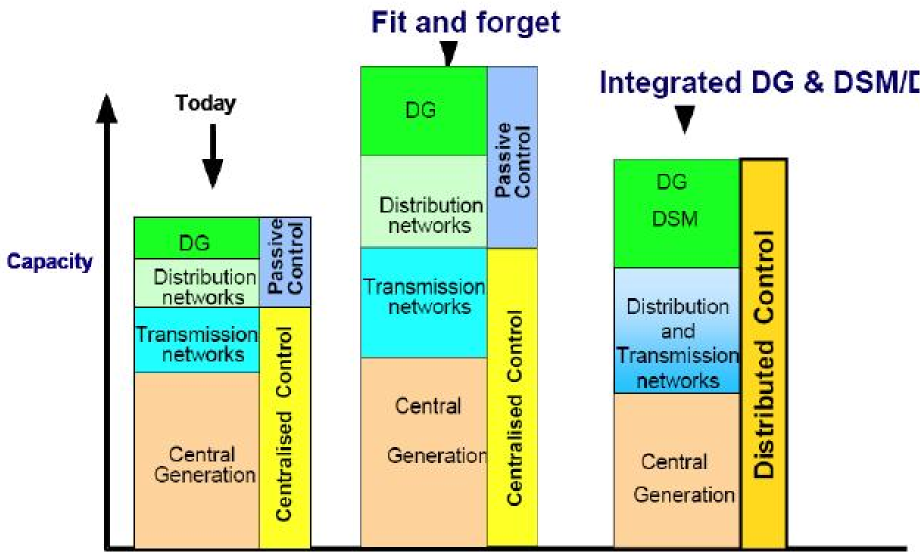
Suomen Automaatioseuran seminaari

SMART GRIDS

The motivation of Smart Grids is to enable integration of renewable power generation, distributed energy resources and energy efficiency in power and energy systems.



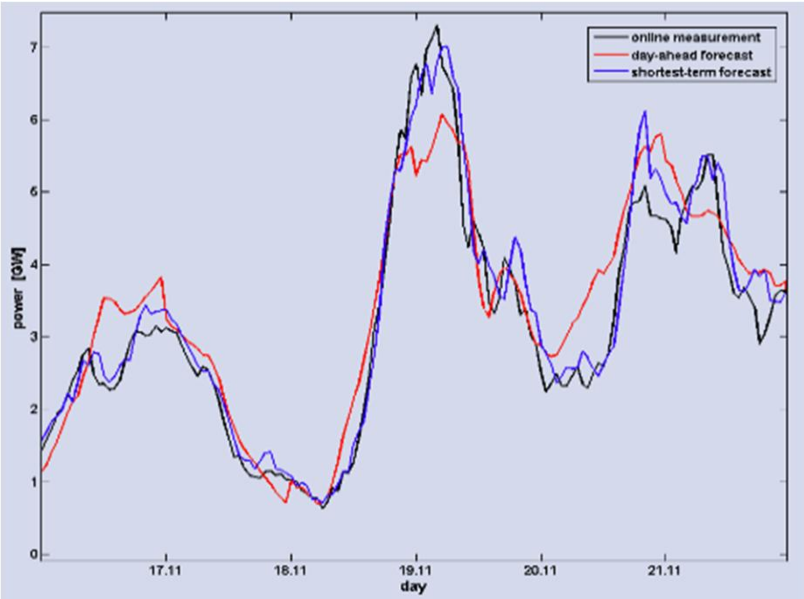
Integrating renewables and distributed resources



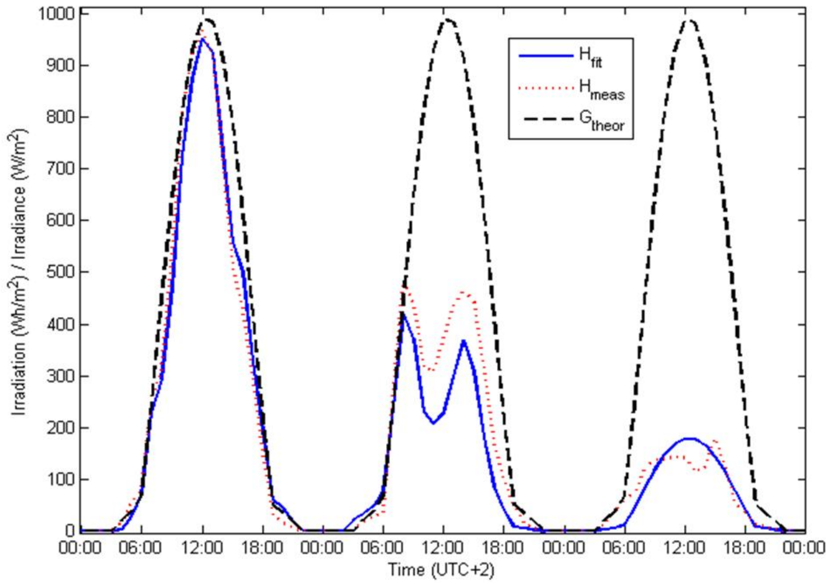
The active control of power system is extended over the Distribution system till the customers resources ⇔ As a control problem this is huge !

Challenge of renewables: intermittent production and power balance

Variation of wind power in
Three subsequent days in Germany



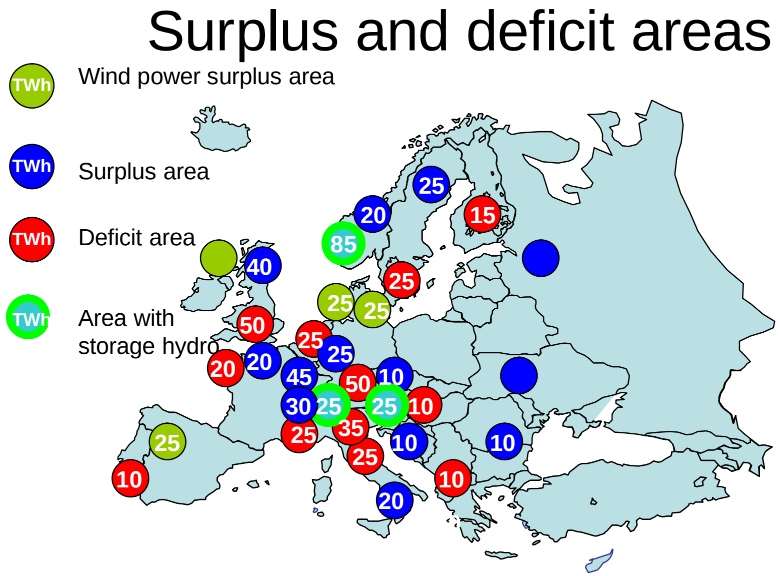
Variation of PV production in three subsequent days in Finland

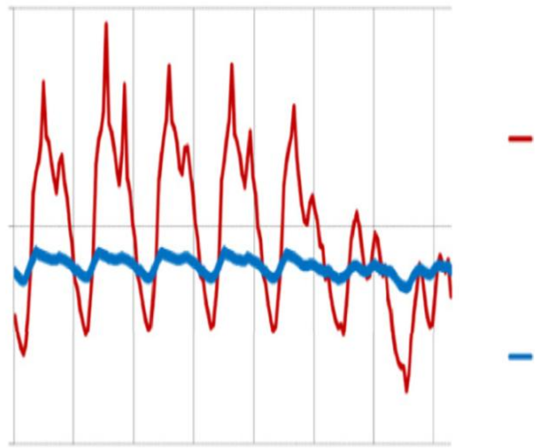


Smart Grids and Power Balance

- In present power systems even moderate share of renewables cause difficulties:
  - In Denmark wind production frequently exceeds power demand ⇔ negative prices in electricity exchange !
  - In Germany 3% share ot PV production has led to 50.2 Hz problem ⇔ requirements to tune down PV production !
- Substantial increase of renewable power generation, both in centralized plants and at distributed locations, is impossible without better control of power balance using Smart Grid technologies

