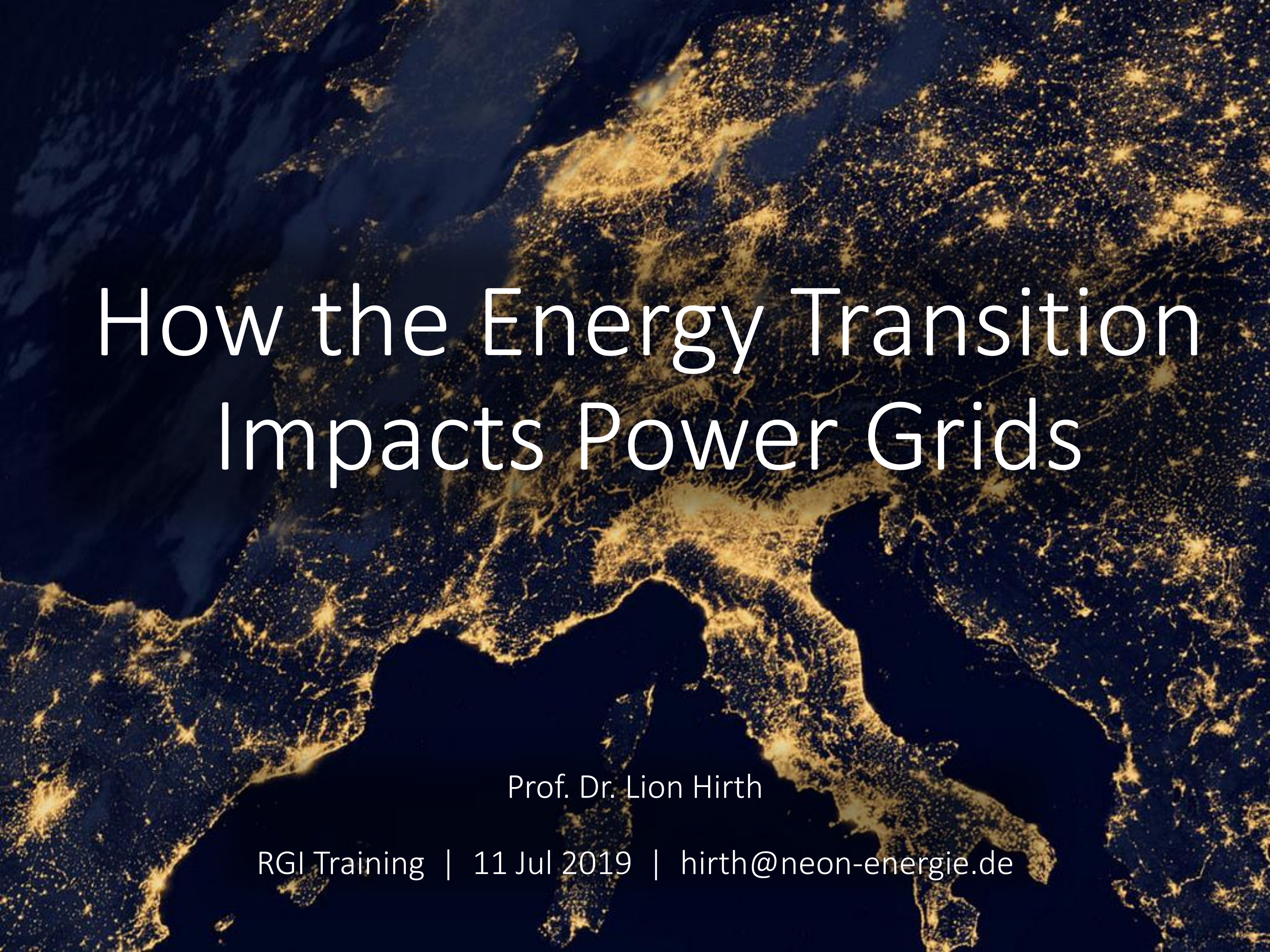


How the Energy Transition Impacts Power Grids

Prof. Dr. Lion Hirth

RGI Training | 11 Jul 2019 | hirth@neon-energie.de

Objectives of this session: four pieces of essential knowledge

Electricity markets

- How markets and networks interact
- How power plant dispatch and electricity prices are determined

Why we need grid expansion

- Four reasons why we need more electricity networks

Load flow and redispatch

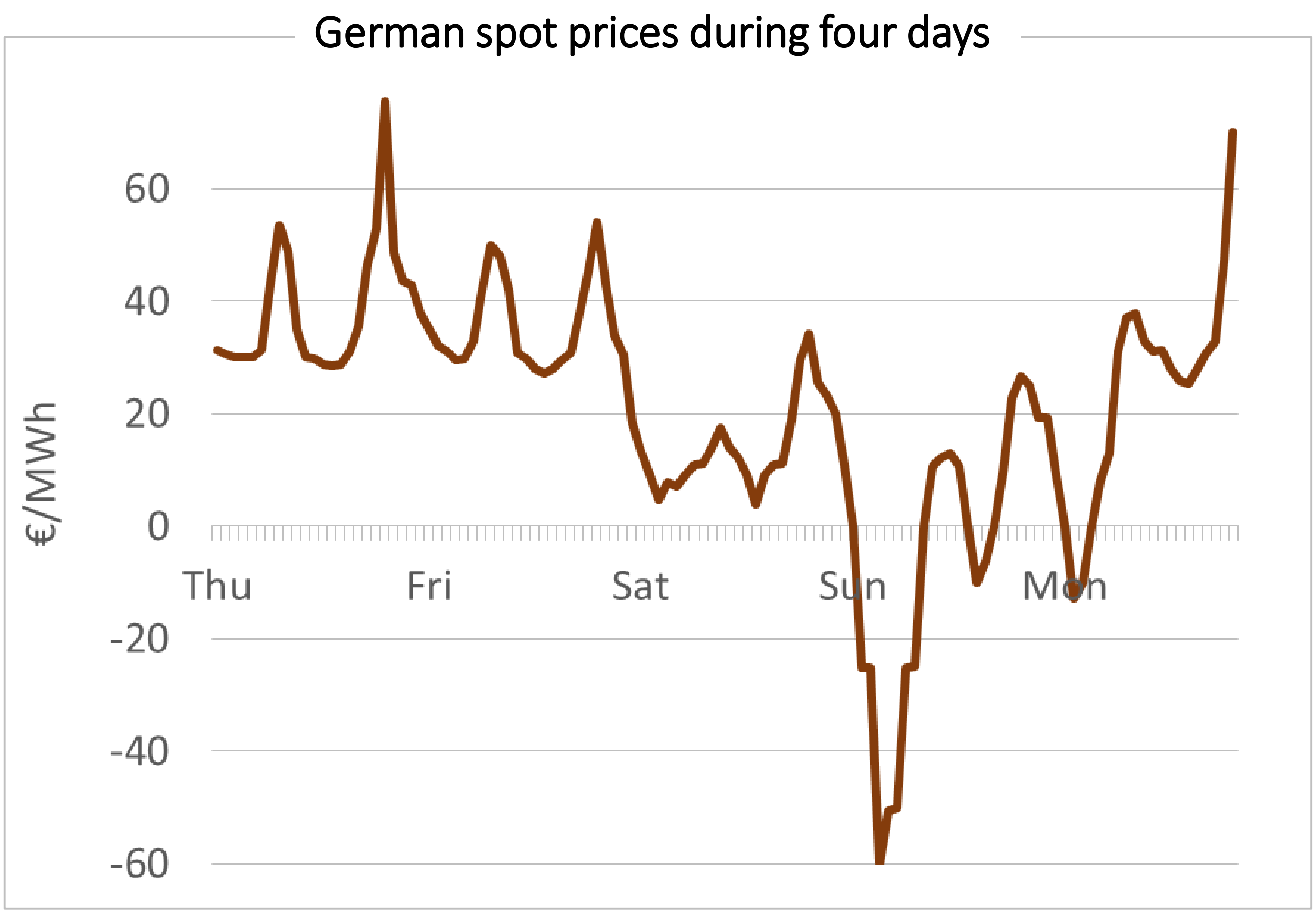
- How electricity flows through grids
- How system operators avoid overload through congestion management

