Smart Grids & Storage:
Keys to a Decarbonized Future

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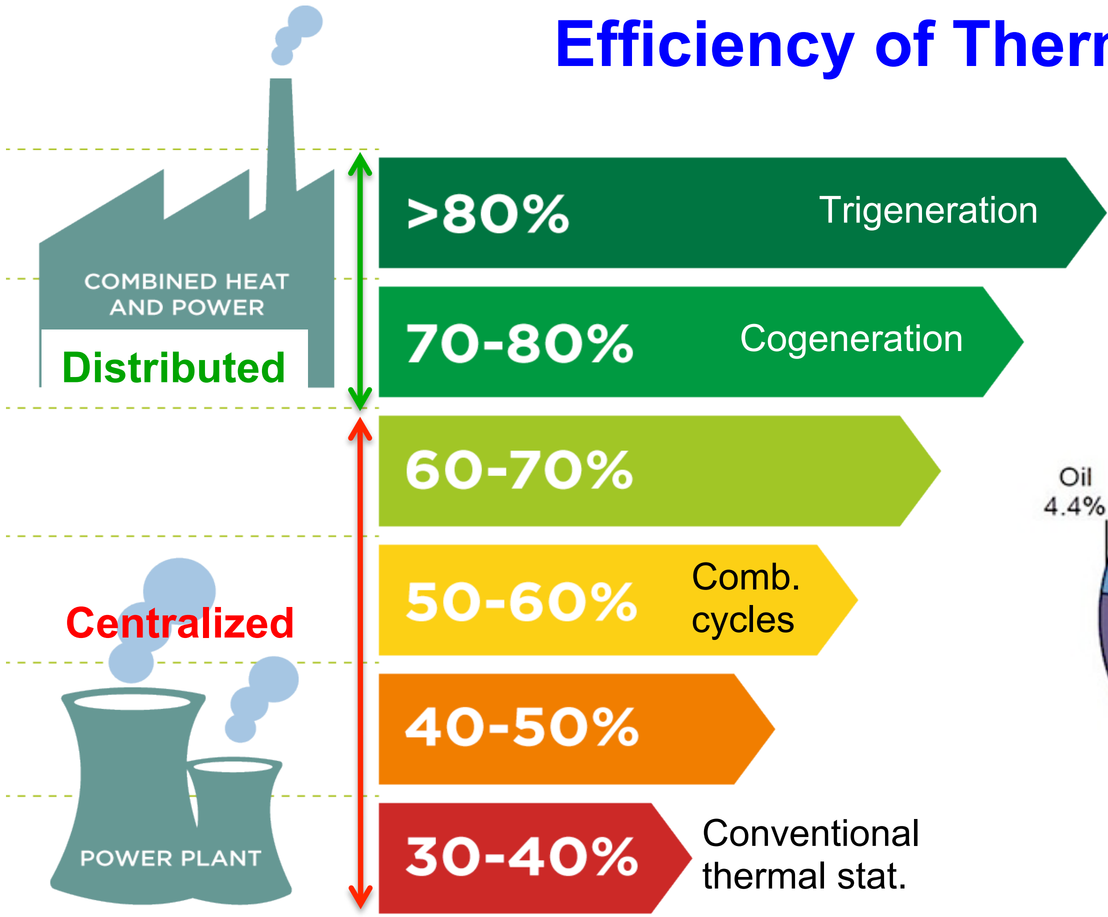
November 8, 2017

Contents

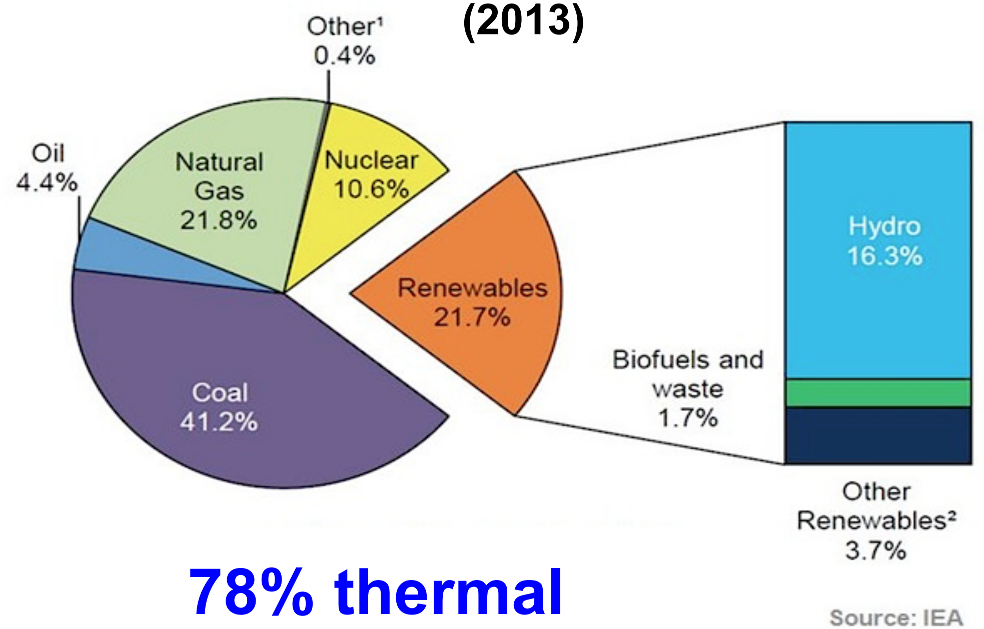
- Renewable energy: current status & prospects
- Technical barriers
  - Generation
  - Transmission
  - Distribution
- Enabling technologies
  - Smart renewable generation interfaces
  - Smart T&D grids
  - Ubiquitous storage systems

20th Century Generation Paradigm

Efficiency of Thermal Stations



Global electricity production (2013)

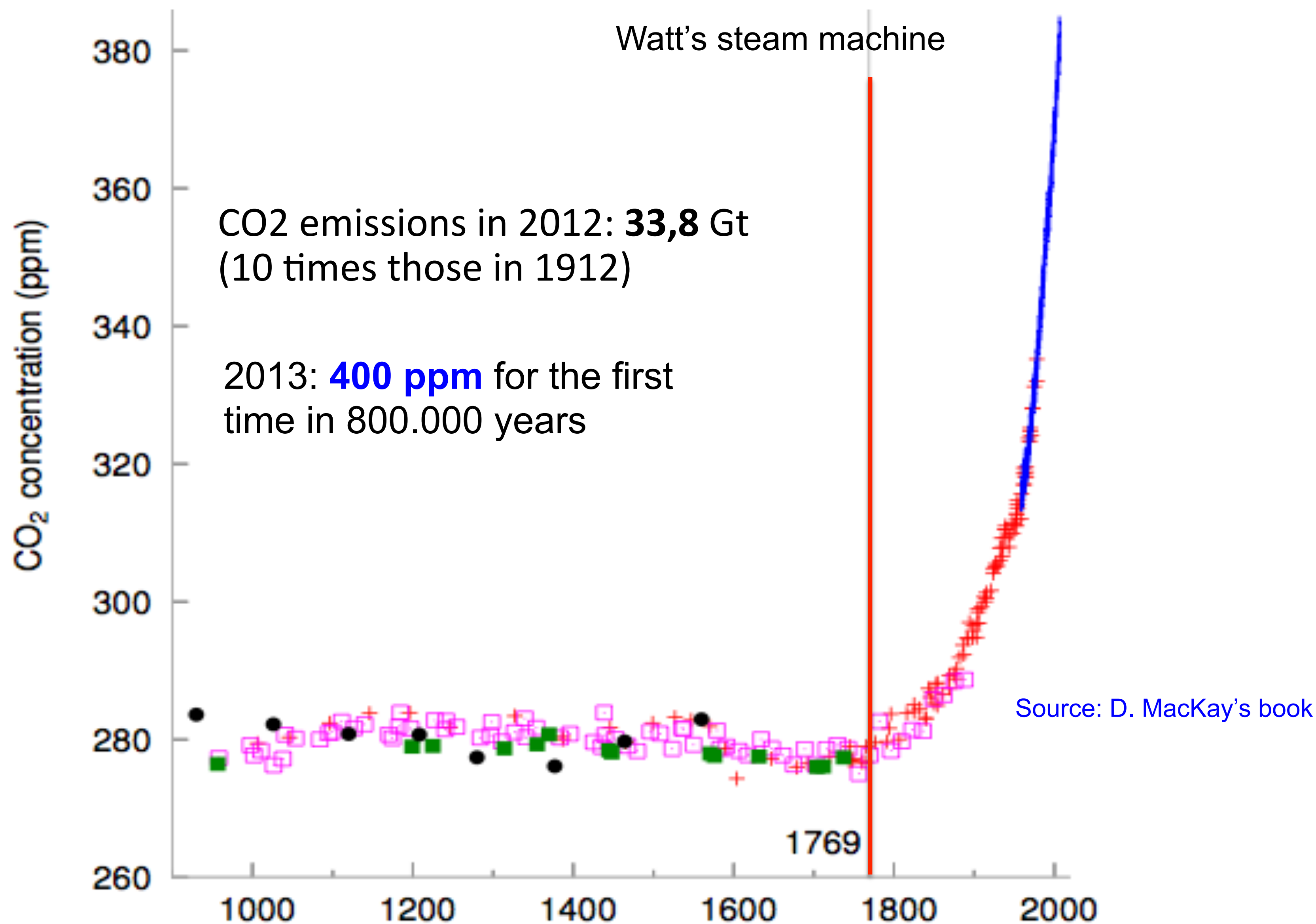


78% thermal

(mean efficiency: 31.5%)

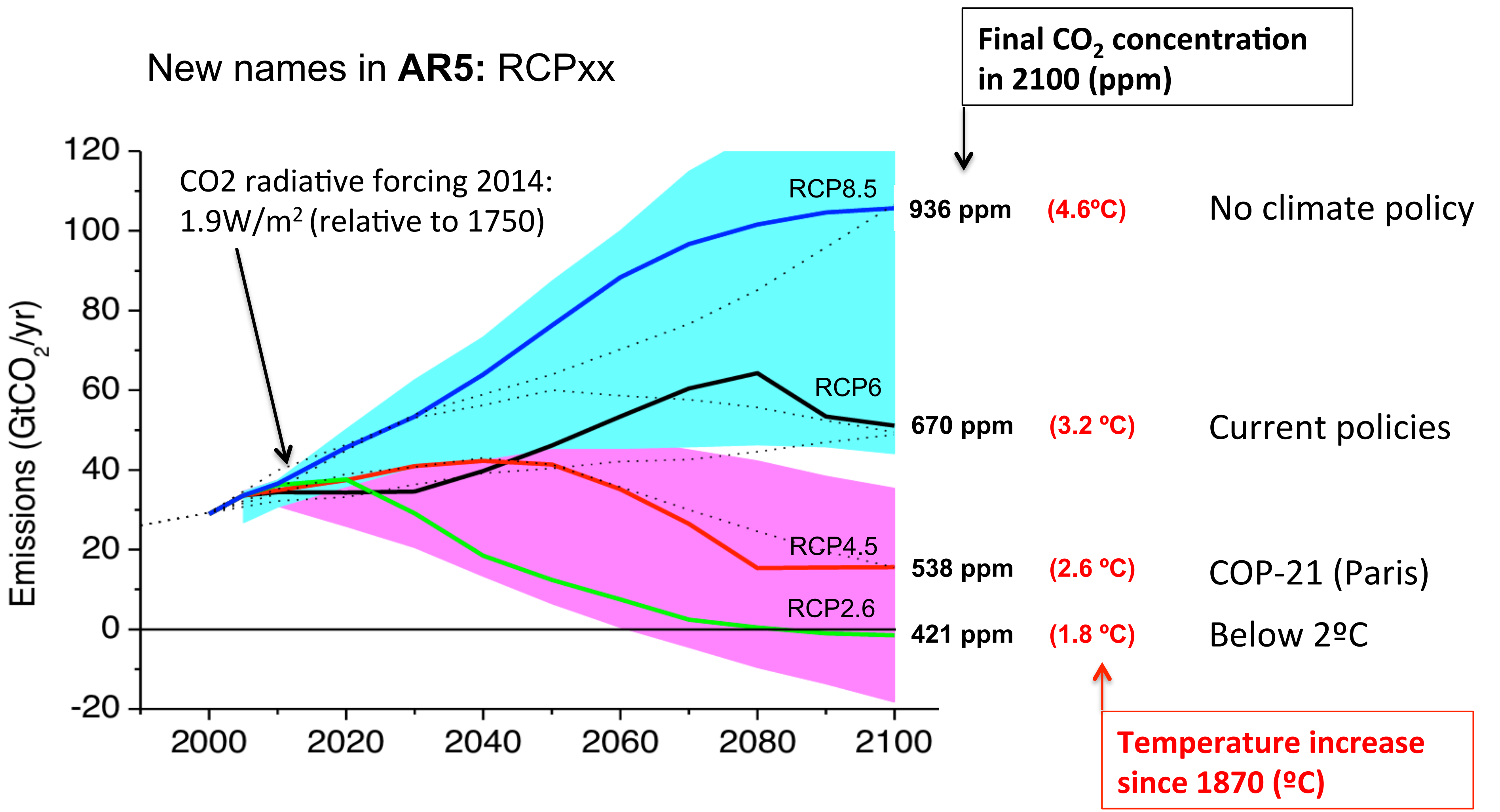
Fuente: The Association for Decentralized Energy (http://www.theade.co.uk)

Evolution of CO_2 emissions



IPCC Scenarios up to 2100

New names in **AR5:** RCPxx



Source: van Vuuren et. al., "The representative concentration pathways: an overview", Climatic Change, Vol. 109(1), pp 5-31, 2011.

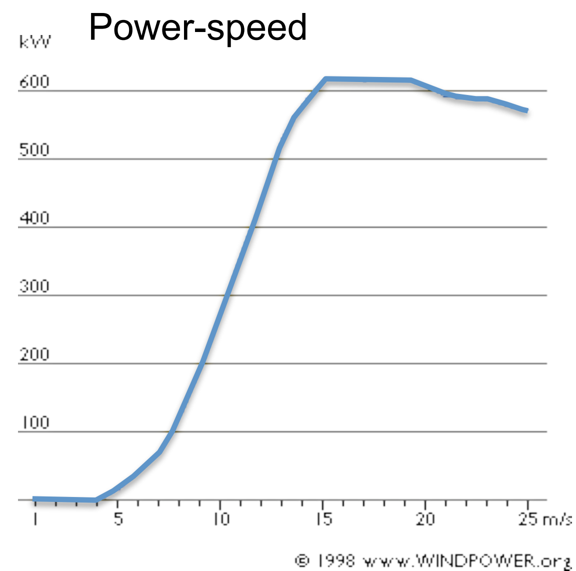
See also: G. P. Wayne, "The Beginner's Guide to Representative Concentration Pathways", en Skeptical Science: http://www.skepticalscience.com/docs/RCP_Guide.pdf

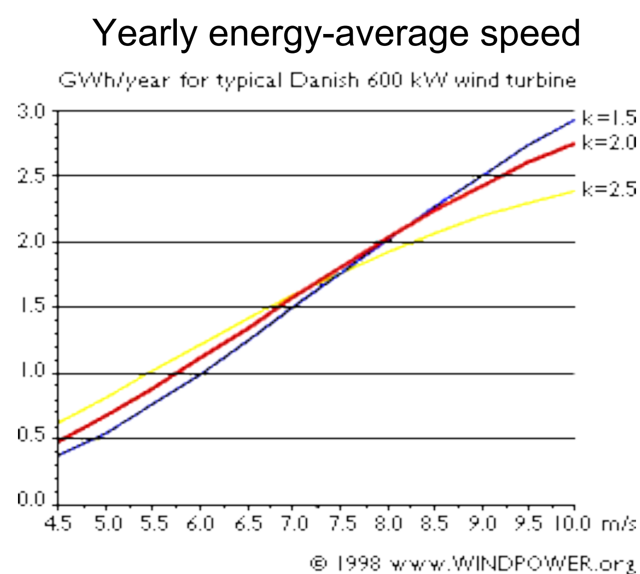
CO2 abatement urgently needed

1. Massive **renewable penetration** in energy mix
2. **Electrification** of most energy uses
    - Electric transportation
    - Cooling & heating
    - Industrial processes
3. Energy **efficiency**
    - Industry, buildings, appliances
4. Carbon capture & storage **??**
5. New generation of bio fuels **?**
6. New generation of fission reactors **?** Fusion **??**

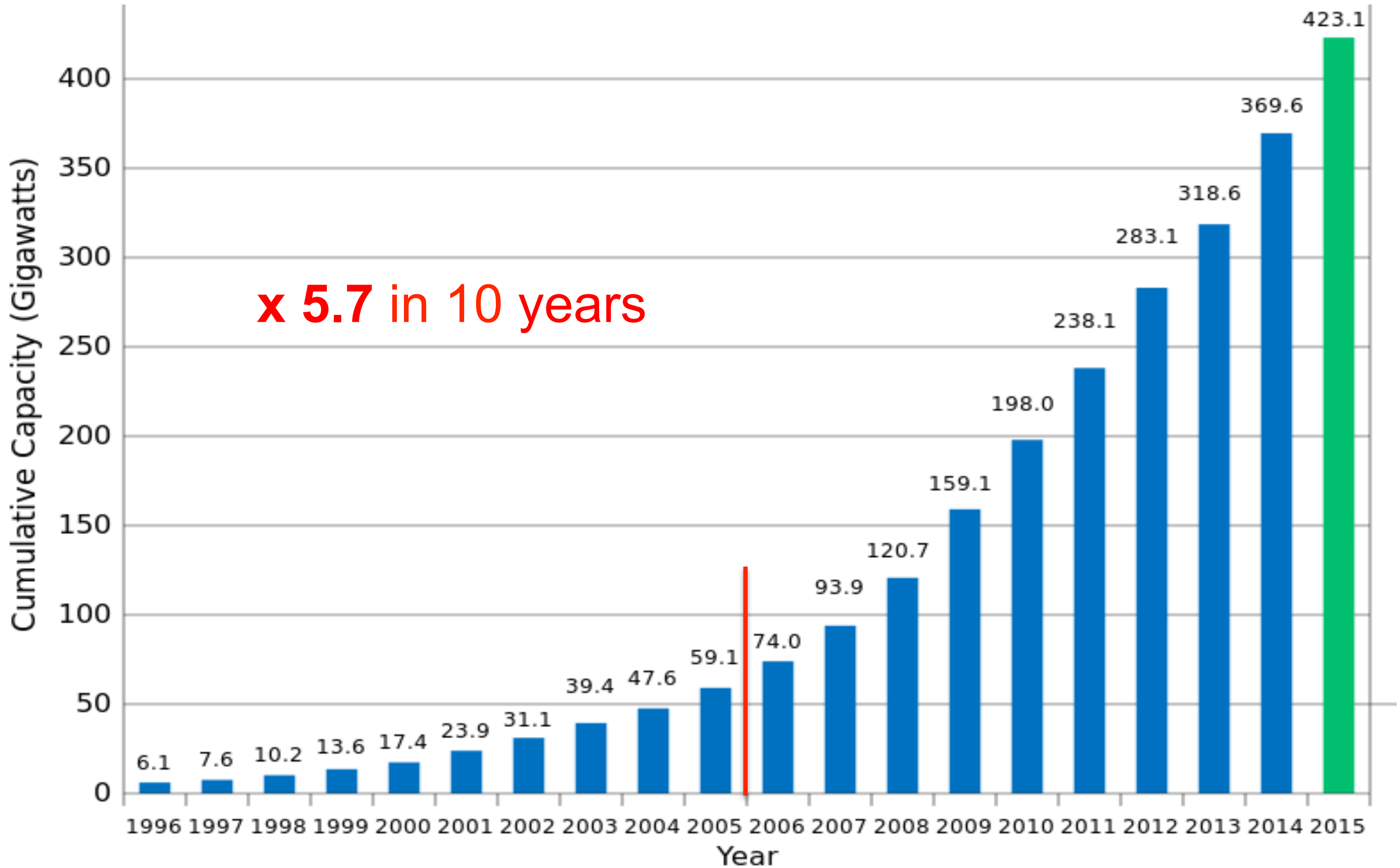
Wind Energy: the pioneers

27.000 turbines in Germany
(1.7MW average power)