DEVELOPMENT OF MARKETS – PRICE VOLATILITY AND BALANCE MANAGEMENT DUE TO RENEWABLES

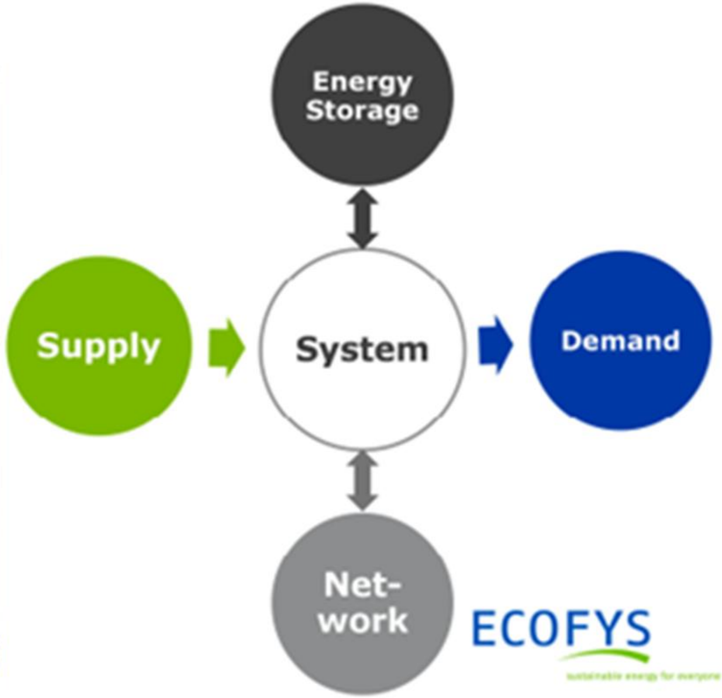




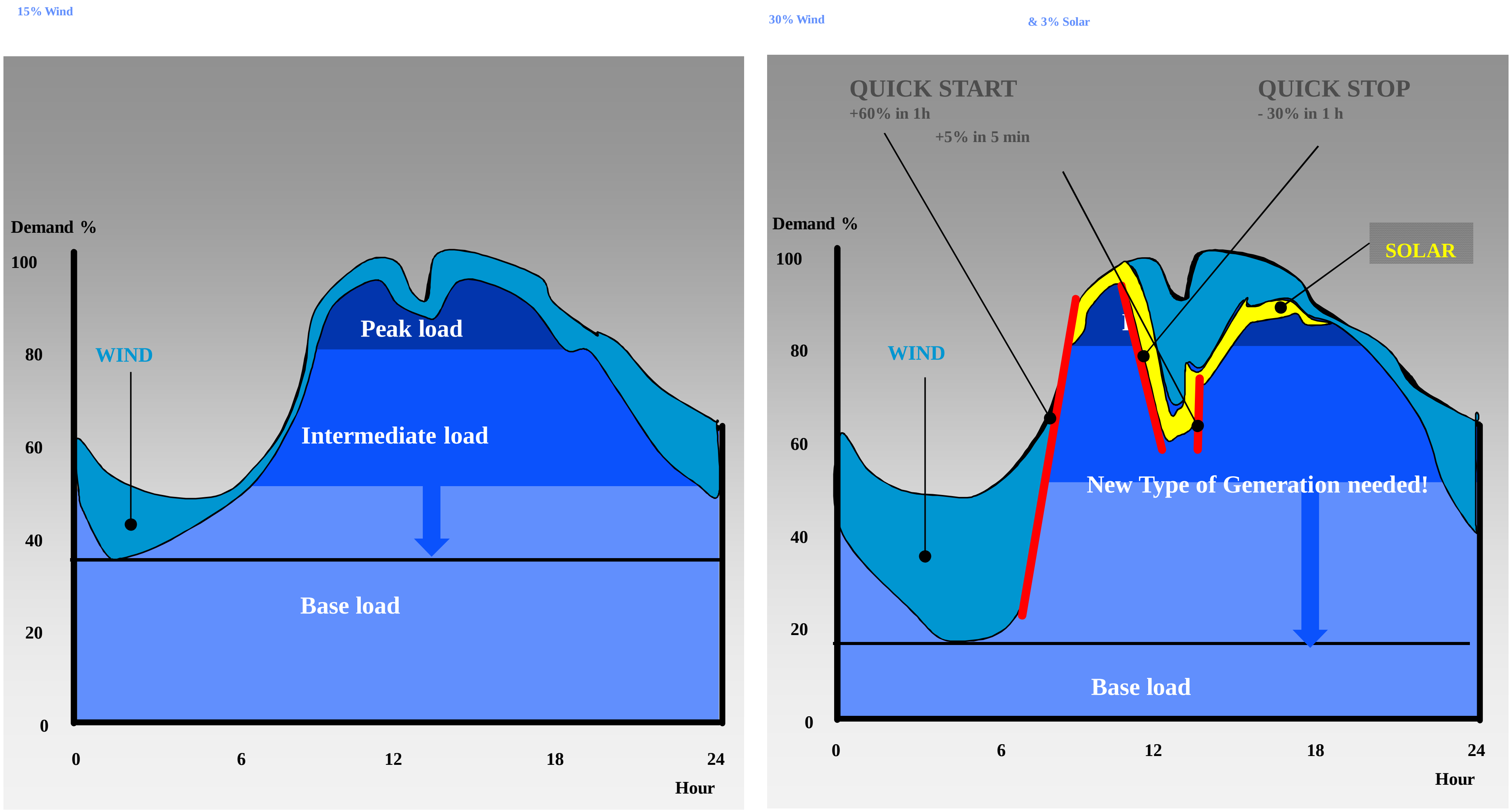
Picture: M. Supponen

- **When markets integrate, energy balance gets more challenging also in Nordic countries**
- **Nordic hydro used more for leveling German wind and solar…**
- **Prices of power today more volatile in Central Europe (red: german, blue Nordic), what about in future ….**

