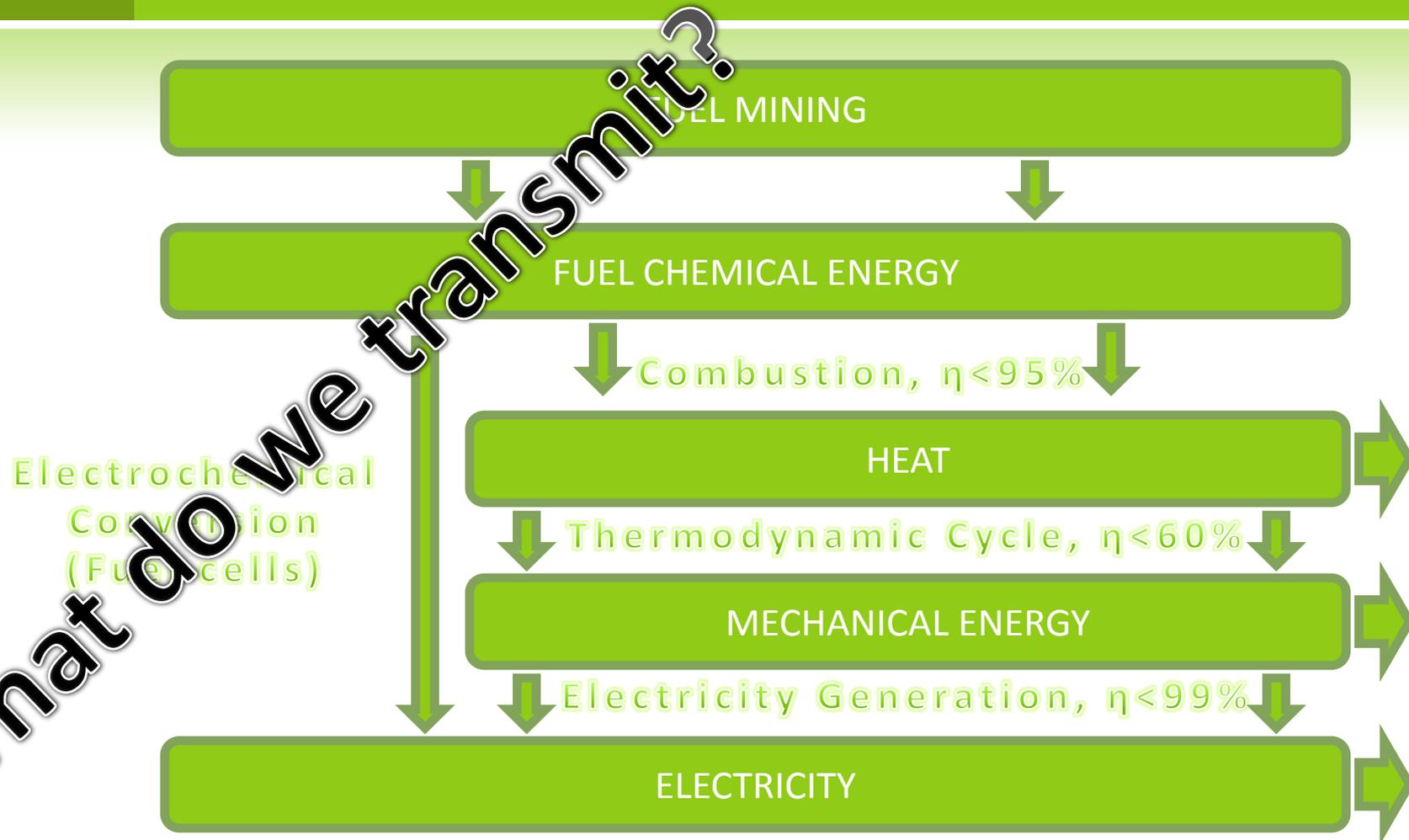




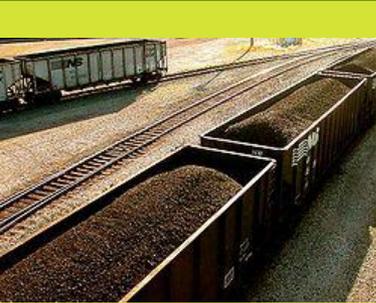
POWER GRID

SUPPLYING ELECTRICITY TO THE CUSTOMERS
AND KEEPING THE ENERGY BALANCE

FOSSIL FUELS ENERGY CONVERSION CHAIN



TRANSMITTING ENERGY



Fuel transmission – energy generation at consumer's site

- Fuel transport may be expensive and requires energy consumption
- Energy conversion at site must be flexible enough to meet variable demand – if the demand is variable
- Does not really work for small customers



Electricity transmission

- Allows to centralize generation – higher efficiencies
- Grid development sometimes difficult and expensive
- Transmission losses

WAR OF CURRENTS AC OR DC?

Low voltage = high losses

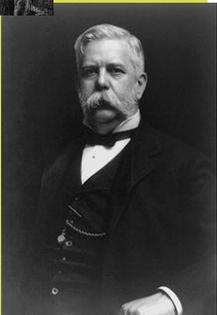
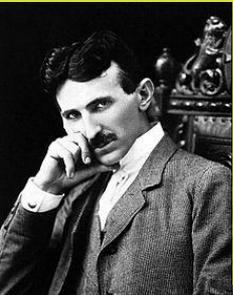


DC transmission

- Transforming into higher voltage difficult with 19th century's technology
- Promoted by Thomas Edison

AC transmission

- Low cost transformers – easy transmission and distribution at high voltages
- Promoted by George Westinghouse & Nikola Tesla



DC TRANSMISSION EDISON'S CONCEPT

Single voltage level

- 110 V chosen for all equipment from generator to consumer due to:
 - Safety reasons
 - Impracticable voltage conversion for DC system

Three-wire system

- +110 V, 0 V, -110 V conductors

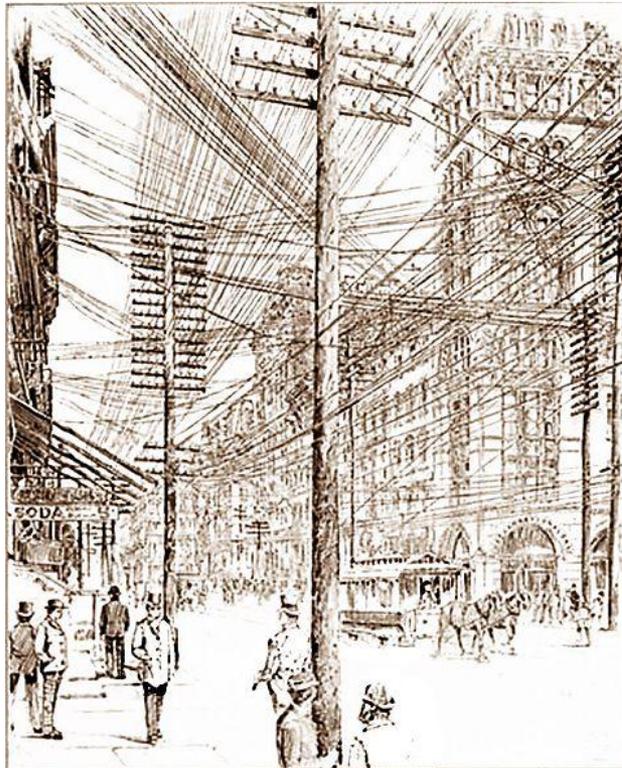
High losses – low distance

- Due to resistance only distances of up to 1 mile considered practicable
- Distributed generation

FIRST DC LONG-DISTANCE TRANSMISSION LINE

- ⊙ Miesbach – Munich, 1882
- ⊙ Power from a steam engine to international electricity exhibition to drive an artificial waterfall
- ⊙ Power rating 2.5 kW (only!)
- ⊙ Length 57 km
- ⊙ Rated voltage 2000 V

DC GRIDS, NYC, 1880s



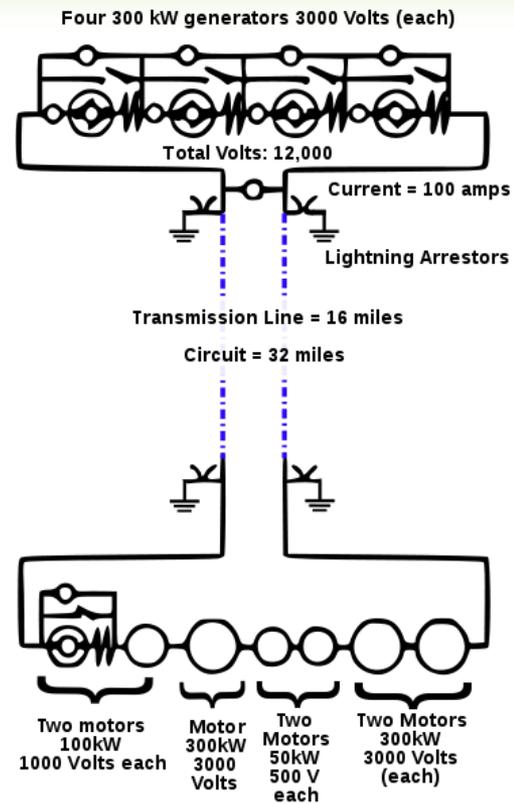
- ⊙ Separate system for each voltage level – different consumer groups:
 - ⊙ Lighting
 - ⊙ Electric motors
- ⊙ Impracticable
- ⊙ Unsustainable in urban environment

HVDC THURY SYSTEM

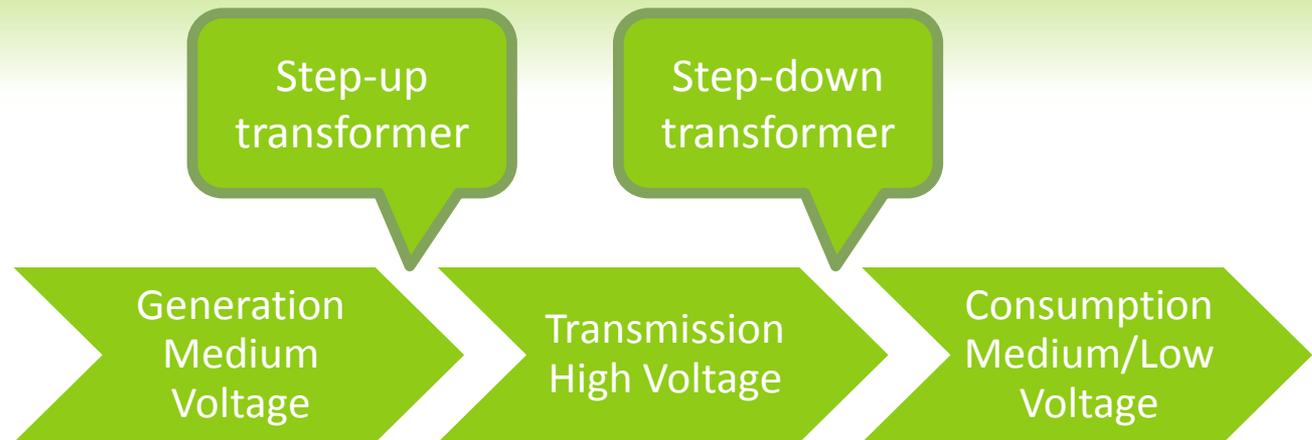


- ⊙ Conversion into high voltage DC (HVDC) for transmission with series-connected motor-generator sets
- ⊙ Series-connected consumers
- ⊙ First operated in 1889, 15 systems in operation by 1913
- ⊙ High energy loss in rotating machinery
- ⊙ High maintenance needs
- ⊙ Not practical

HVDC THURY SYSTEM



AC GRID CONCEPT



Three-phase system patented by Nikola Tesla 1887-88

First transmission of AC 3-phase current: 1891, Frankfurt

Voltage: 25 kV, overhead line

Distance: 175 km, route Lauffen – Frankfurt

**AC system won war of currents
thanks to availability and low cost
of transformers**

WHY THREE-PHASE?

Cheap

- Polyphase cheaper than single-phase – less conductor material

Stable

- At balanced loads on each phase there is almost no current in the neutral conductor – allows to minimize its cross-section
- At balanced phase loads vibrations of three-phase equipment (generators!) are reduced

INCREASING THE VOLTAGE

110 kV

- 1907, Croton-Grand Rapids, Michigan, USA – first tests
- 1912, Lauchhammer-Riesa, Germany – first commercial operation

220 kV

- 1923, Pit River – Cottonwood – Vaca Dixon, California, USA
- 1929, Brauweiler-Hoheneck, Germany

380 kV

- 1952, Harsprånget – Hallsberg, Sweden

735 kV

- 1965, Hydro-Québec, Canada

1150 kV – the highest operational voltage

- 1988, Ekibastuz-Kokshetau, USSR (now Kazakhstan)

OVERHEAD TRANSMISSION

Cheap

Easy to build

Low capacitance losses

...but corona discharge losses present...

