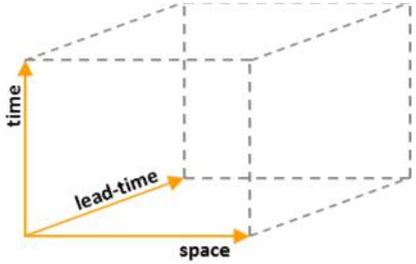
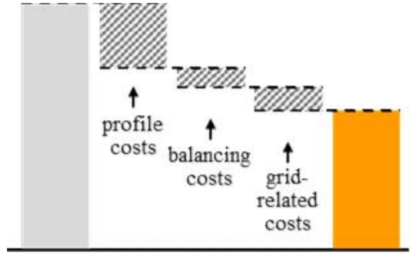
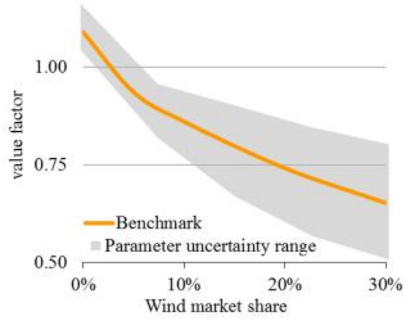
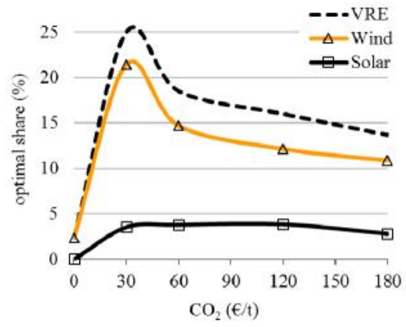
The Economics *of* *Wind & Solar Variability*