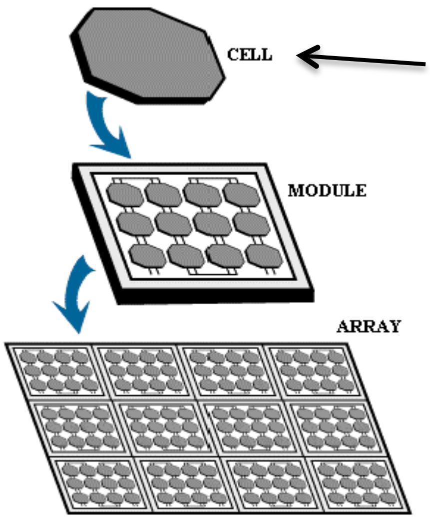


Global installed capacity: wind



Typical power density (at 6 m/s): 2 W/m^2

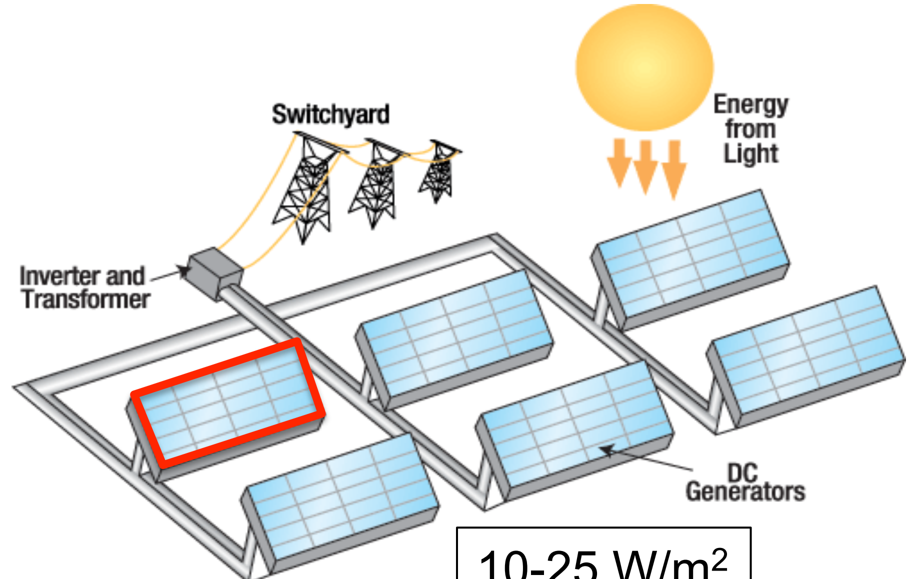
Photovoltaics: "power to the people"



6cm ⃠
0,5A-0,5V
90W/m^2

Modular

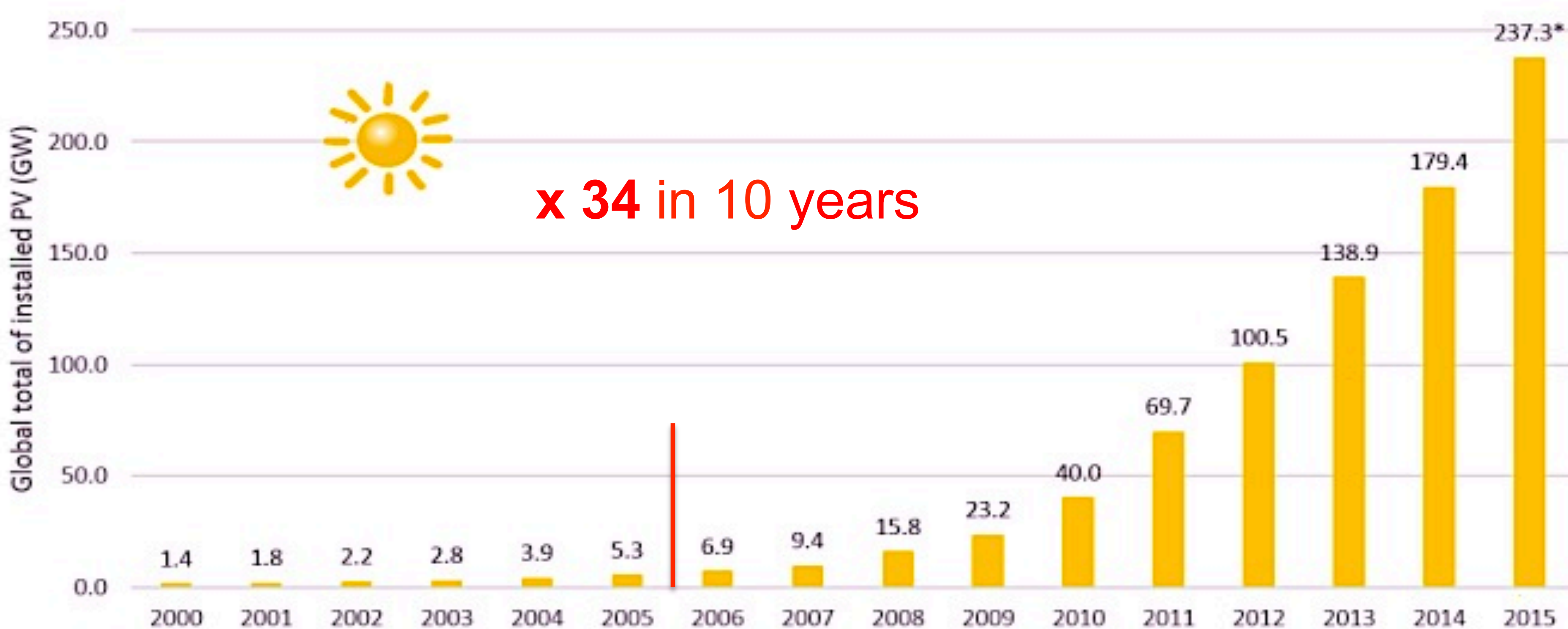
Highly scalable



10-25 W/m^2

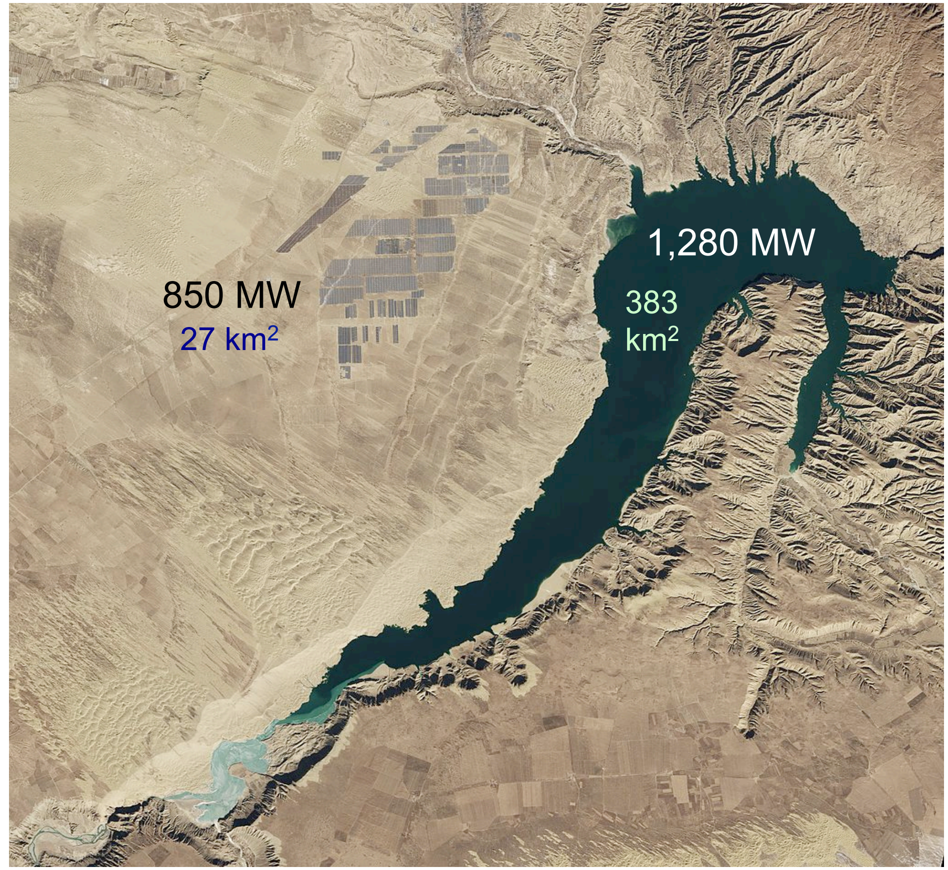
Global installed capacity: PV

The photovoltaic *“boom”*



(number of smartphones: x 17)

Large-scale PV (centralized)



Record since 2015: 850 MW, Longyangxia Dam Solar Park (China), 4 million panels, 27 km^2 (11% capacity factor)

New record 2017: 900 MW, Kurnool Ultra Mega Solar Park (India)

Small-scale PV (distributed)

Distributed vs centralized: influence of local regulation and policy

Germany: 80% distributed, 20% centralized

Spain: 80% centralized, 20% distributed

Examples of renewable penetration

- **Denmark: annual** wind record in 2015: 42% of demand (37.6% in 2016, after seven years of growing share)
- **Germany: monthly** renewable record, 44% of demand (October 2017)
- **Portugal: 4 consecutive days**, 100% hydro, wind and solar (May 7-10, 2016)
- **Germany: hourly** renewable record, 78% of demand (July 25, 2015, from 14-15h)
- **Spain: instantaneous** wind record, >70% of demand (November 21, 2015, at 4:50h)

Drastic cost reductions (maturity)

Canada (Ontario)

- 1299.5 MW **Wind** at ~USD 66/MWh[a]
- 140 MW **Solar** at ~USD 120/MWh
- 15.5 MW **Hydro** at ~USD 135/MWh

USA

- 26 MW **Solar** at USD 26.7/MWh

Mexico

FIRST AUCTION

- 620 MW **Wind** at ~USD 54.3/MWh
- 1 100 MW **Solar** at ~USD 44/MWh

SECOND AUCTION

- 1038 MW **Wind** at ~USD 36.2/MWh
- 1 853 MW **Solar** at ~USD 32.8/MWh

Denmark

- 600 MW **Offshore Wind** at USD 53.9/MWh

Netherlands

- 700 MW **Offshore wind** at ~USD 80.4/MWh

Morocco

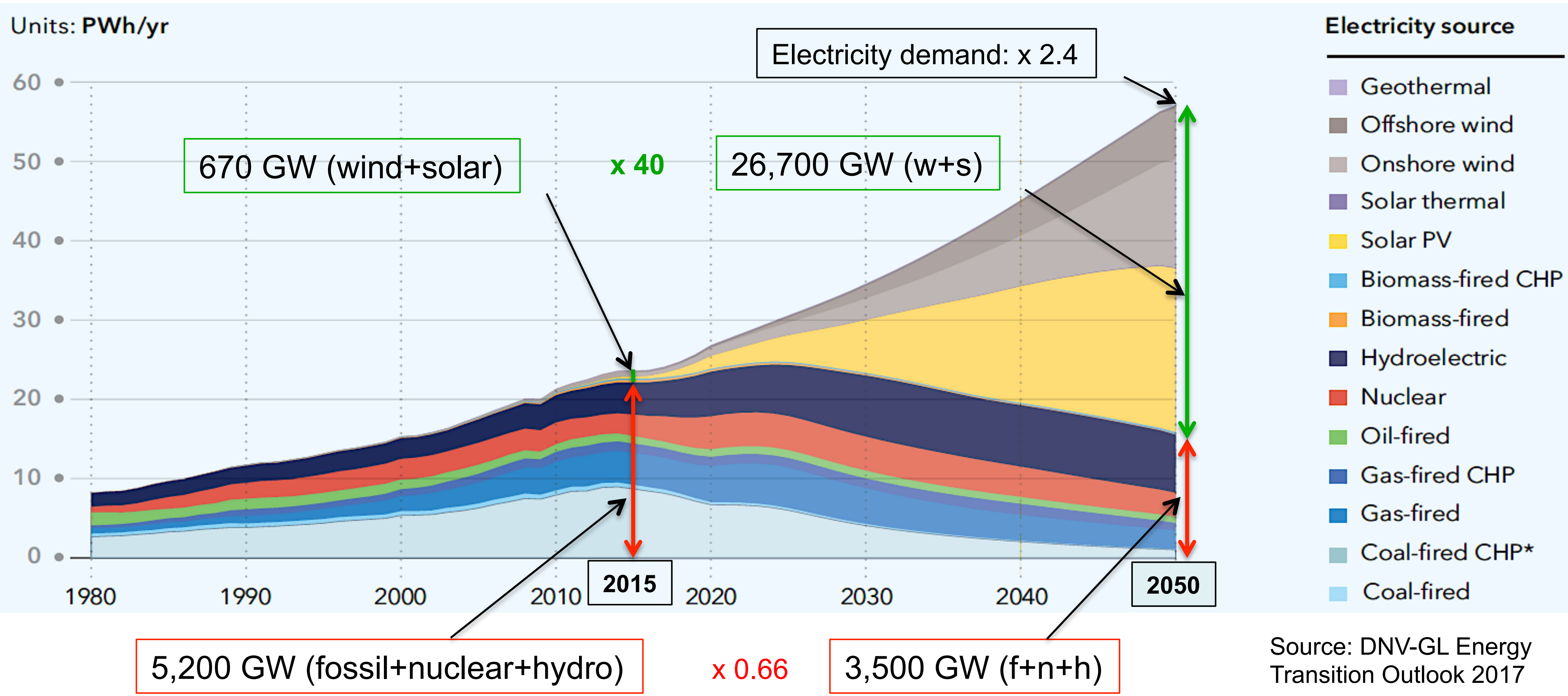
- 850 MW **Wind** at ~USD 30/MWh

LCOEs according to IRENA 2016 ($/MWh)

	Min	Mean
PV	53	131
On-shore wind	24	56
Off-shore wind	96	123
CSP-PTC	182	242

http://resourceirena.irena.org/gateway/dashboard/?topic=3&subTopic=1057

Main challenge: huge investments ahead

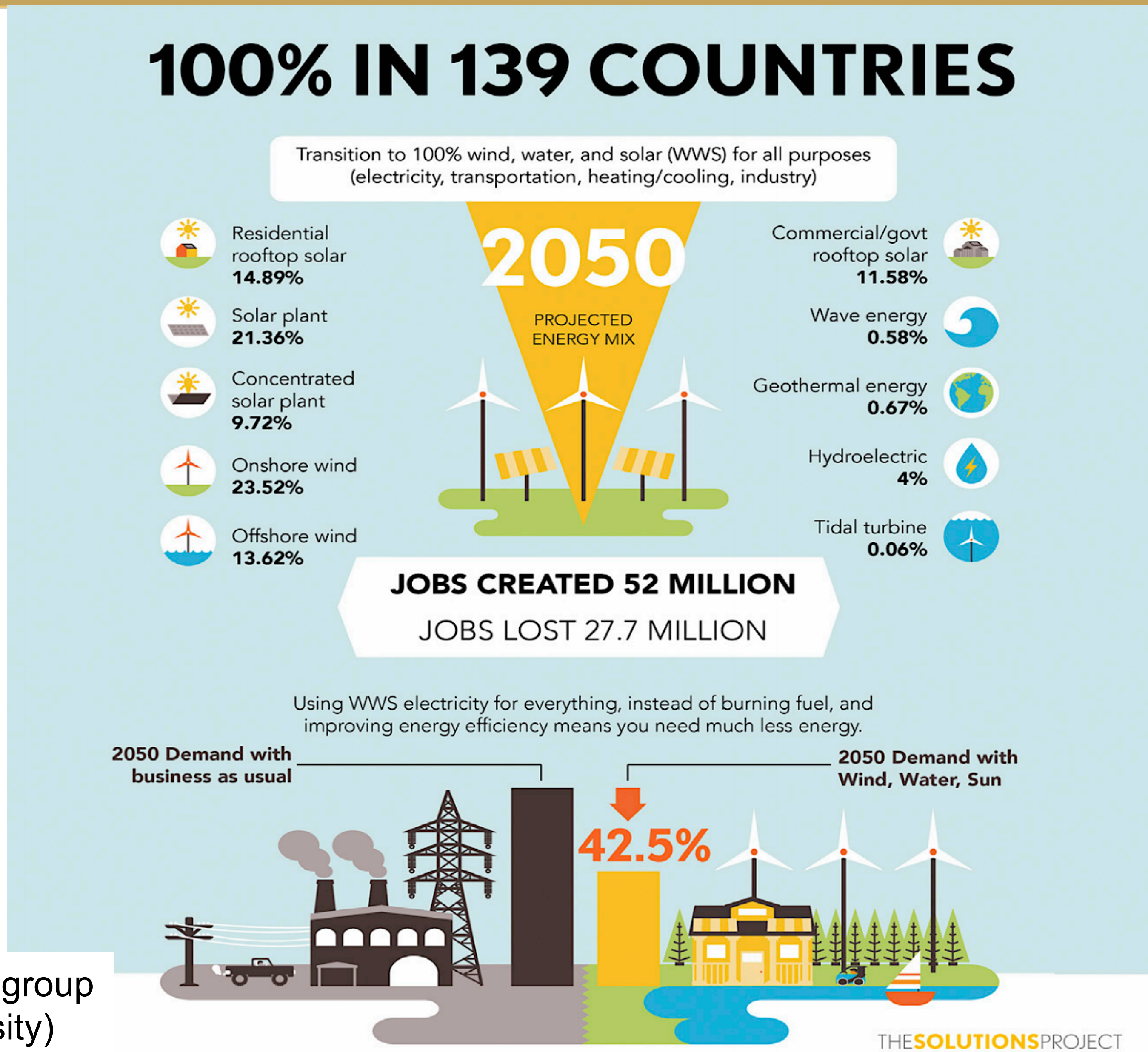


Source: DNV-GL Energy Transition Outlook 2017

Wind+solar average growth rate needed: **750 GW/year** **(1,000 billion/year?)**

(installed capacity in 2016: **132 GW**)

Towards a 100% renewable world?



Prof. Jacobson's group
(Stanford University)

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Technical challenges: generation

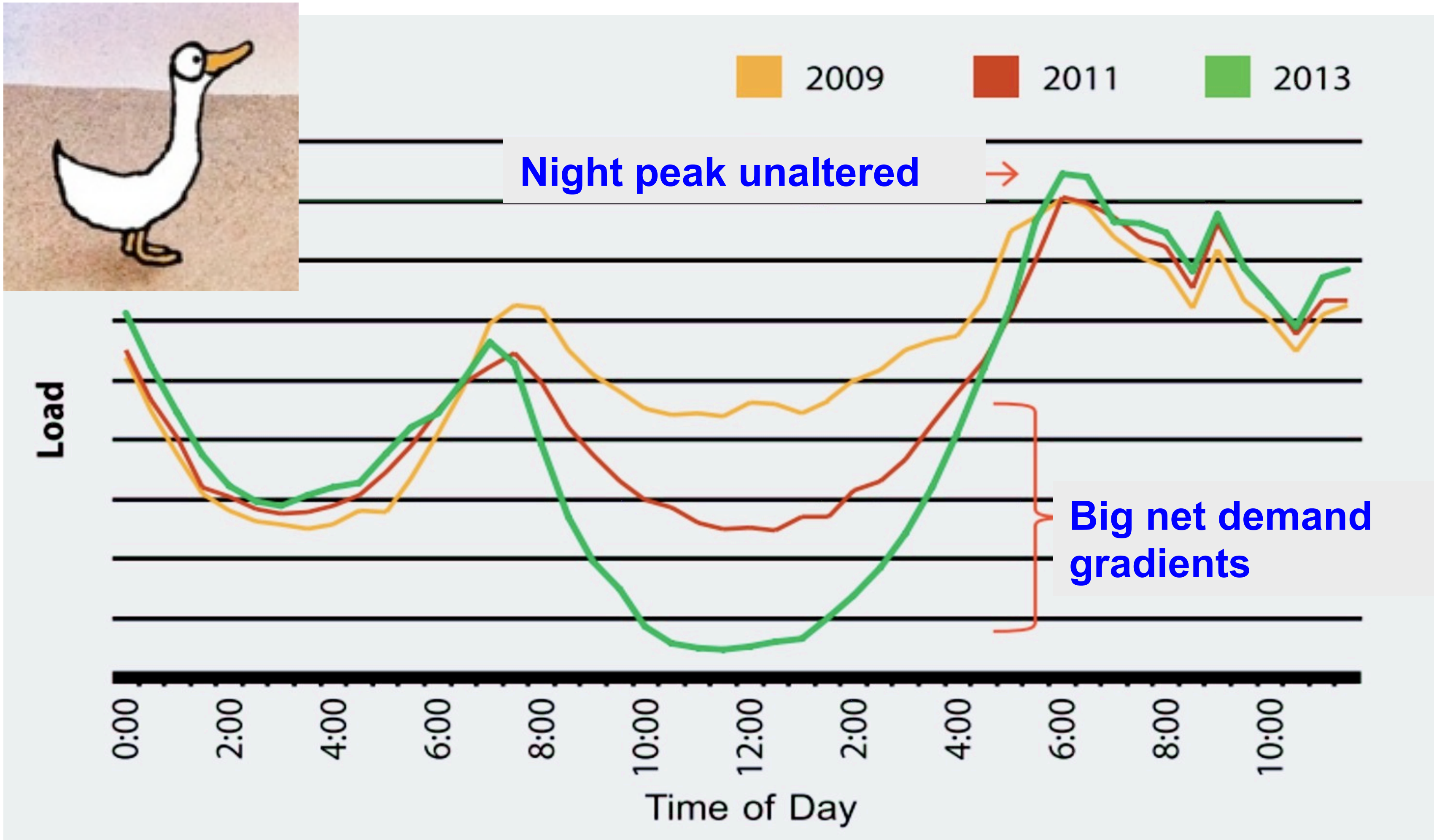
- **Real time:** frequency regulation
  - Low or null inertia
  - No contribution to synchronizing power
  - Limited capability to regulate P (decrease only?)