...and it is hard to construct in a built-up area

UNDERGROUND LINES

Densely populated urban areas

Areas where land is unavailable or planning consent is difficult

Rivers and other natural obstacles

Land with outstanding natural or environmental heritage

Areas of significant or prestigious infrastructural development

Land whose value must be maintained for future urban expansion and rural development

SOME ADVANTAGES OF UNDERGROUND POWER CABLES:

Less likely damage from severe weather conditions (mainly wind and freezing)

Greatly reduced electromagnetic fields (EMF) emission (additional shielding)

Underground cables need a narrower surrounding strip of about 1- 10 meters

MODERN HVDC SYSTEMS



- ① Introduction of mercury valves in 1930s-1940s allowed to easily convert AC into HVDC
- ① Now mercury-based equipment replaced by thyristors
- ① Popularized after world war II for limited applications
- ① Used for transmission between two AC systems

HVDC vs AC TODAY

Cost

- HVDC transmission line cheaper (more power per conductor)
- AC substations cheaper
- HVDC better for long-distance routes

Losses

- Smaller losses at HVDC lines

Capacitance

- At HVDC no capacitance losses in long (undersea) cables

Reliability

- HVDC less reliable due to extra conversion equipment
- Limited overload capacity for inverters (HVDC lines)

Grid development

- Building multiterminal HVDC systems is difficult (control difficulties)

MODERN HVDC APPLICATIONS

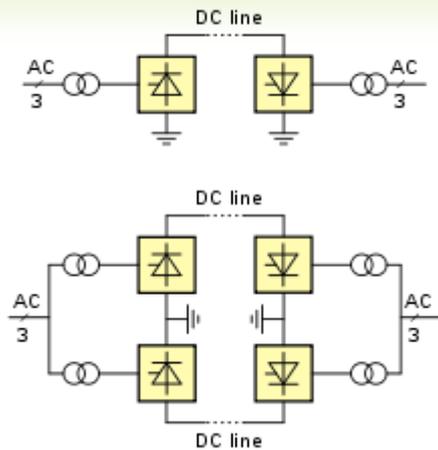
Interconnection

- Links between unsynchronized AC systems
- Links between AC systems with different frequency
- Undersea cables
- Back-to-back (B2B) DC links („zero” length)

Long haul point-to-point lines

- Bulk power transmission from large remote sources (hydro power, off-shore wind farms)

MODERN HVDC DESIGN



Monopole

- Return by earth (possibly with metallic conductor)

Bipolar

- Pair of conductors at high potential with respect to the ground, opposite polarity

Rectifying
system



Transmission
line



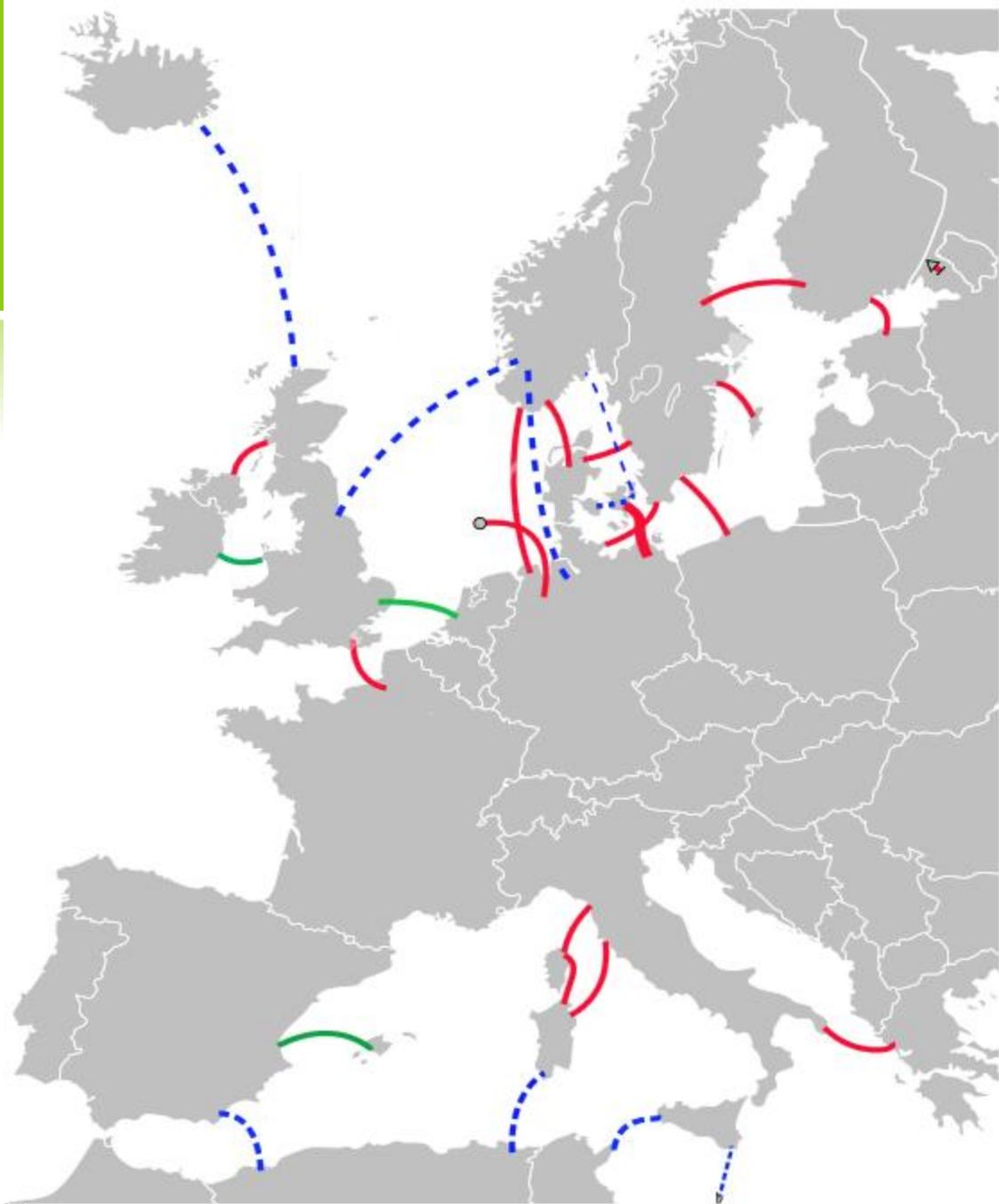
Inverting
system

HVDC LINKS IN EUROPE

Existing

Under construction

Planned

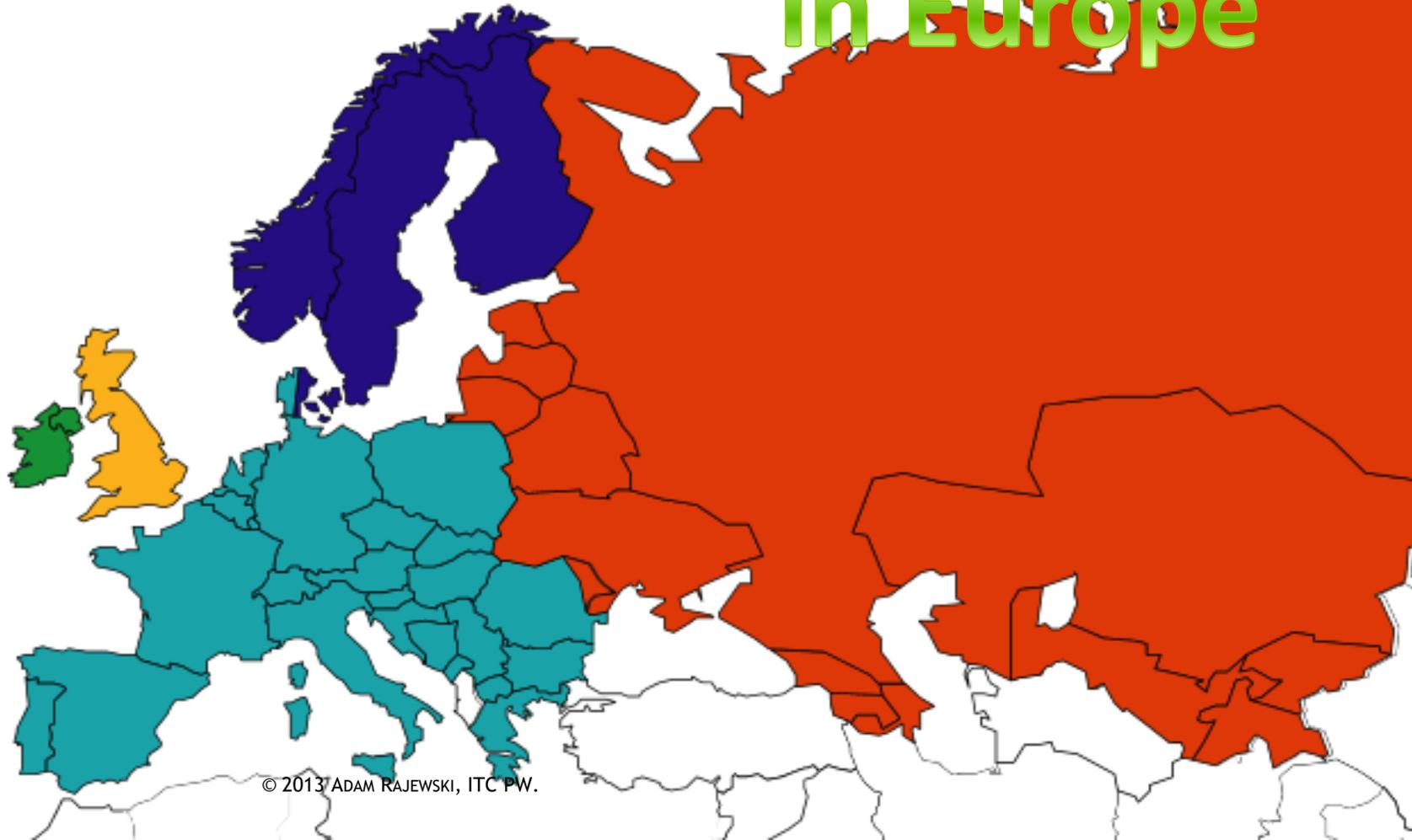
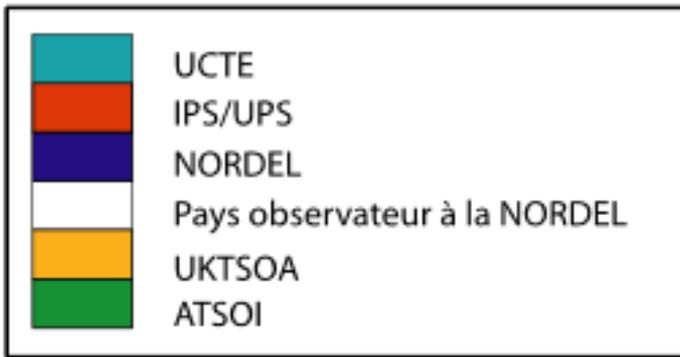


PACIFIC DC INTERTIE

- ⊙ Delivering hydroelectric power to Southern California
- ⊙ Jointly developed by GE and ASEA
- ⊙ 1342 km overhead line, bipolar, 525-550 kV
- ⊙ Joint capacity:
 - ⊙ 2 GW in bipolar mode
 - ⊙ 1.55 GW with earth return
- ⊙ 2 inverter stations, 2 grounding stations



Synchronous Grids in Europe



ELECTRIC GRIDS TODAY

Electricity Generation

- Power stations – centralized and distributed

Electricity Transmission

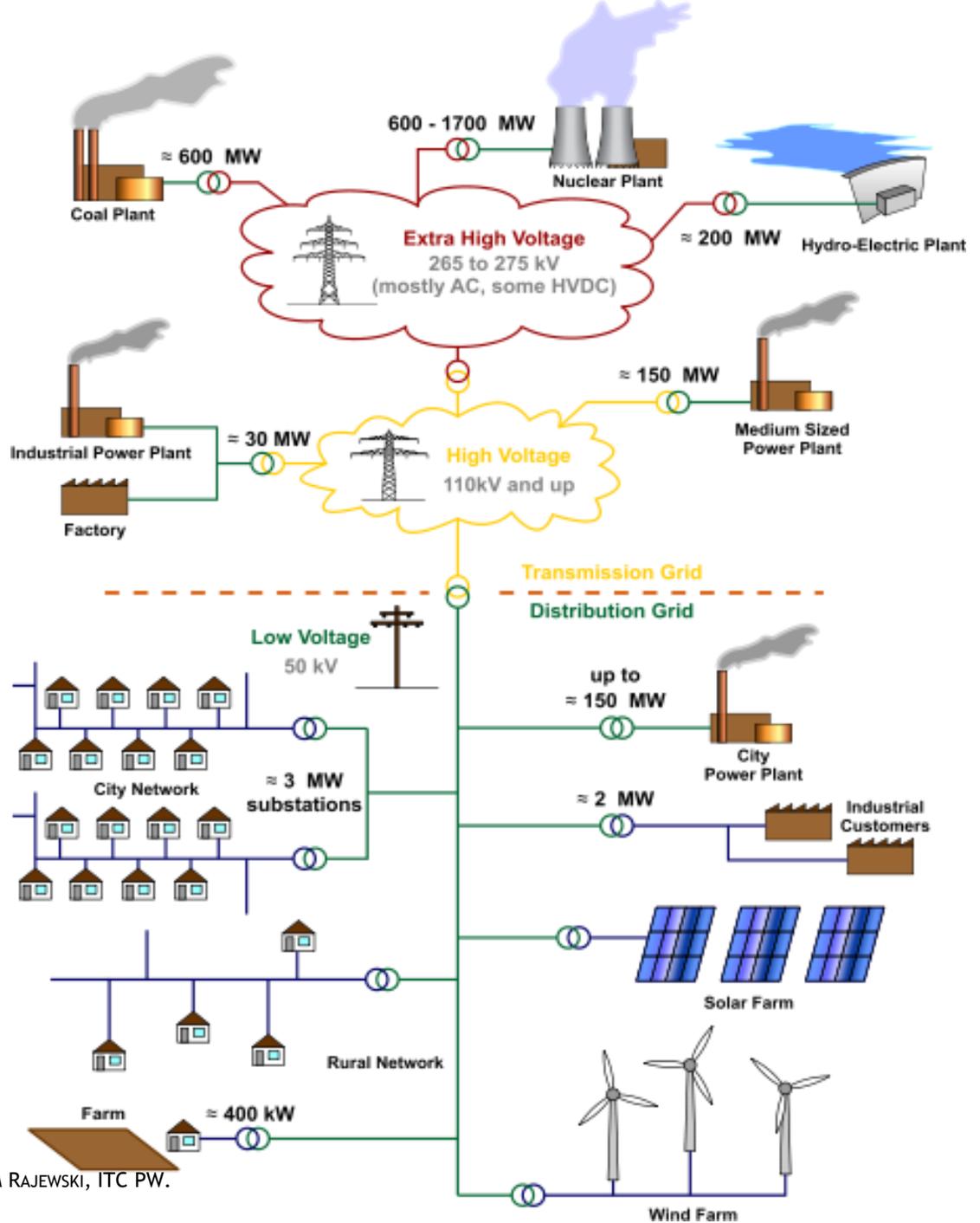
- Overhead lines, 220 kV and more
- Some DC links (e.g. undersea, between non-synchronized systems)