Alternatives to grid expansion

- Cabling, optimization and upgrades
- Steering investment to the right location

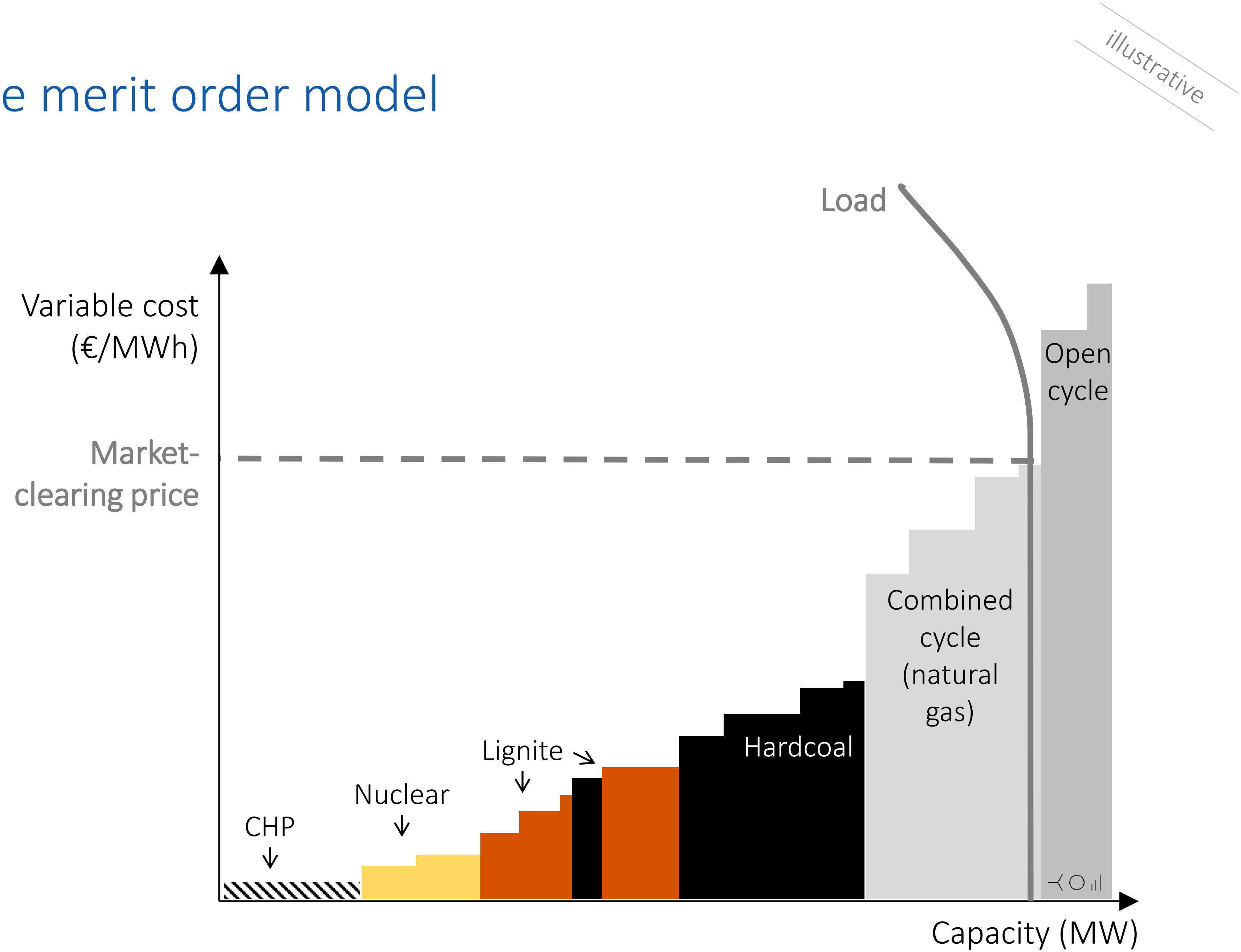
Electricity Markets

For economics, it matters *when* electricity is produced



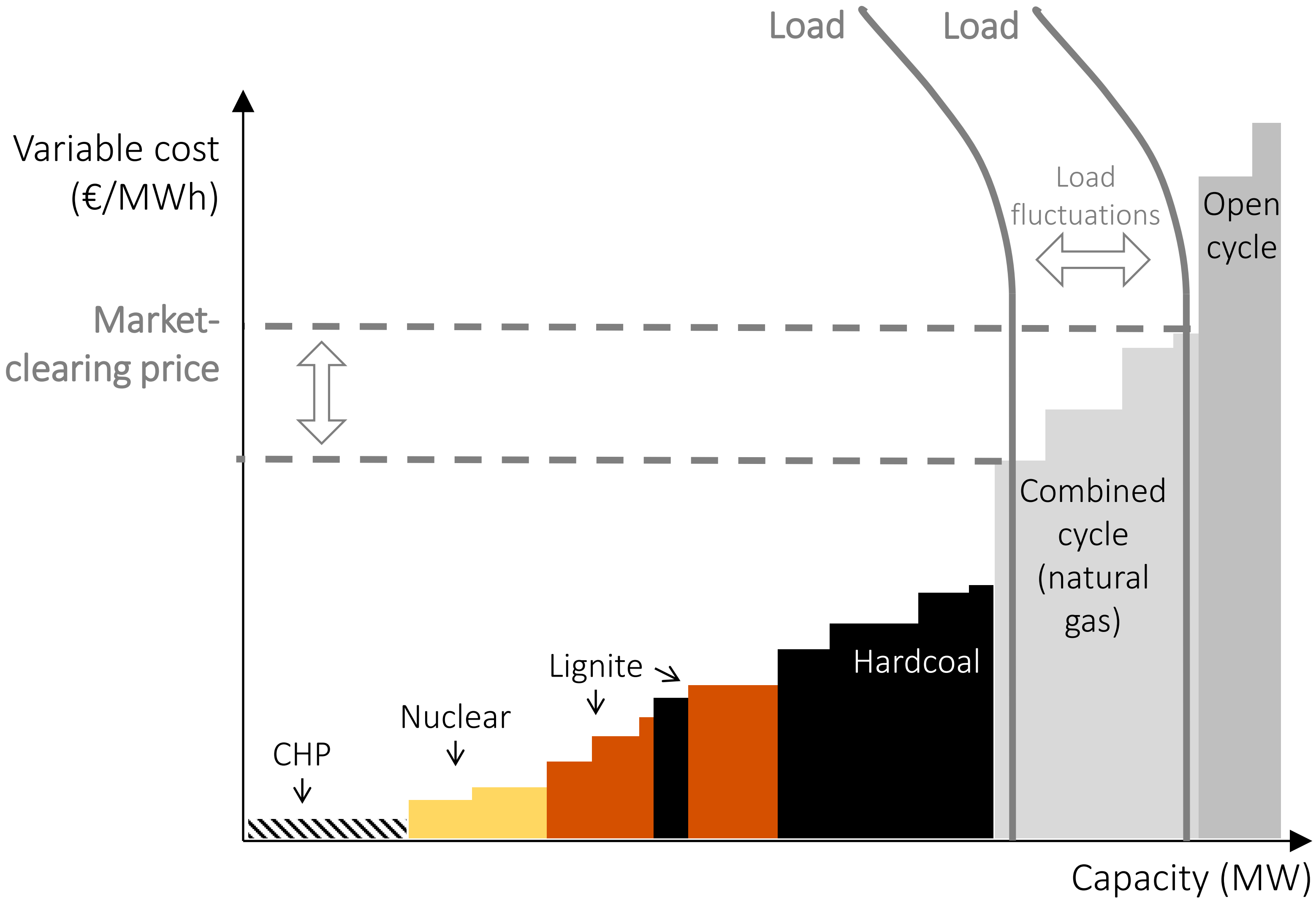
German day-ahead spot price. 13-17 March 2014. On Sunday morning, the instantaneous wind penetration rate exceeded 50%.