- **Daily energy balance** (short term)**:**
  - Production uncorrelated with demand
  - Much larger and more frequent net demand gradients

- **Seasonal energy unbalance** (long term)**:**
  - Surplus of solar energy in summer and shortage in winter

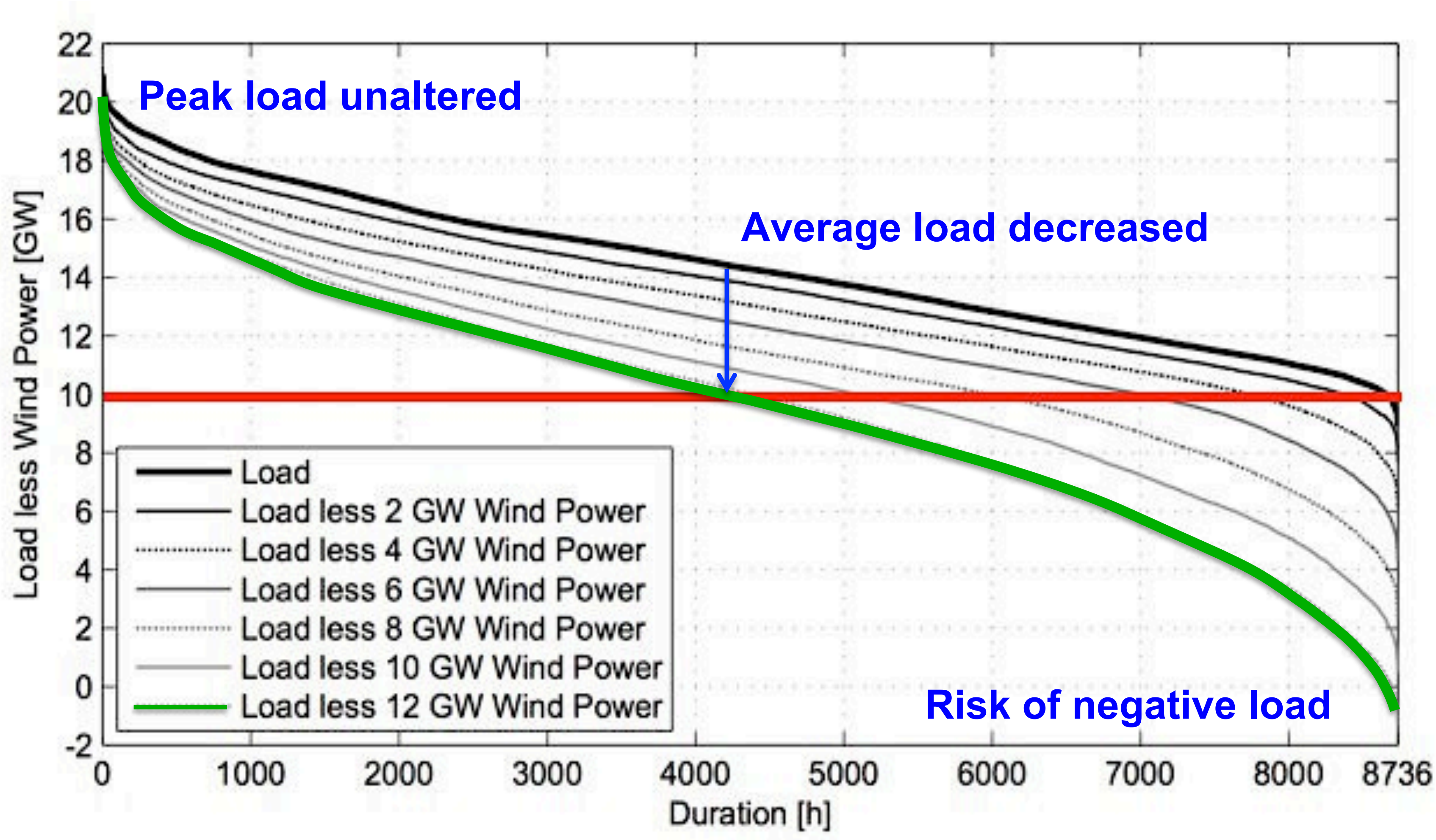
- **Wholesale markets:**
  - Not designed for high renewable penetration (negative prices)

PV effect on net load demand (Australia)



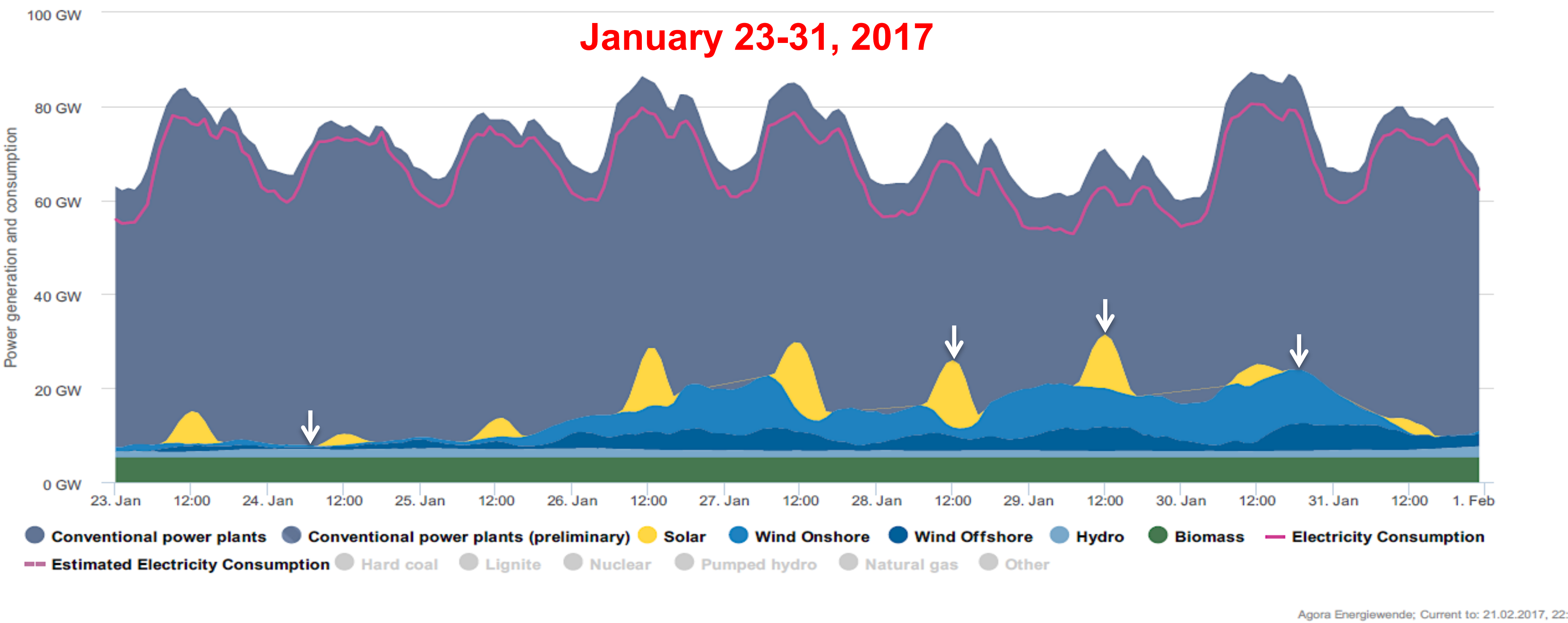
Wind effect on net load demand

Typical load-duration curve (Sweden, Poland)



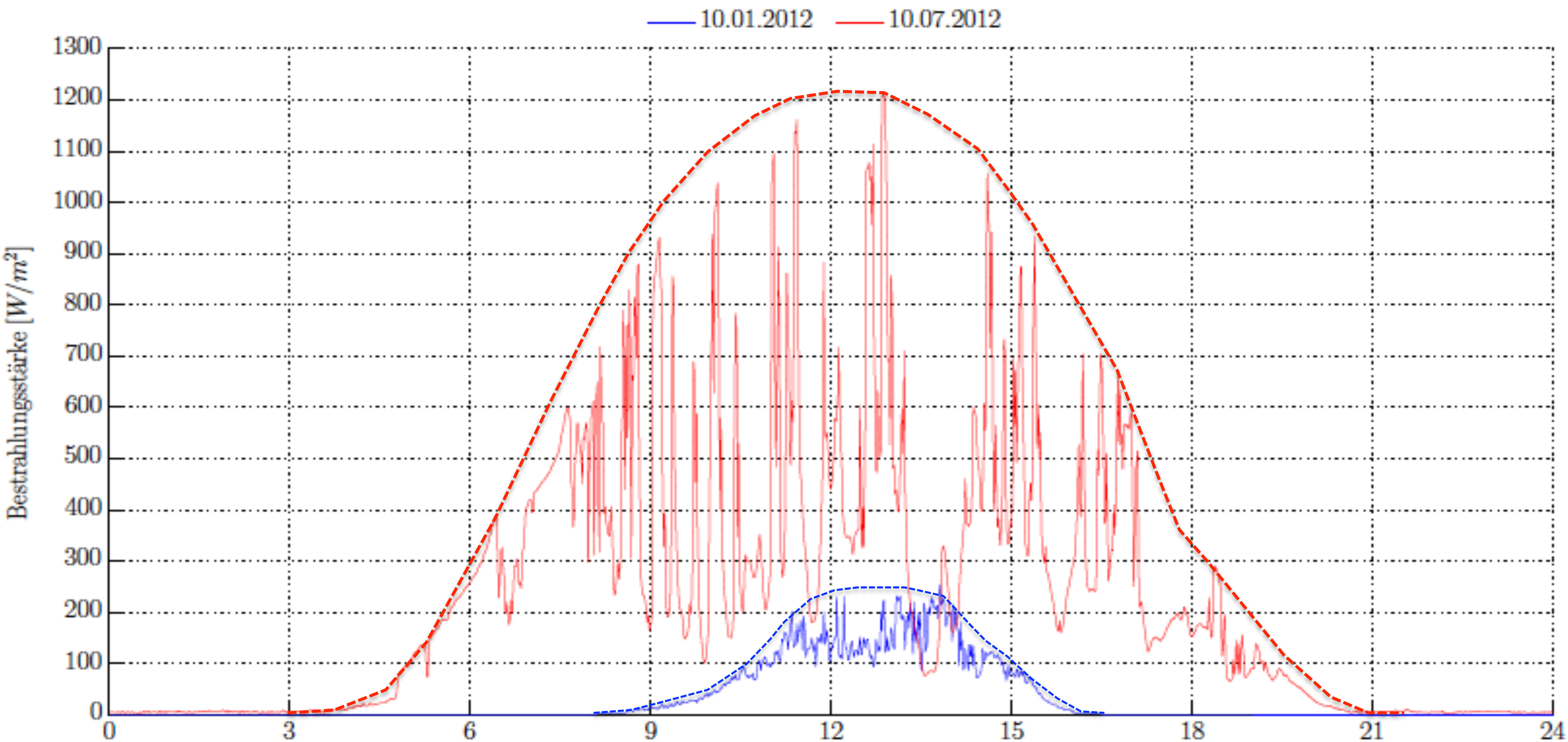
Production uncorrelated with demand (Germany)

Installed power end of 2016 — PV 40 GW (6.9% energy share); Wind 46 GW (14.2% energy share)



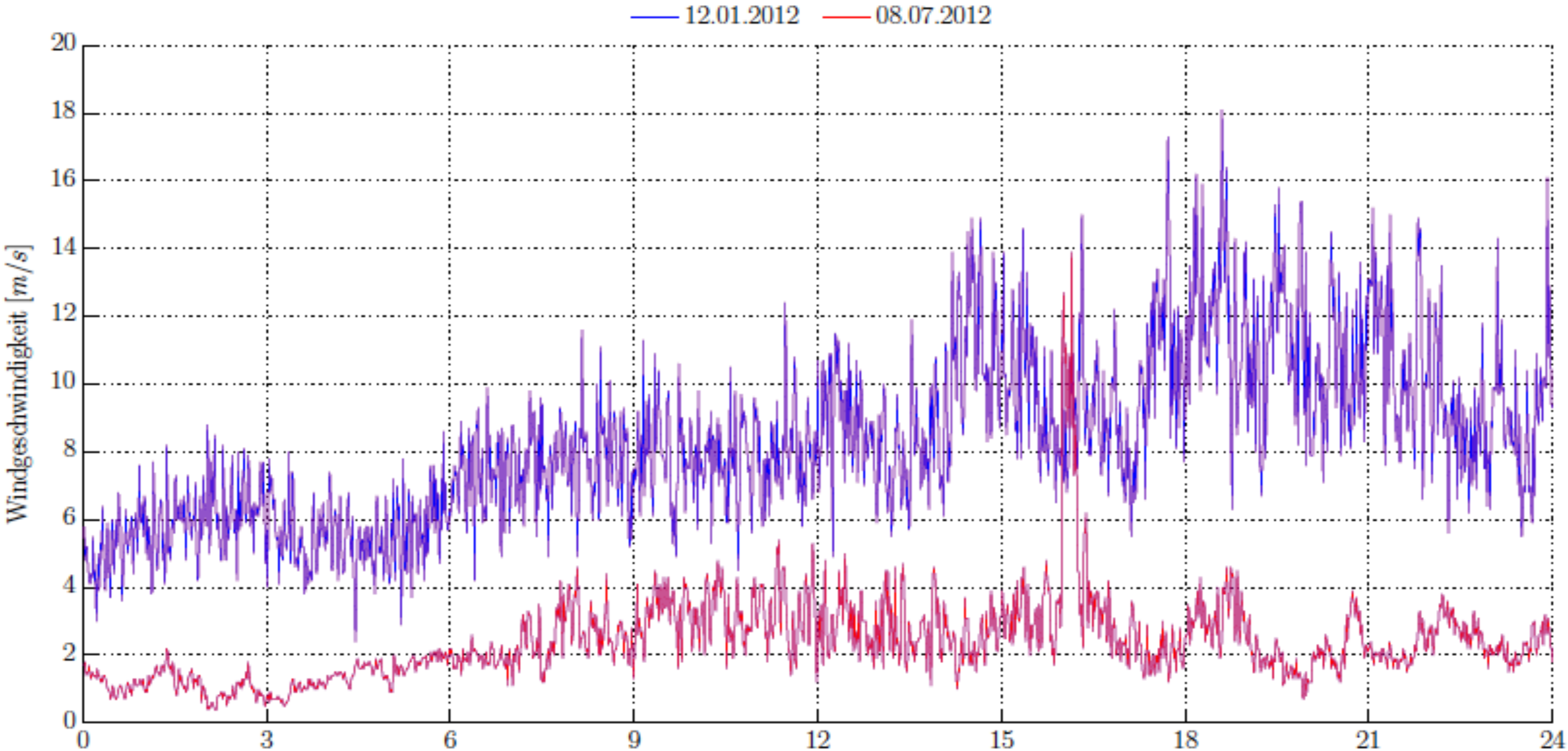
Source: Agora Energiewende

The seasonal imbalance (Germany)



Solar radiation in January and July

The seasonal imbalance (Germany)



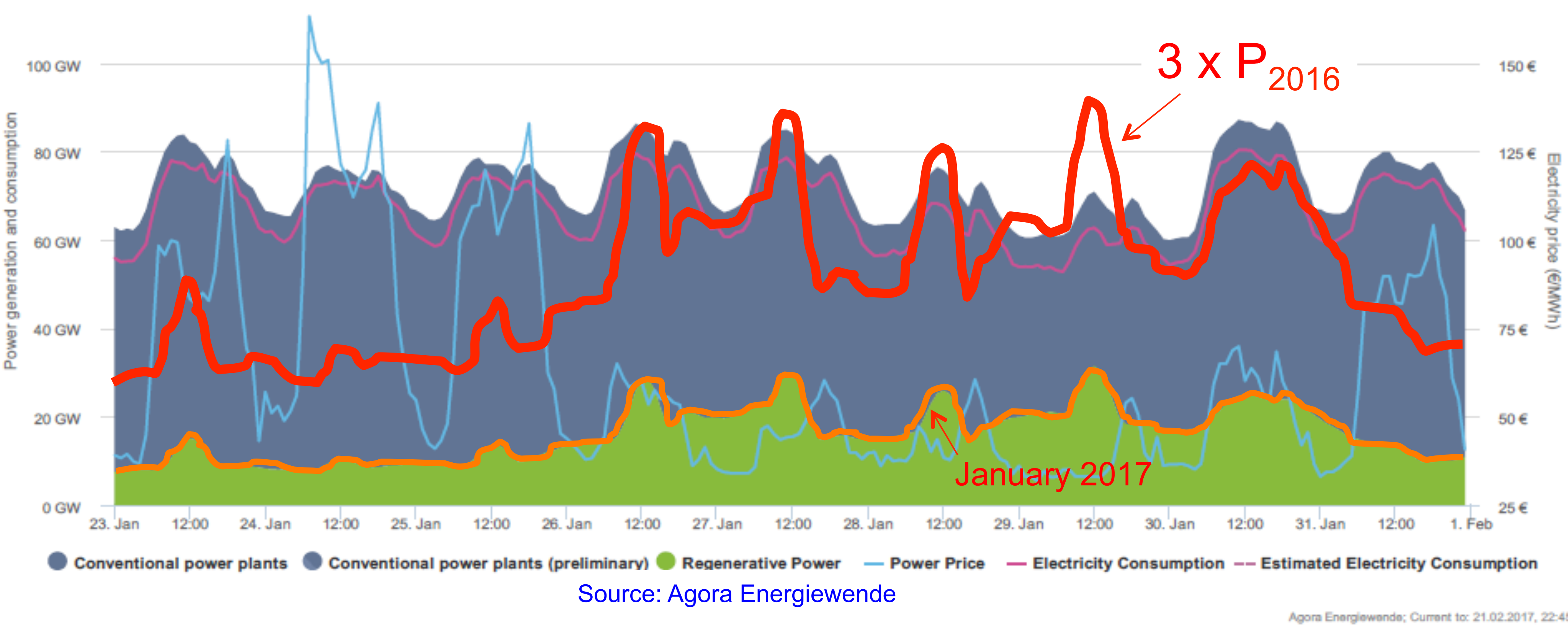
Wind speed in January and July

The seasonal imbalance (Germany)

Forecasted capacity around 2040
(3 times that of 2016)

PV	120 GW	(20% energy share)
Wind	150 GW	(45% energy share)