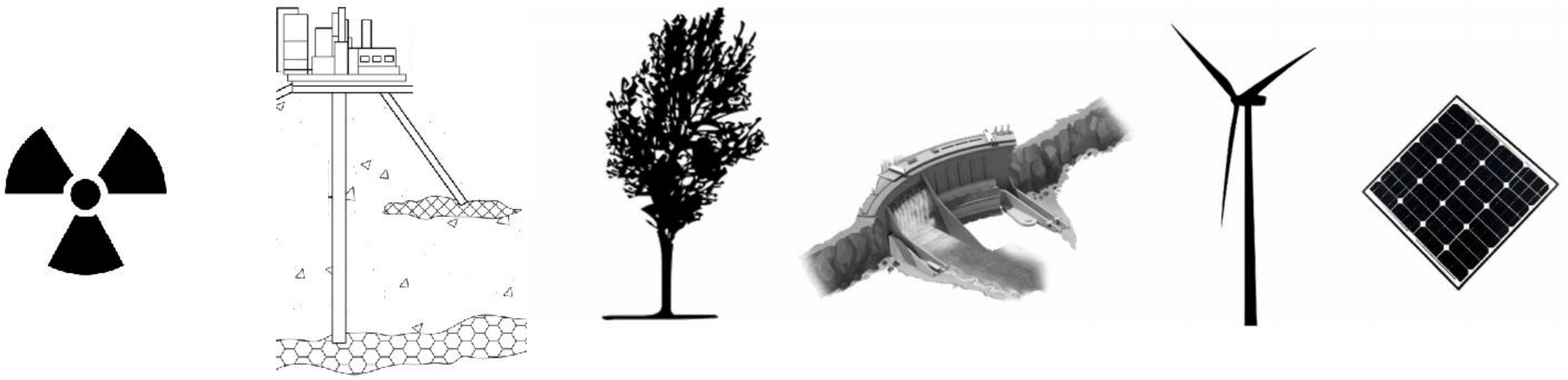


PhD disputation

Lion Hirth

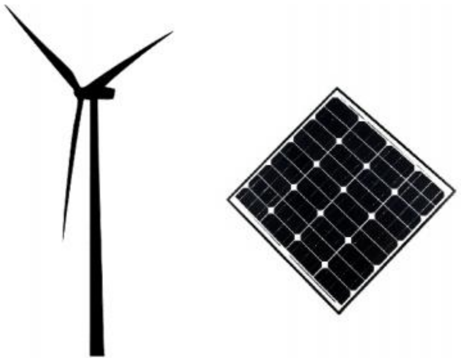
14 November 2014

Six options for low-carbon electricity generation



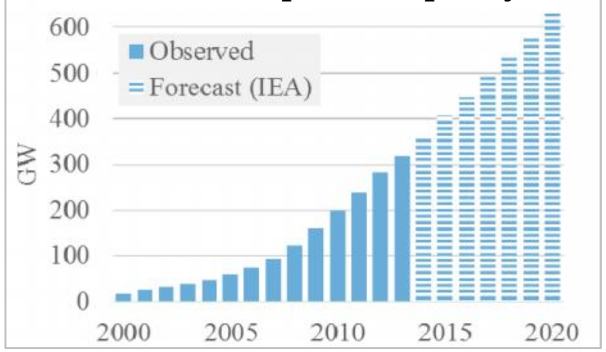
“the Energiewende is all about wind and solar power”

(Agora Energiewende 2013)