The merit order model

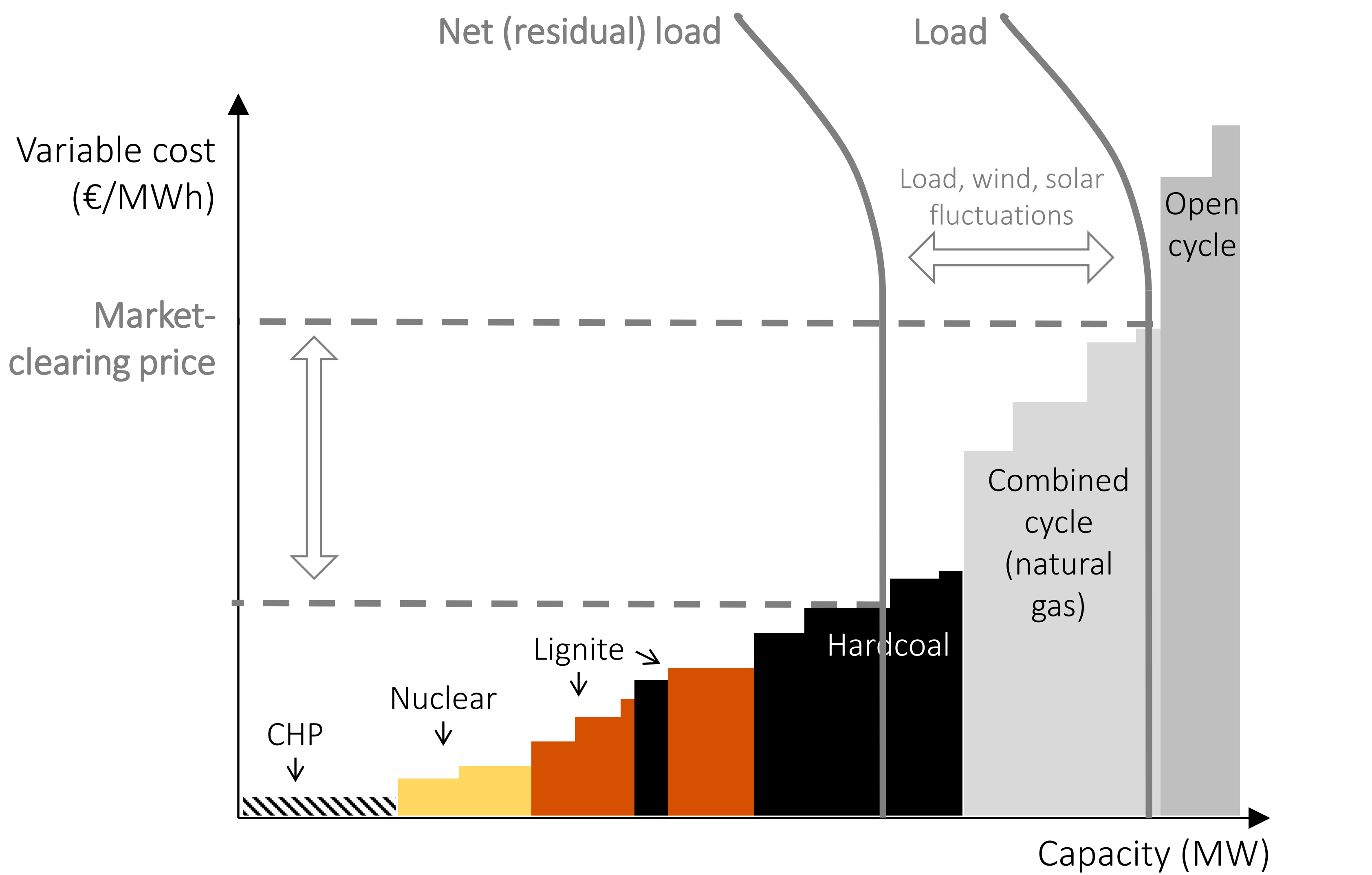


The merit order model

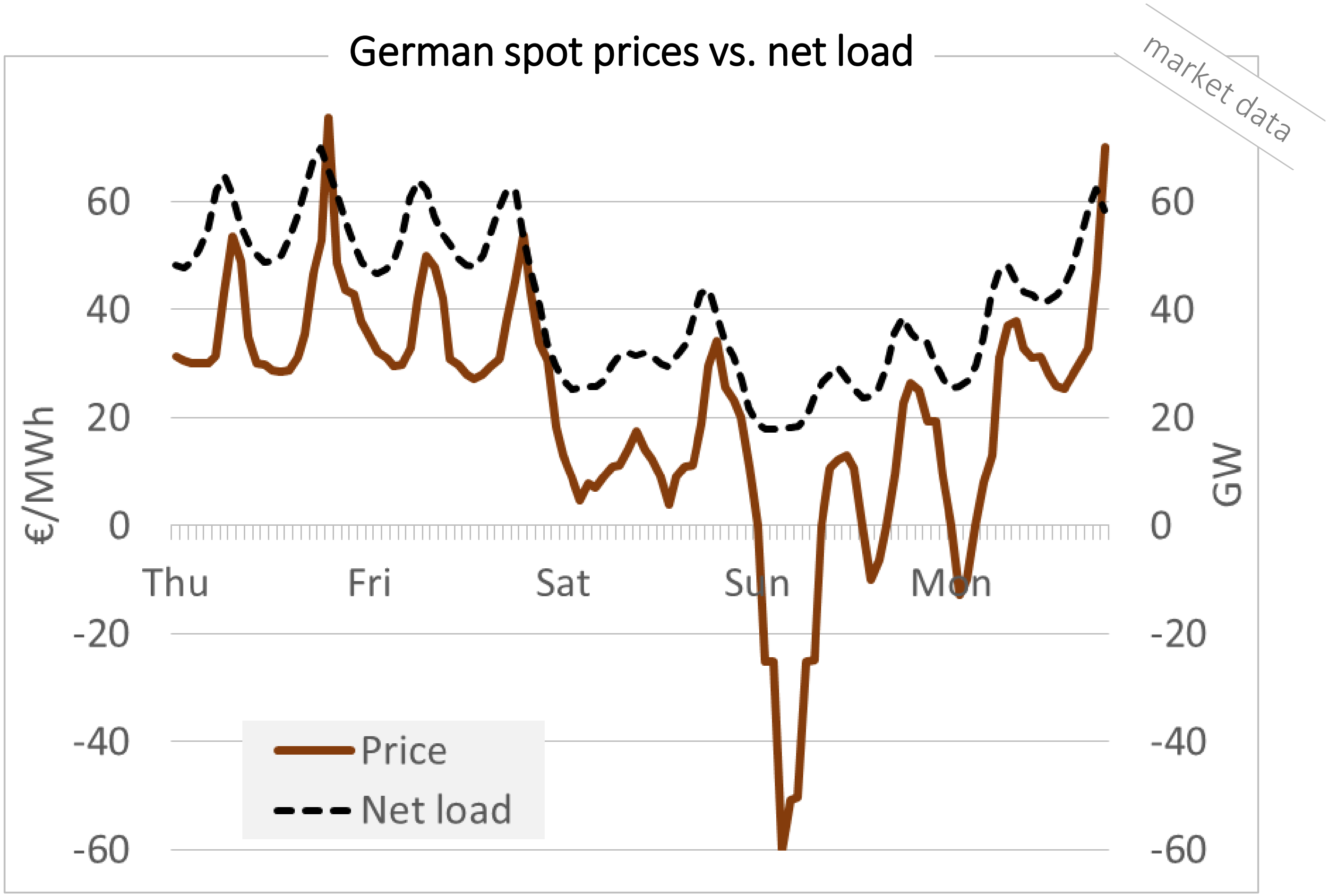
illustrative



The merit order model



Empirically, net load and prices match fairly well



German day-ahead spot price. 13-17 March 2014. On Sunday morning, the instantaneous wind penetration rate exceeded 50%.

Electricity prices can be well described as a – non-linear – function of net load.

Zonal pricing

- In Europe, electricity trade is geographically organized in "bidding zones"
- Within one bidding zone, the TSO guarantees market actors that all trade is freely possible
- As a consequence, within any zone, there is always one electricity price
- Bidding zones mostly follow national borders

Interconnectors

Interconnectors

- Zones are linked with “interconnectors” (U.S. terminology: “interties”)
- If interconnector capacity is not fully used, prices equalize across zones
- If interconnectors are congested, prices diverge between zones

Trade between zones

- The trade on interconnectors can be organized differently
- Explicit / implicit / flow-based market coupling

Drivers for Grid Expansion

Why do we need electricity grids?

It is cheaper, or necessary, to produce electricity far away from human settlements

- Conventional plants: transport cost, emissions (coal), safety (nuclear)
- Wind power: wind speeds
- Renewables: land availability and prices, visual impact, acceptance

There are huge benefits of integrating system

- Smooth out demand
- Smooth out wind and solar generation
- Redundancy and security of supply
- Economies of scale (large power stations are much more efficient)

→ Small, autarkic power systems are extremely expensive and quite unreliable

This has always been true …

- … but becomes more pronounced in renewables-based systems

Reasons for increased stress on Europe’s grids

Three factors explain the increased pressure on European networks

- Expansion of wind and solar power – huge increase in installed capacity
- Fading effect of integrated monopolies who invested in local supply
- European market integration: larger imports/exports

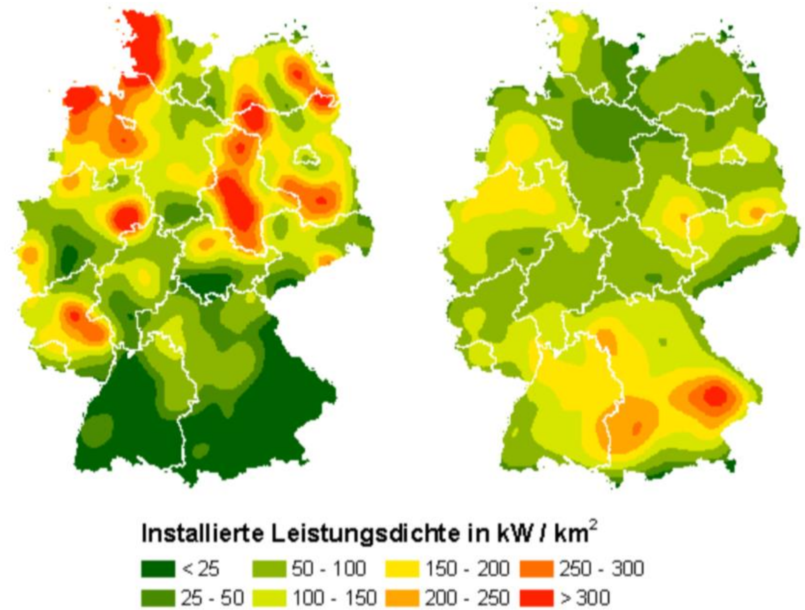
Another important driver is at the horizon

- New consumers – electrification of heating and mobility

Renewables

Geographic mismatch

- Geographical mismatch between renewables and demand
- Wind and solar requires much land
- People tend to not settle in wind areas

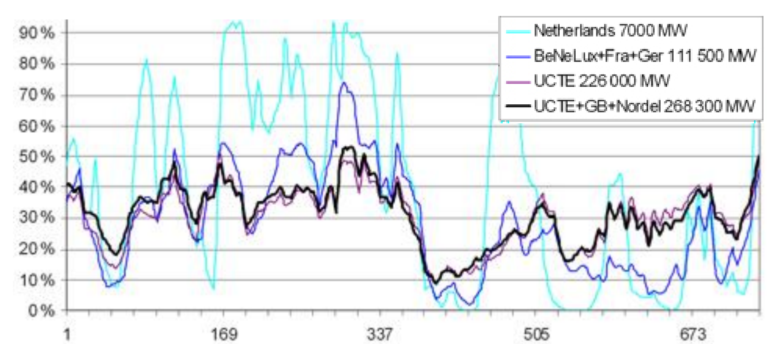


High capacity – low running hours

- Wind power has capacity factors of 20-30%, solar of 10-20%
- We will have much more overall generation capacity than in the past

Geographic smoothing

- An important way to smooth overall RE generation is geographic diversification



The fading legacy of regional monopolies

The pre-2000 electricity industry

- Starting from the late 1990s, the European electricity sector was reformed and liberalized
- Prior to this, electricity supply was provided by integrated utilities that had regional monopolies
- Between these monopolies, electricity trade was more the exception than the rule
- Generation capacity was built close to demand centers, regardless of cost

The benefits, and side-effects, of liberalization

- The regional autarky led to massive over-capacity
- After market restructuring, about a third of capacity – mostly old, dirty fossil fueled plants – were decommissioned
- New investment is located where it is cost-efficient: coal and wind power tend to be close to the coast

European market integration

Integrating European markets has large benefits

- Use geographic diversity also across countries to smooth demand and supply
- Produce electricity where it is cheapest

What “market integration” means

- Alignment of market rules and regulations (“market design”)
- Allowing more imports and exports

Managing congestion through limiting trade

- In the past, system operators have often reduced internal congestion by limiting imports or exports
- With new EU regulation coming, there is less and less room to do so

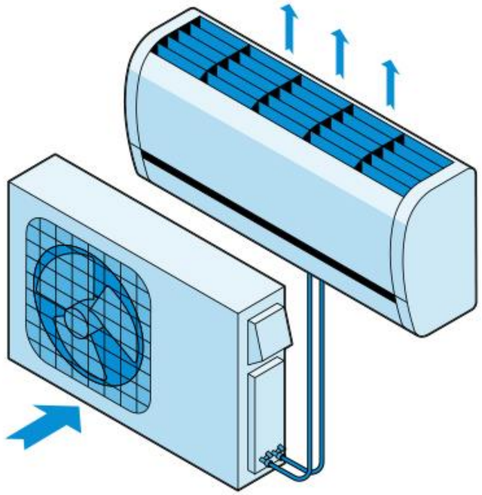
Electric heating and transport

Electrification

- For deep decarbonization, it is necessary to electrify transport (e-mobility) and heating (heat pumps)

Implications for the distribution grid

- These new consumers will be connected to the distribution grid
- Possibly, they will consume electricity much more simultaneous than other types of demand (cold winter days, after coming home from work)

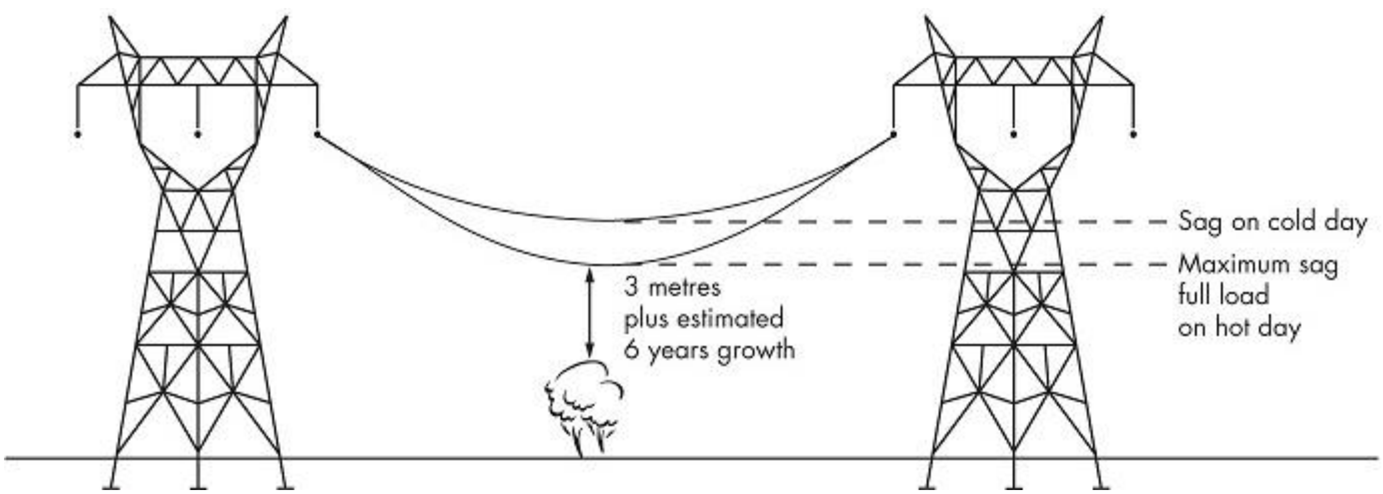


Load Flow and Redispatch

What limits load flow in grids?