Assuming same demand and production pattern as in 2017



Source: Agora Energiewende

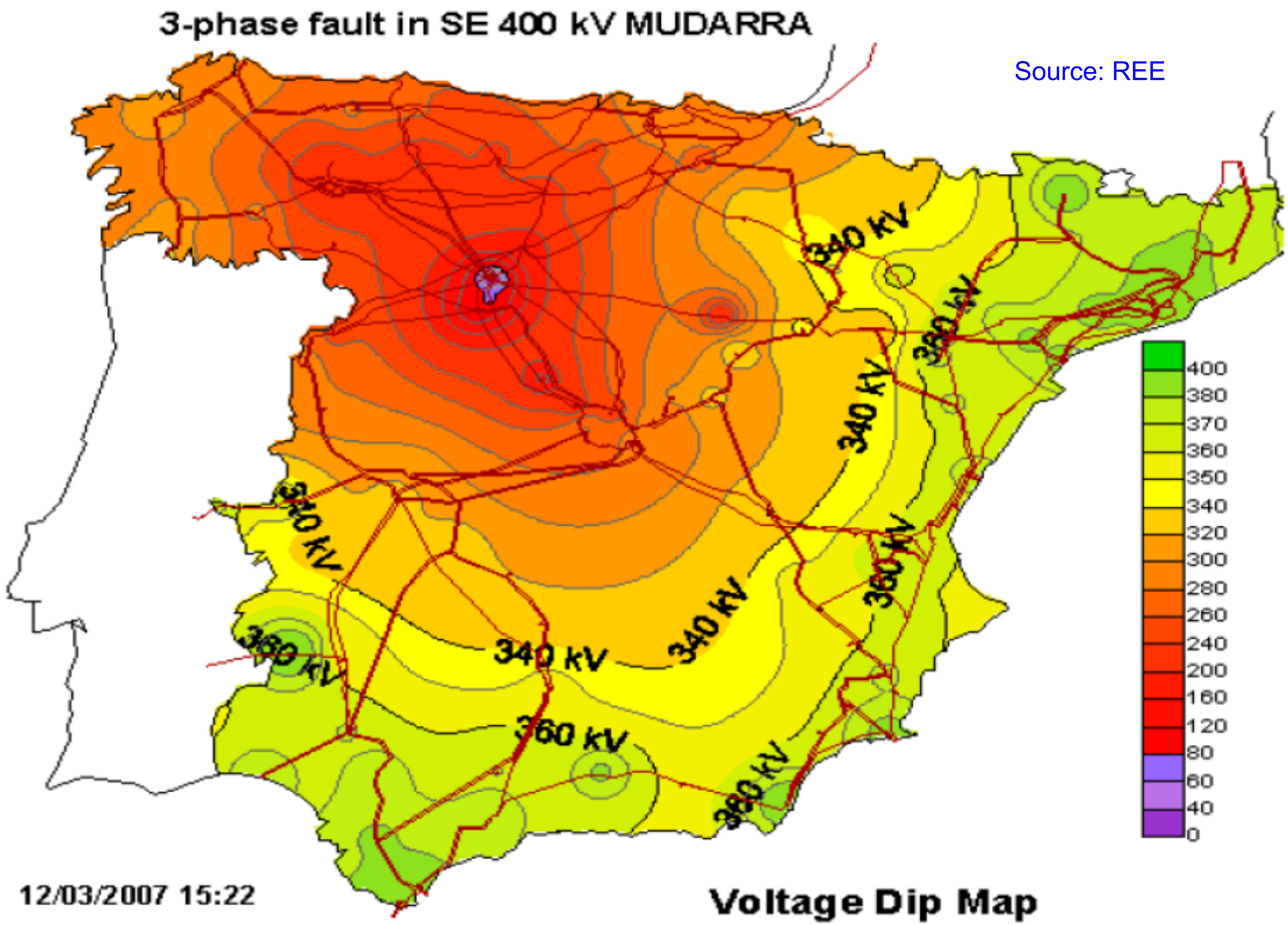
Technical challenges: transmission

- **Longer distances between generation and major load centers**
  - Huge investments needed in grid assets (HVDC)
- **System stability threatened:**
  - Sudden disconnections (voltage dips, strong winds, clouds)
  - Limited Q-V control capability (smarter interfaces)
- **Network congestions** (loop flows)
  - Need for more control devices (FACTS, phase shifters)

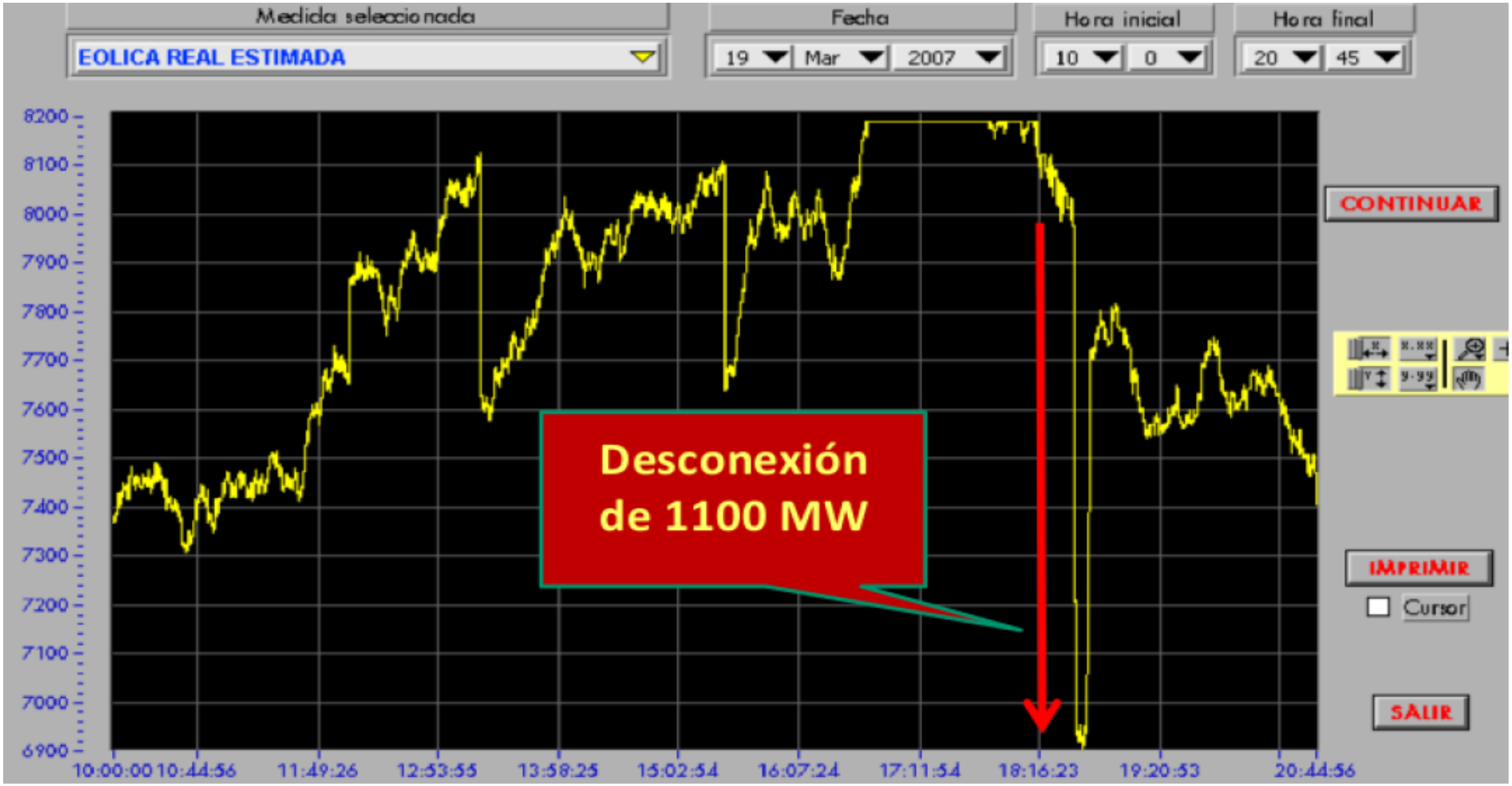
↓

Ancillary services (flexibility)
Higher costs

Example of voltage dip



Consequence of voltage dip (early days)



Source: REE

Consequence of multiple voltage dips (today)

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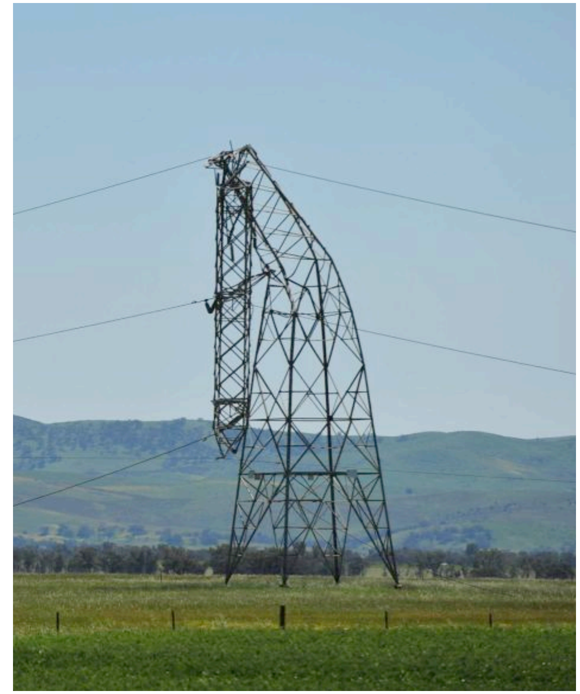
Renewable energy mix played role in SA blackout, third AEMO report confirms

By Nick Harmsen

Updated 12 Dec 2016, 2:01pm

South Australia's renewables-heavy power mix was a factor in the statewide blackout in September, a new report by the Australian Energy Market Operator (AEMO) has confirmed.



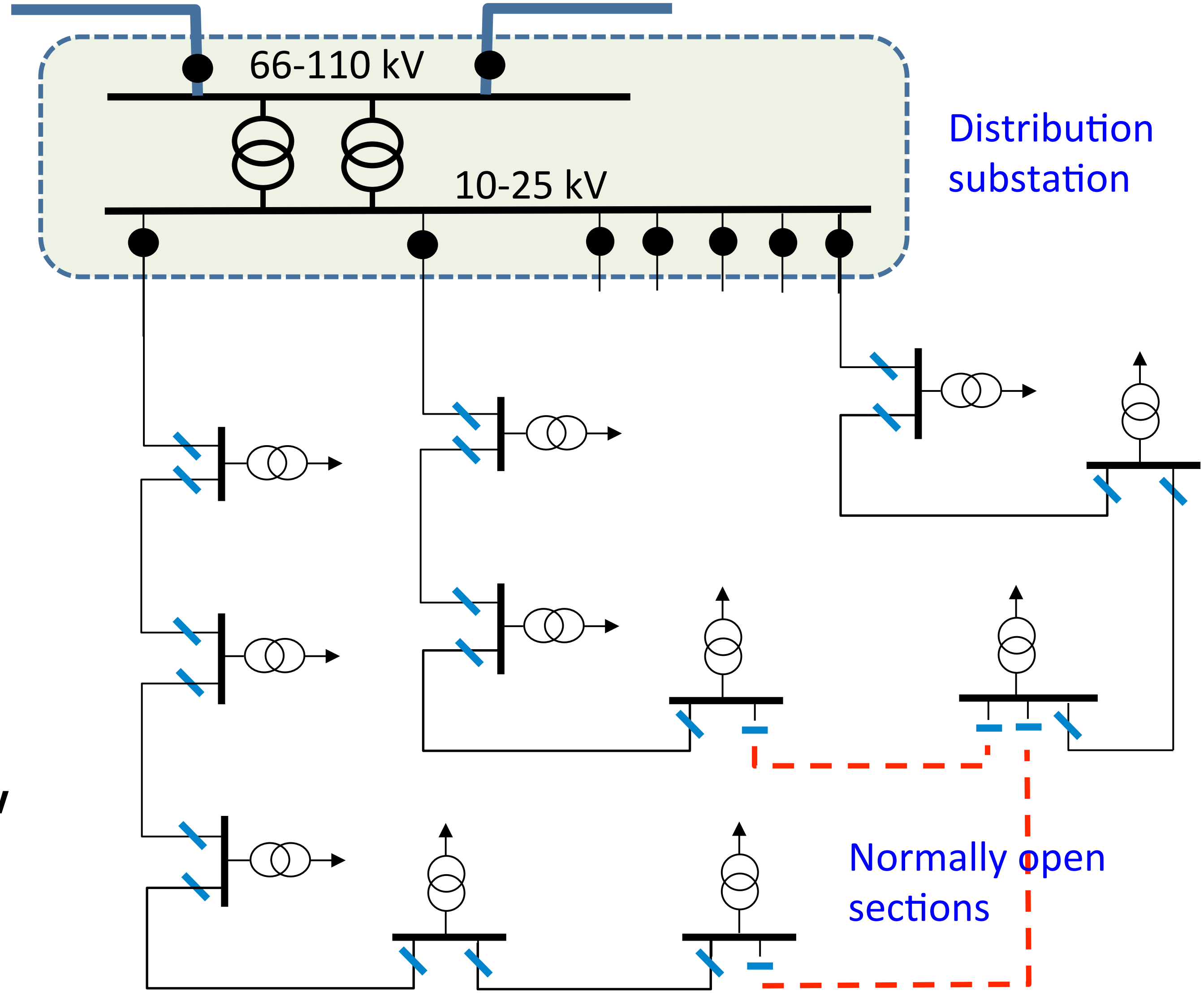
- 880MW wind, 330MW thermal and 613MW interconnection with New South Wales
- Severe thunderstorms with many tornados
- Many HV poles destroyed (interconnector off)
- **Several voltage dips**: 460MW wind lost

Full blackout in South Australia (1.7 mill. people)

Technical challenges: distribution

Urban feeders:

- Few laterals
- **Radially operated** (normally-open switches)
- **Spare feeder capacity** (temporary support under faults)
- Designed and operated for **unidirectional** power flows
- Passive loads: relatively **low simultaneity coefficients** (oversized feeders)



Technical challenges: distribution

DG and EV:

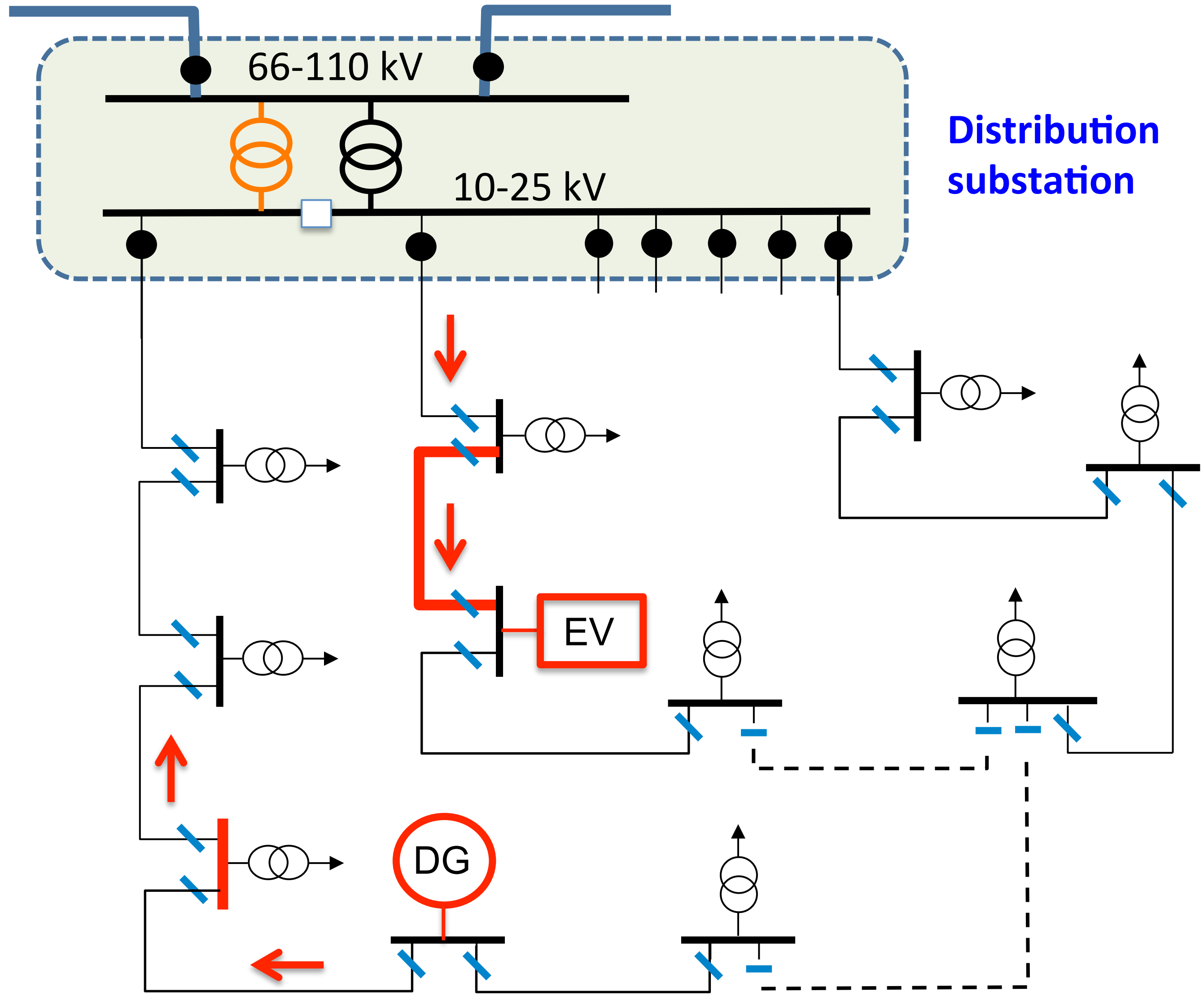
- Bidirectional flows
- **Much higher simultaneity coefficients**

Congestions:

- Ampacity
- Voltage violations
- Primary transformer

Short circuit levels

Protections



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Smarter renewable generators

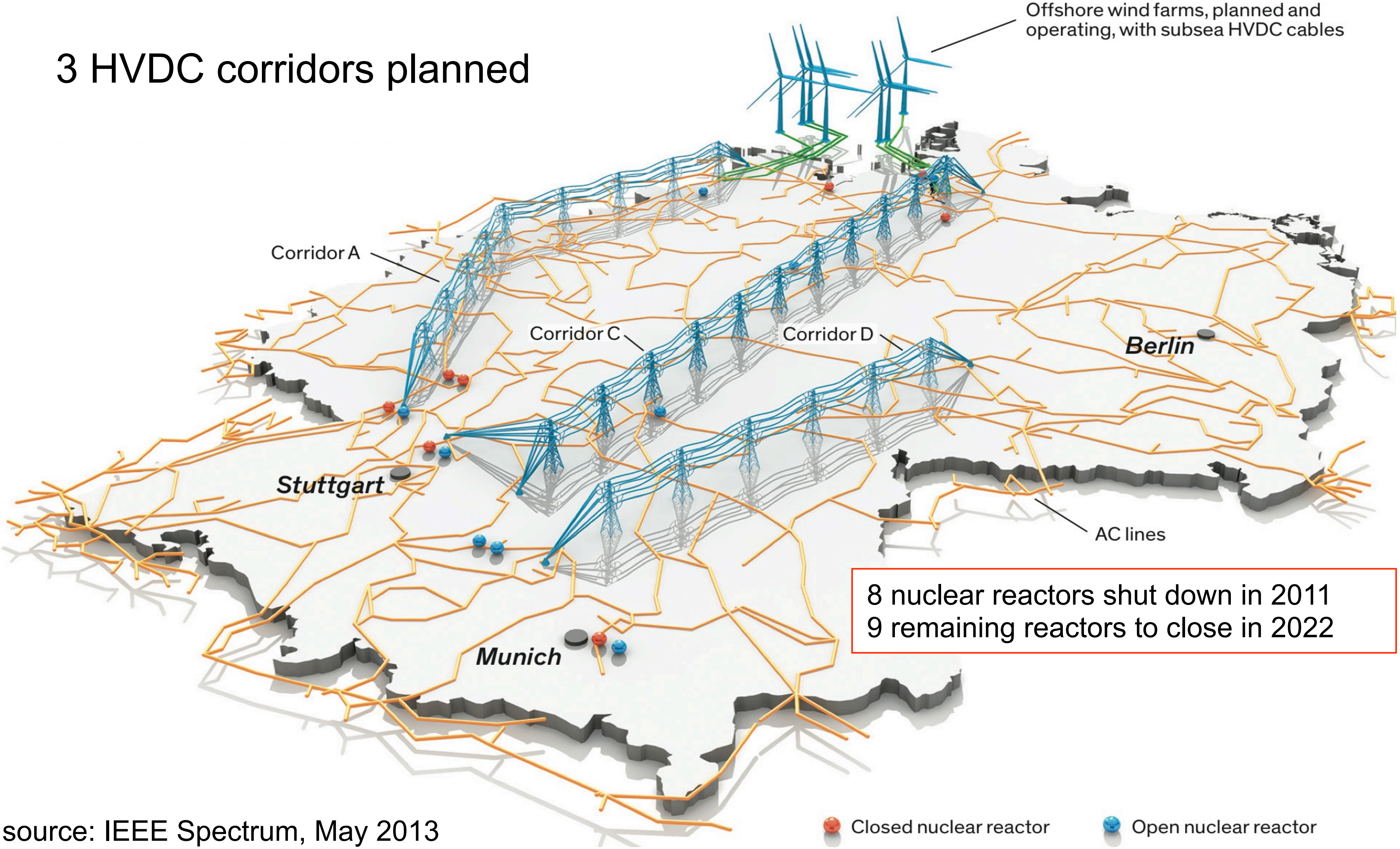
- **Contribution of renewables to ancillary services**
  - Voltage and frequency regulation
  - Emulation of synchronism
  - Black-start and grid-forming capability (microgrids)
- **Need for ubiquitous storage systems**
  - Renewables built-in storage
  - Autonomous (new agents?)