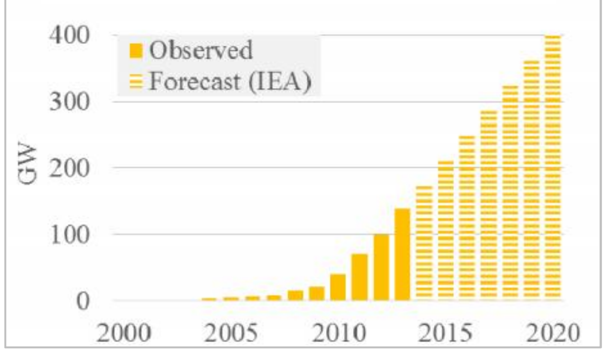


Wind & sun deliver 15+% of electricity in some regions

Global wind power capacity

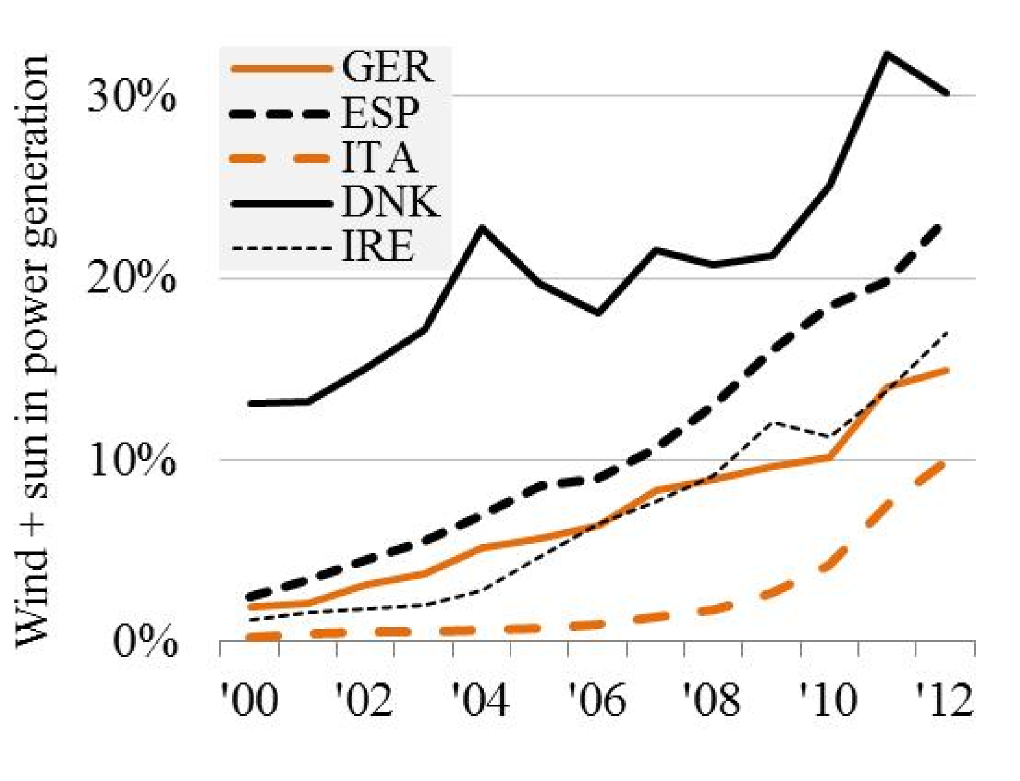


Global solar power capacity



Data source: REN21 (2014), IEA (2014)

Share of wind + solar in selected power systems



Data source: IHS (2013)

The intermittency challenge

Wind and sun: “intermittent” or “variable” sources

1

Wind does not always blow

2

Good sites are far from consumption

3

Difficult to predict

“variability“

Wind and solar power are ”variable renewable energy sources” (VRE)
(intermittent, non-dispatchable)

Identify, explain, and quantify the economic consequences of wind and solar power variability.

What are the economic implications of variability?

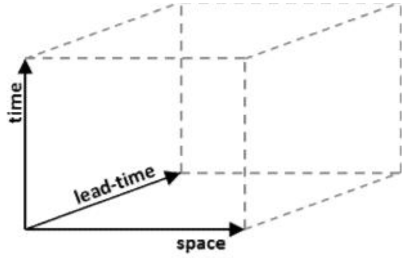
... in terms of (integration) costs?

... in terms of value (loss)?

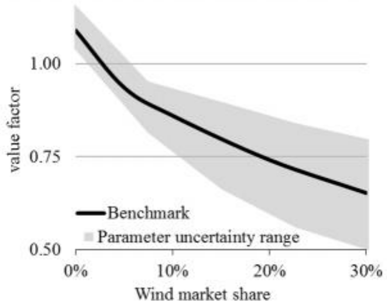
... in terms of optimal deployment?

Six papers on the economics of wind and solar variability

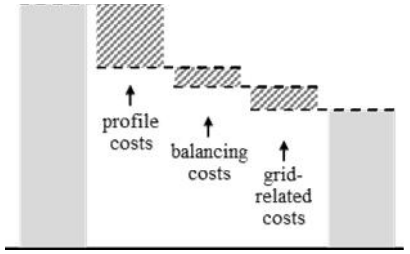
Economics of Electricity
The Energy Journal (under review)
with Falko Ueckerdt & Ottmar Edenhofer



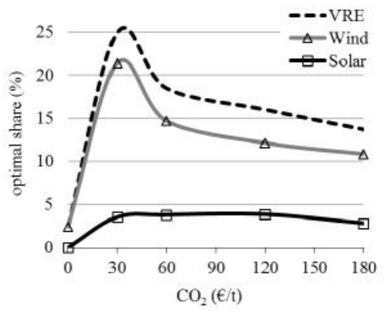
Market Value
Energy Economics



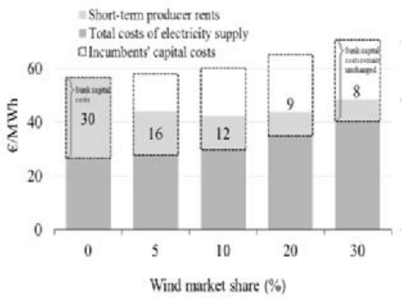
Framework
Renewable Energy
with Falko Ueckerdt & Ottmar Edenhofer