Thermal limits

- Lines (conductors) themselves also have some resistance
- This makes them heat up
- This causes the material to become weak (soft) and the lines to sag
- Also, insulators and transformers can be damaged
- Sag depends on outside temperature, solar irradiance, wind → "dynamic rating"



What limits load flow in grids? (cont'd)

Voltage limit (also reactive limit)

- Voltage drops with line length
- Voltage cannot exceed upper limit, e.g. 400 kV – safety issue
- Voltage cannot fall below lower limit, e.g. 380 kV – to deliver sufficient power
- (That is why you sometimes read "400 kV line" and sometimes "380 kV line")

Stability limits

- Limit related to AC current
- The phases of the alternating current must be sufficiently close all across the grid

Kirchhoff’s laws

Electricity is different

- Most transport (trucks, ships, aviation) can be directed, i.e., routing can be determined by dispatch center
- This is not the case for electricity
- The flow of electricity in electricity grids is determined by the law of physics

The two laws of Kirchhoff

- Kirchhoff’s current law: “total current or charge entering a node is exactly equal to the charge leaving the node as it has no other place to go except to leave, as no charge is lost within the node“
- Kirchhoff’s voltage law: “in any closed loop network, the total voltage around the loop is equal to the sum of all the voltage drops within the same loop” which is also equal to zero
- Collectively, they govern the distribution of electricity flow over “alternative” lines
- In meshed networks, this leads to surprising (and sometimes frustrating) results

“DC load flow” model

AC systems are complicated

- We abstract from many issues related to AC

Flows are calculated “as if they were DC”

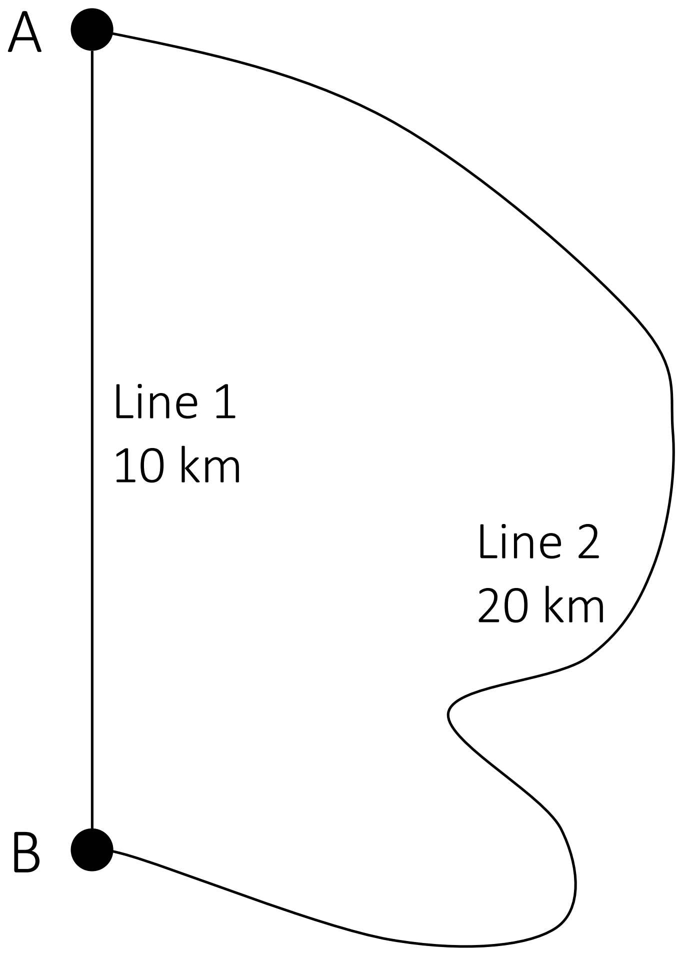
- Impedance (AC) is identical to resistance (DC)
- The distribution of flow is *inverse to the resistance* (i.e., more resistance, less flow)
- Electricity flowing from A to B will take *all possible pathways*

Further simplifications

- Resistance are proportional to length of line
- No losses

The simplest load flow example

- Two nodes
- Connected by two lines
- Line 2 is twice as long as line 1
- Overall, there is a flow of $P = 1\ MW$ from A to B
- How much of this will flow through each line?



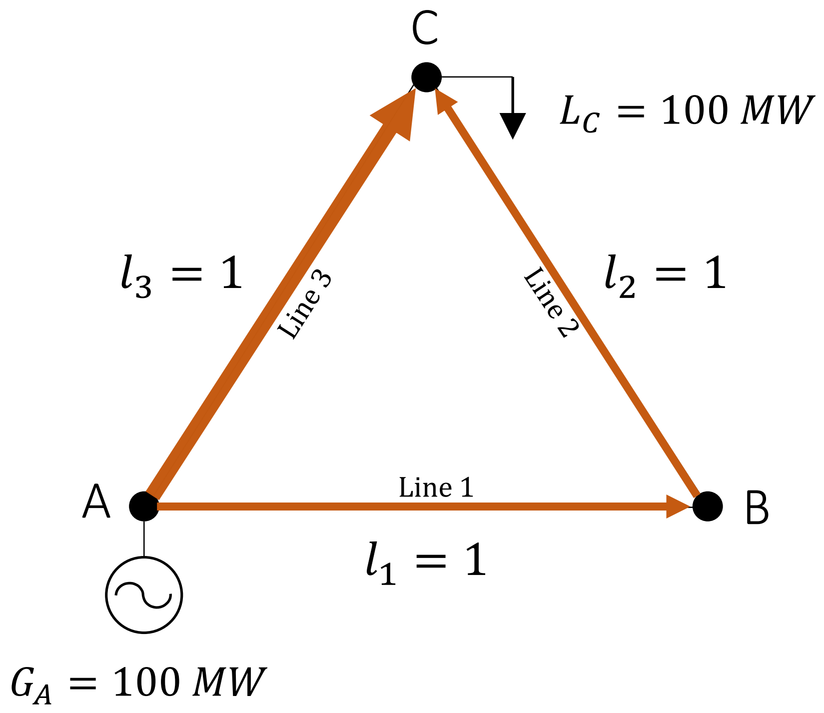
A simple load flow example

The network

- Three nodes A,B,C (think of substations)
- Three lines 1,2,3 with length l and unconstrained transmission capacity
- Generator at A, consumer at C

1. Power flow

- 100 MW are generated at node A and consumed at node C
- What is the power flow on each line?



Network constraints

The network

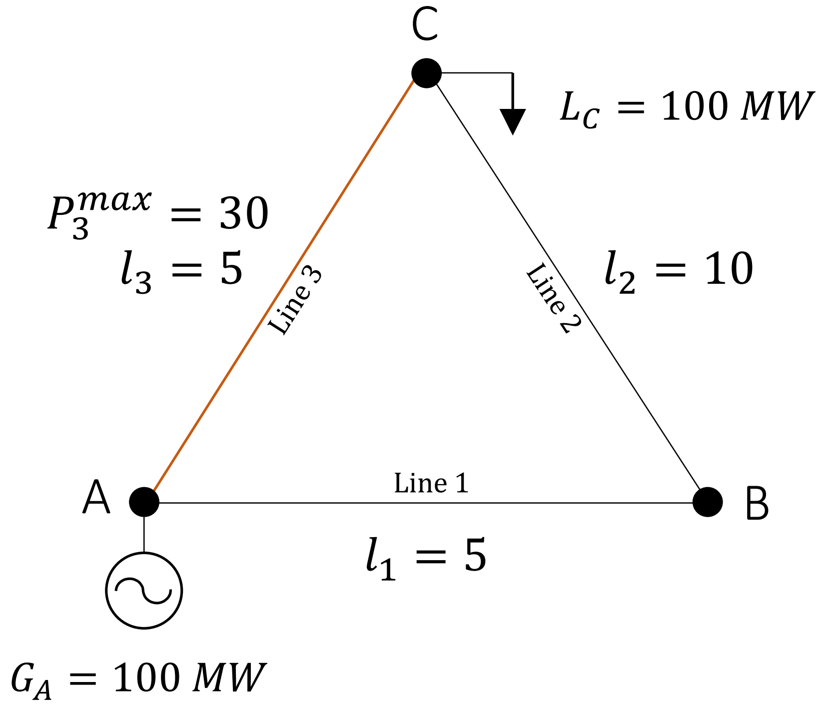
- As above

1. Power flow

- 100 MW are generated at node A and consumed at node C
- What is the power flow on each line?

2. Network constraints

- Due to its maximum capacity, the flow of line 3 is limited to $P_3^{max} = 30MW$
- Lines 1 and 2 have unlimited capacity
- What is the maximum power that can be consumed?



Congestion management

Congestion management = dealing with the limited capacity of the electricity grid

- Measures to avoid line overloading and to remain within voltage limits

By actions that affect ...

- ... the network
- ... the geographic distribution of electricity generation
- ... the geographic distribution of electricity consumption
- ... the geographic distribution of electricity imports/exports

Different names

- Congestion management in zonal markets on an operational time scale: “remedial actions”

Congestion management

Solving internal congestion

- At borders of bidding zones, market coupling is used to avoid line overload
- Within zones, no such mechanism is available
- Line overload has to be solved by congestion management

Option 1: Impact load flow directly

- Phase-shifting transformers / FACTS
- Such equipment exists only in few places, but are increasingly common

Option 2: Topology changes

- Change the topology of lines, e.g. open a line

Option 3: "Redispatch"

- Reduce generation in oversupplied region ("before the constraint")
- Increase generation in undersupplied region ("behind the constraint")
- This has to be done in an out-of-the-market transaction

How can the system operator change load flows?