Smarter transmission grids

- **FACTS devices** and phase shifters
- **VSC-HVDC lines** (multiterminal, meshed?)
- **Supergrids:** UHV-AC & UHV-DC (overlay grids)
- **Grid codes** (standarization)
- **More advanced EMS**
    - Regional (multi-area) systems and markets
    - PMU-based WAM/WAC
- **Storage systems for ancillary services**

New HVDC links: Germany

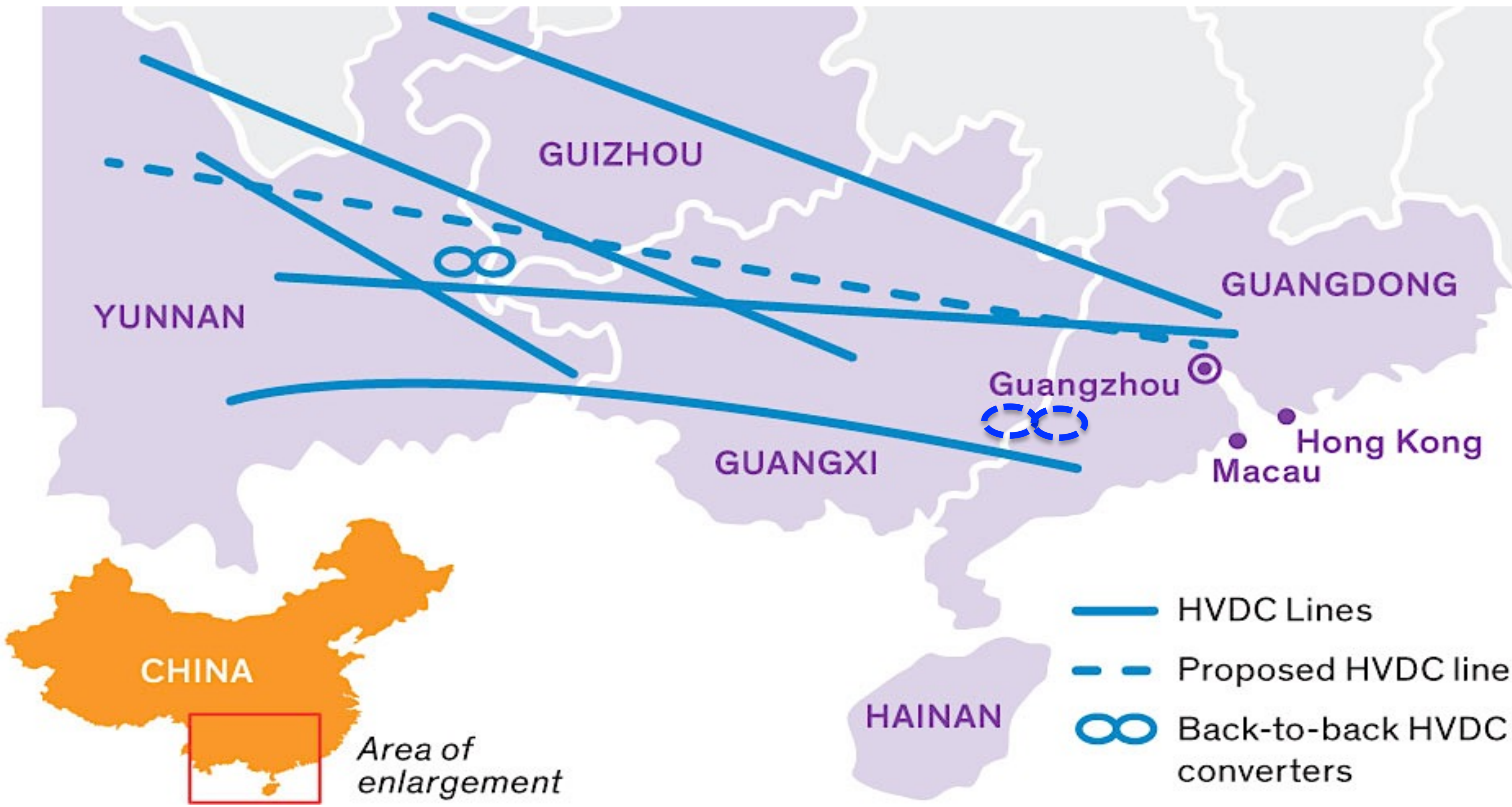
3 HVDC corridors planned



8 nuclear reactors shut down in 2011
9 remaining reactors to close in 2022

source: IEEE Spectrum, May 2013

Overlay HVDC grids: China



Why Southern China Broke Up Its Power Grid: An abundance of high-voltage DC makes big AC grids unstable, IEEE Spectrum.

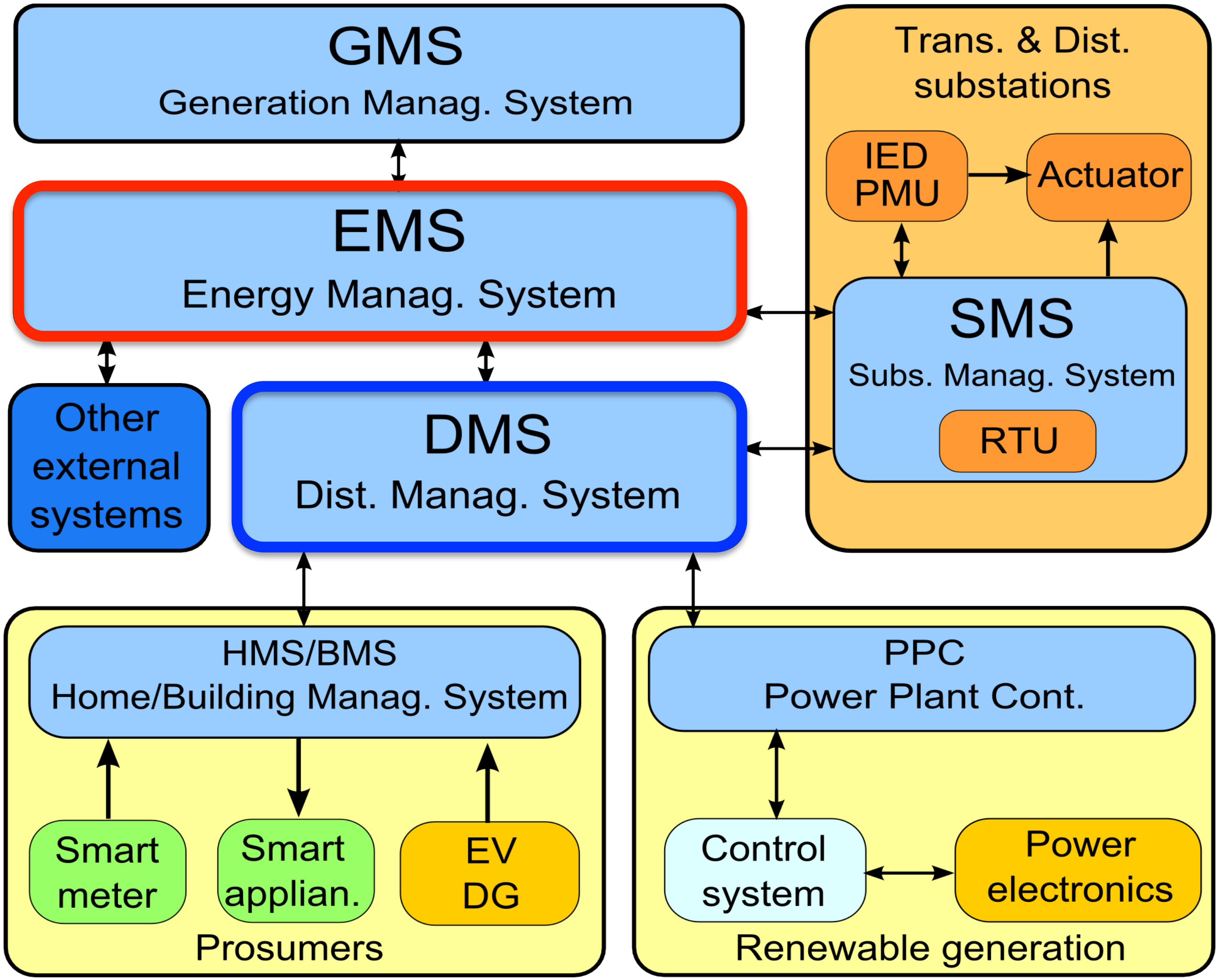
AC/DC Grids

Multiterminal HVDC systems

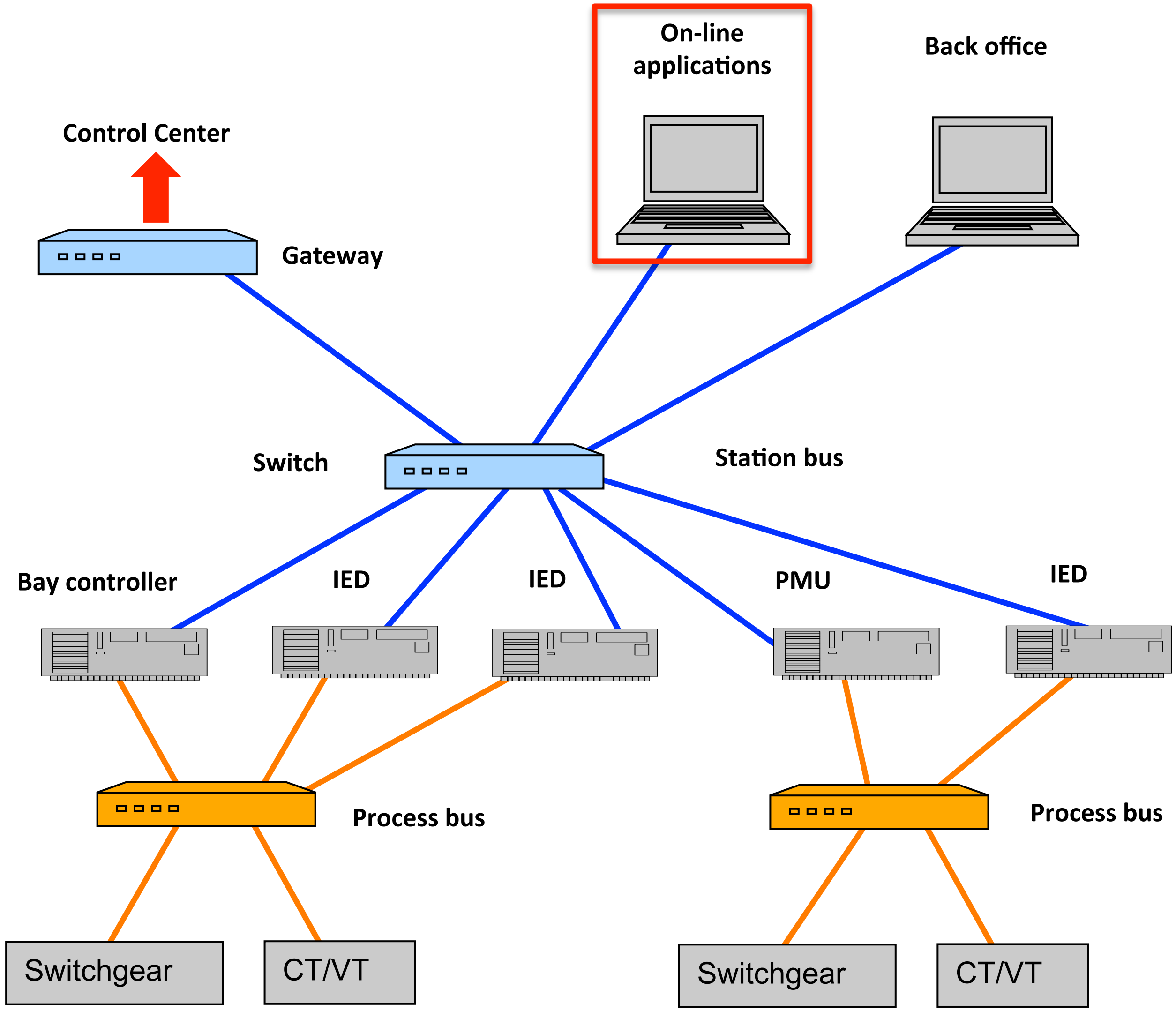
Atlantic Wind Connector: **10-terminal** ±320kV, VSC-HVDC

- Grid Congestion Causes High Electricity Prices in PJM system
- Social objections to new overhead lines
- Integration of wind energy from the Atlantic
- Increased security and reliability

New EMS roles, interactions and applications



61850-based Substation Management System



Standard for Ethernet comm. in substations (2004)

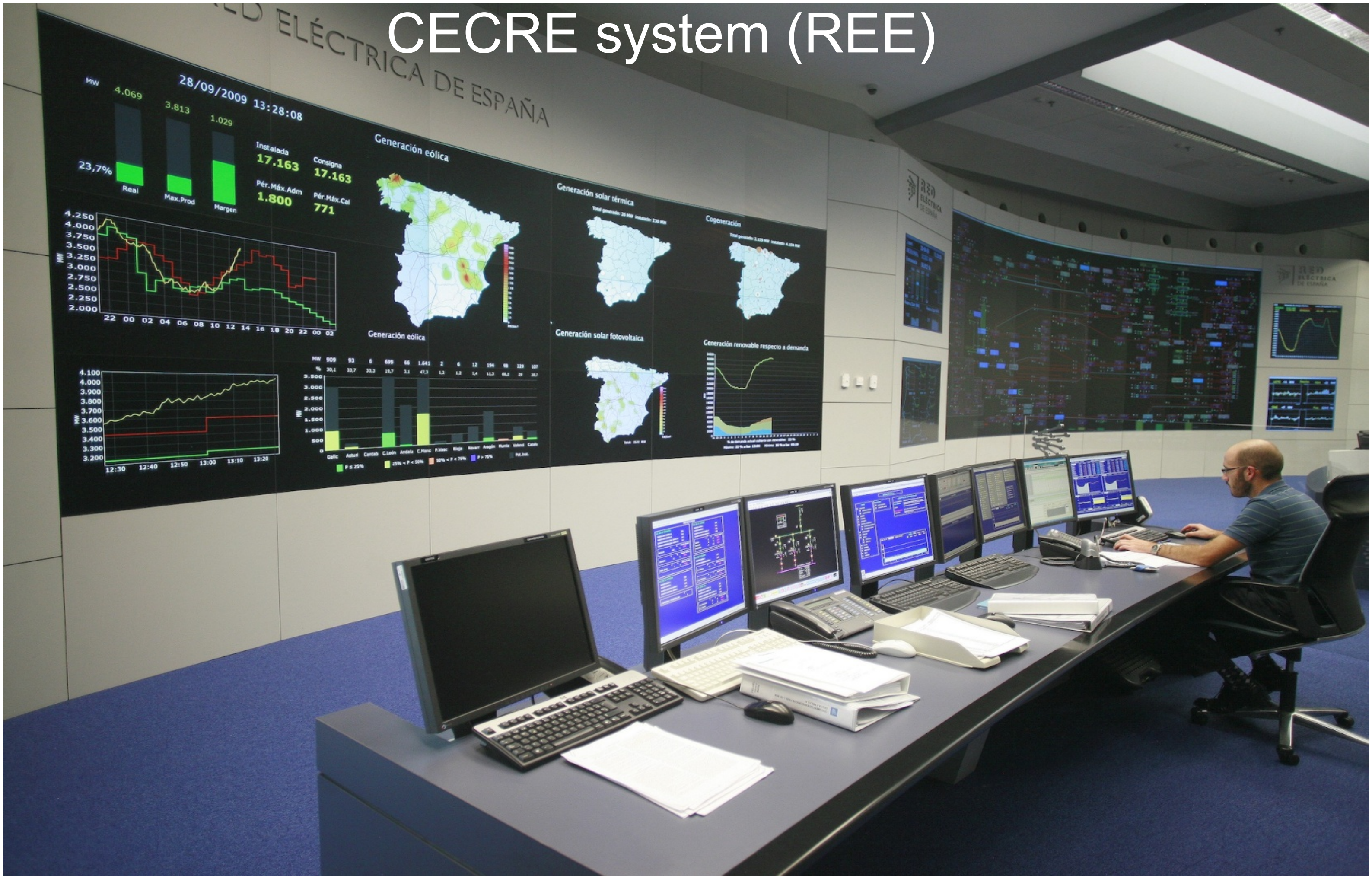
Enriched recently with IEC 61850-8-1 and 61850-9-2

Basis for a

Substation_Management System (SMS)

- Horizontal and vertical communications
- Local processing of raw information

Advanced EMS for renewable integration



Forecasting, reserves, tie-line capacity, …

Advanced EMS for renewable integration

CECRE main functions:

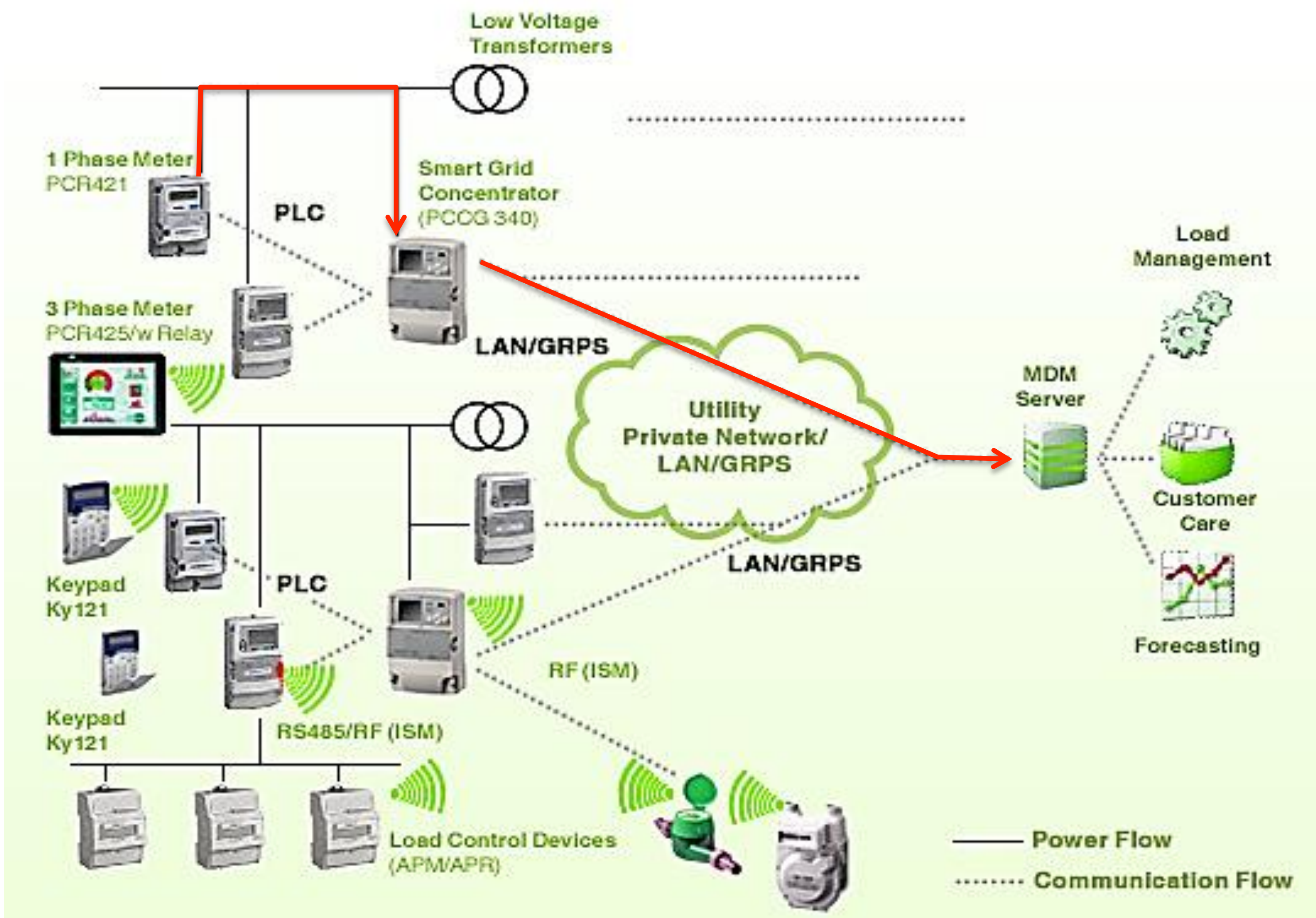
- Forecast short- and medium-term renewables production
- Monitor and track real-time renewables production (P>5MW)
- Re-schedule (reduce) renewables production (P.O. 3.7):
  - Transmission network congestions
  - Risk of transient instability after a fault (voltage dips)
  - Excessive production for the available spinning reserve (secondary & tertiary)

- Renewable facilities aggregated by transmission nodes
- International connections also closely monitored

Smarter distribution grids: a true DSO?