Electricity Distribution

- Overhead and cable lines, 110 kV and less

System Control

- Maintaining demand-supply balance



ELECTRICITY FLOW

Generation
Medium Voltage (2 – 30 kV)

Transmission
High Voltage (220-1150 kV)

Distribution
Medium (High) Voltage (6-110 kV)

Consumption
Low or Medium Voltage (0.4, 6, 15 kV)

GOOD TRANSMISSION SYSTEM

High voltage – low losses

- Today 400 kV lines

Redundancy – high supply security

- Dual-circuit lines
- Closed loops

Availability of balancing power

- Peakload power stations in all control areas

Available to all users (generators, distributors)

- Independent TSO

ELECTRIC GRID IN POLAND

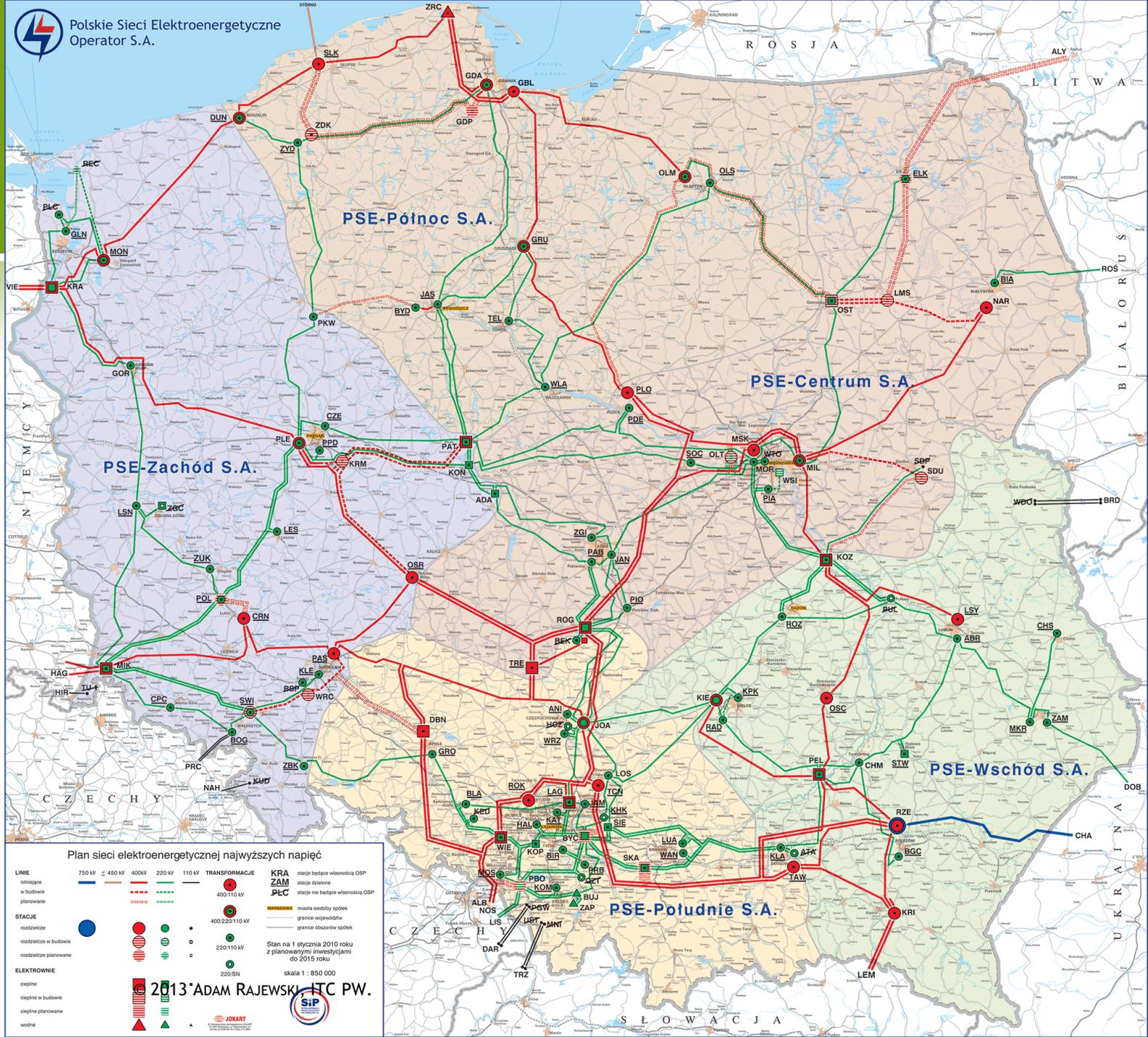
Transmission system Operated by PSE-Operator

- Single extra-high voltage line 750 kV – 114 km (not in operation)
- Extra-high voltage network 400 kV – 66 lines, 4920 km
- High-voltage network 220 kV – 165 lines, 7919 km

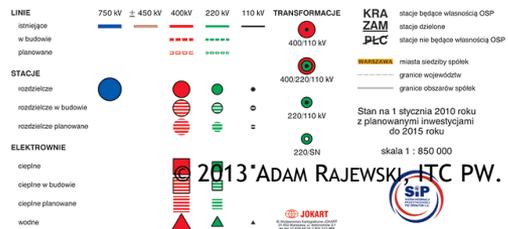
Distribution system Operated by local Distribution System Operators

- High-voltage network 220 kV – 232 km
- High-voltage network 110 kV – 32,475 km
- Medium voltage networks – 300,511 km
 - 15 kV (most popular)
 - Local systems on 60 kV (Silesia), 30 kV (Hel Peninsula), 20 kV, 10 kV
 - 6 kV (mostly old districts of cities, no longer developed, replaced with 15 kV)
- Low voltage network 0.4 kV (230/400 V) – 423,886 km

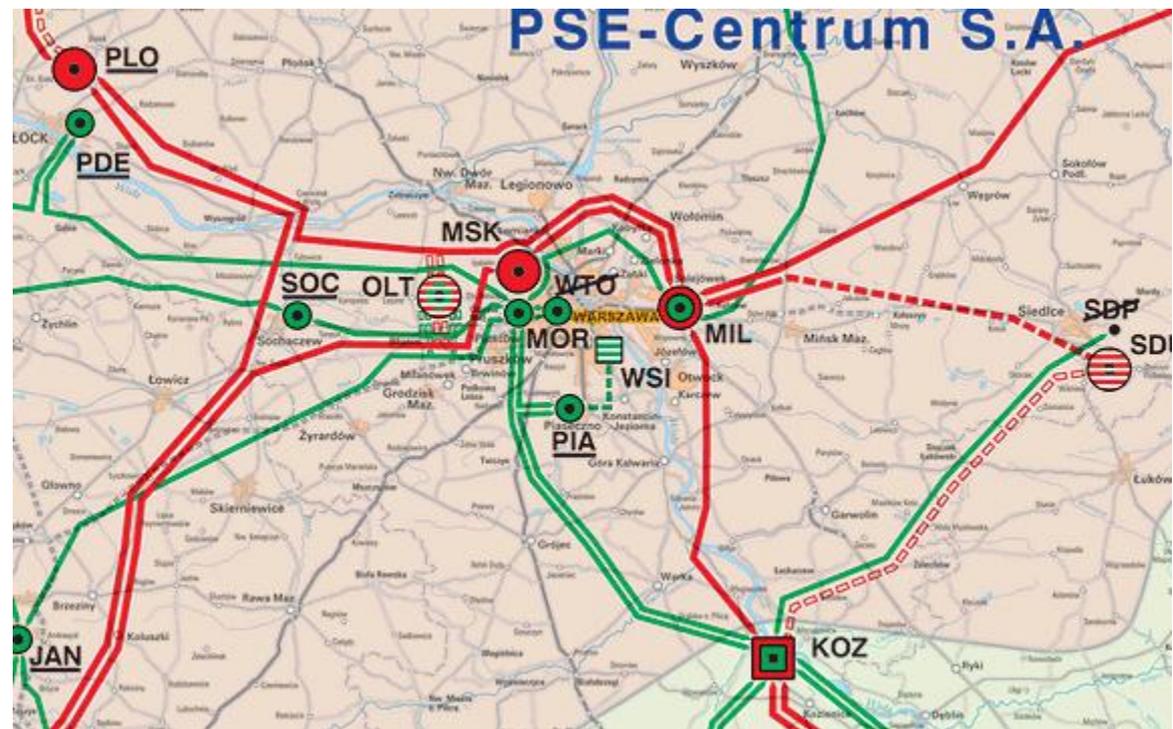
750 kV
400 kV
220 kV



Plan sieci elektroenergetycznej najwyższych napięć



POLISH TRANSMISSION SYSTEM



POLISH CROSS-BORDER CONNECTIONS

Germany

- Krajnik-Vierraden, 2 × 220 kV, 930 MVA (planned upgrade to 400 kV)
- Mikułowa-Hagenwerder/Kisdorf, 2 × 400 kV, 2 × 1385 MVA
- Turów-Hirschwelde, 110 kV

Czech Republic

- Boguszów-Porici, 110 kV
- Kudowa-Nachod, 110 kV
- Wielopole-Albrechtice/Nošovice, 2 × 400 kV, 2 × 1385 MVA
- Bujaków/Kopanina-Liskovec, 2 × 220 kV, 394+362 MVA

Slovakia

- Krosno/Iskrzynia – Leměšany, 400 kV, 2 × 1385 MVA

Ukraine

- Rzeszów-Khmel'nitskaya NPP, 750 kV, 1300 MVA (shut down in 1993, to be recommissioned with DC link)
- Zamość-Dobrotwór, 220 kV, 362 MVA (synchronized with Polish grid – radial system)

Belarus

- Wolka Dobrzyńska-Brest, 110 kV (private line connected to Polish distribution grid)
- Białystok-Ros, 220 kV, 362 MVA (shut down in 2004, planned for reconstruction with DC link to Narew)

Sweden

- Słupsk-Starno, 450 kV DC, 600 MW

DISTRIBUTION SYSTEM OPERATORS IN POLAND



GRID STABILITY ISSUE

SYSTEM BALANCING

“Traditional” system

- Known generation capacity
- Predictable load patterns
- Reserves mainly for emergencies

Modern system

- Generation capacity difficult to predict
- Increasing load volatility
- Reserves needed for both emergency situations and normal operation to compensate for unpredictable generation