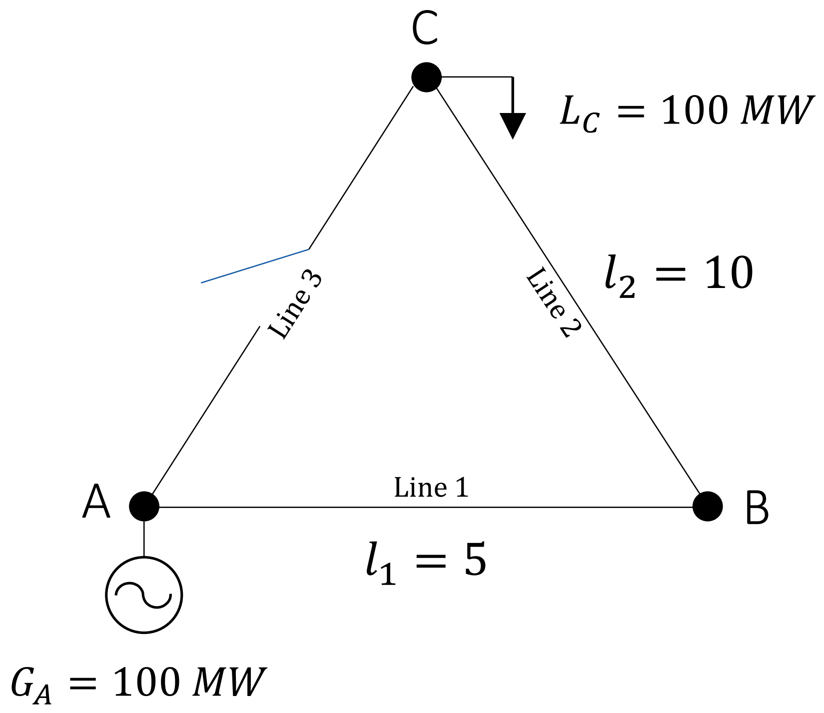
Power flow cannot be directly controlled

- How to avoid line overload?

Two options for system operators

1. Change topology (disconnect a line)

- Free of cost (generation unchanged)
- Reduced redundancy
- Increased losses



How can the system operator change load flows? (cont'd)

Power flow cannot be directly controlled

- How to avoid line overload?

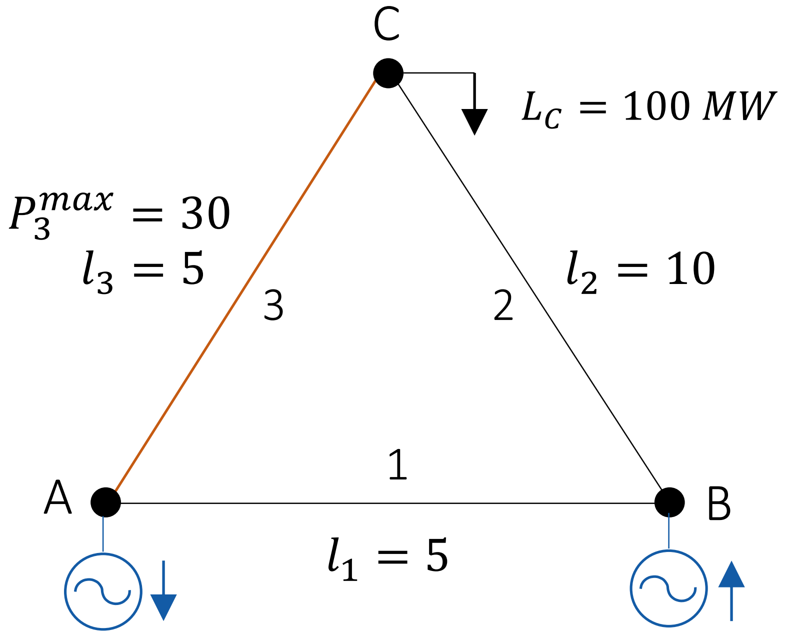
Two options for system operators

1. Change topology (disconnect a line)

- Free of cost (generation unchanged)
- Reduced redundancy
- Increased losses

2. Redispatch

- Change generation/load pattern



Redispatch

Definition of redispatch

- "The rescheduling of generation and controllable demand by TSO(s) within a bidding zone, in order to operate the transmission system within technical limits, in particular limits on the power flow on lines."
- "A shift in power generation from one or more units 'in the (zonal energy) market' to other units 'out of the market' in order to relieve congestion on certain network elements."

Redispatch is *locational* in nature

- Done at a nodal scale

Redispatch vs. balancing

- The above definition excludes the activation of resources in order to stabilize the net supply-demand balance of a bidding zone ("balancing")
- In fact, many European TSOs handle redispatch and balancing as an integrated process and use the same resources for both

Redispatch in Germany

How redispatch works

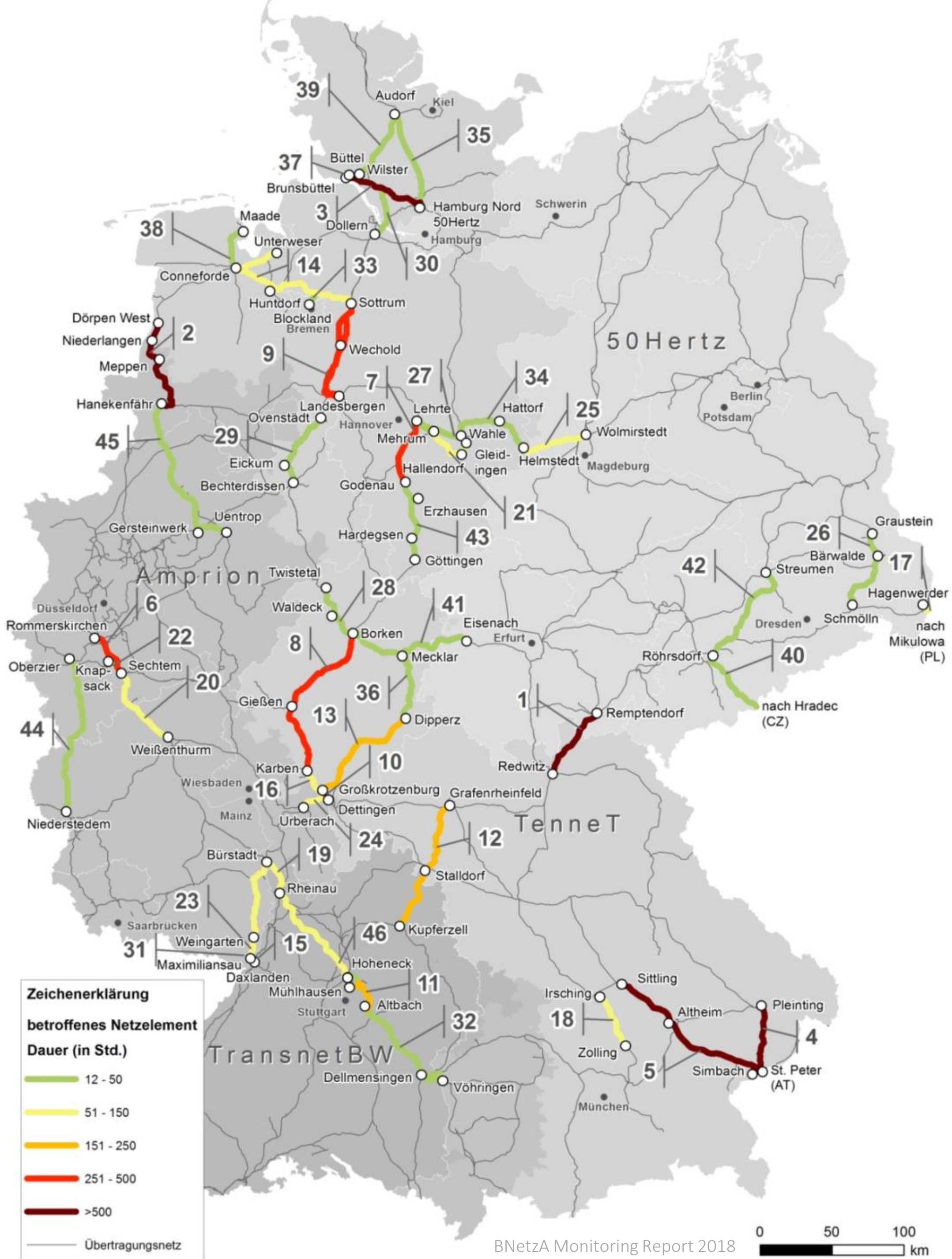
- Reduce generation in oversupplied region (“before the constraint”)
- Increase generation in undersupplied region (“behind the constraint”)

Implementation in Germany

- *Redispatch* for conventional plants
- *Einspeisemanagement* (EinsMan) for plants under support scheme (RE curtailment)

Regulatory redispatch with cost-based compensation

- Congestion management is ordered by TSO or DSO
- Power plants are obliged to participate
- Plant owners are compensated for costs and forgone profits