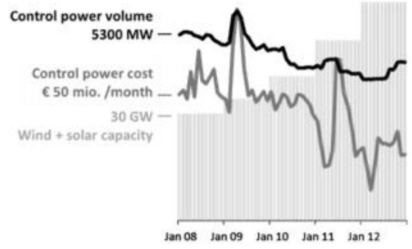
Optimal Share
The Energy Journal



Redistribution
Energy Policy
with Falko Ueckerdt

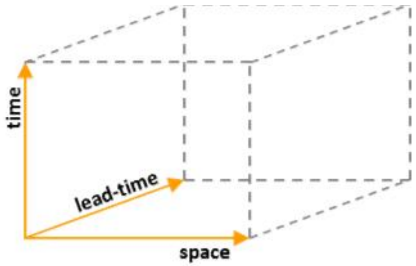


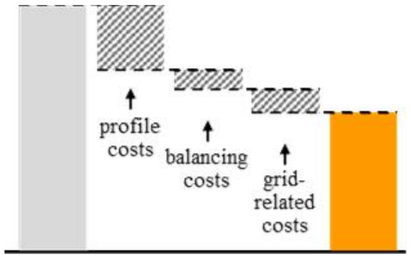
Balancing Power
Renewable Energy (under review)
with Inka Ziegenhagen

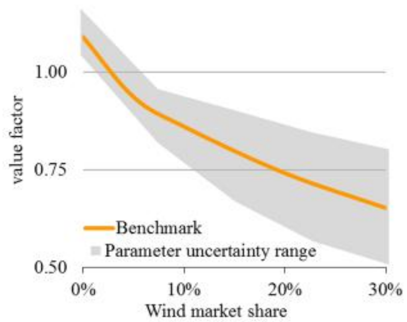


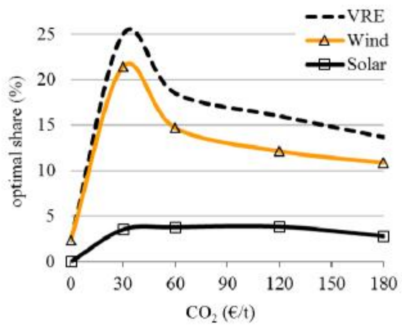
Theory & Concepts → Quanti-fication → Distributive impact → Market design

1. *Economics of Electricity*
2. *Integration costs*
3. *Market value*
4. *Optimal deployment*



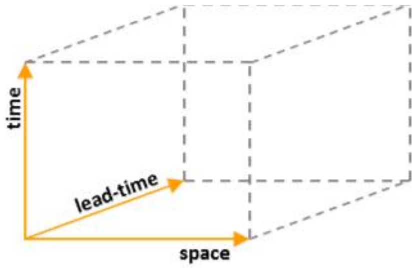


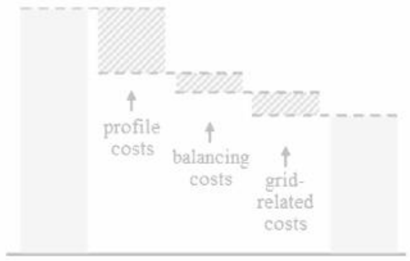


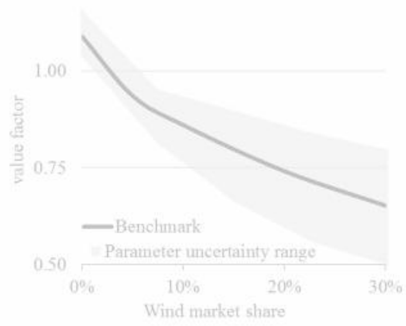


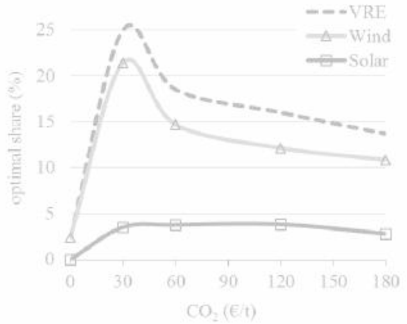
1.