THE CHALLENGE

Holistic view on power systems

1. ELECTRICITY PRODUCTION

- Matching supply and demand
- Optimal capacity mix for matching the load

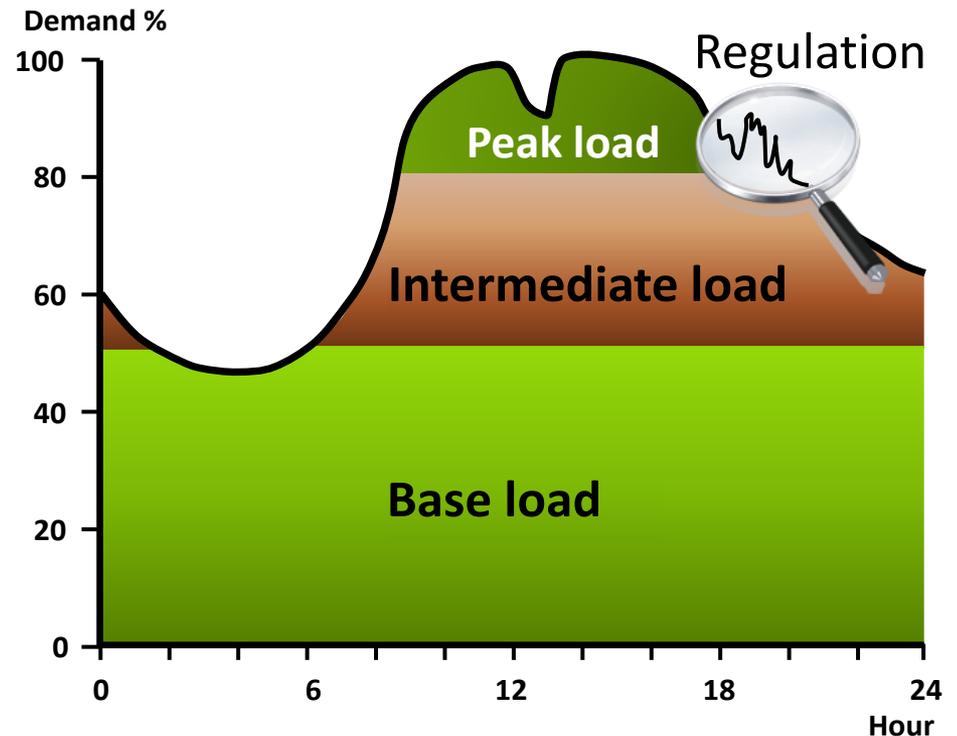
→ *Electricity market is the main tool*

2. SYSTEM STABILITY

- Balancing
- Regulation (50/60 Hz)
- Voltage control
- Contingency reserves

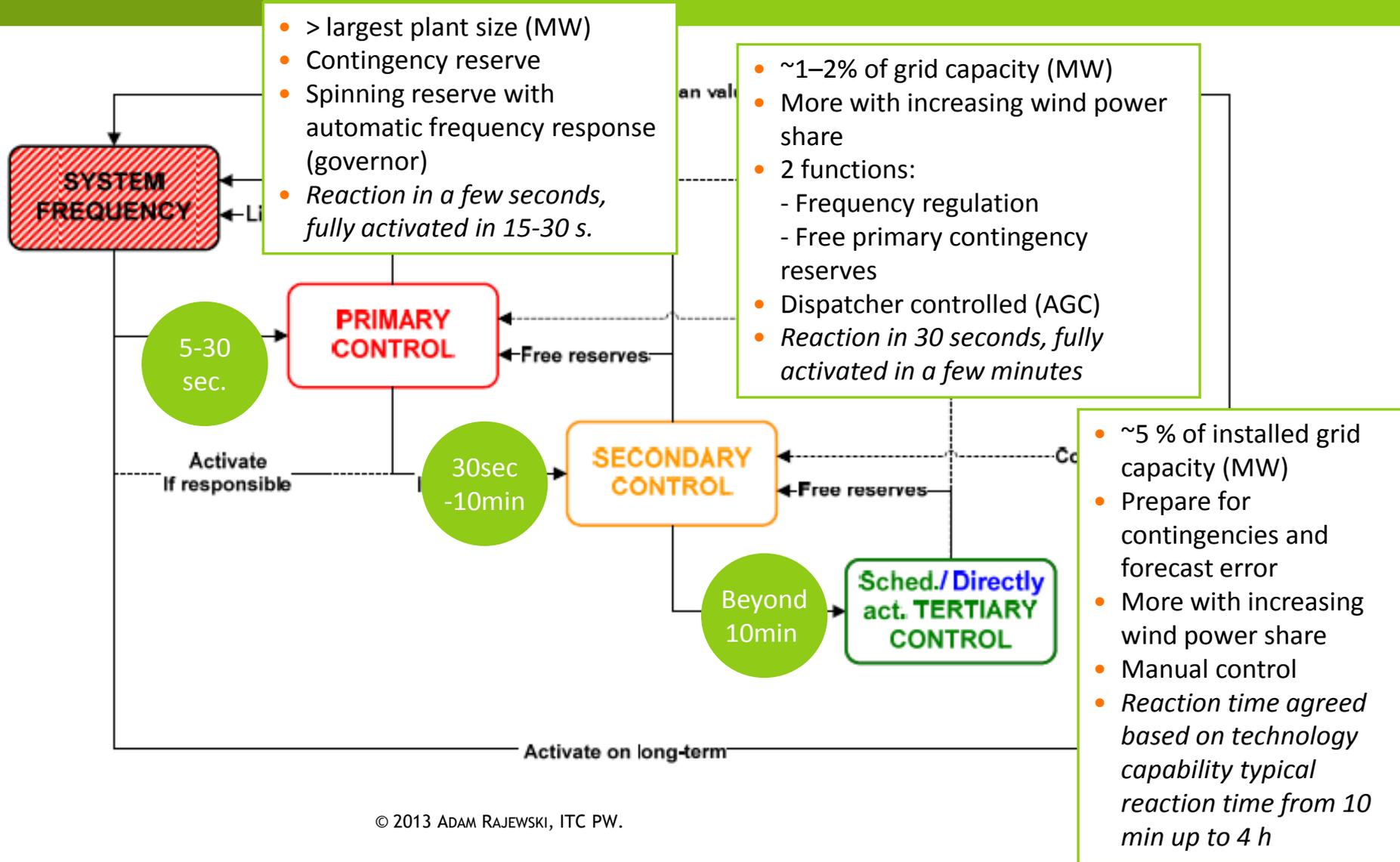
→ *System operator responsible*

Daily load curve



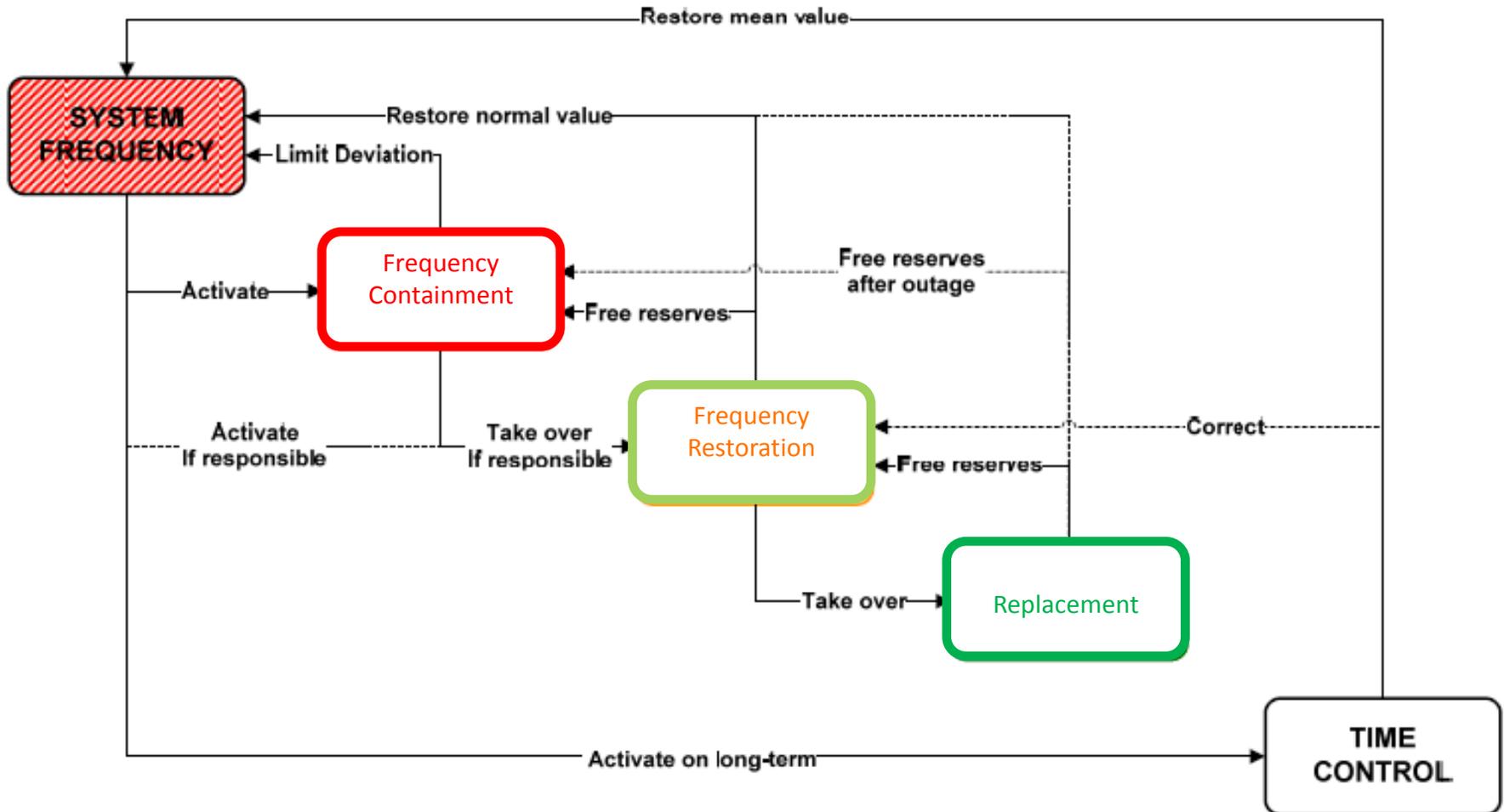


ENTSO-E FREQUENCY CONTROL SCHEME





NEW ENTSO-E VOCABULARY





THE THREAT

WIND POWER VARIABILITY

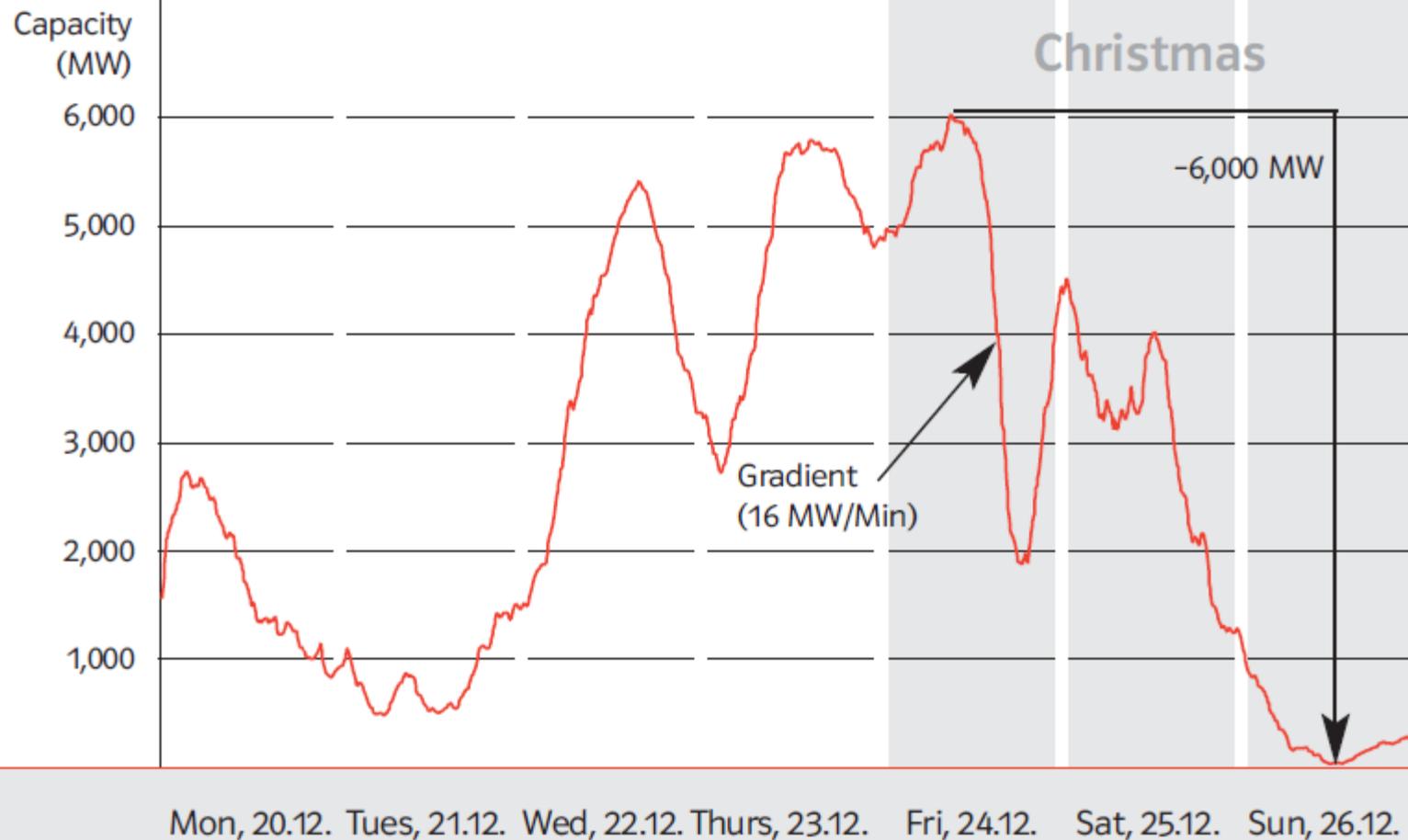
39

Source: E.ON-Netz

4

6. Short-term drop

in wind power feed-in over Christmas 2004



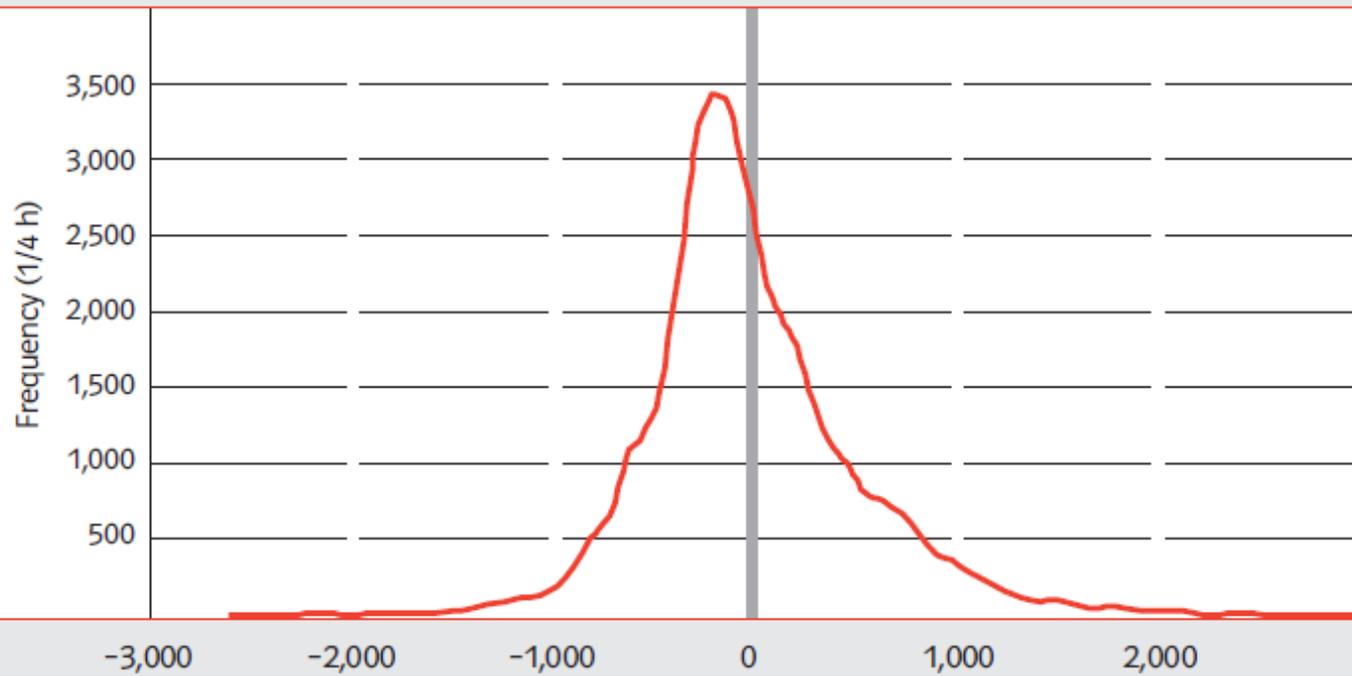
WIND POWER FORECASTING ERROR, E.ON-NETZ, 2004