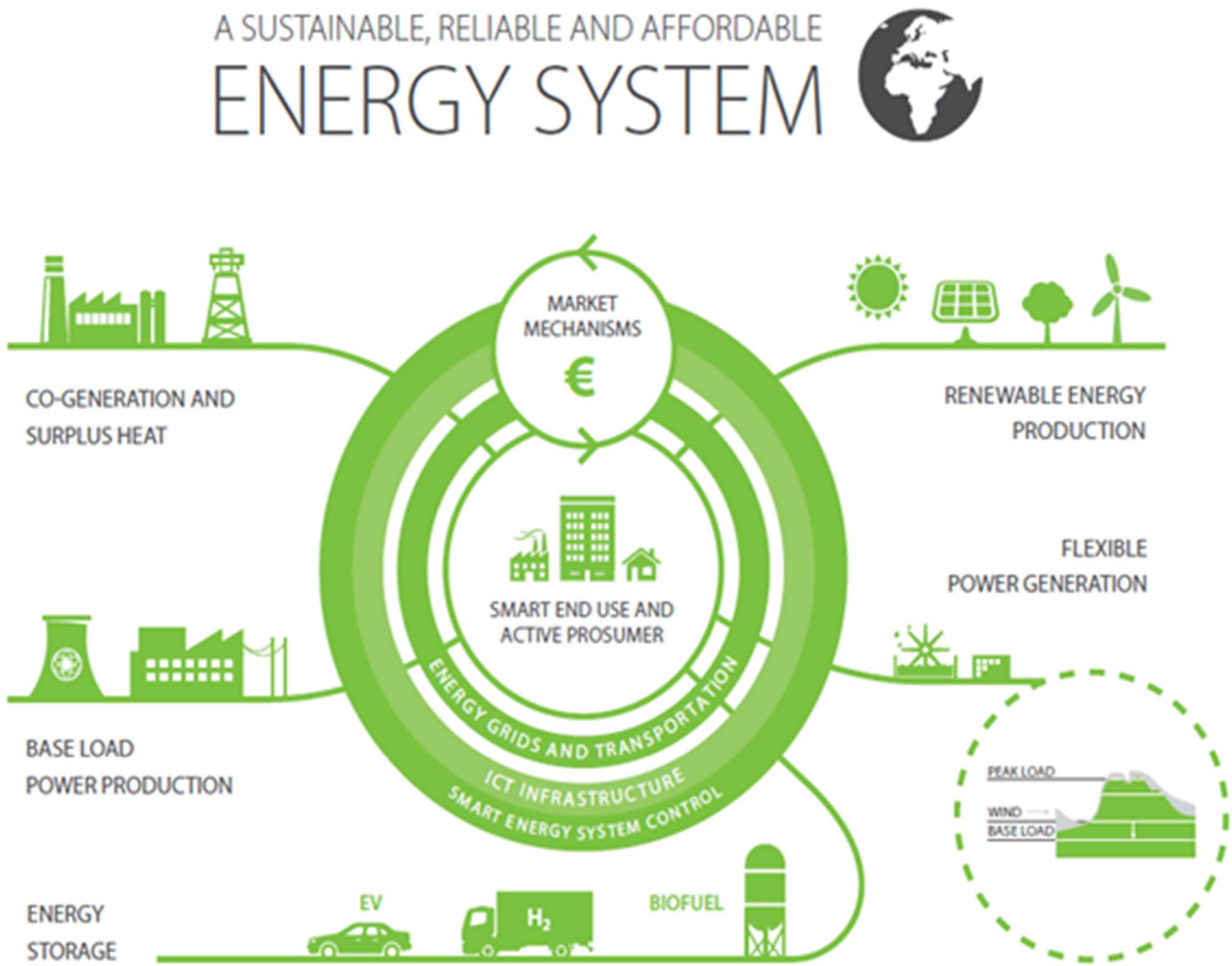
Flexibility gap and options



Load variations in power systems with wind



Present electricity markets are based on selling energy (kWh's) and do not reward dynamic flexible capacity adequately to encourage investments


A SUSTAINABLE, RELIABLE AND AFFORDABLE
ENERGY SYSTEM
MARKET
MECHANISMS
€
CO-GENERATION AND
SURPLUS HEAT
RENEWABLE ENERGY
PRODUCTION
SMART END USE AND
ACTIVE PROSUMER
FLEXIBLE
POWER GENERATION
ENERGY GRIDS AND TRANSPORTATION
ICT INFRASTRUCTURE
SMART ENERGY SYSTEM CONTROL
BASE LOAD
POWER PRODUCTION
PEAK LOAD
WIND
BASE LOAD
ENERGY
STORAGE
EV
H_2
BIOFUEL

Resources for Power Balance and Energy Efficiency

- Control of local generation
  - Local wind and PV are intermittent, not suitable for control
  - Local microCHP (based on biofuels) – high control potential
- Energy Storages
  - Thermal storages
  - Batteries & Electric Vehicles Smart Charging
- Demand Response (DR)
  - Large share of loads suitable for shifting timely use
  - Generation / load balancing & as reserve capacity
- Energy use monitoring and control
  - Analysis and monitoring of energy use
  - Energy efficient control functions

Future energy system control levels

- Control architecture for Smart Energy System, levels:
  - Transmission: Balance management – Markets – Renewables integration – system security
  - Distribution: Aggregation of customer resources to VPP – local renewables – network disturbance management – retail market operations
  - Customer & Prosumer level: Production, storages, EV charging control – energy efficiency monitoring and control & demand response
- States: Normal state energy optimization (hrs) – Local network disturbances (min) – system security & capacity adequacy (sec)

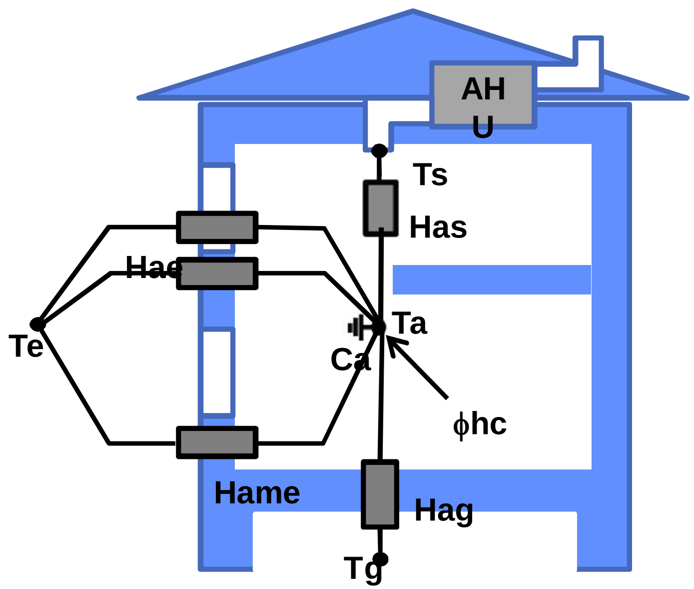
Challenges of the control architectures

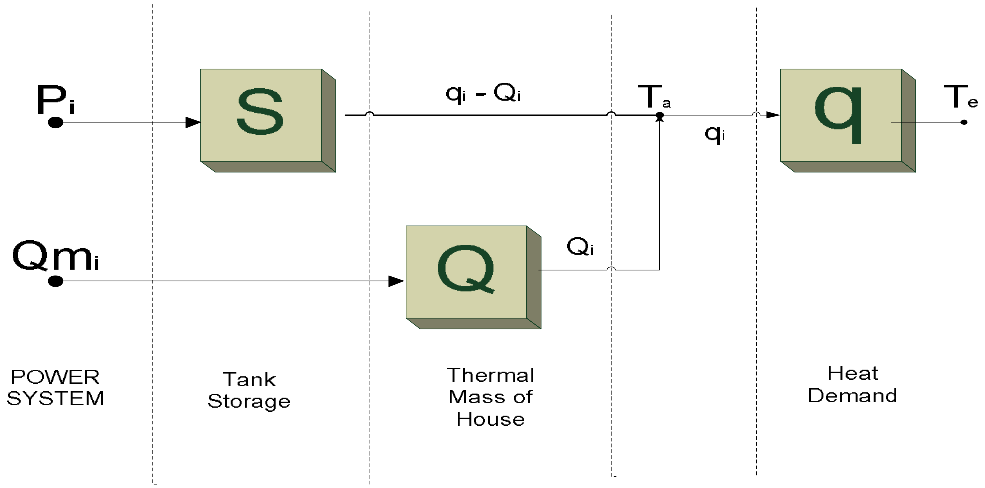
- Three system levels – three system states
- Quick and complicated transitions between states
- Millions of actors
  - Distributed architectures needed
  - Interactions between players in same system level
  - Interactions between players in different levels
- Agent based architectures needed
  - Different types of agents in different levels
  - Market, Power, Energy, Network related functions
  - Transitions between normal and disturbance states
  - Challenges of communication and data interfaces