Zeichenerklärung
betroffenes Netzelement
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51 - 150
151 - 250
251 - 500
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Übertragungsnetz
50Hertz
Amprion
TenneT
TransnetBW
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Audorf
Kiel
Büttel
Wilster
Brunsbüttel
Hamburg Nord
50Hertz
Hamburg
Schwerin
Dollern
Maade
Unterweser
Conneforde
Huntdorf
Blockland
Bremen
Sottrum
Dörpen West
Niederlangen
Meppen
Wechold
Hanekenfähr
Landesbergen
Ovenstädt
Hannover
Lehrte
Mehrum
Wahle
Gleid-ingen
Hattorf
Helmstedt
Wolmirstedt
Magdeburg
Berlin
Potsdam
Eickum
Bechterdissen
Hallendorf
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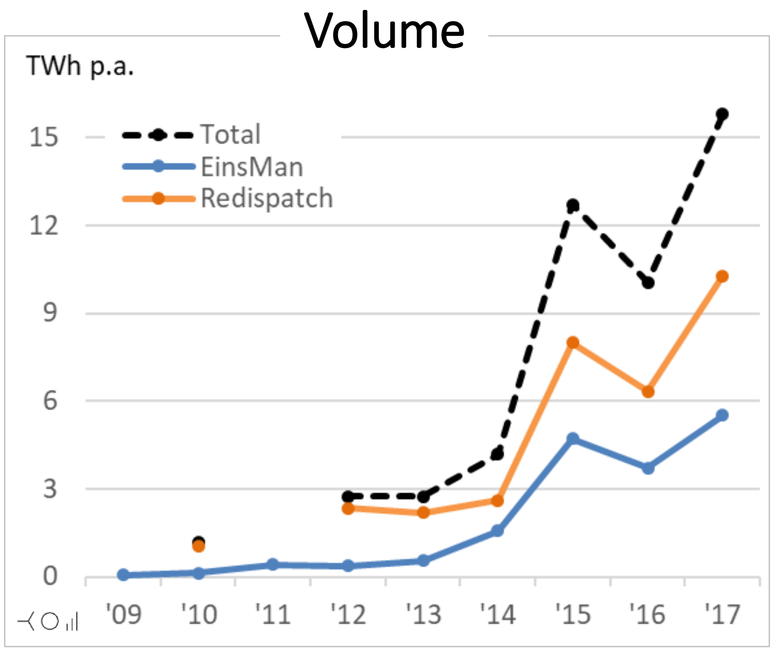
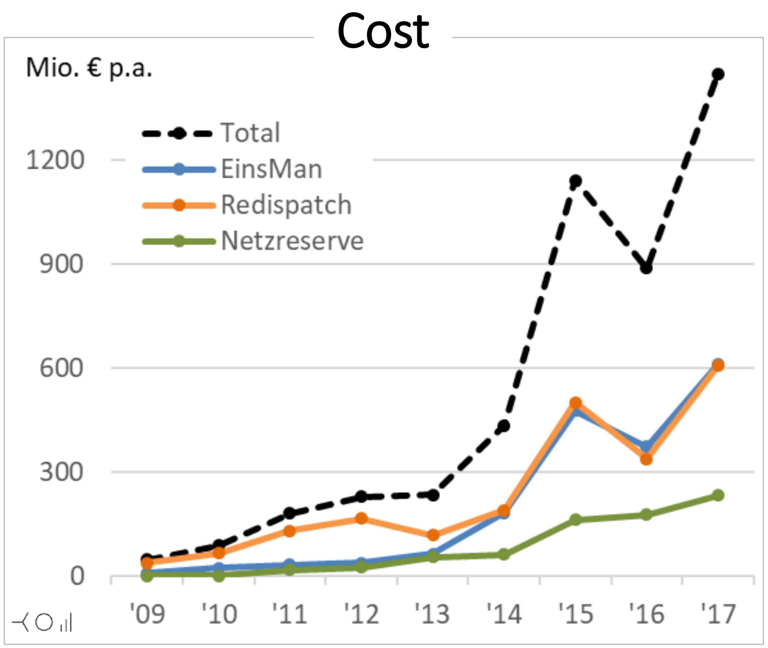
Congestion management in Germany



Neon analysis.



The volume of congestion management increased 5-fold since 2012.

The costs for congestion management increased similarly.

Alternatives to Grid Expansion

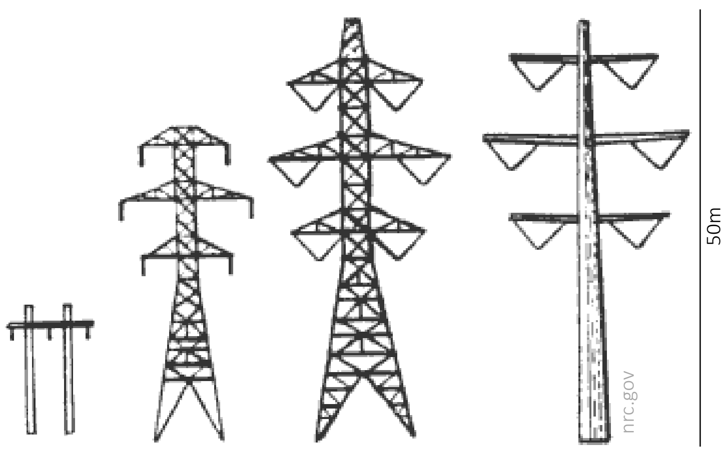
Overhead lines and underground cables

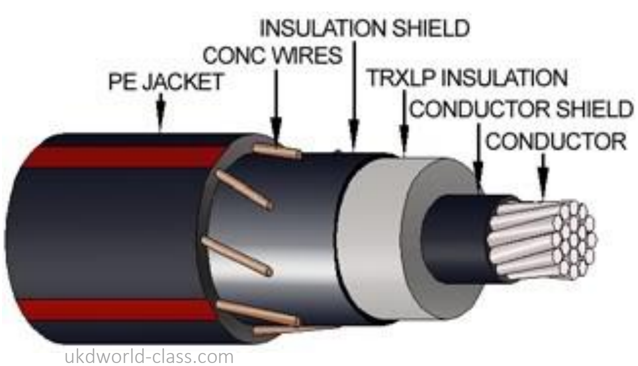
Overhead lines

- Passive cooling
- Air is a good electrical insulator
- Large gap between lines reduces capacitance and hence reactance
- Visual impact
- The most common option for transmission lines

Underground cables

- Proximity of conductors leads to high capacitance and reactance
- Cooling is an issue at high voltage, AC requires active cooling
- In Europe, most common option for medium and low voltages, especially in urban areas
- Transmission grid: DC only viable option





Transmission grid optimization

Constructing new lines is costly and a (very) lengthy process

- Alternatives exist to increase transmission capacity without building new lines

Overhead lines / transmission grid

- Temperature and/or sack monitoring
- High-temperature conductors (carbon or glass fiber core)
- Conductors with increased diameter
- Upgrading existing routes to higher voltages
- Adjusting network topology
- Parallel systems (more circuits)

Underground cables / distribution grid

- Cables with increased diameter
- Dynamic transformers (voltage-adjustable)

Smart grids and “smart markets”

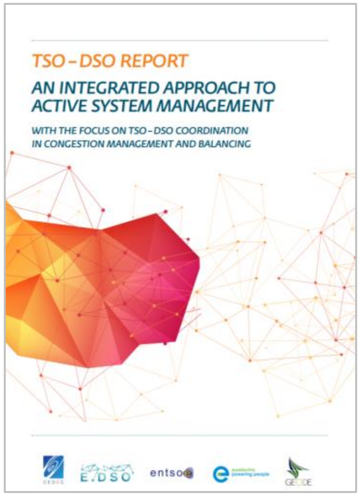
Avoid grid expansion by smart grids and “smart markets”

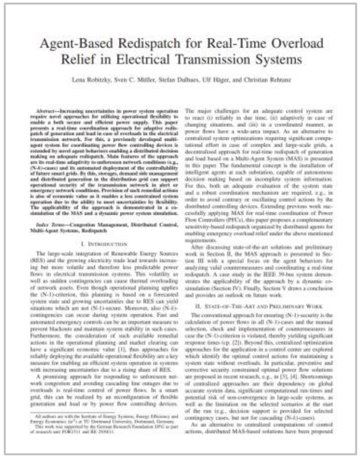
- Market-based redispatch
- Markets for local flexibility

A mechanism …

- … to avoid/relief congestion in the distribution and/or transmission grid
- … through redispatching generation / loads / storage
- … with voluntary participation