- **Power electronics:** D-FACTS, tap changers
- **Distribution automation**
  - *Self-healing*, dynamic feeder reconfiguration
- **Information & communication systems**
  - Smart meters, big data
- **More advanced DMS**
  - Feeder monitoring (state estimation), var & V control, losses, …
- **Demand management:** Prosumers (DG, EV), aggregators
- **Microgrids, cogeneration, local markets:** Efficiency
- **Distributed storage systems**
  - Owned by DSO or by third-parties

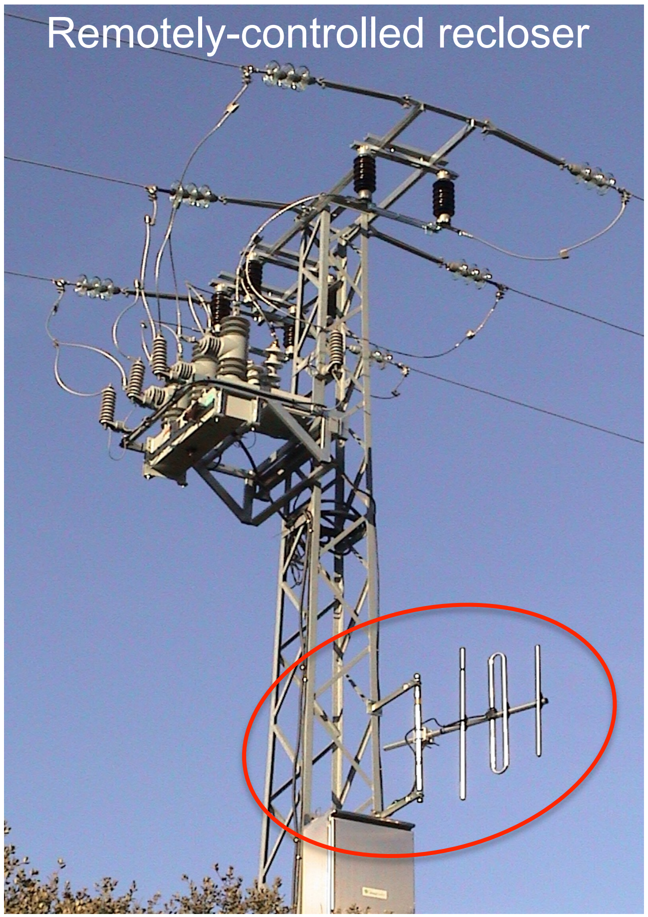
Smart meters & AMI

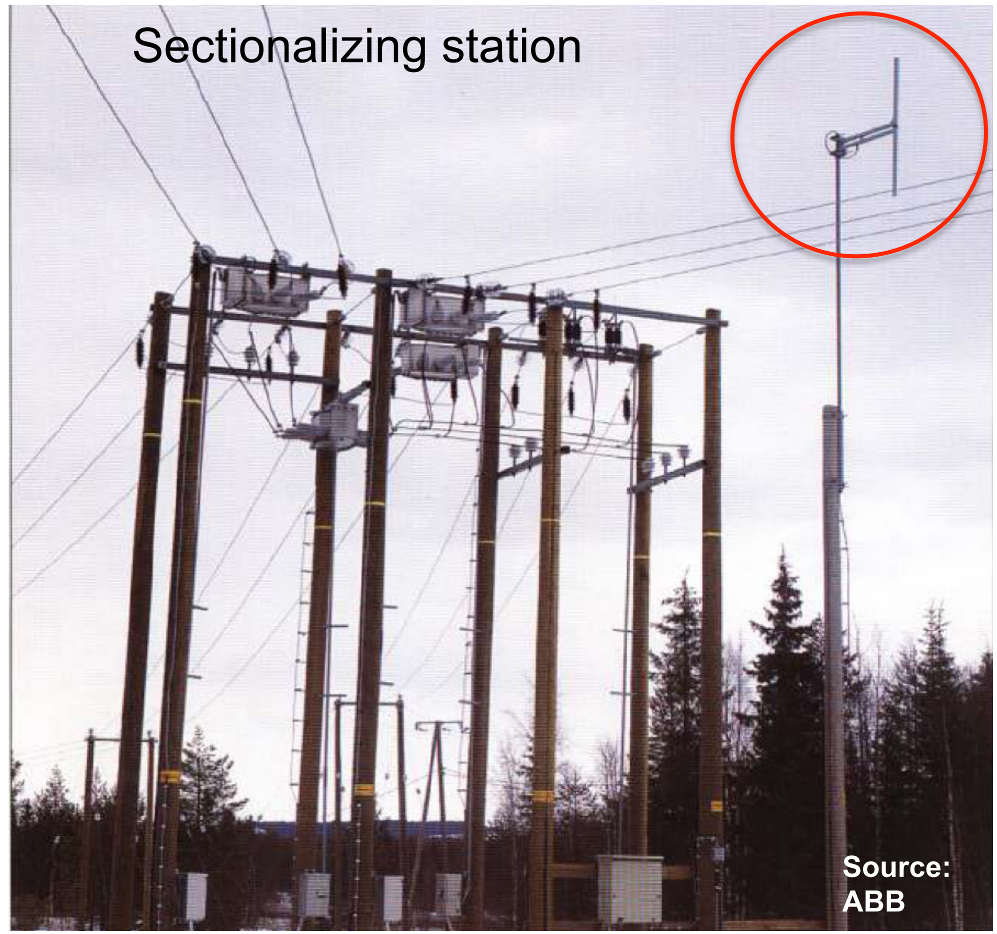


source: http://www.pcma.co.za/System-And-Services/

Distribution Automation

- New comm. channels for reclosers, fault locators,...
- At modest additional cost they can act as RTU (V & I meas.)

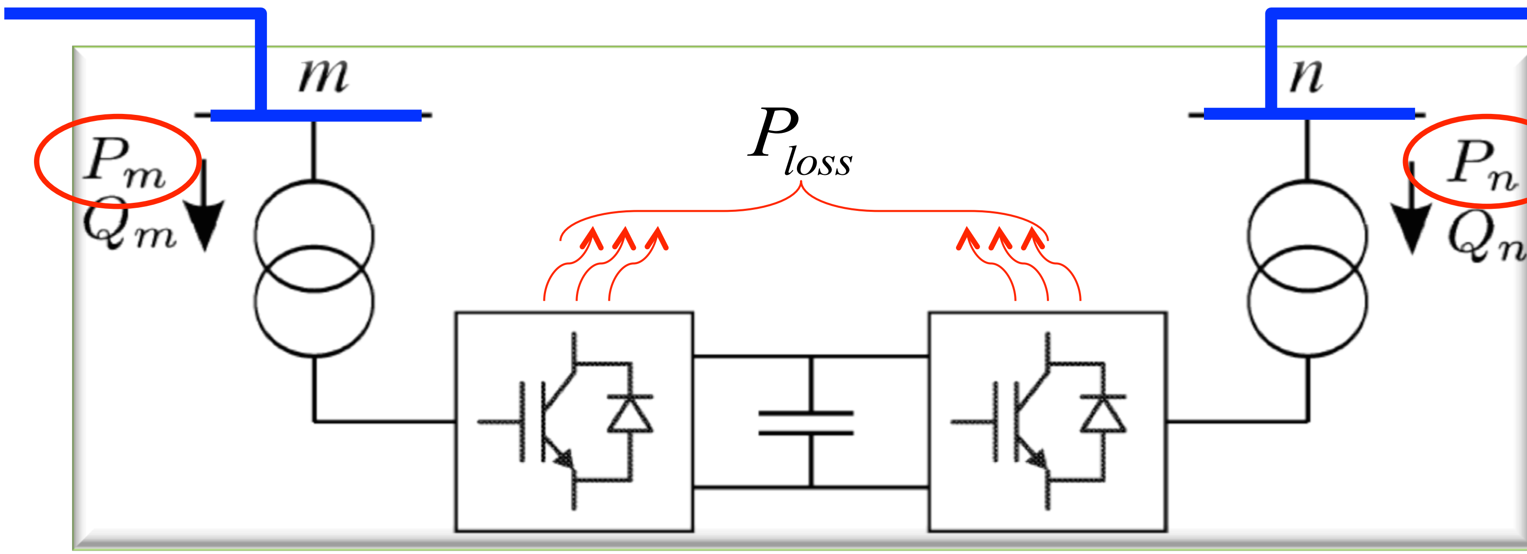




Power flow and voltage control by DFACTS

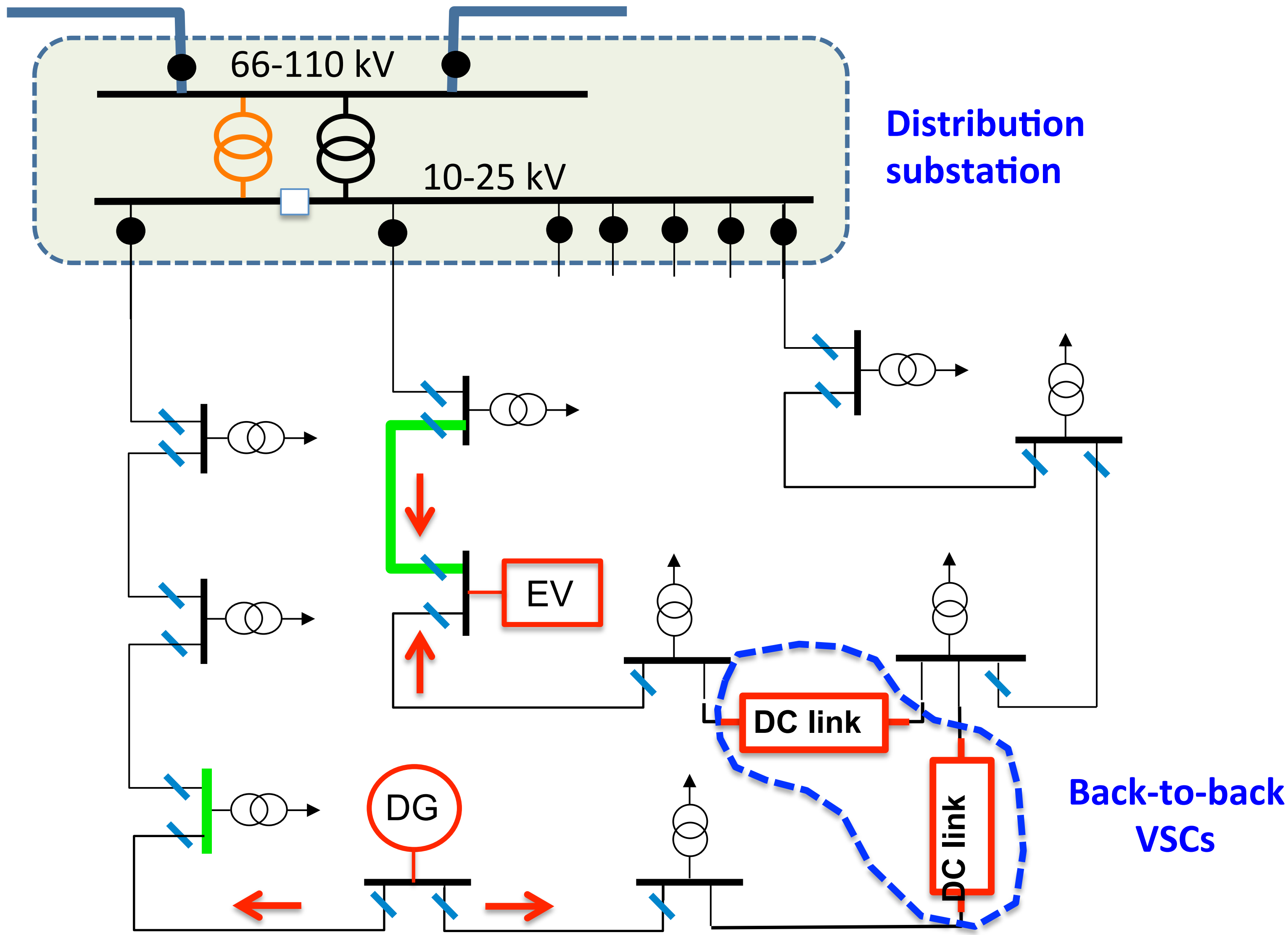
Asynchronous links between radial feeders:

Back-to-back PWM Voltage Source Converters (VSC)



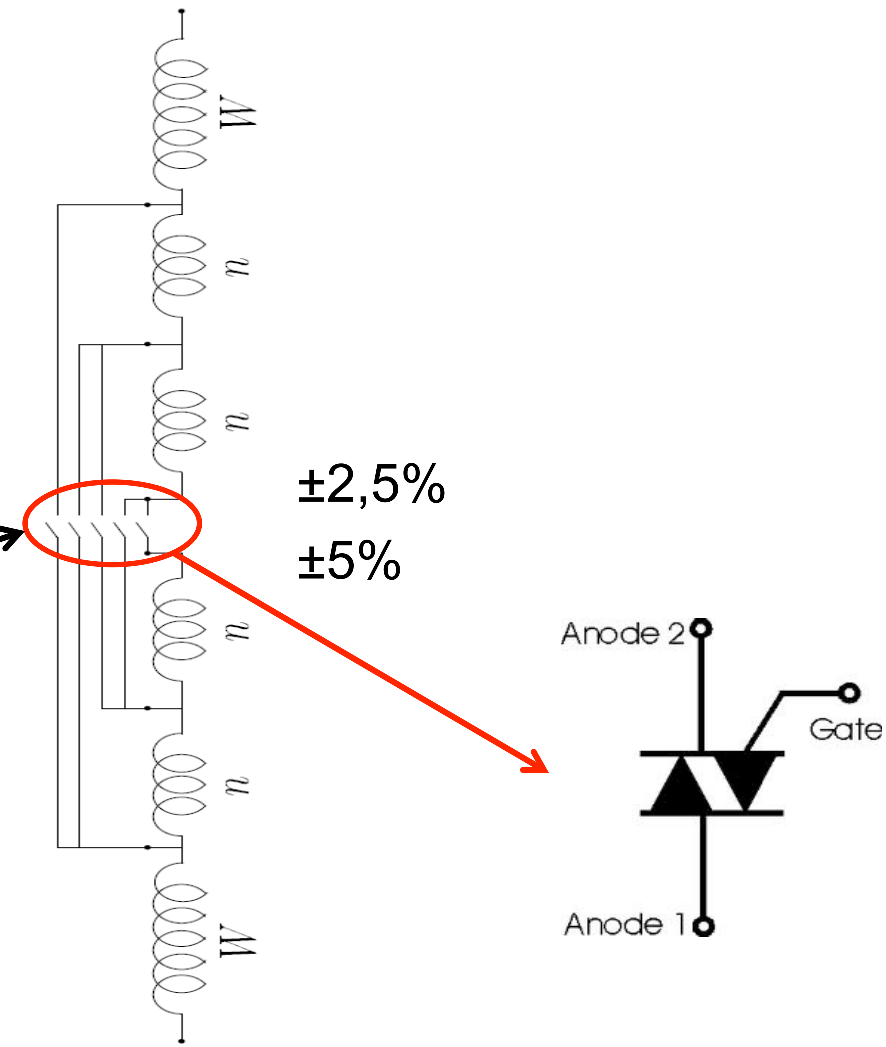
- Three degrees of freedom: P, Qm, Qn
- Short-circuit levels not affected (fast response)
- Same frequency, small voltage drop

Power flow and voltage control by DFACTS



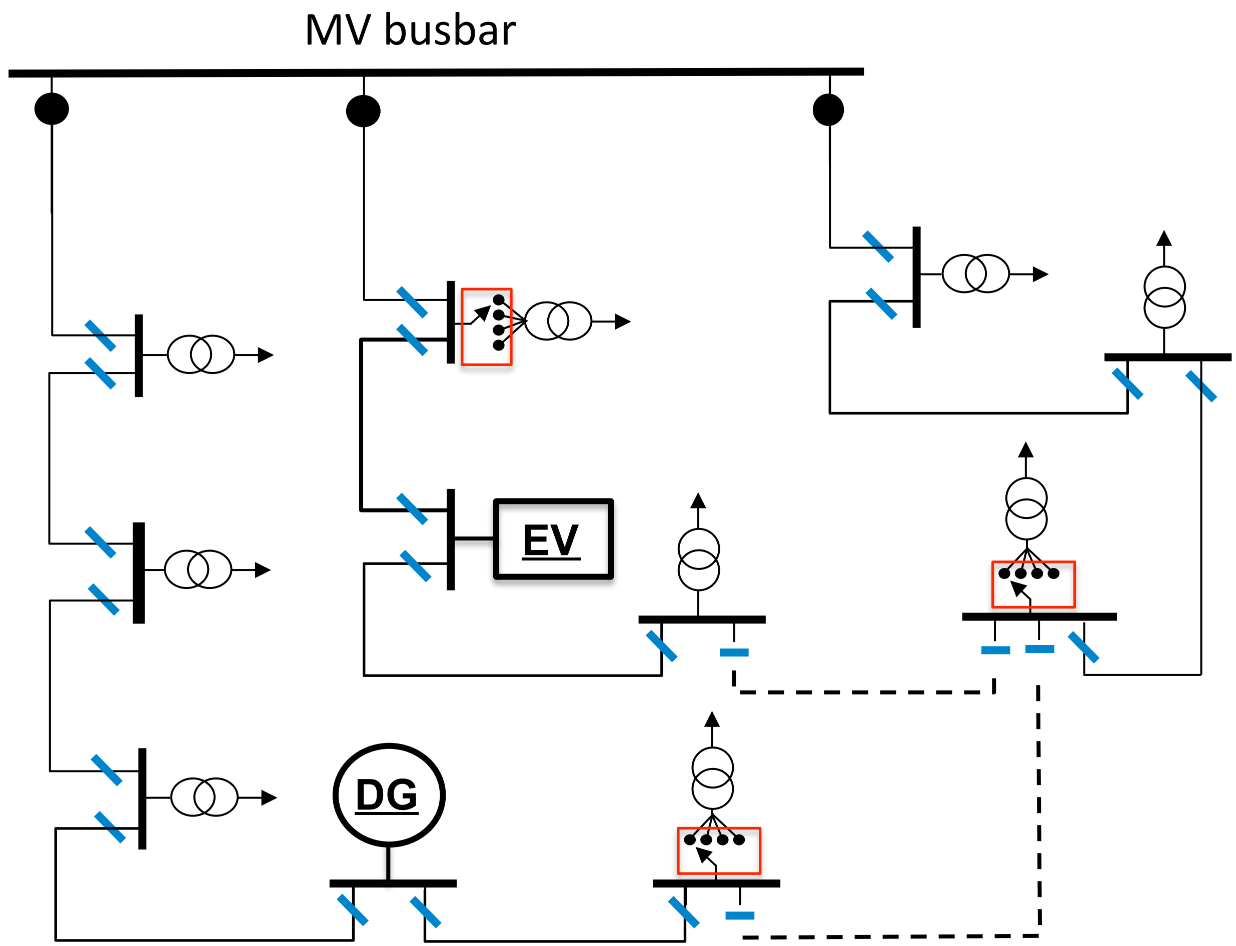
Voltage control by solid-state tap changers

Replace (fixed) off-load tap changers of secondary distribution transformers by electronic switches