Energy system control hierarchy

STATE: SYSTEM LEVEL:	LOCAL NETWORK DISTURBANCE	DISTURBANCE IN SYSTEM BALANCE	NORMAL POWER TRADE
TSO – GENERATOR	Rescheduling the Generation and Balance power	Power balance and reserve management	Power Exchange Market operation DER integration
DSO - AGGREGATOR	Management of network faults and bottlenecs	Coordination of Ancillary services of Prosumers	Market Integration of DR and DER
CONSUMER-PROSUMER	Prosumers and DR to mitigate Network reserves	Balance control: Ancillary services By prosumers	Demand Response DER control

Model of heating loads for DR



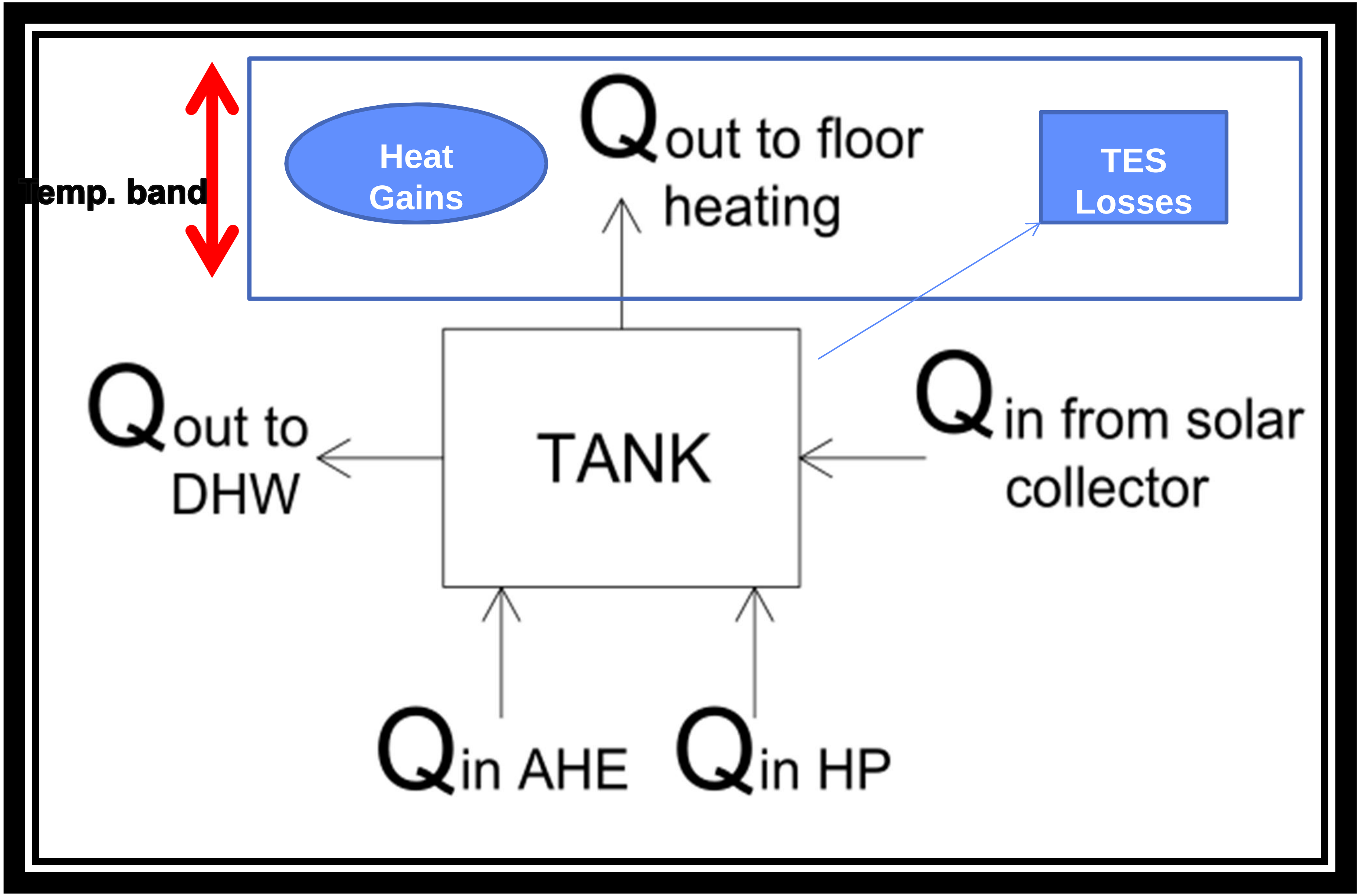


Demand Response in optimizing partial storage

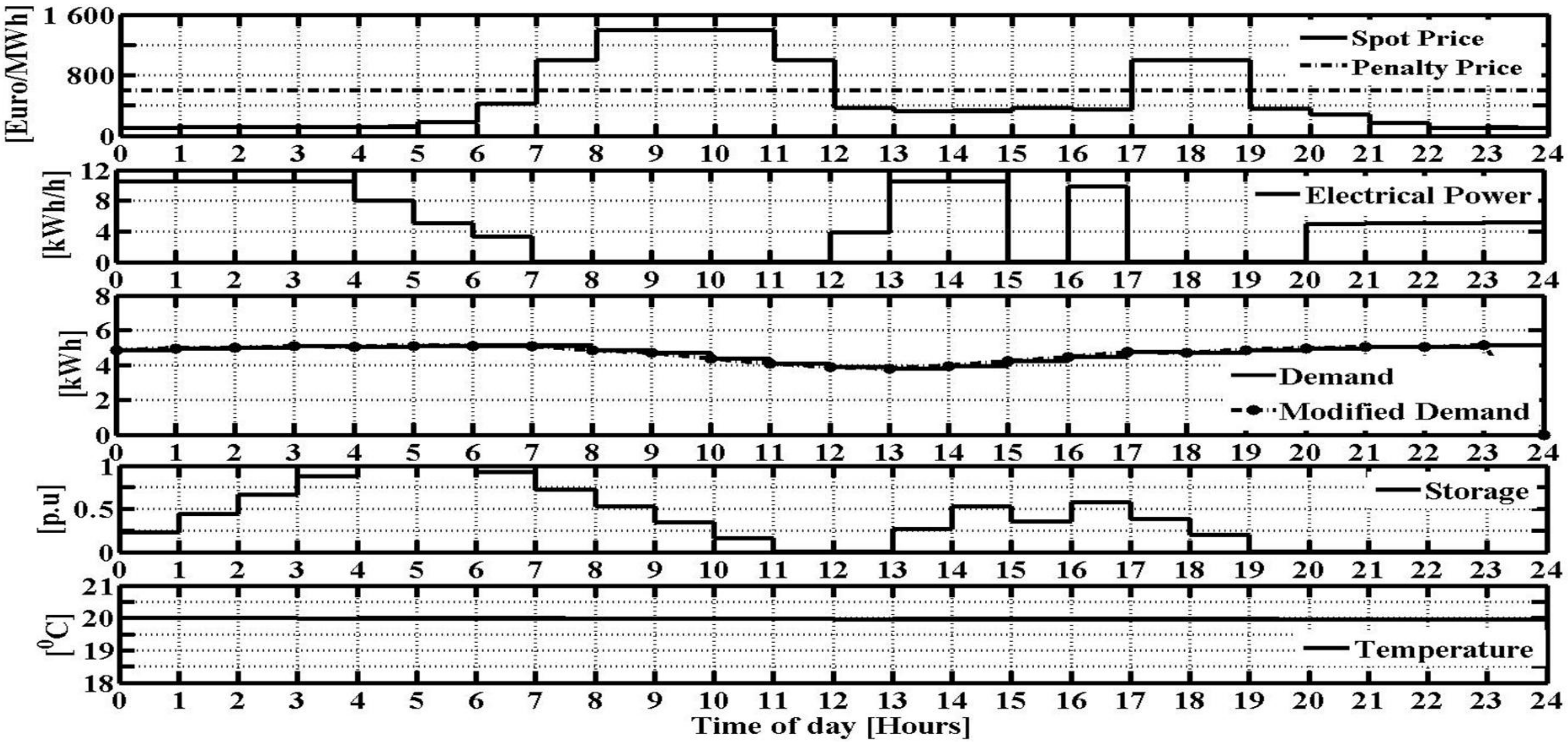