8 h forecasts, 15 min resolution

9. Frequency distribution of the forecast error

for wind power feed-in 2004 in the E.ON control area

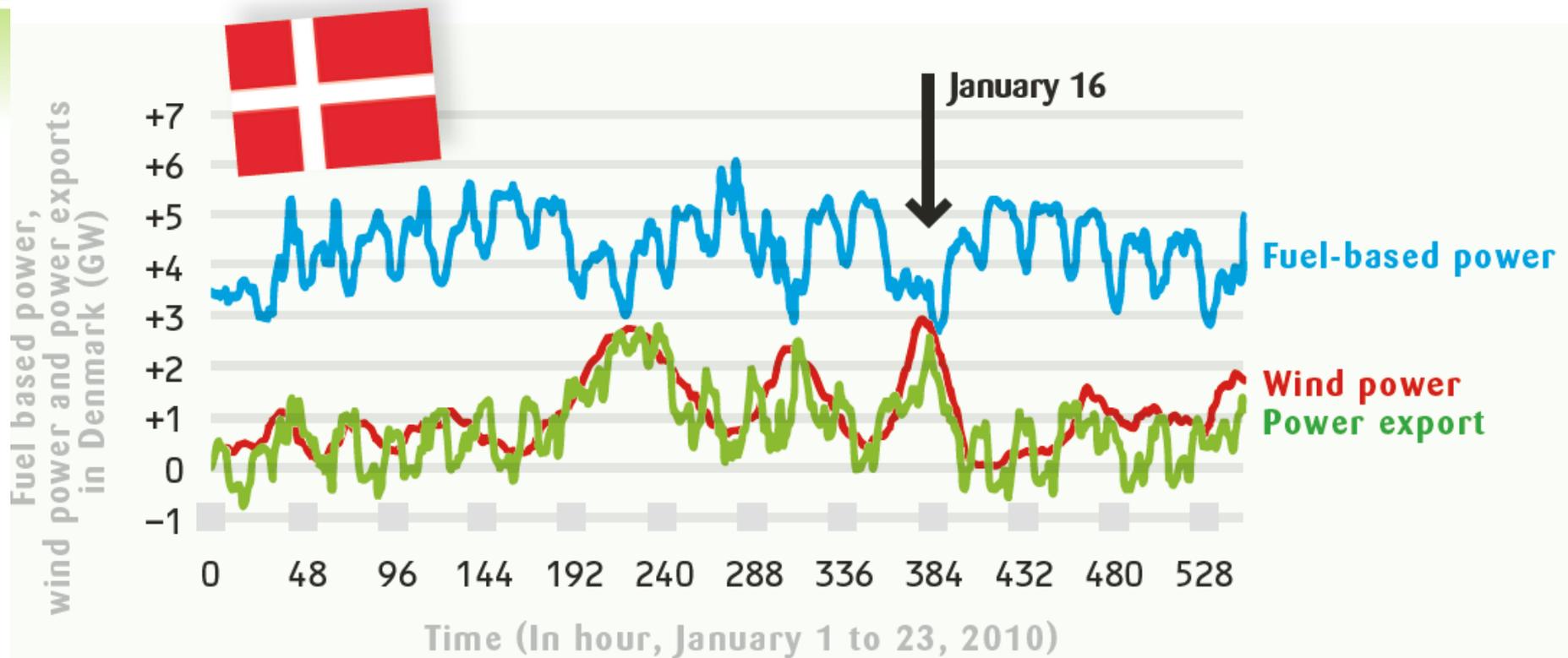


Source: E.ON-Netz

© 2013 ADAM RAJEWSKI, ITC PW.

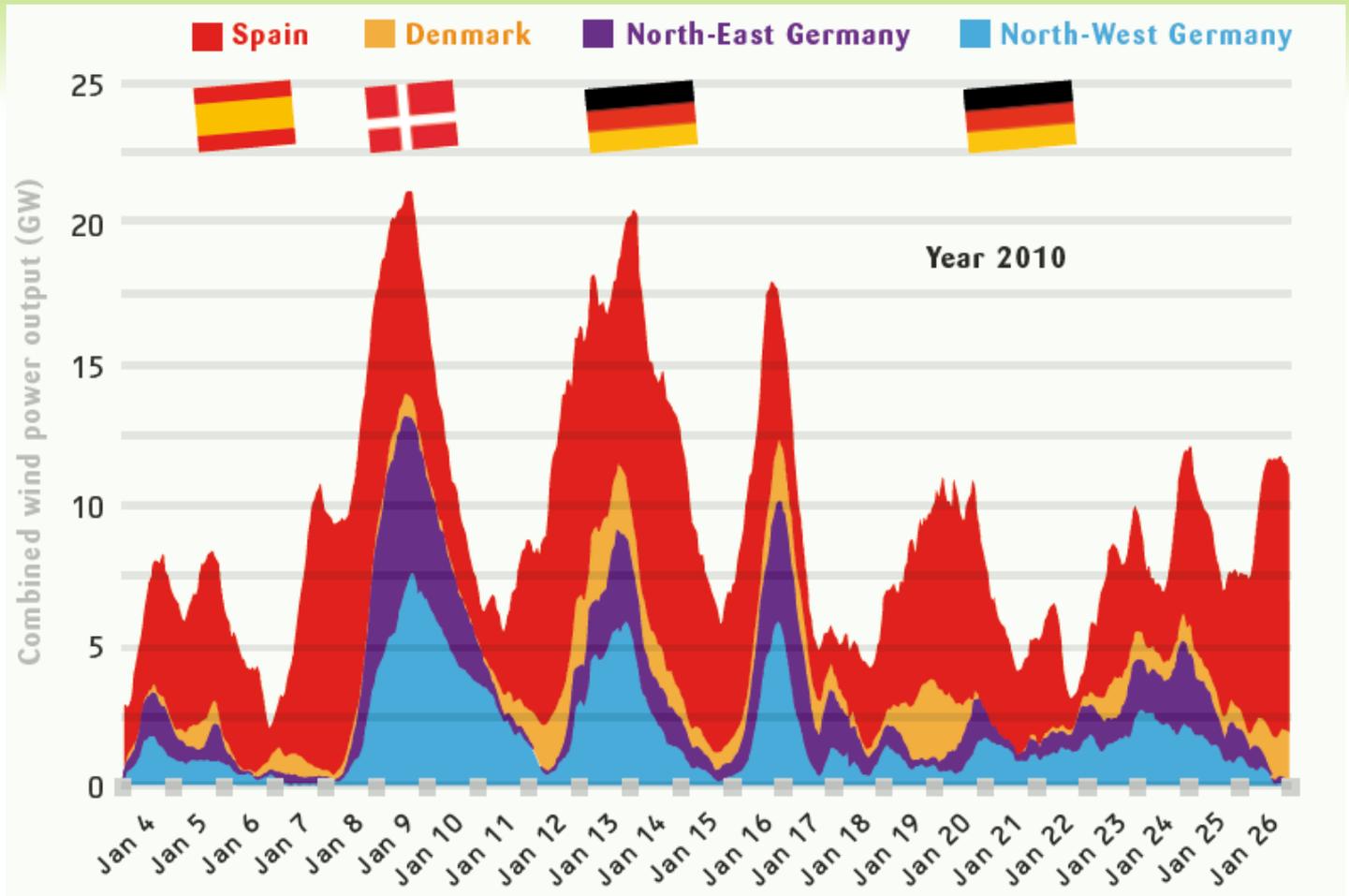
Forecast error in MW (actual minus forecast)

DENMARK - "PERFECT" WIND POWER INTEGRATION

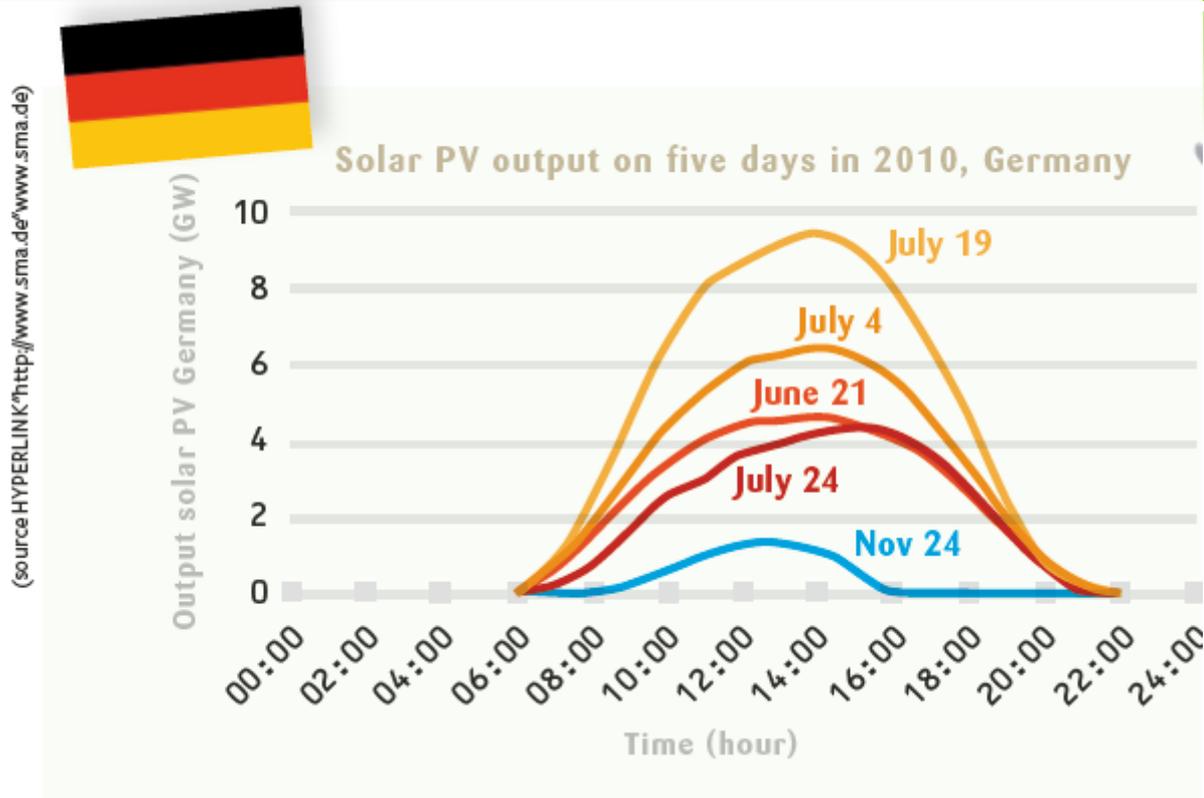


"Integration" by export

SUPER-GRID “SOLUTION”?