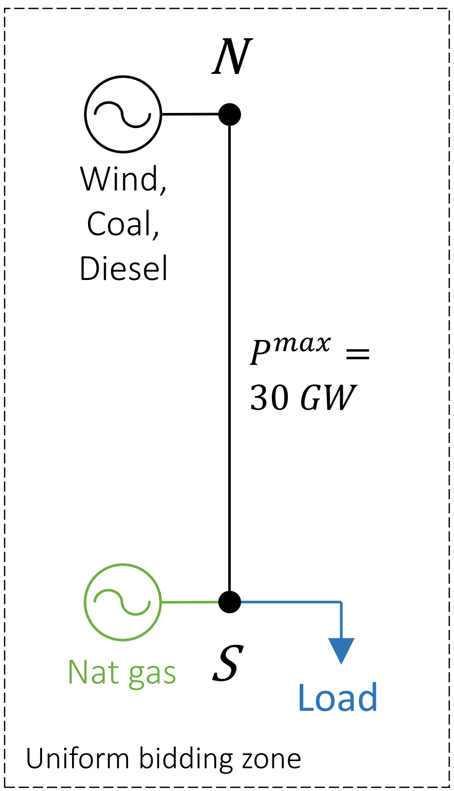
We think this won’t work



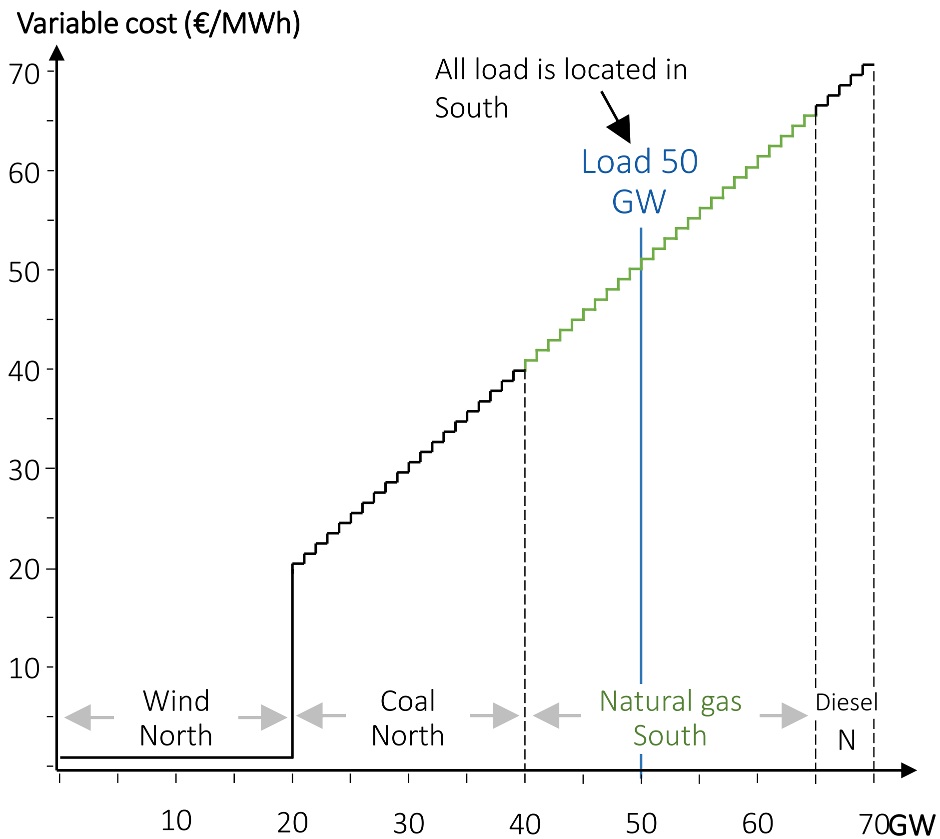


Model setup

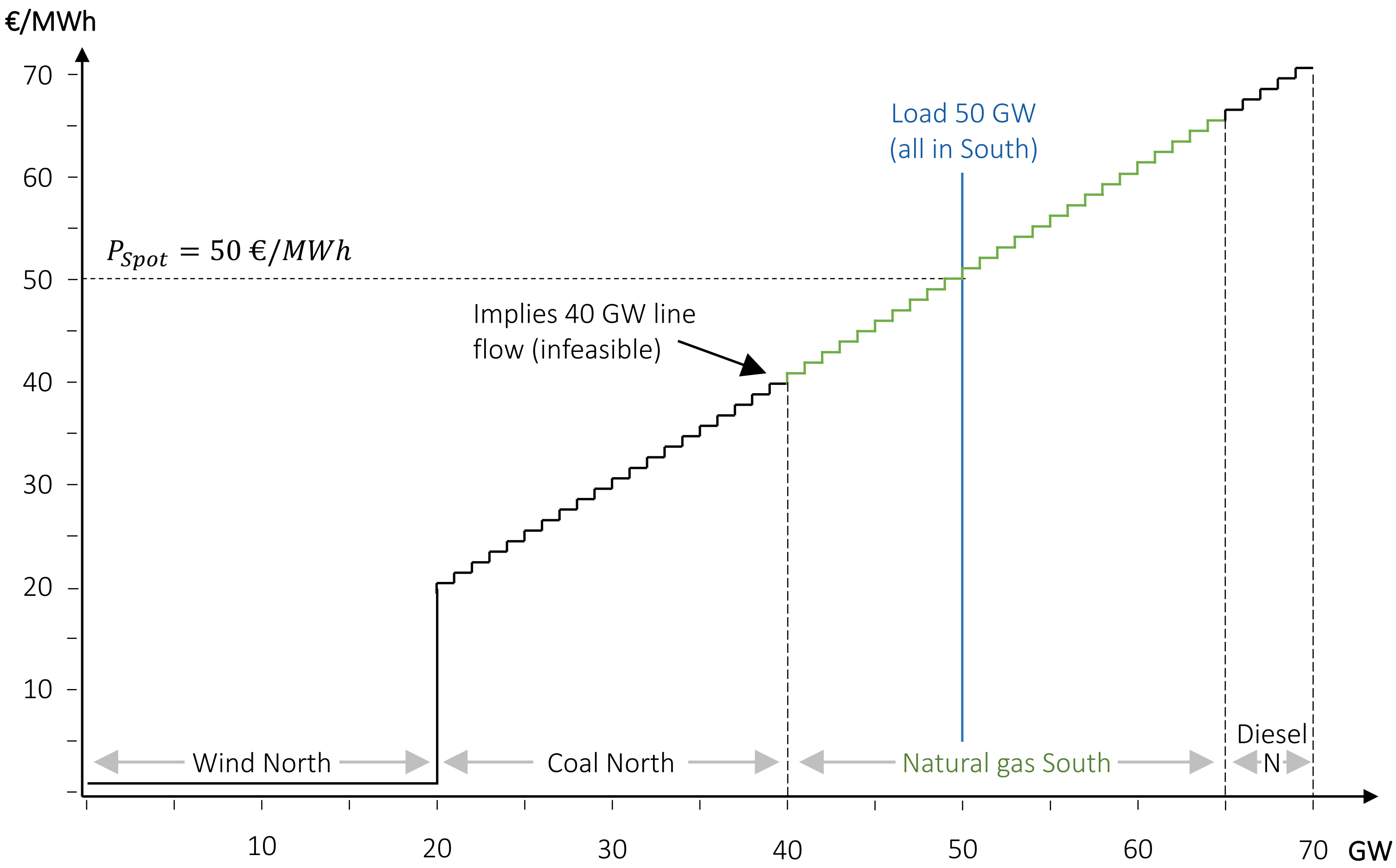
Geography



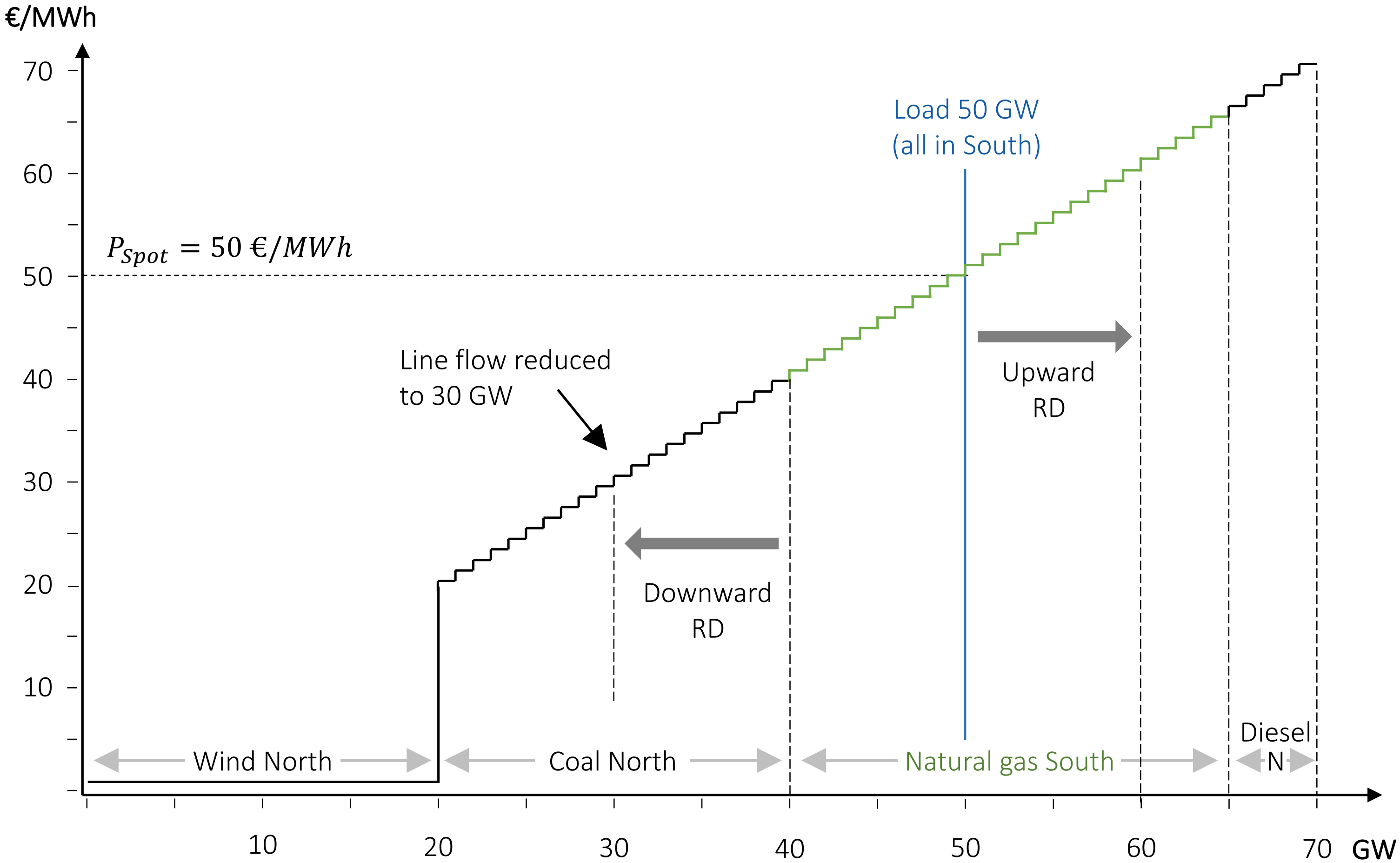
Supply and Demand



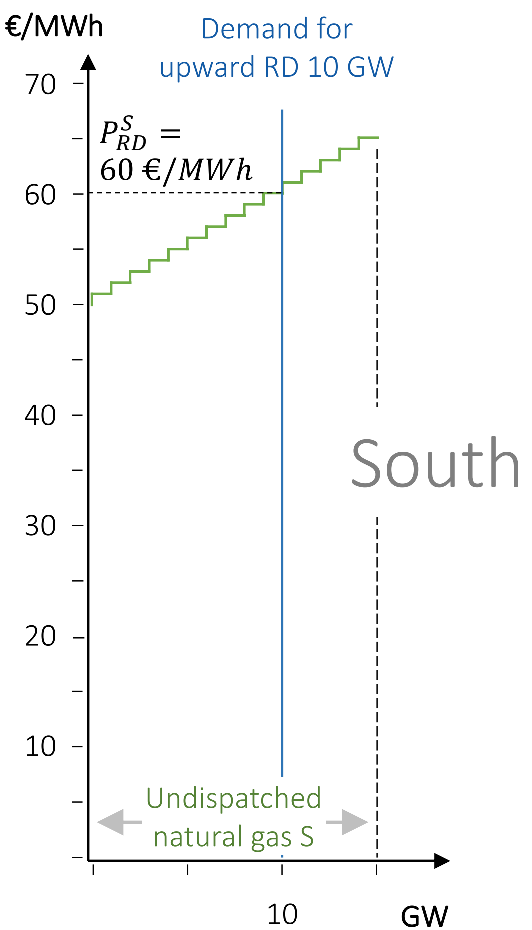
Spot market (regulatory RD)