Economics of electricity









The electricity paradox

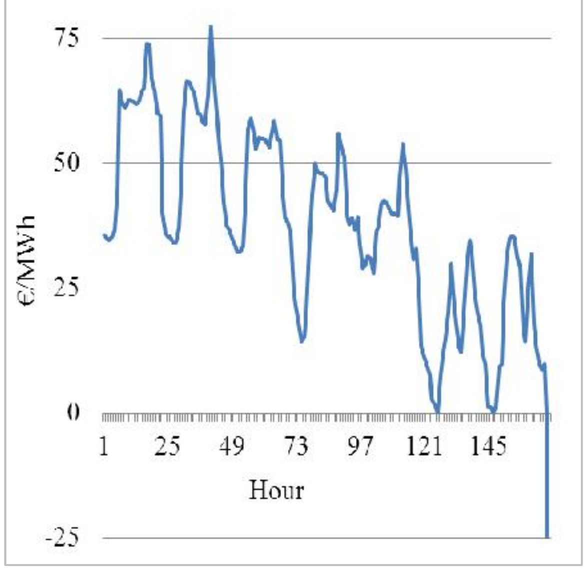
Electricity is a *homogenous* commodity…

- For consumers, electricity from different power plants is exactly the same.
- They cannot even distinguish between different sources.
- Physics: “a MWh is a MWh“
- No physical delivery – ‘electricity pool’
- Power exchanges
- → *The law of one price applies*

→ At one moment, a MWh from wind turbines has *the same value* as a MWh from a coal-fired plant.

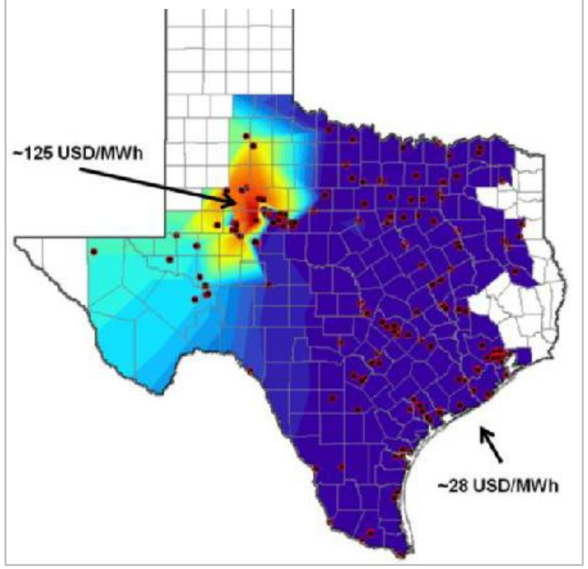
... and at the same time *heterogeneous*: prices vary ...