SOLAR POWER IMPACT

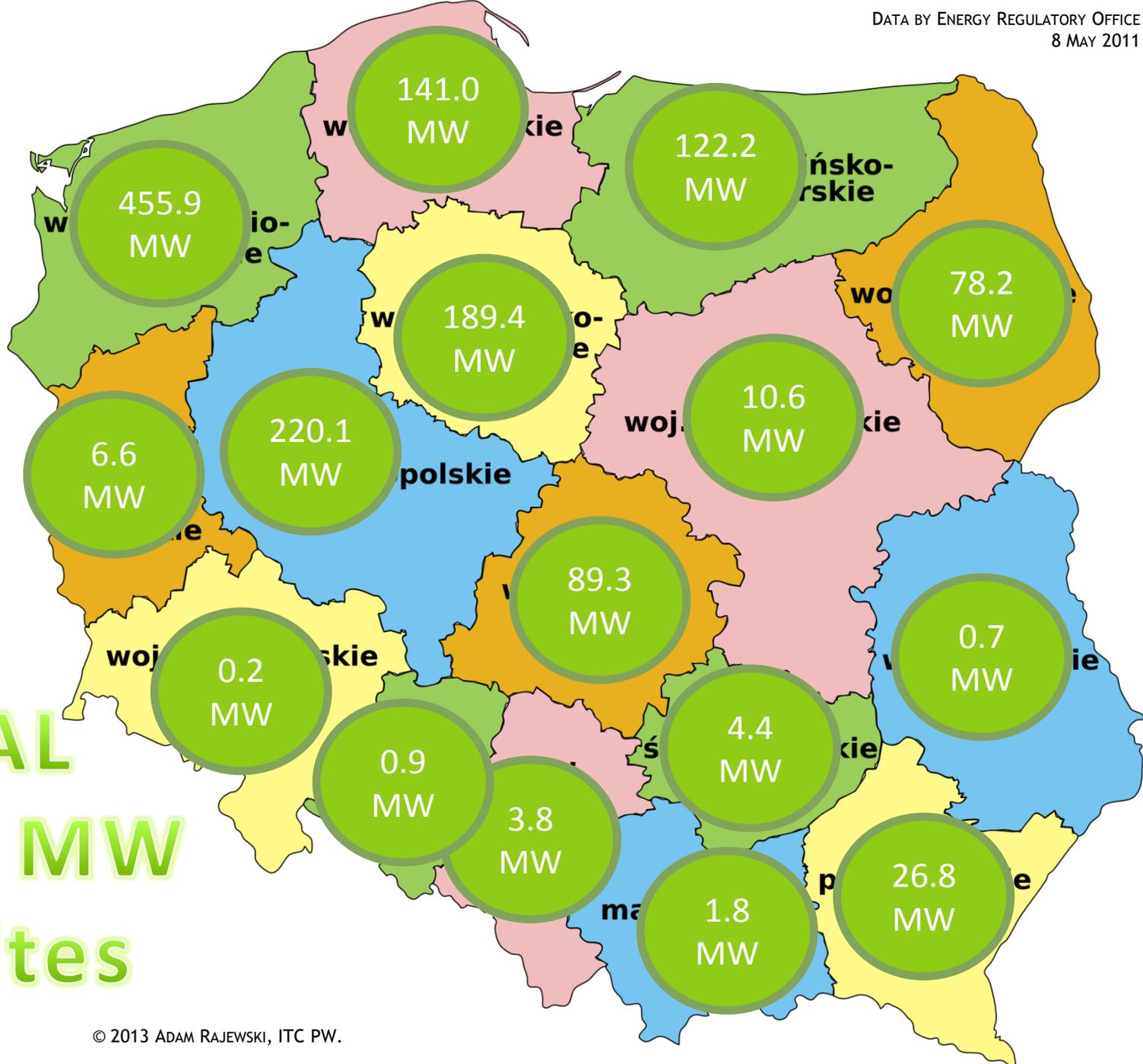


44

MAY

8

2011



TOTAL

1351.8 MW

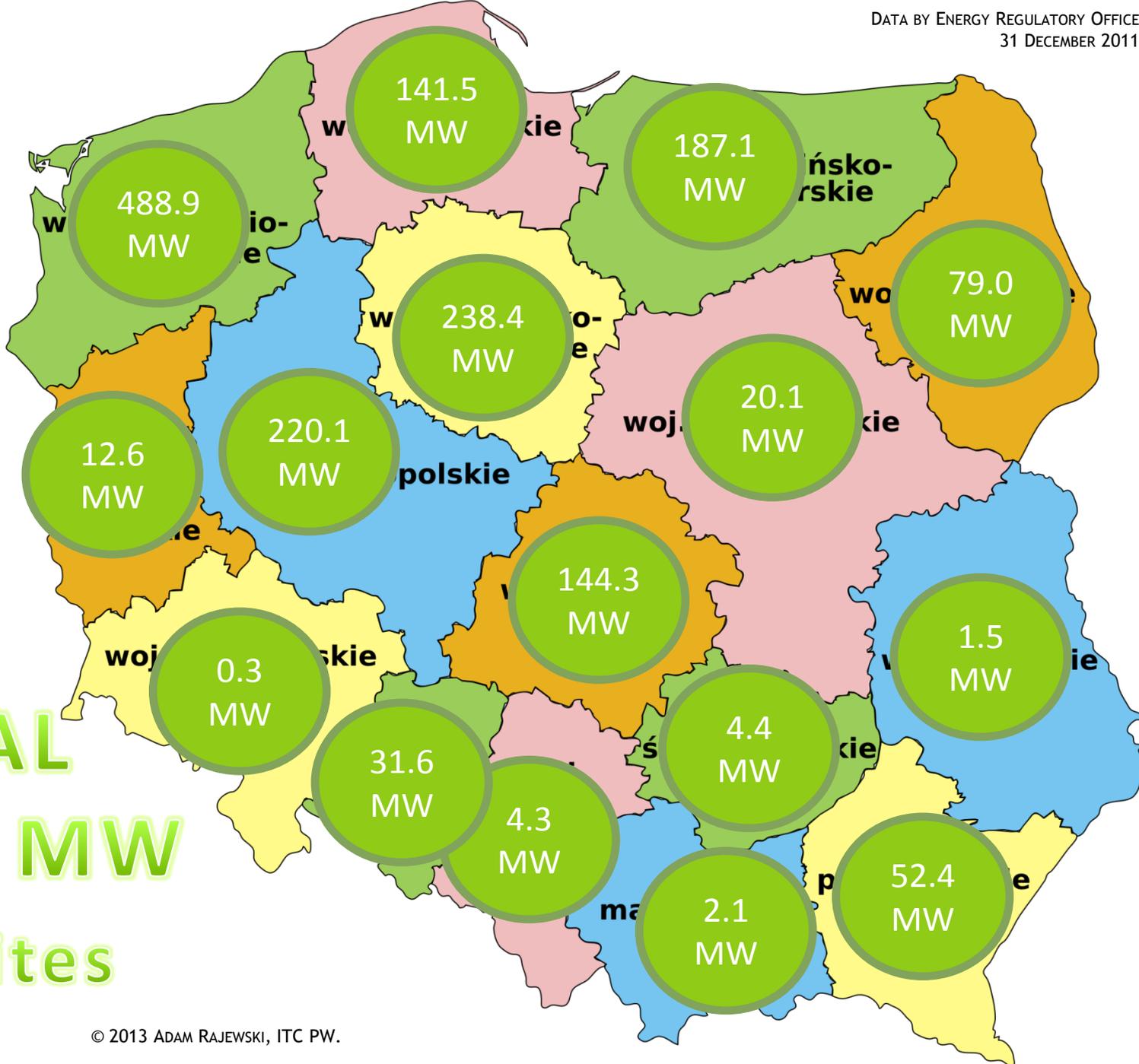
453 sites

45

DECEMBER

31

2011



TOTAL

1616.4 MW

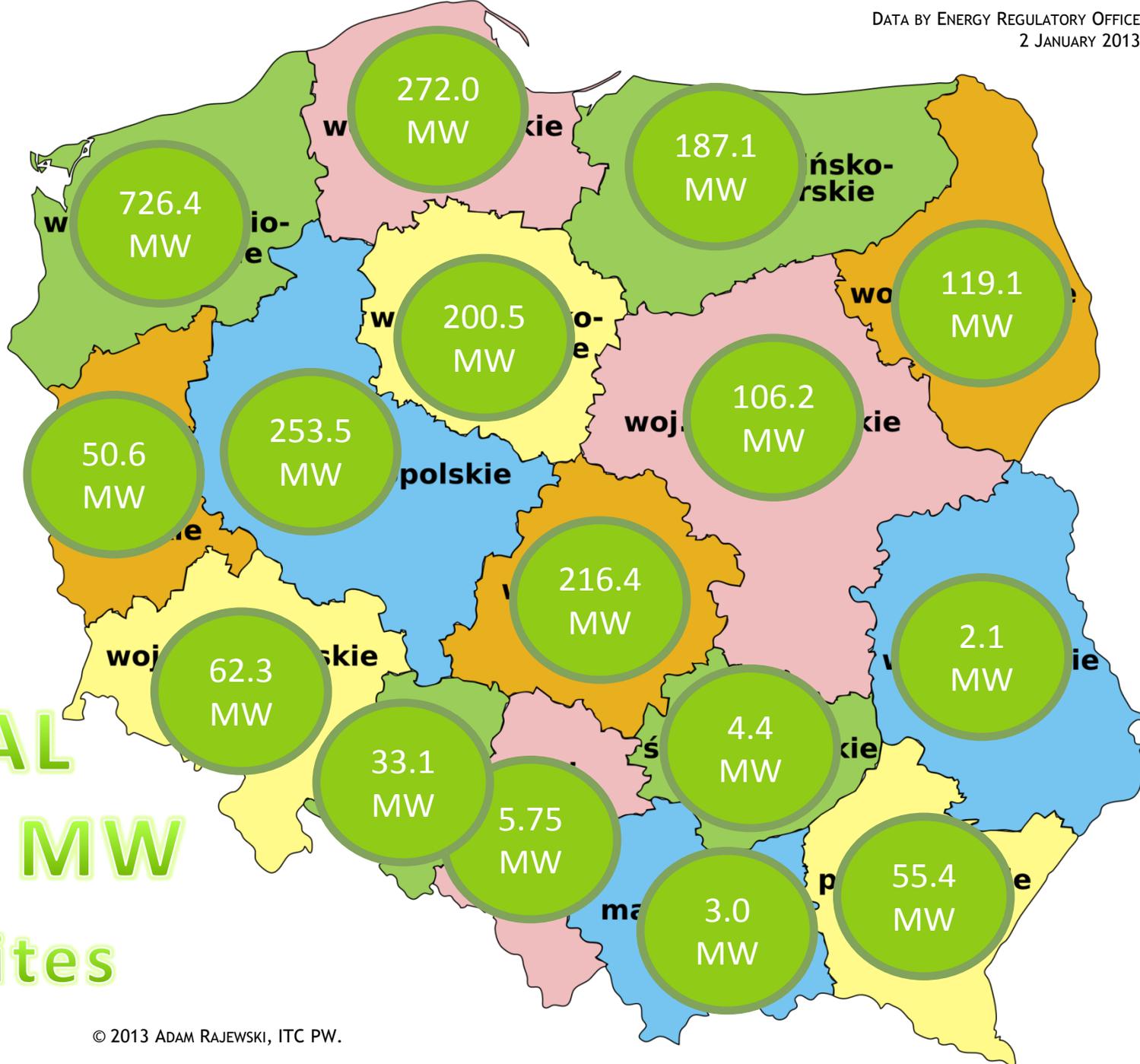
526 sites

46

SEPTEMBER

30

2012

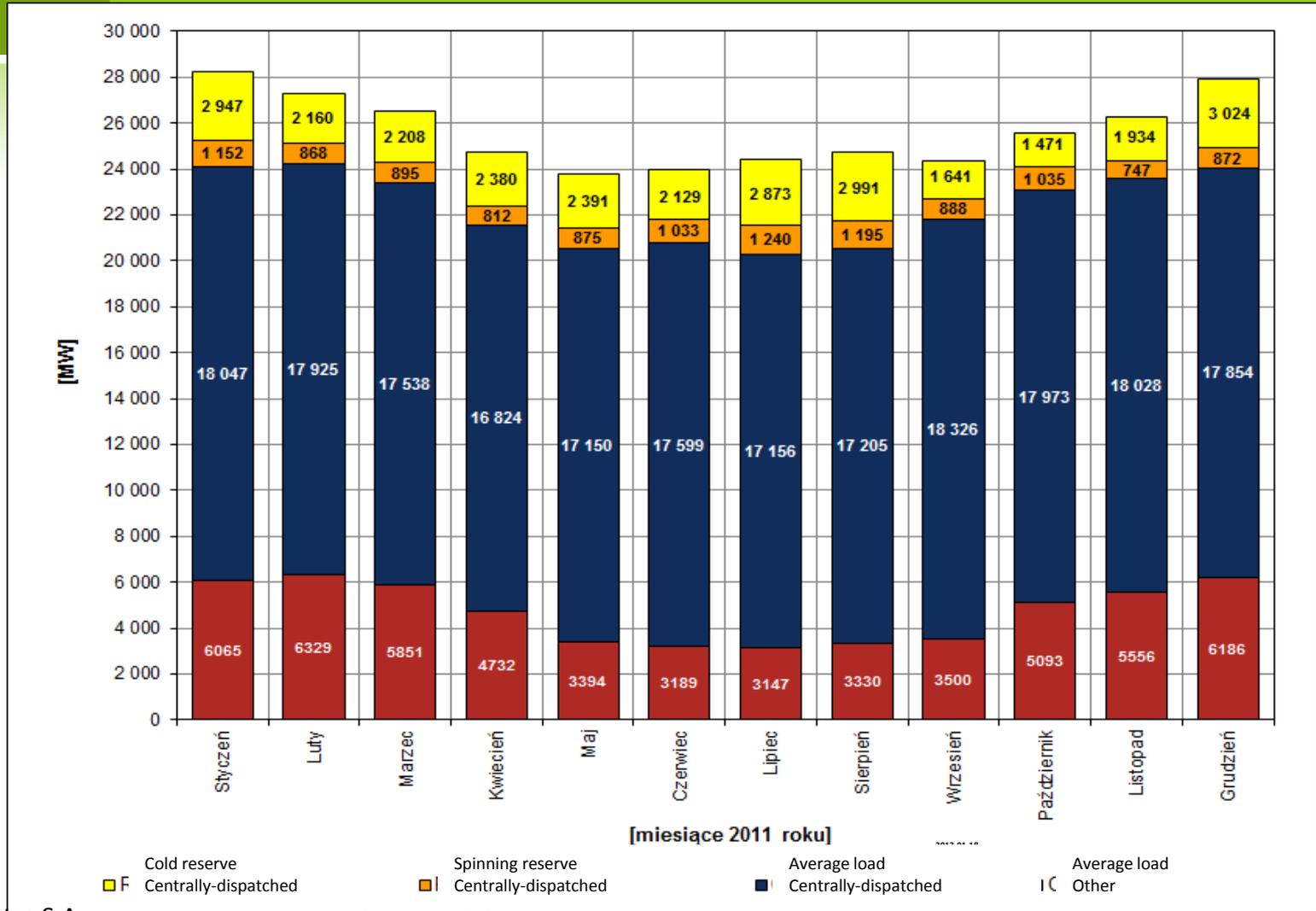


TOTAL

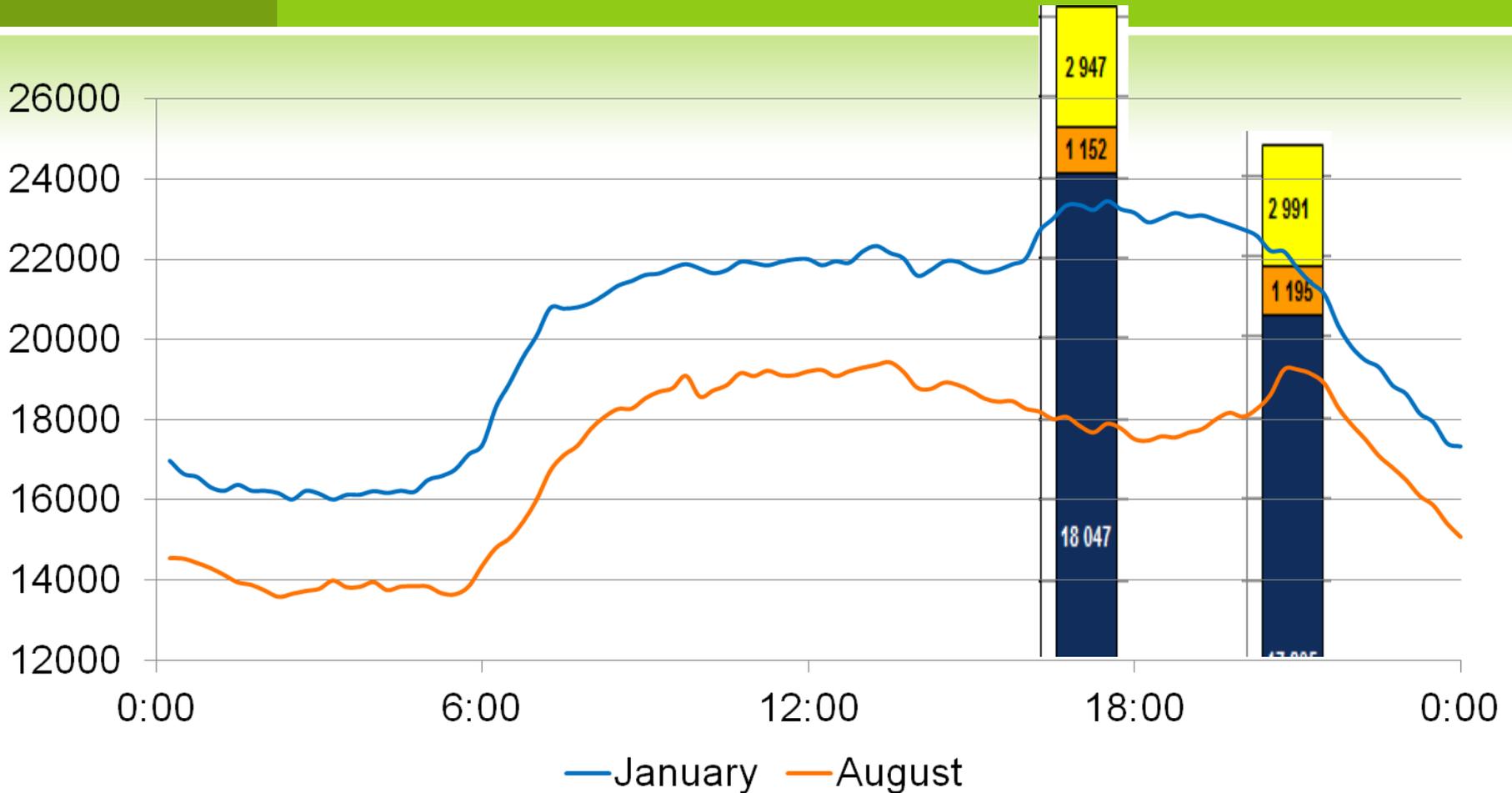
2341.3 MW