Modeling the house (to the left) and

Modeling the controlled targets in heating system

Schematic of Energy Hub



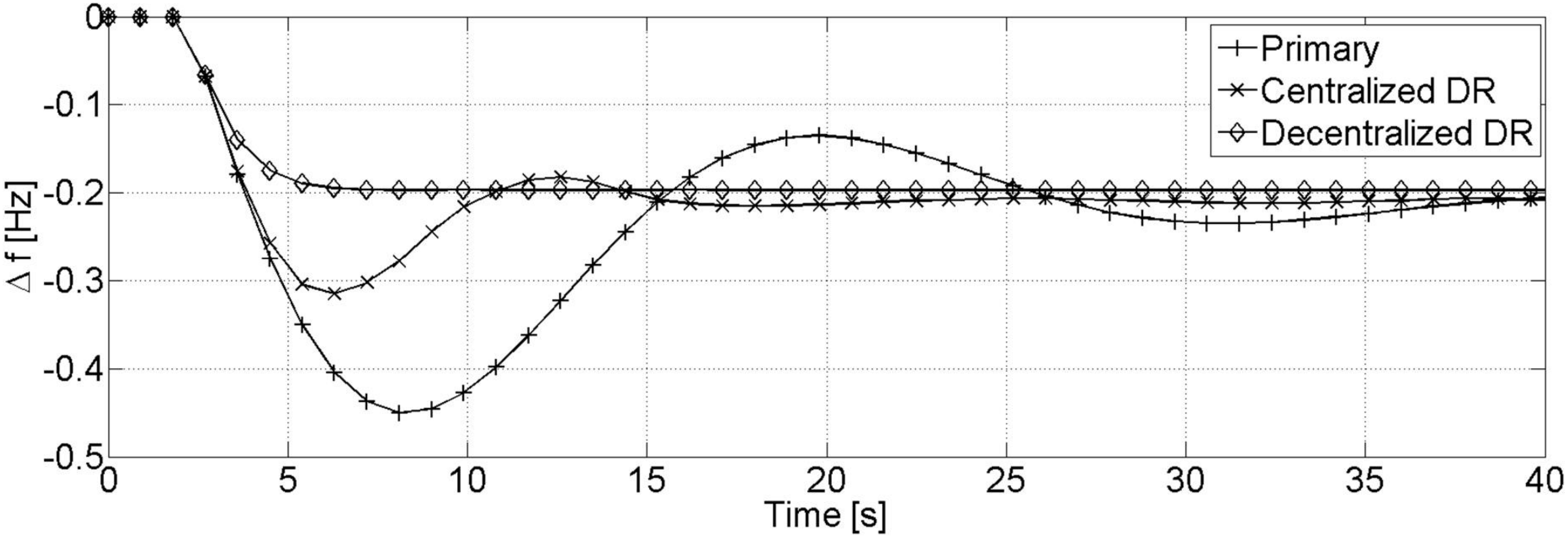
DR in market optimization



Demand Response in optimizing partial storage

Space heating ⇔ shifting demand from peak price

DR in balance management



MAJOR DISTURBANCE IN SYSTEM

CENTRALIZED ⇔ Central control as today

Primary ⇔ Control by DSO & aggregator

Decentralized DR ⇔ Control by Prosumer

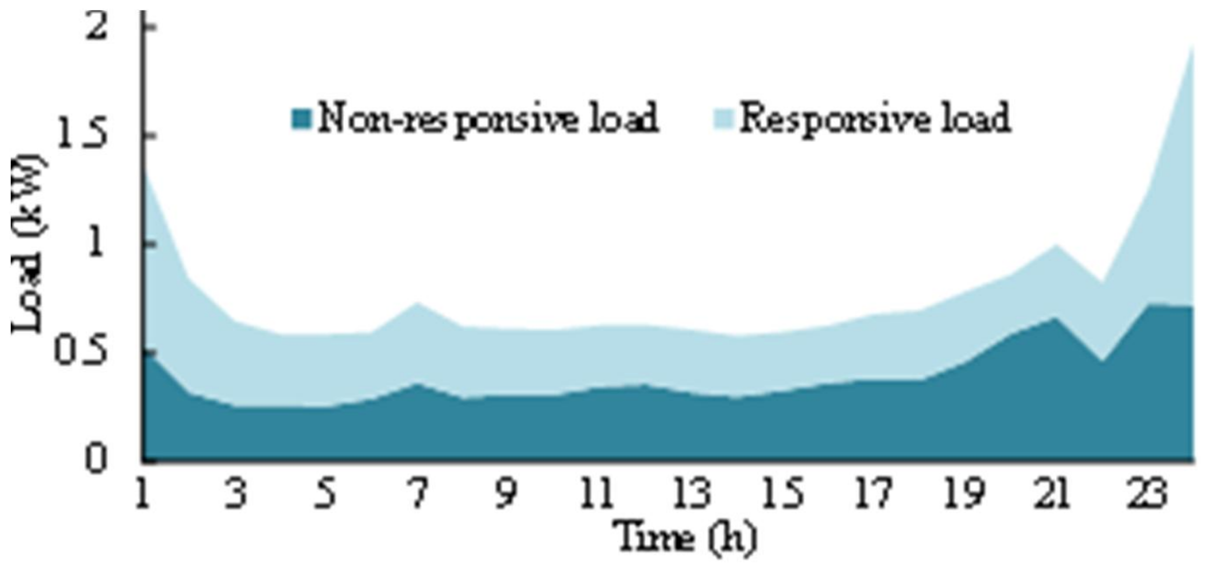
Demand Response potential

Of household loads about 50% are timely flexible

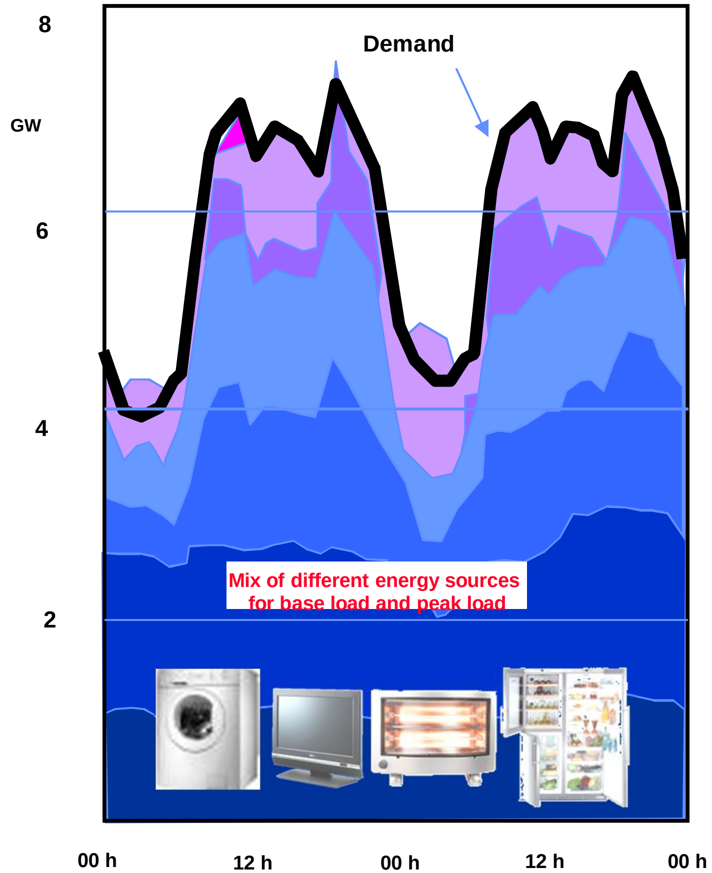
- **This is 10-20% of system peak load**
- **Can be used for leveling renewable variations**