... over time



Day-ahead prices in Germany for one week

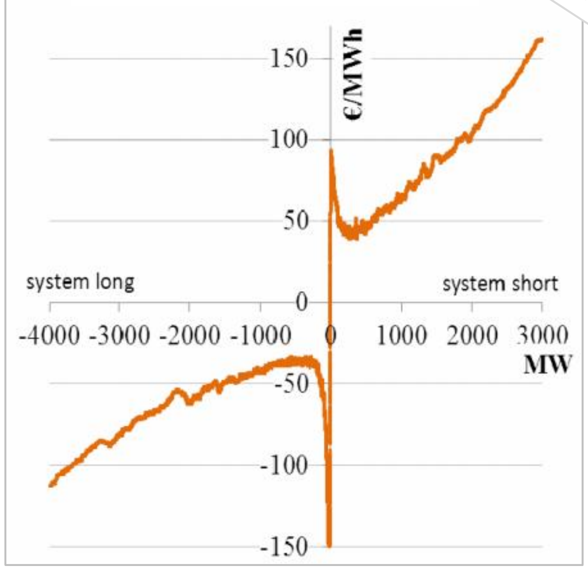
... across space



Day-ahead prices in Texas for one moment in time

... w.r.t. lead-time

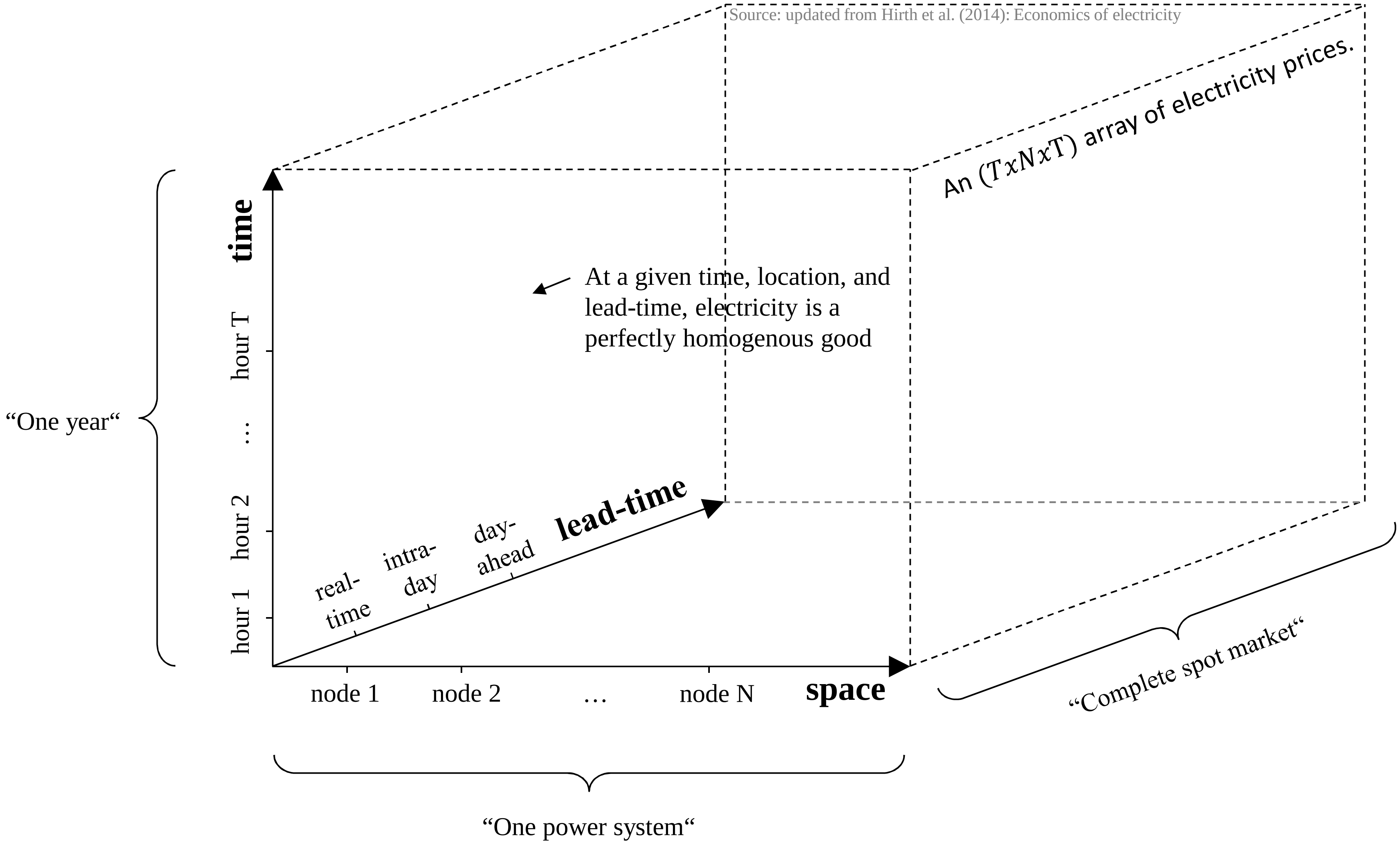
market data



Imbalance spread in Germany in 2011/12

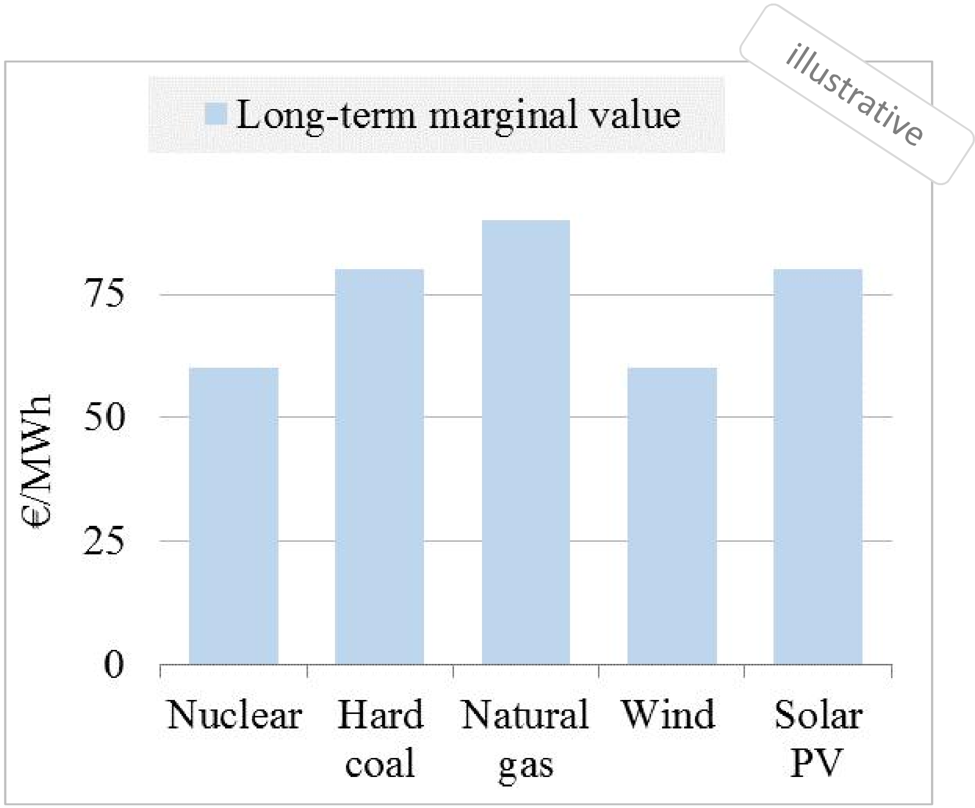
Physics shapes economics

Physics	Electromagnetic energy	Kirchhoff's laws	Frequency stability
↓	↓	↓	↓
Arbitrage constraint	Storage (storing electricity is costly)	Transmission (transmitting elect. is costly)	Flexibility (ramping & cycling is costly)
↓	↓	↓	↓
Dimension of heterogeneity	Time (price differs between hours)	Space (price differs btw locations)	Lead-time (btw contract & delivery)



Source: updated from Hirth et al. (2014): Economics of electricity
An $(TxNxT)$ array of electricity prices.
At a given time, location, and lead-time, electricity is a perfectly homogenous good
time
hour T
…
hour 2
hour 1
"One year"
lead-time
real-time
intra-day
day-ahead
node 1
node 2
…
node N
space
"Complete spot market"
"One power system"

The marginal value of output varies among generators



Source: updated from Hirth et al. (2014): Economics of electricity

Any economic assessment (cost-benefit, profitability) of electricity generation technologies needs to account for differences in value of output (€/MWh).