663 sites

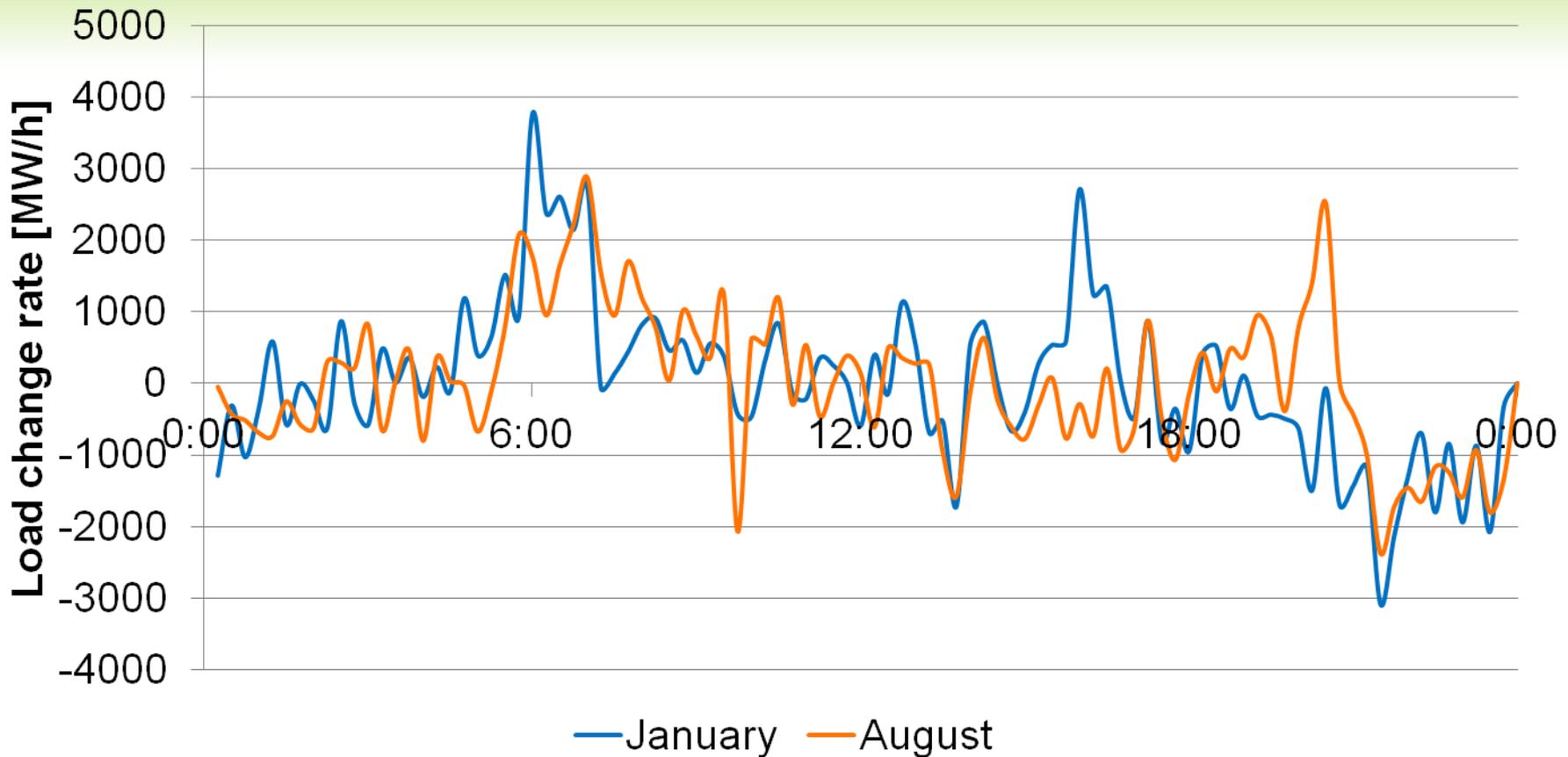
GENERATION POWER & SYSTEM RESERVES IN 2011



TYPICAL DAILY SYSTEM LOAD (WEEKDAY)



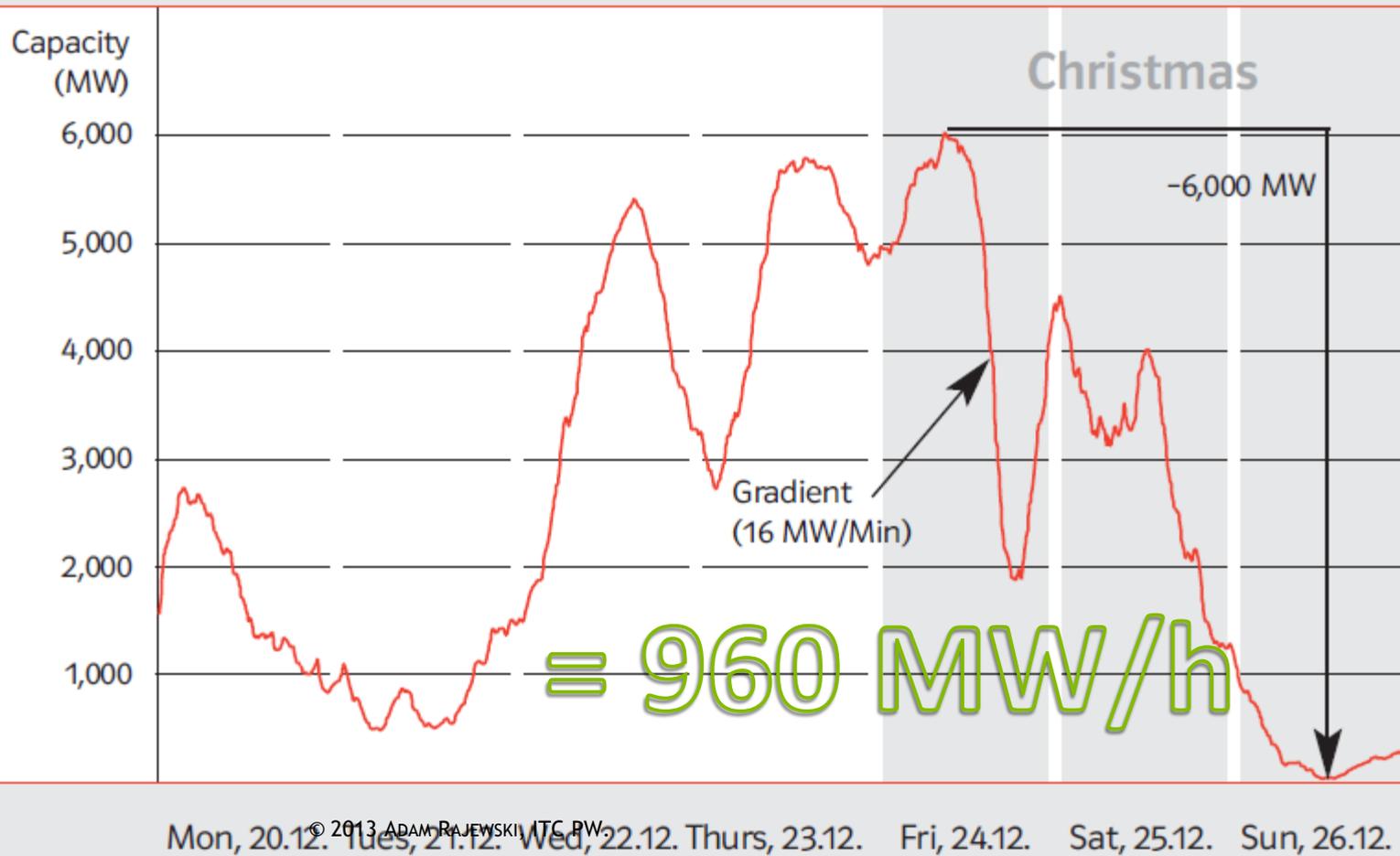
LOAD CHANGE RATES (15 MIN RESOLUTION)



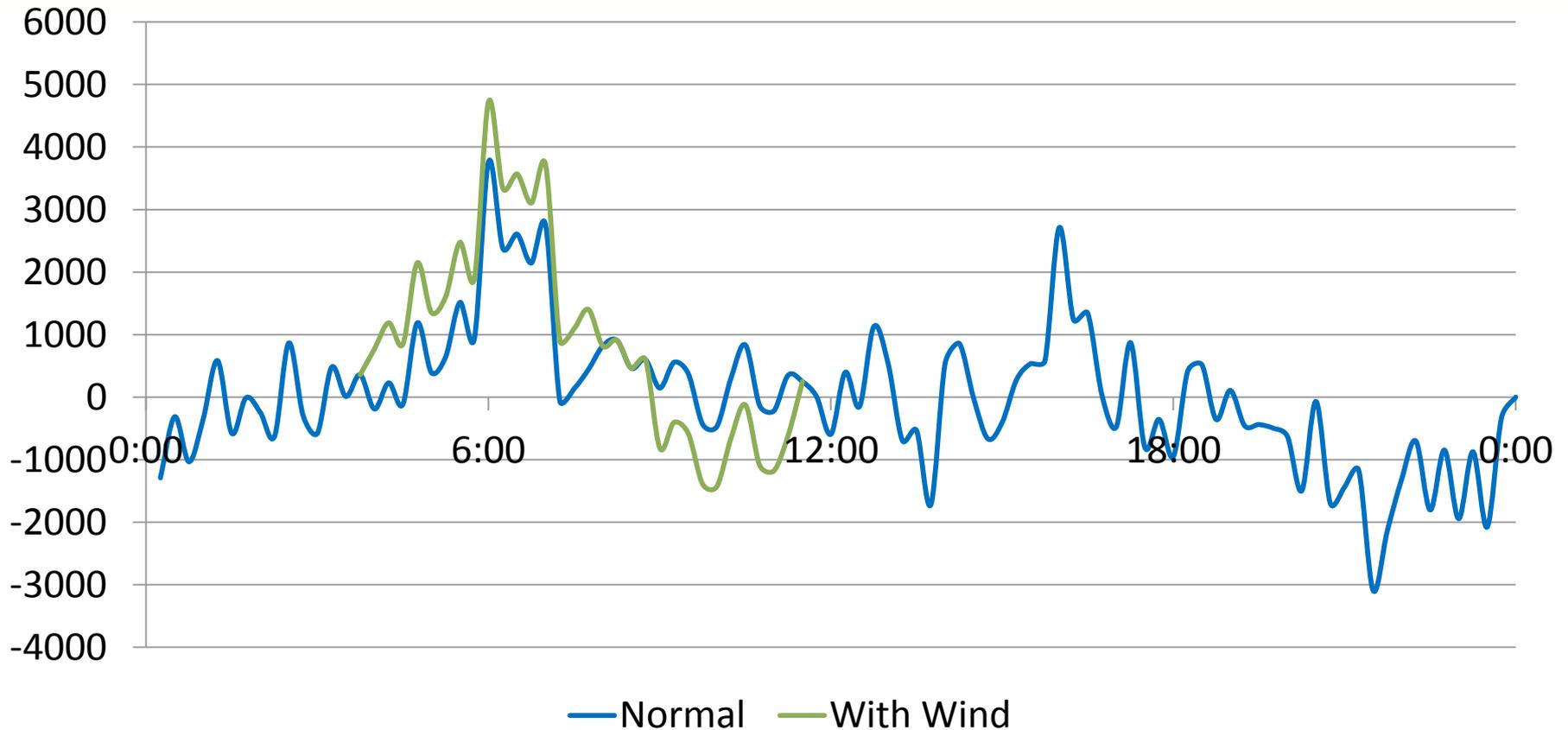
E.ON NETZ DECEMBER 2004

6. Short-term drop

in wind power feed-in over Christmas 2004



LOAD VARIATION [MW/H]