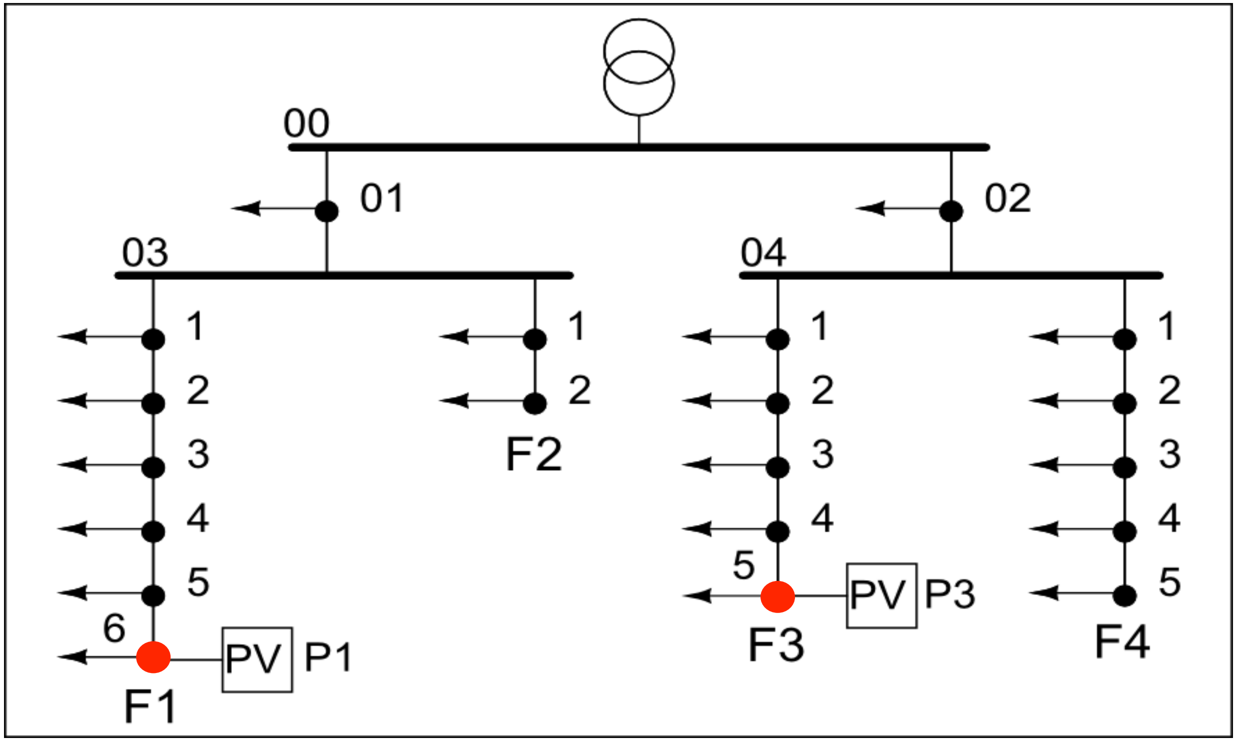
Voltage control by solid-state tap changers

Controllable voltage magnitudes on the LV side (discrete steps)



Integration of distributed renewables

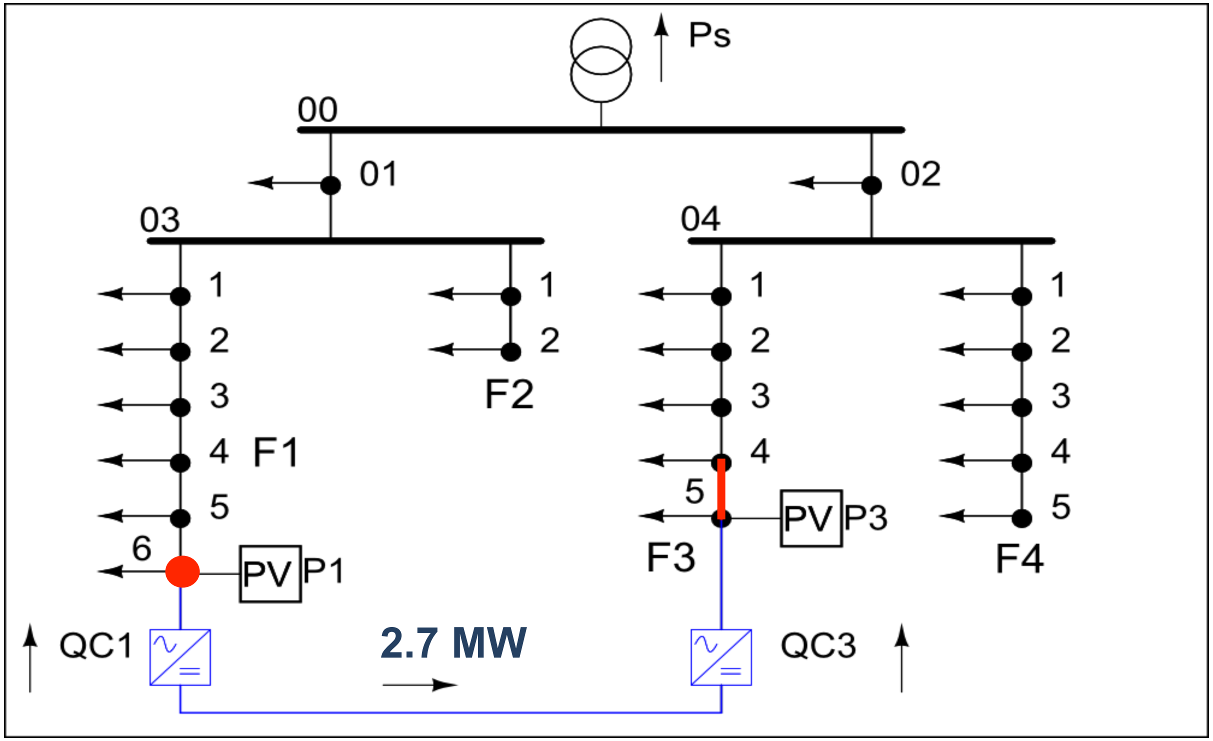
Case study



Base case	P1 + P3 = 8.2 MW

Integration of distributed renewables

Case study



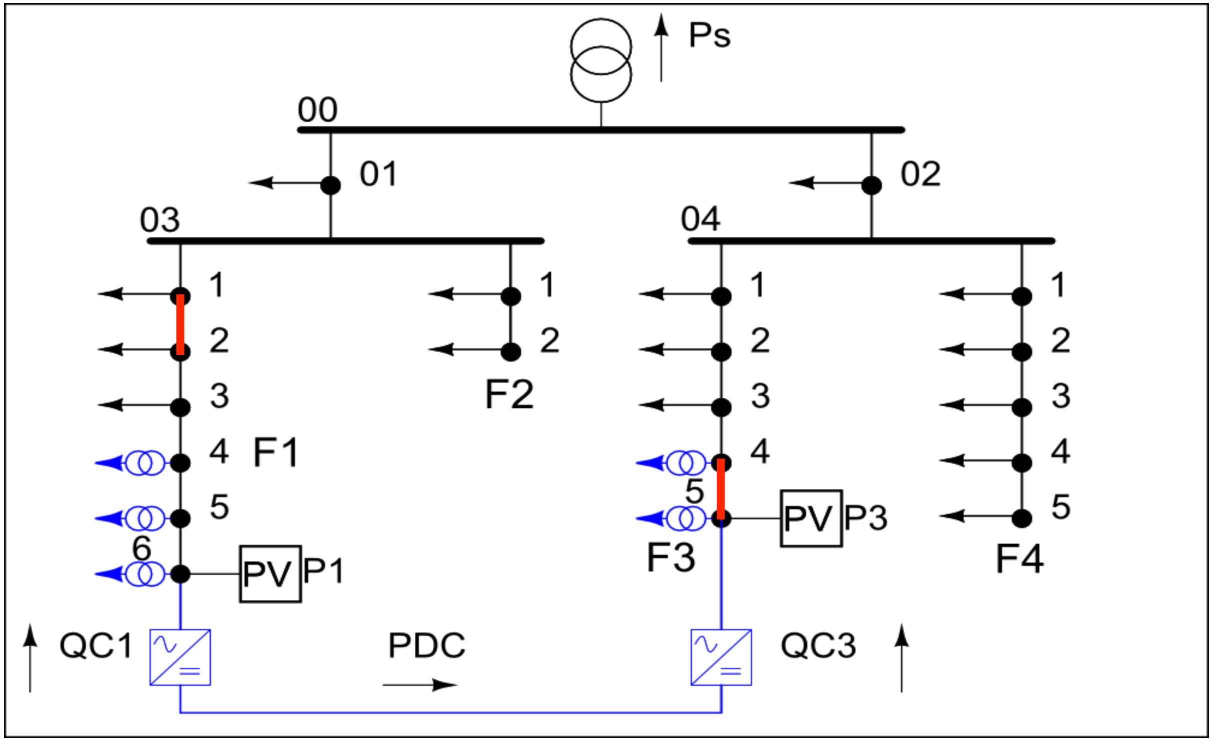
3 control variables

Base case	P1 + P3 = 8.2 MW
Smart link added (3 MVA)	P1 + P3 = 9.8 MW

+ 19.9 %

Integration of distributed renewables

Case study



8 control variables

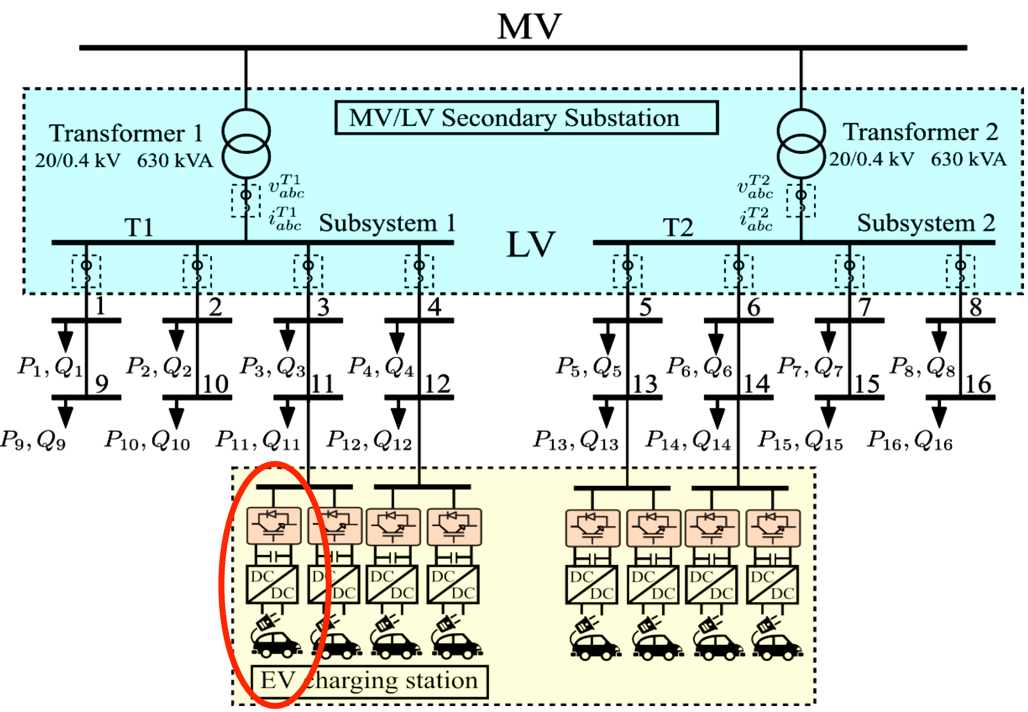
Base case	P1 + P3 = 8.2 MW
Smart link added	P1 + P3 = 9.8 MW
Smart link and tap changers	P1 + P3 = 10.5 MW

+ 28.4 %

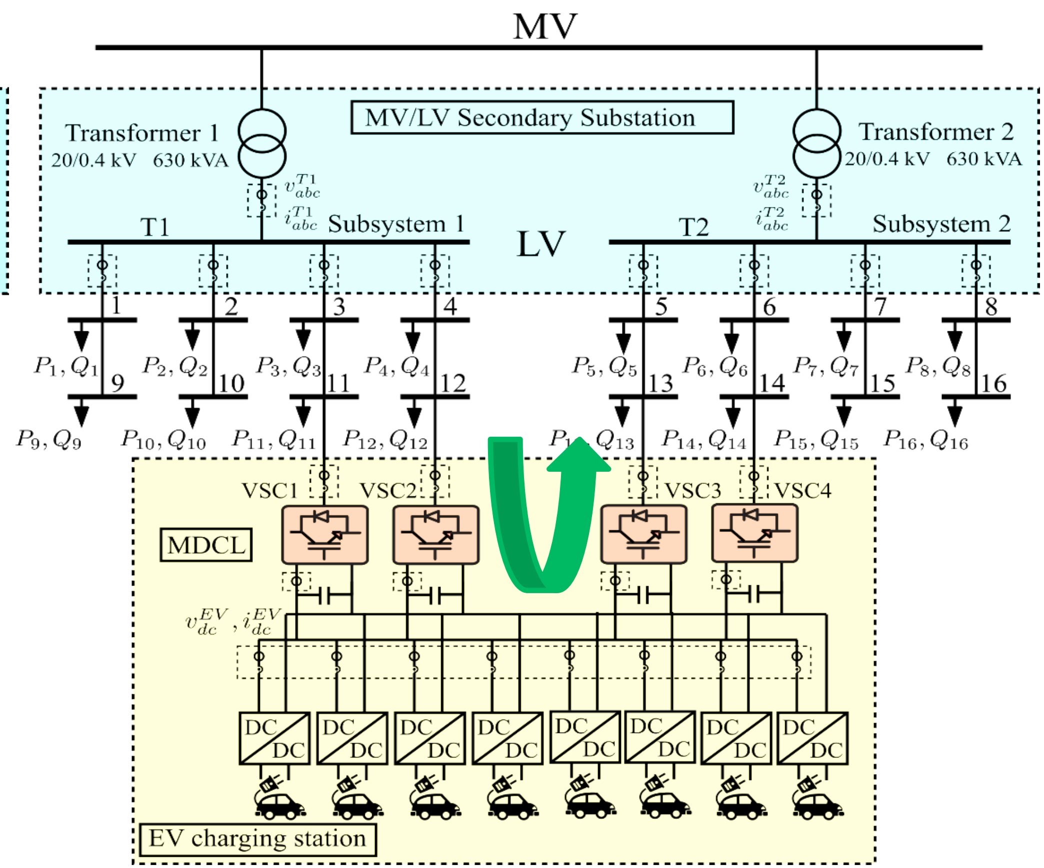
Smarter EV chargers

Fast EV charging in LV networks

Conventional scheme



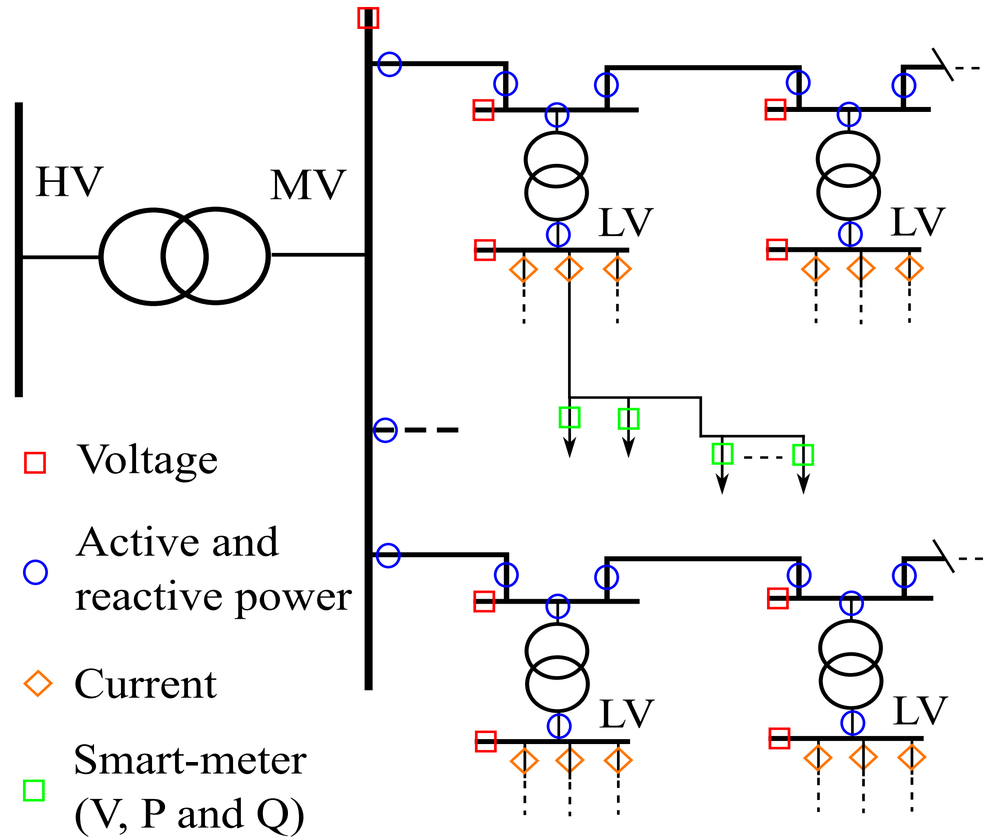
Smart link-based solution



Individual VSC are replaced by parallel VSC with a common DC bus

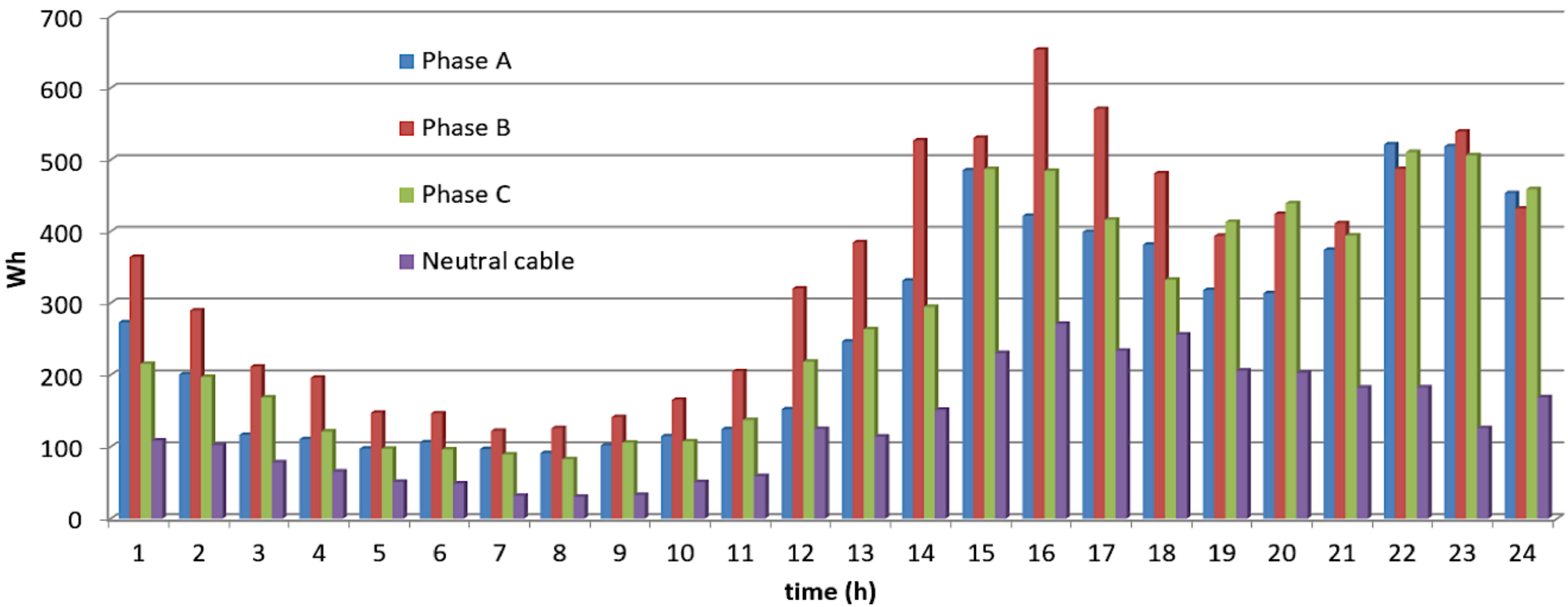
State estimation for distribution grids

MONICA project: *Smartcity* (Malaga)



State estimation for distribution grids

MONICA project: *Smartcity* (Malaga)