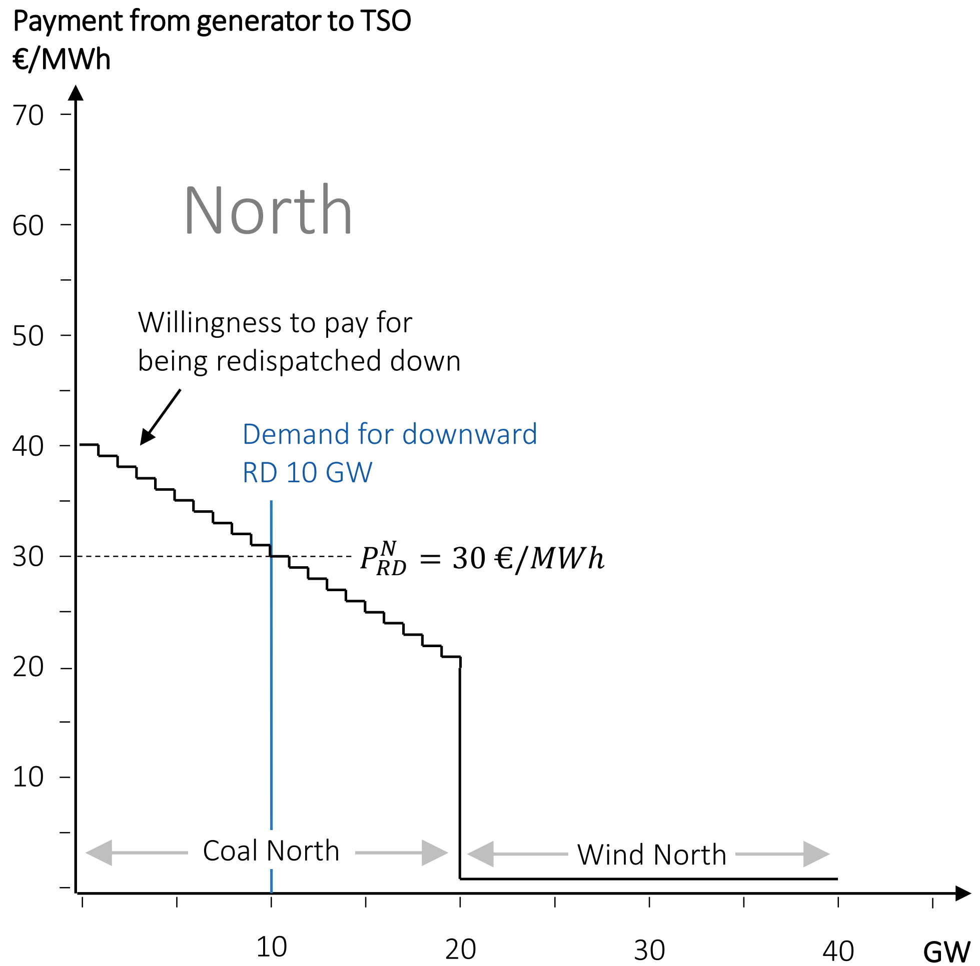


Cost-based redispatch (simple visualization)

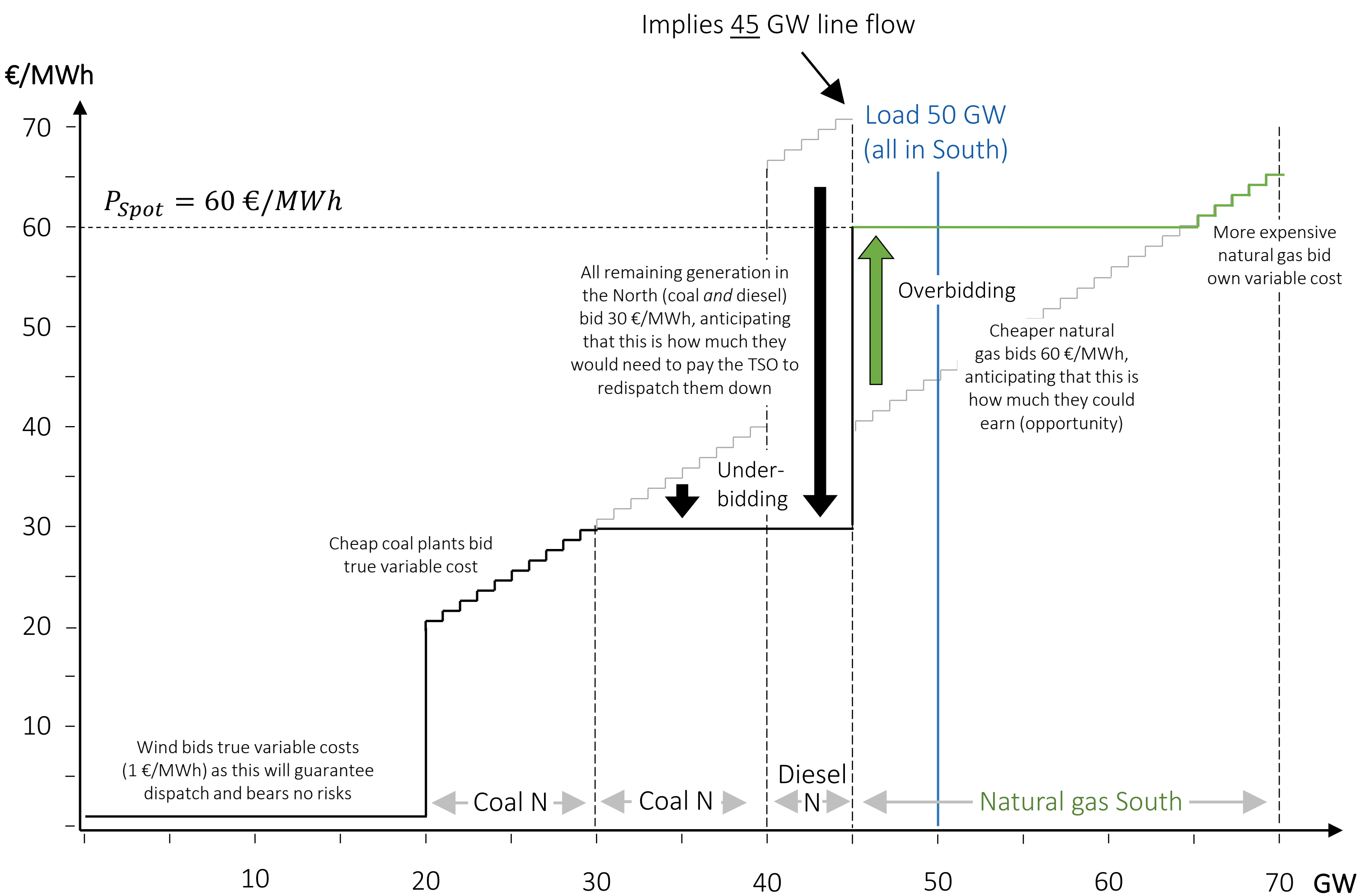


Redispatch markets (no anticipation)





Spot market (with anticipation)



Consequences from inc-dec strategy

Congestion is aggravated

- Higher redispatch volume

Windfall profits

- Profits of generators increase, consumers pay more (mostly through grid charge)

Problematic for financial markets

- Hedging based on spot markets no longer possible (RDM will become relevant market)

Perverse investment incentives

- “Ghost” plants which are built but never produce

Two market stages with differing locational resolution: Inconsistent

- Feedback effects: spot is not independent from redispatch market

Steering generation investment where it is needed

Locational prices at the wholesale market

Additional instruments outside the electricity market:	Large zone	Small zones	Nodal Pricing
Deep grid connection charges			
Grid usage charges			
Support schemes for renewable energy			
Capacity markets			

Can be combined (with each other and with all wholesale markets)

Concluding thoughts

The energy transition requires a massive expansion of power grids

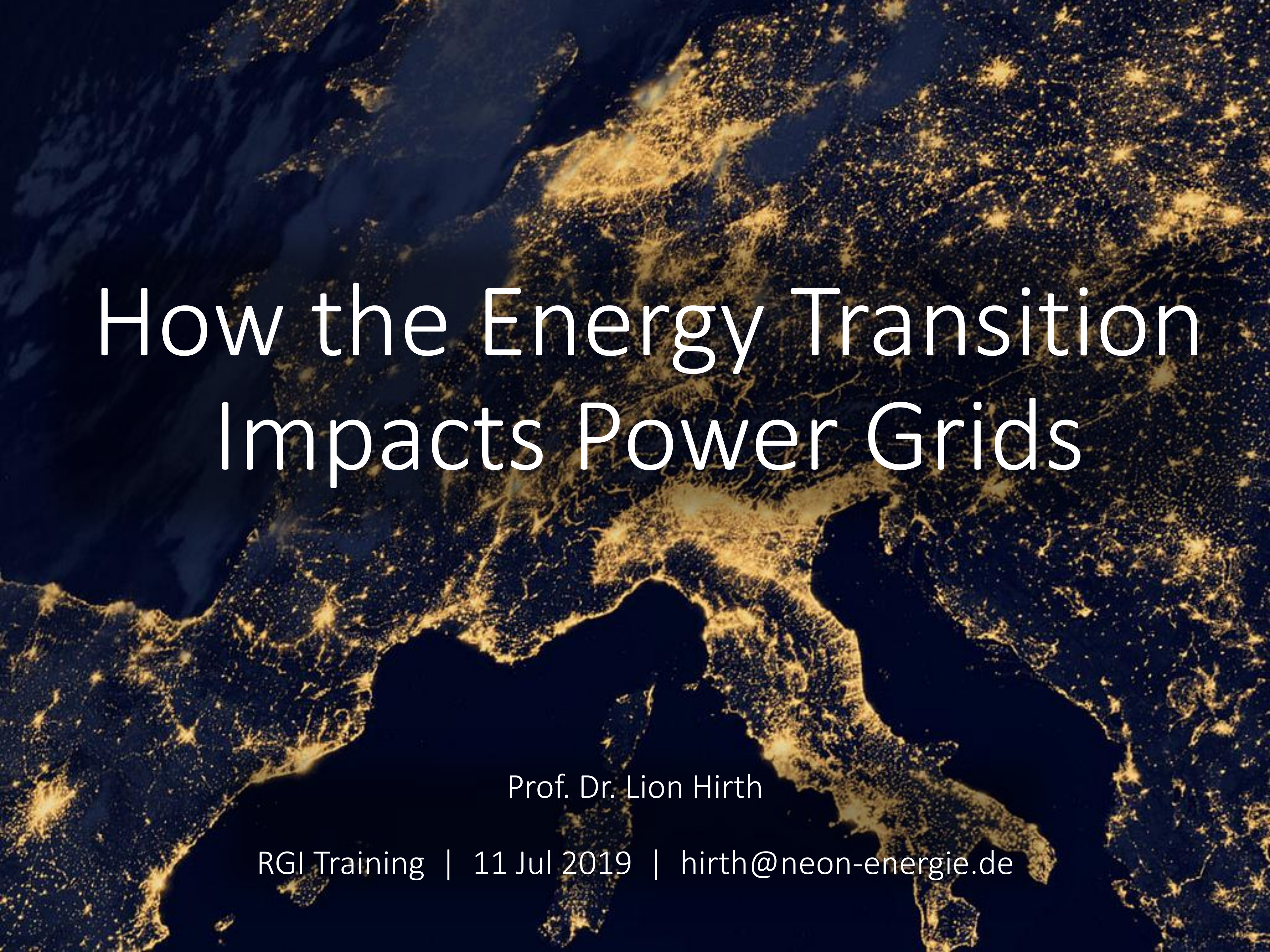
- Wind and solar energy
- Fading legacy of old, inefficient monopolies
- Electric mobility and electrification of heating
- European integration

This is visible today

- Massive increase in redispatch volumes and costs

There are no convincing alternatives

- Optimization: necessary, but not sufficient
- Smart markets: inc-dec gaming
- Moving renewables closer to consumers: to some degree necessary, but difficult to implement, limited potential – see next session



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