GRID (IN)STABILITY

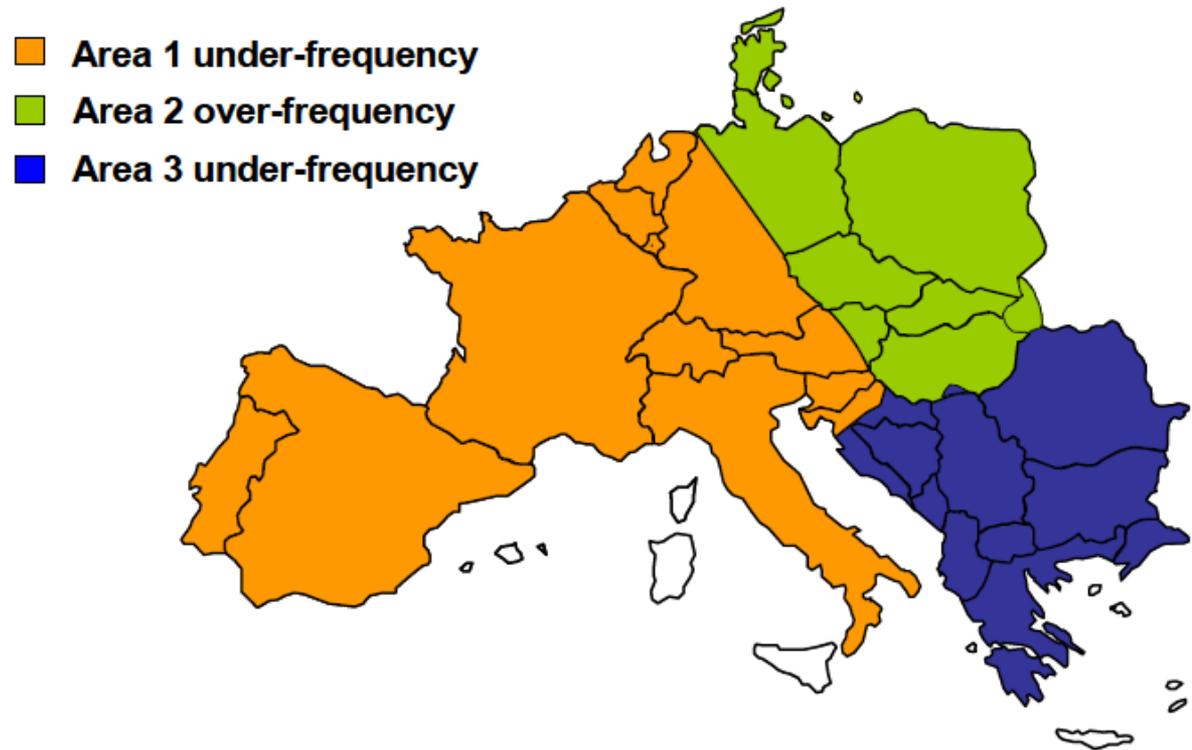
4 NOVEMBER 2006

After disconnecting Conneforde-Diele 380 kV line in Germany (to let a ship pass) UCTE system broke into 3 unsynchronized sub-systems.

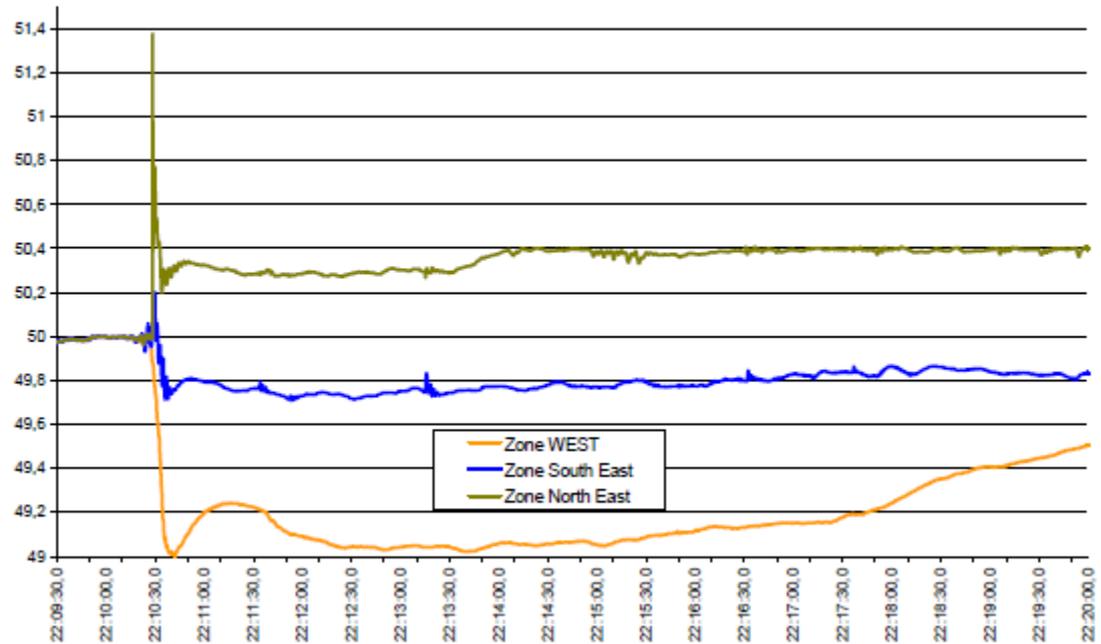


GRID (IN)STABILITY

4 NOVEMBER 2006



GRID (IN)STABILITY 4 NOVEMBER 2006



GRID (IN)STABILITY

4 NOVEMBER 2006

Wind Impact

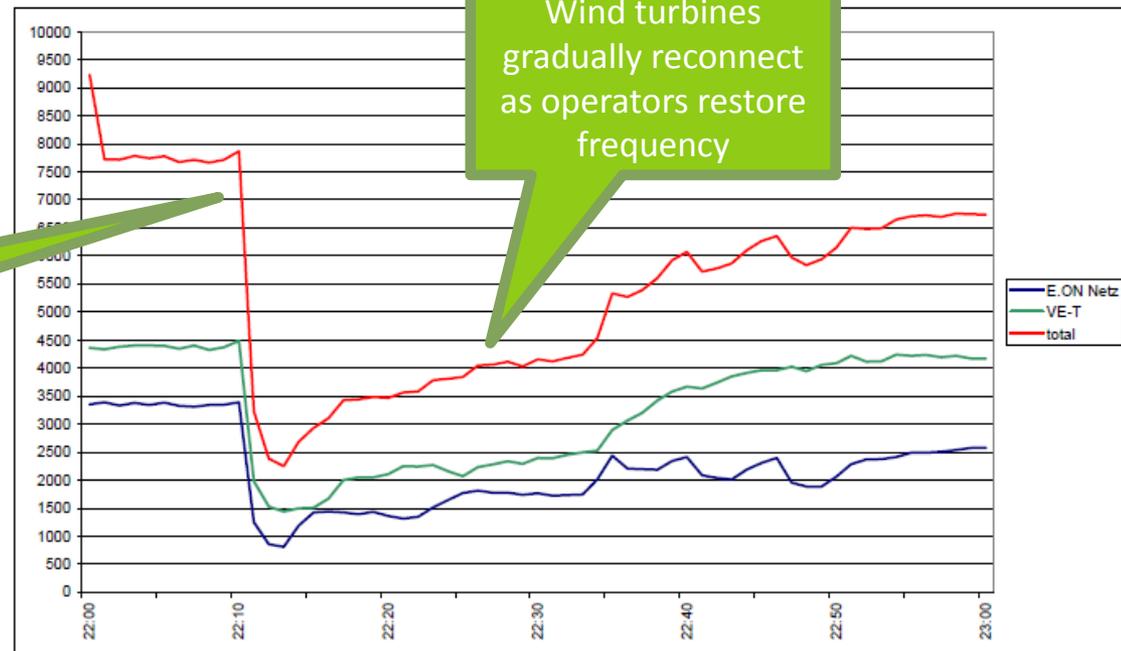


Figure 13: Output of windmills (VE-T, E.ON Netz, from 22:00 to 23:00)

Wind turbines disconnect due to excessive frequency deviation

Wind turbines gradually reconnect as operators restore frequency

Processes beyond operators' control!

SOLUTIONS

POSSIBLE SOLUTIONS

Increasing reserves

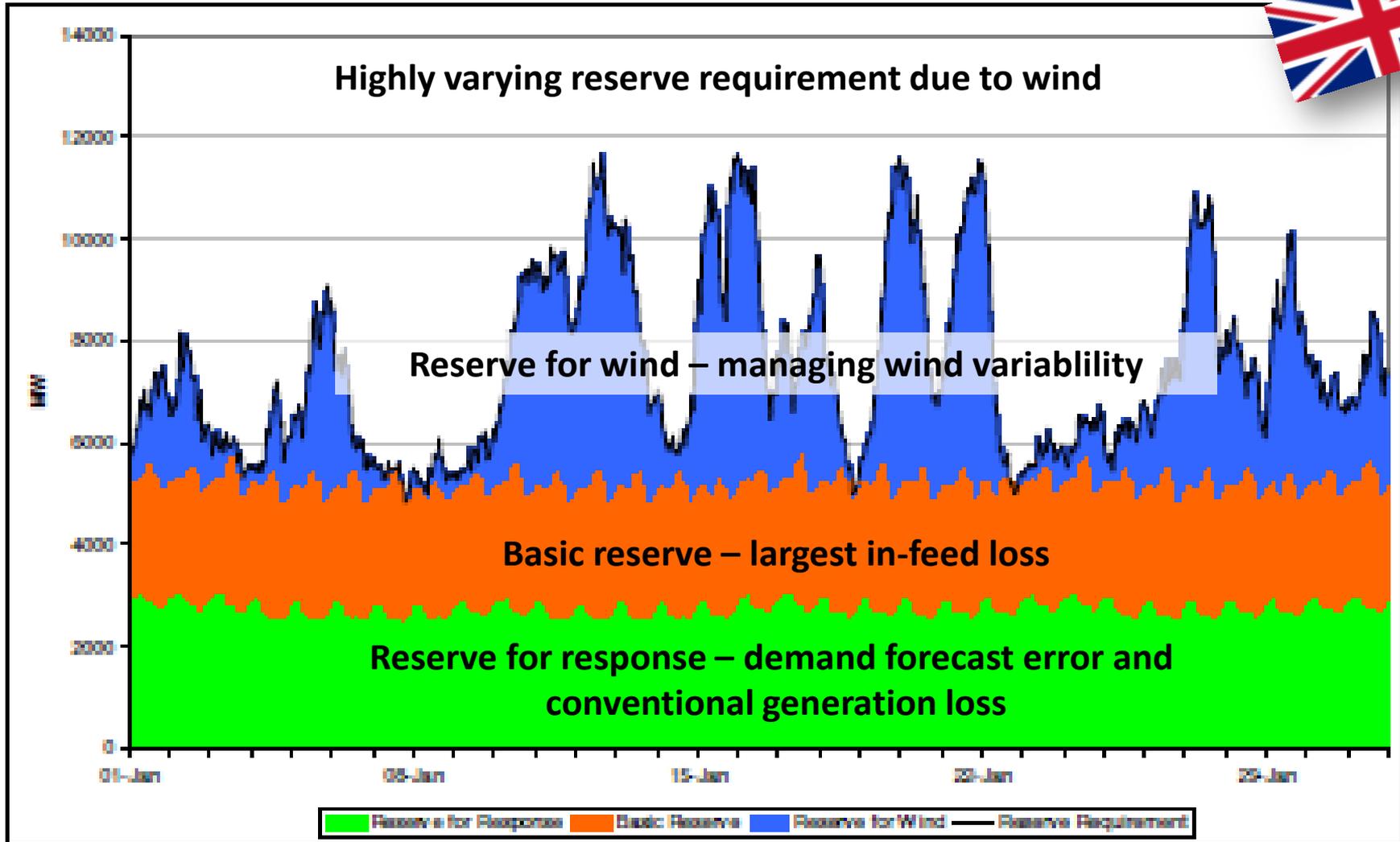
- Additional spinning reserves → inevitable energy losses
- Reserve capacities

Consumption control

- Demand Side Management

OPERATING RESERVE REQUIREMENT UK JANUARY 2020

58



Reserve requirement in the Gone Green scenario, National Grid 2011

GRID-STABILITY POWER PLANTS

Required features

- Short start-up time (unscheduled)
- High flexibility
- High start-up reliability
- Low investment cost

Possible technologies

- Hydroelectric plants
- Reciprocating engines
- Open cycle gas turbines
- CAES

TECHNICAL SOLUTIONS FOR GRID STABILITY PLANT

1. Dedicated stand by grid emergency reserve

- Used only in major technical or market failure – i.e. last resort / insurance capacity that helps when system otherwise fails

2. Dynamic grid stability reserve

- Flexible power plants for emergency capacity and active use in ancillary services
- E.g. Elering Kiisa 250 MW grid stability plant

3. Multipurpose capacity

- Providing emergency reserves, ancillary services and energy depending on the need
- E.g. Danish examples of combining combustion engine power plant, conventional boiler, heat accumulator (storage) and electric boiler

KIISA DYNAMIC GRID STABILITY POWER PLANT, ESTONIA

- ⊙ EPC cost 129 M€
- ⊙ Dual-fuel installation (LFO/natural gas)
- ⊙ 27 reciprocating engines, totally 250+ MW
- ⊙ Start-up time to full power: 5 minutes
- ⊙ Owner & operator: Elering AS, Estonian TSO
- ⊙ Planned operation up to 200 h/a
Emergency operation only
(identified by market failure)
- ⊙ 500 €/kW of installed capacity

THANK YOU!