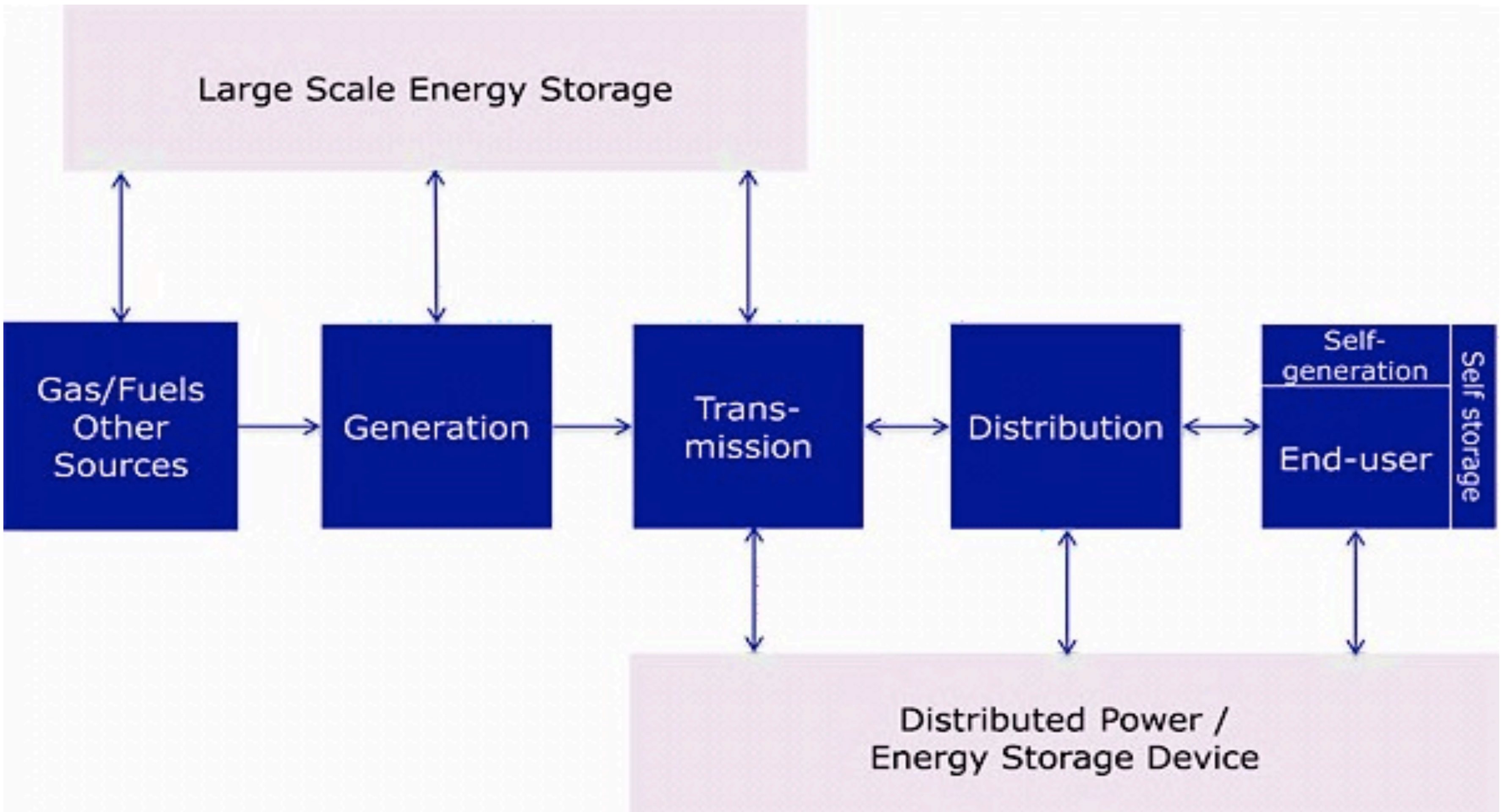
Microgrids

Rural DC electrification in India

- 20% of population in India has no access to electricity
- Much cheaper and efficient: PV and DC microgrids

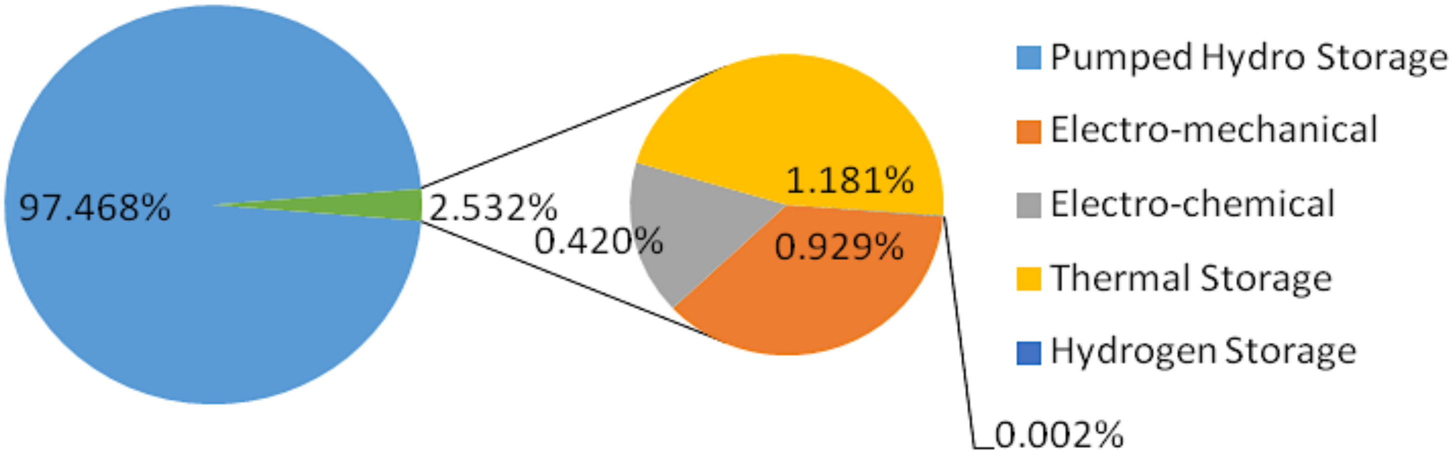
Energy storage: the “Holy Grail”

How, when and where?



Energy storage: installed capacity

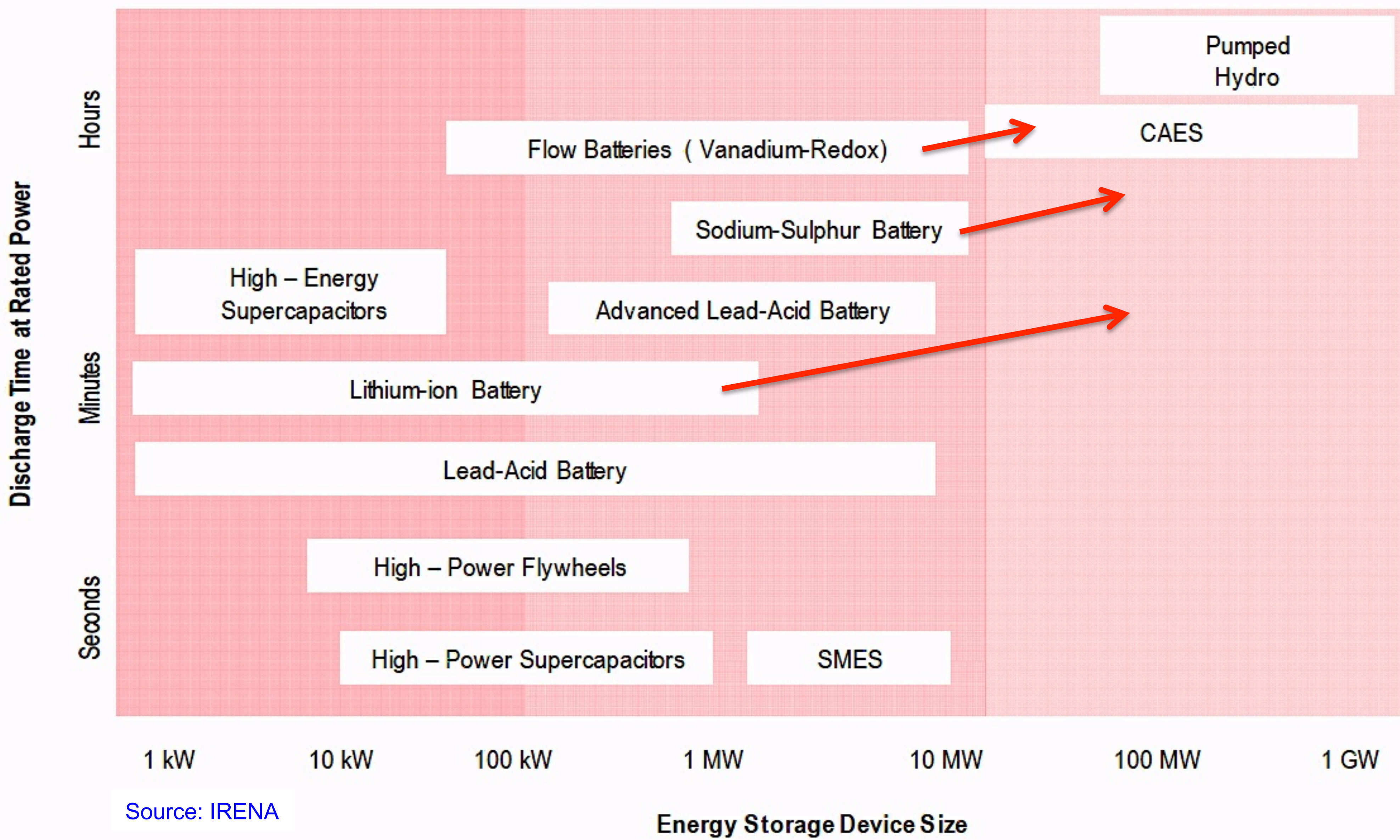
Source: DOE, October 2015



Technology	Power (MW)
Pumped Hydro Storage	142,087.5
Electro-mechanical	1,354.9
Electro-chemical	611.6
Thermal Storage	1,722
Hydrogen Storage	2.9
Total	**145,778.8 MW**

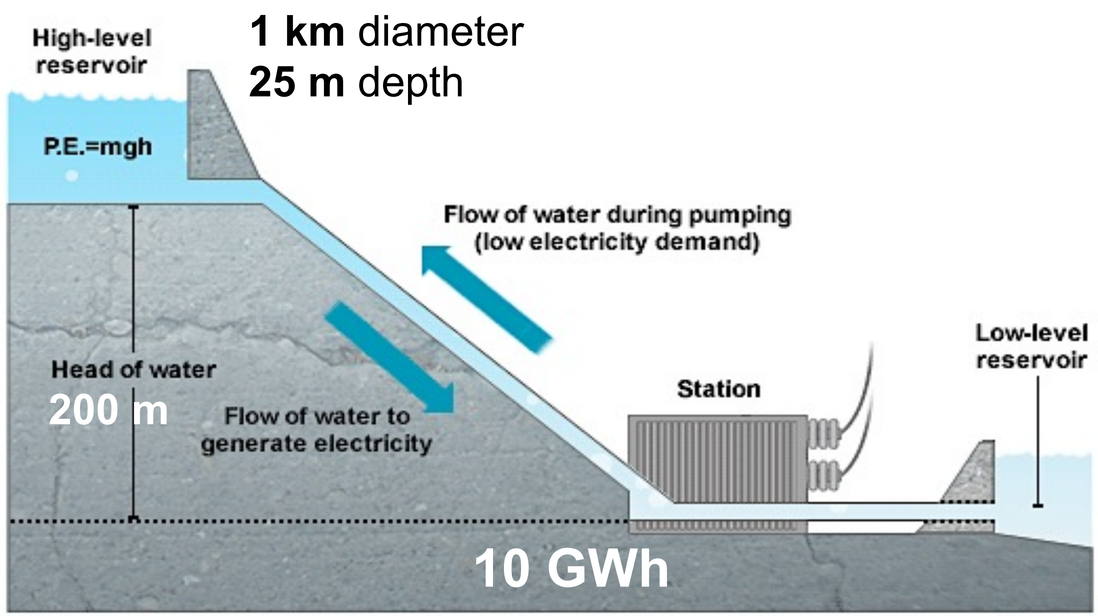
2.5% of gen. installed power

Energy storage: technologies



Source: IRENA

Pumped Hydro Storage



Efficiency: 76%-85%

La Muela (Spain)
Capacity: 1500 MW
(10 GWh)
Height: 420 m

Compressed air energy storage

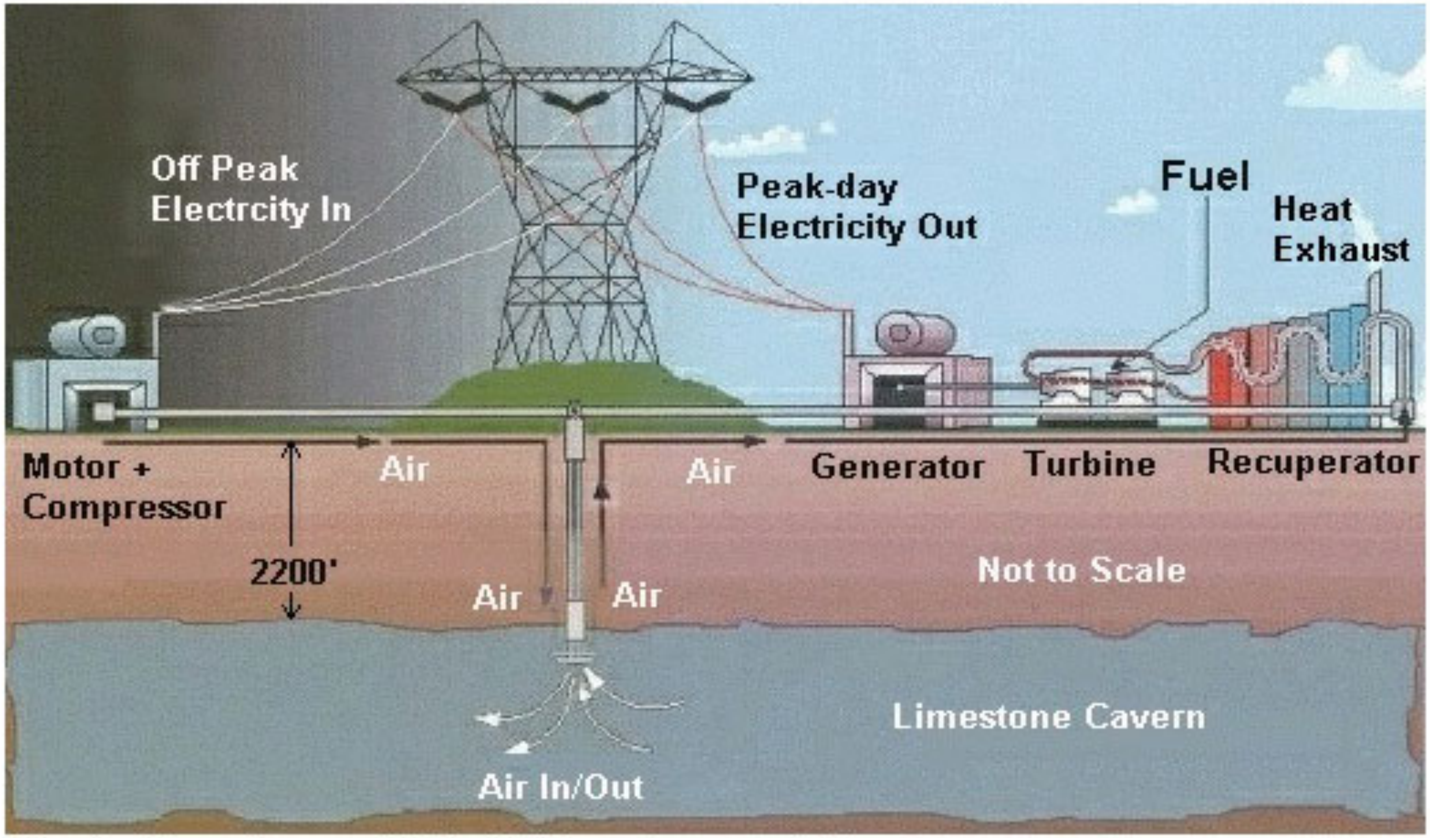
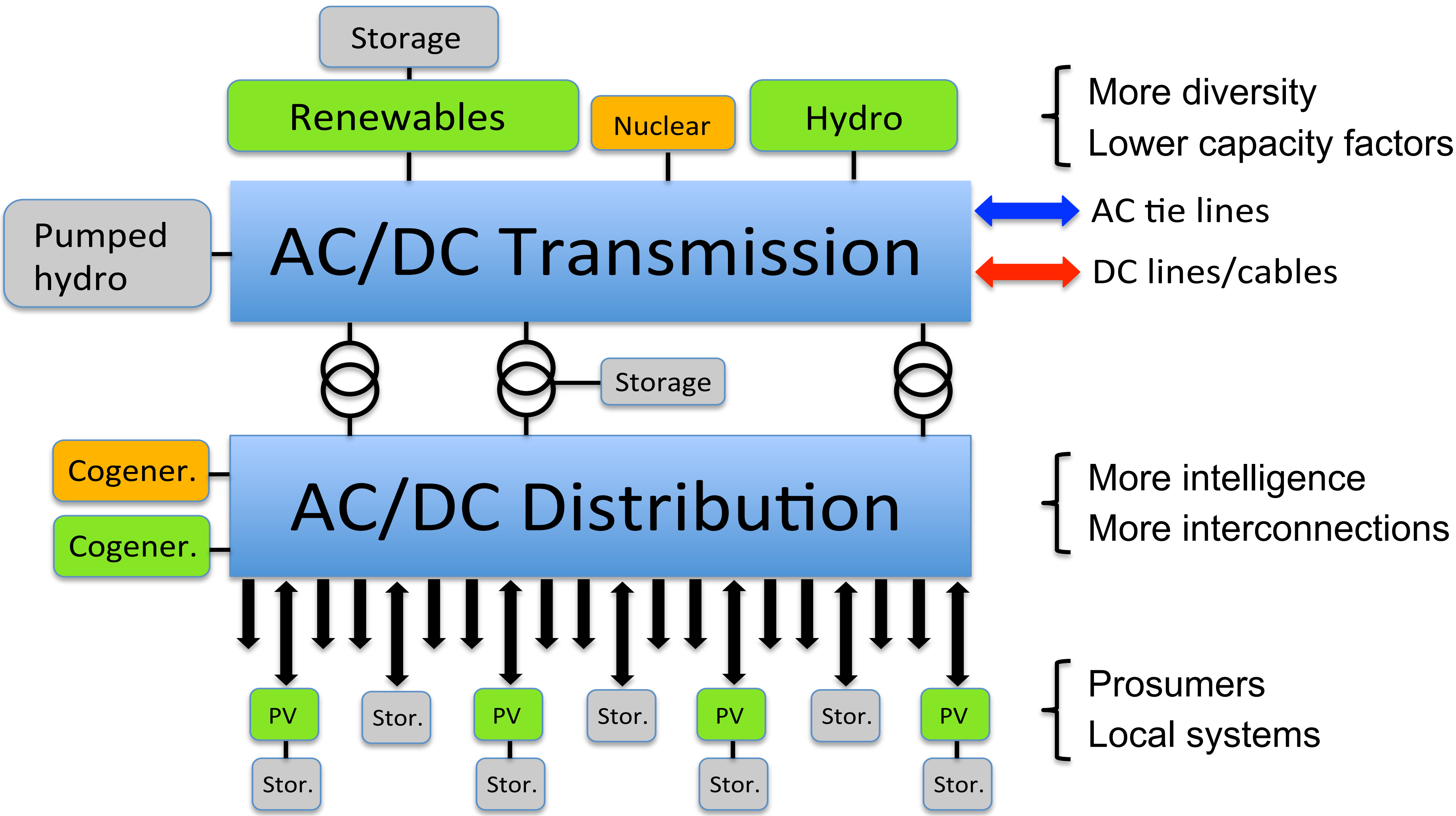


Photo Courtesy of CAES Development Company

Efficiency:

- Conventional (diabatic): **42-56%**
- Advanced (adiabatic): **<70%** (no natural gas needed)

XXI Century Paradigm




“I’d put my money on the sun and solar energy. **What a source of power!**
I hope we don’t have to wait until oil and coal run out before we tackle that.”
[THOMAS EDISON, 1931]
Thanks for your attention