In future, another 10-20% can be obtaned

From intelligent EV charging



DR and distributed resources



- To ensure power balance flexibility is needed both in generation, in system (networks) and in loads (DR)
- With increase od intermittent renewables the reserve capacity comes more crucial
- Many load equipment have a capacity of short term DR, but for longer time periods this capacity decreases
- DR alone is not enough, also storages are needed (BES, TES)

Future energy system is a mix of DR, storages and flexible generation units

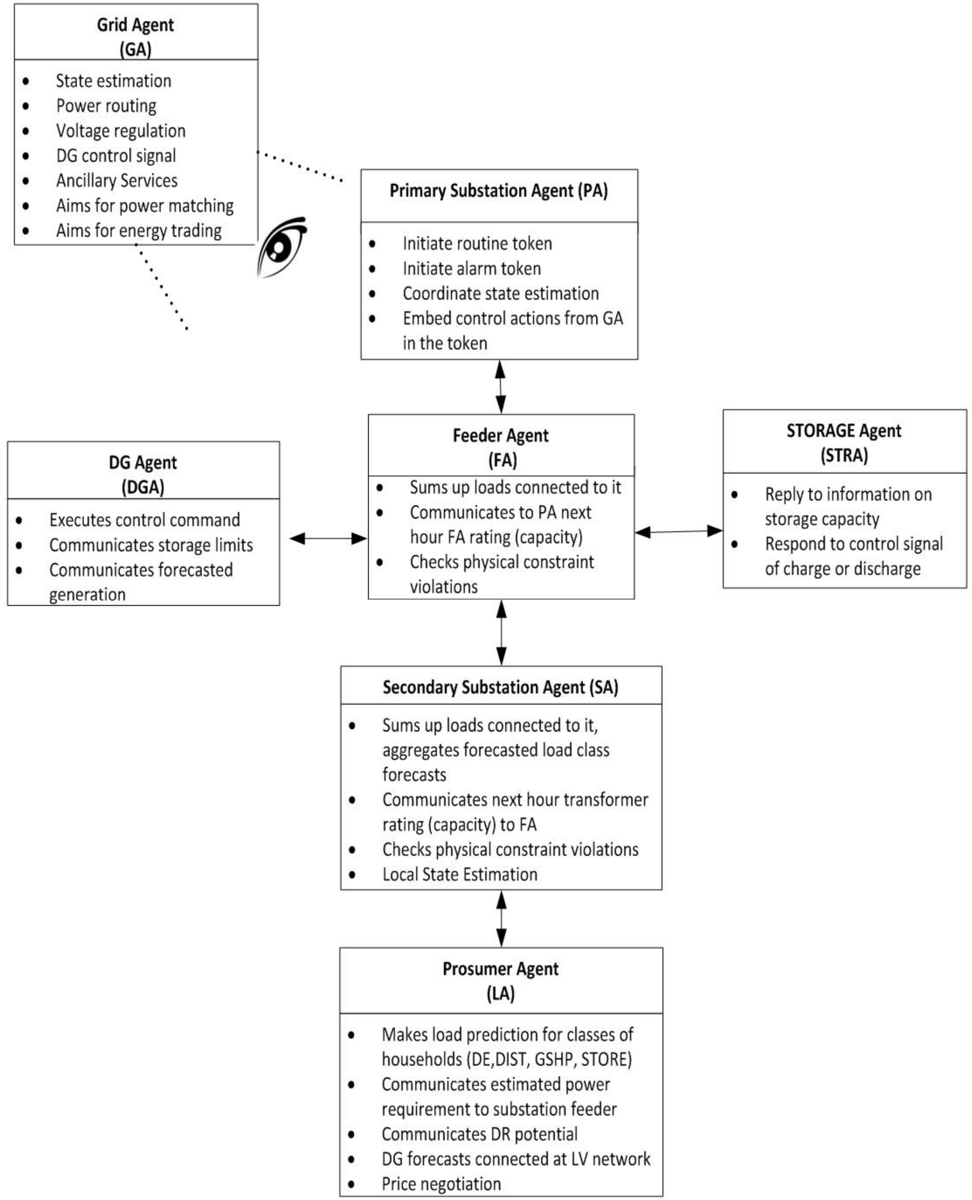
A Smart Grid Control Architecture for DER and DR

TSO/Aggregator:
Generation scheduling
Balance management
System disturbance management

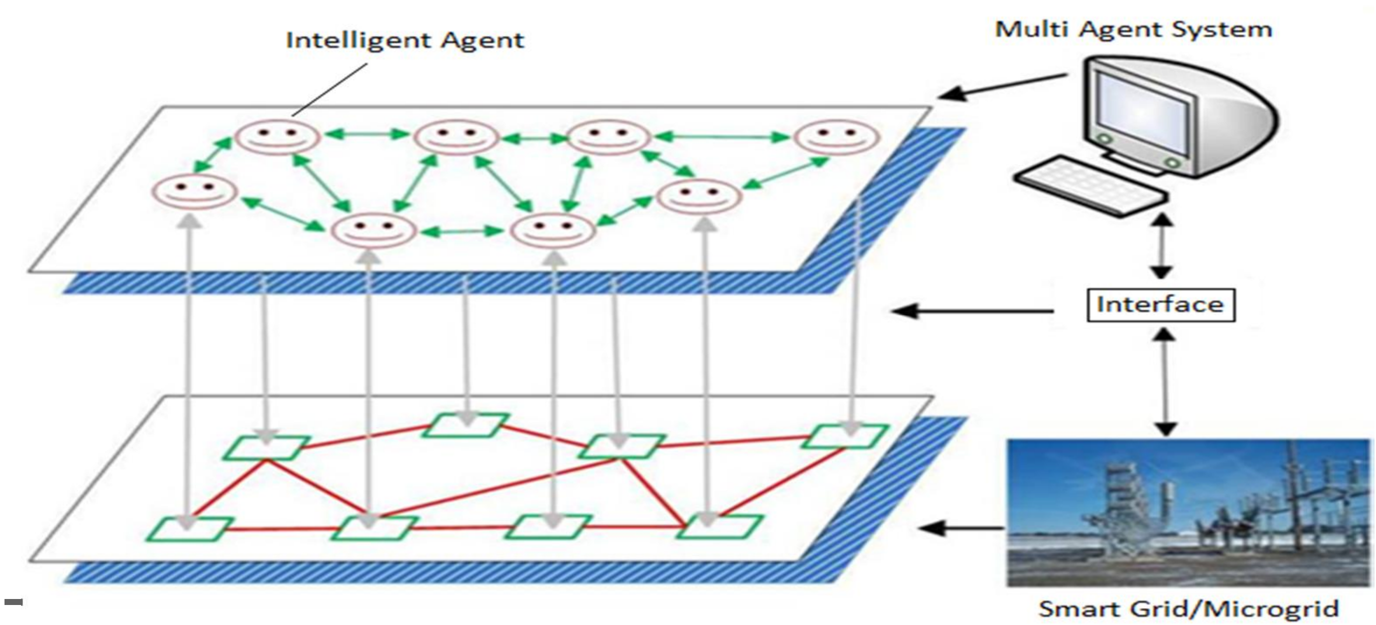
DSO/Aggregator:
Aggregation of DER
- Local production
- Demand Response

Local network management
- Capacity congestions
- Local disturbances
- Self-healing networks

Prosumer
- Optimizing local energy use
- Participation in markets
- Balance management resource
- Network mitigation resource



Distributed fault management – self healing networks



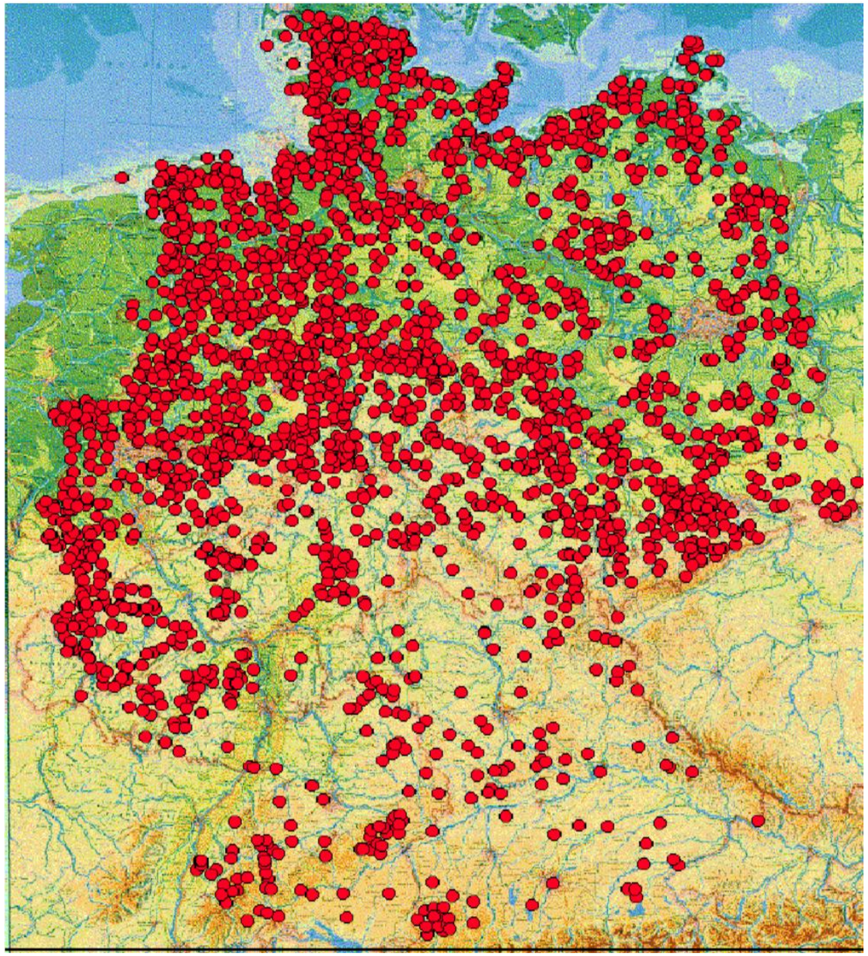
Control Strategies	Communication hops		Delay time due to communication hops	
	M_{MIN}	m_{max}	M_{MIN}	m_{max}
Centralized	$\boldsymbol{n^2+7n+5=1253}$	$\boldsymbol{n^2+7n+5=1253}$	**1253Δ*t***	**1253Δ*t***
Distributed Agent	$\boldsymbol{2m_{min}+2=4}$	$\boldsymbol{2m_{max}+2=66}$	**4Δ*t***	**66Δ*t***
Autonomous Agent	**4**	$\boldsymbol{m_{max}+5=37}$	**4Δ*t***	**6Δ*t***

Time delays in network fault management. Number of substations n = 32, for different faulty sections between substations m = 1…n. And Δt is the communication latency.

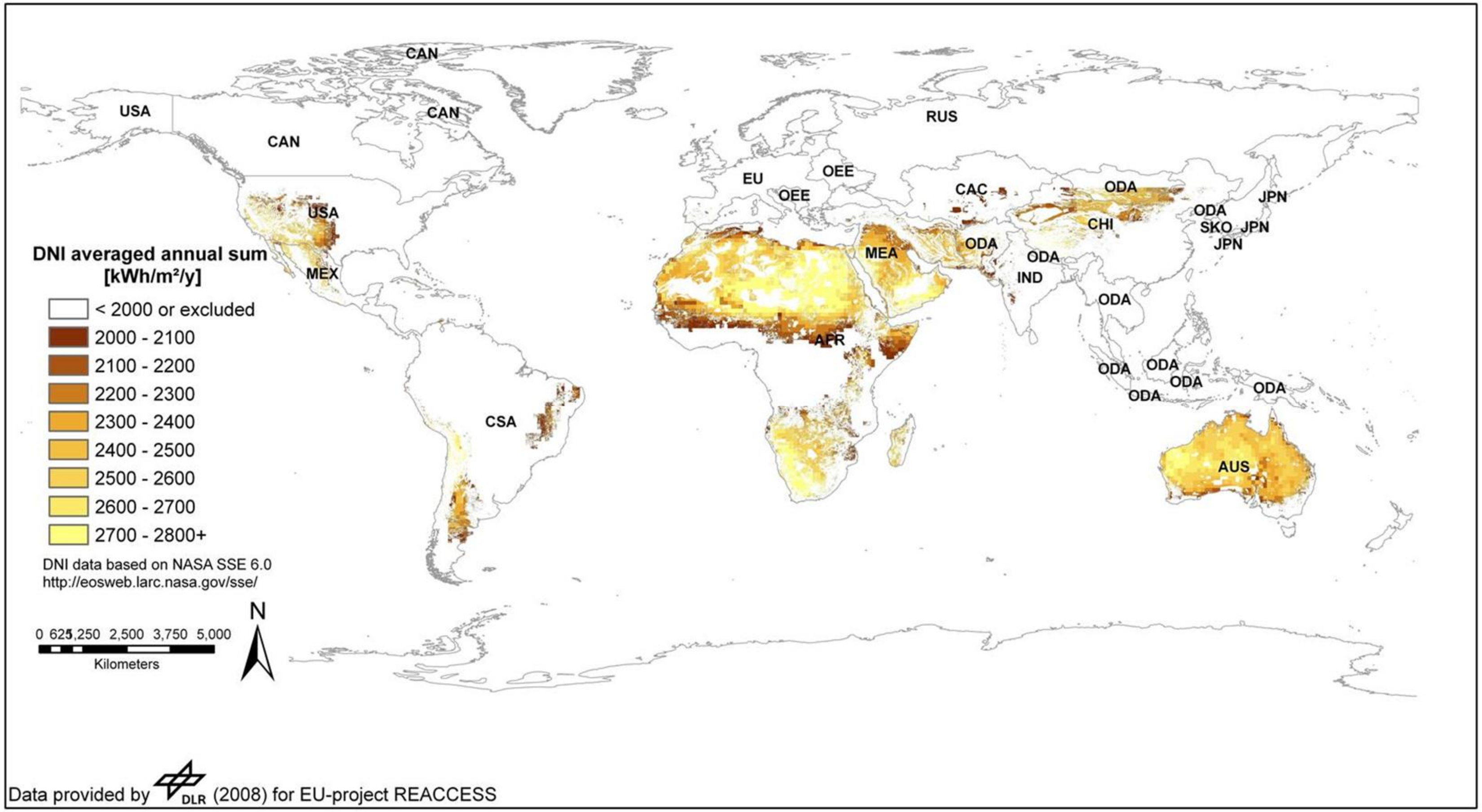
WIND POWER PARKS IN GERMANY

FAST INCREASE IN WIND CAPACITY IN GERMANY:

August 2013 72 GW of renewables (wind, PV, biomass)

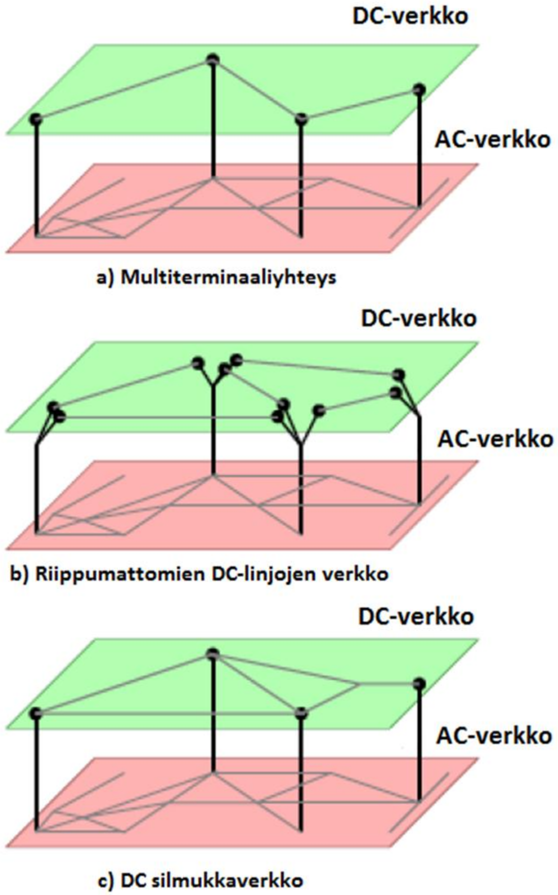


POTE NTIAL OF SOLAR POWER

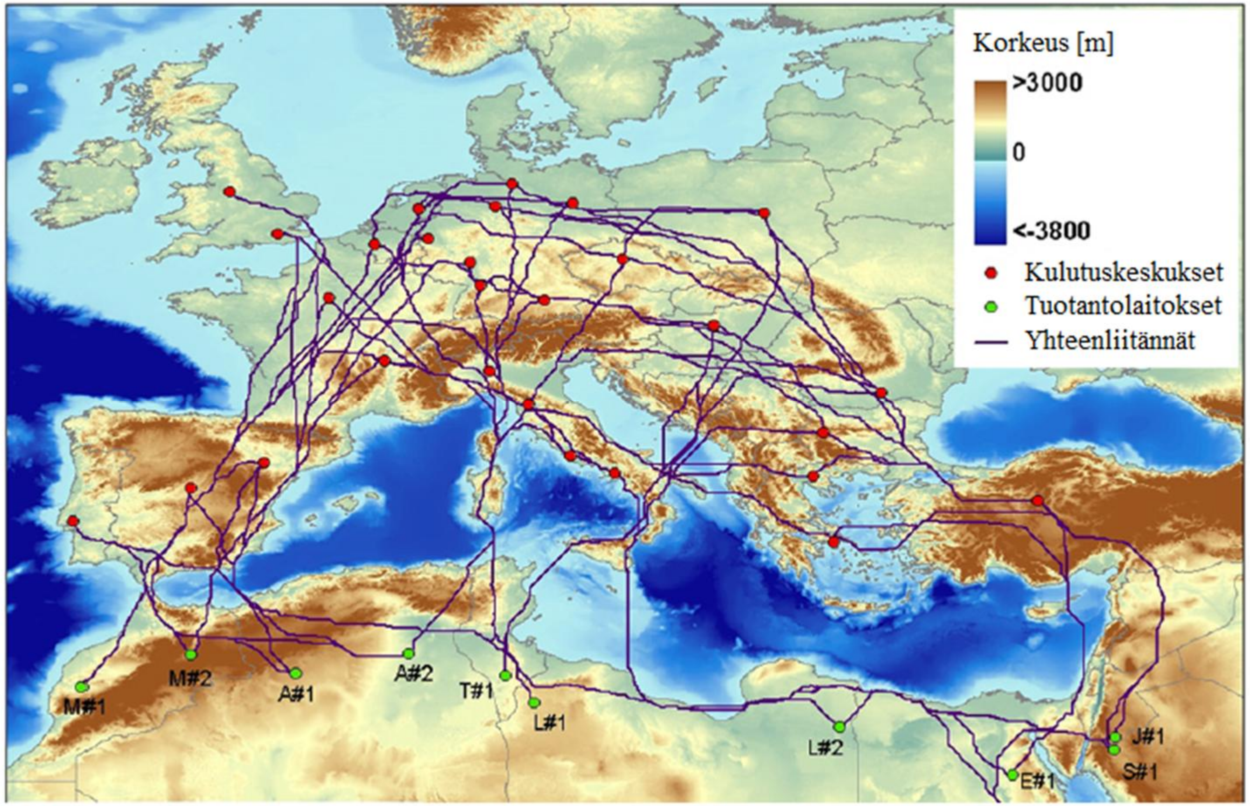


Smart Grid ⇔ Supergrid

Voltage	735 kV AC	500 kV DC	800 kV DC
losses/1000 km	6,7 %	6,6 %	3,5 %
Capacity	3 GW	3 GW	6,4 GW



Desertec – solar power from North-Africa to Europe ?



Mahdollisia HVDC-linjoja Euroopan kulutuskeskuksille CSP-tuotantolaitoksilta (keskittävä aurinkovoimalaitos)