Long-term marginal value:
the marginal value of output of a technology ($/MWh), accounting for timing, location, and uncertainty of generation:

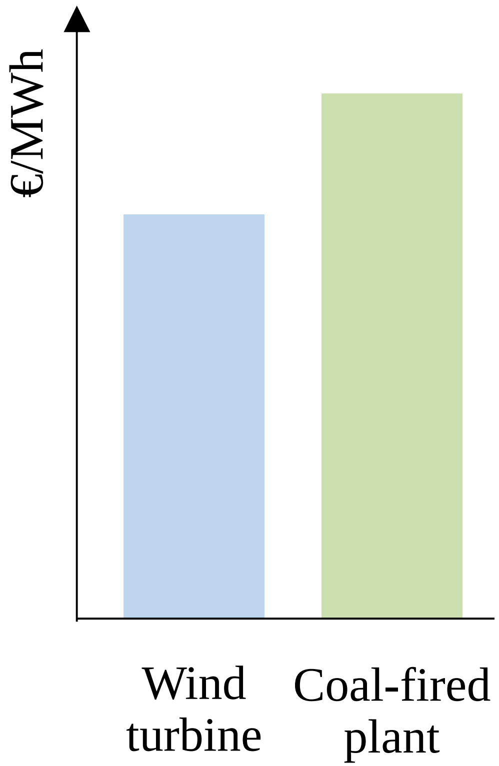
$$\bar{v}_i' = \sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{\tau=1}^{T} g_{i,t,n,\tau} \cdot p_{t,n,\tau}$$

→ On average, a MWh from wind turbines has a *different value* than a MWh from a coal-fired plant.

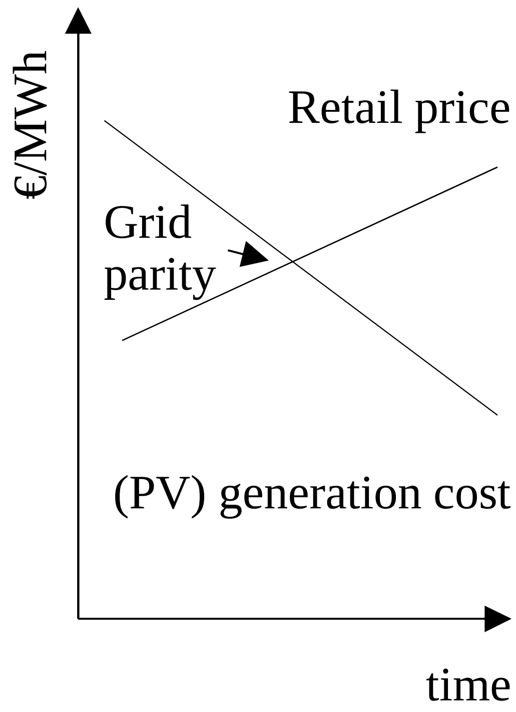
→ They produce different economic goods

Three tools ignore value differences

Levelized cost (LCOE)



Grid parity



Multi-sector models

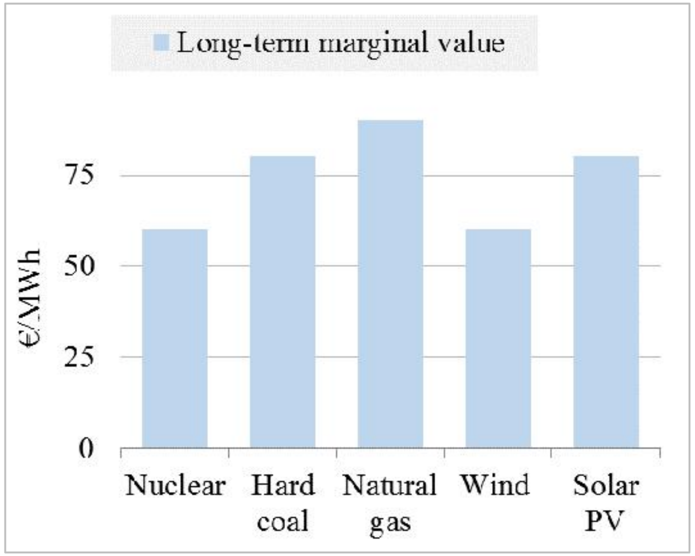
	(1)	(2)
(1) …		
(2) Power		
(3) …		

Input-output table
(IAMs, CGEs, …)

→ often it is readers, not authors, that misinterprete these tools

Ignoring value differences introduces two biases

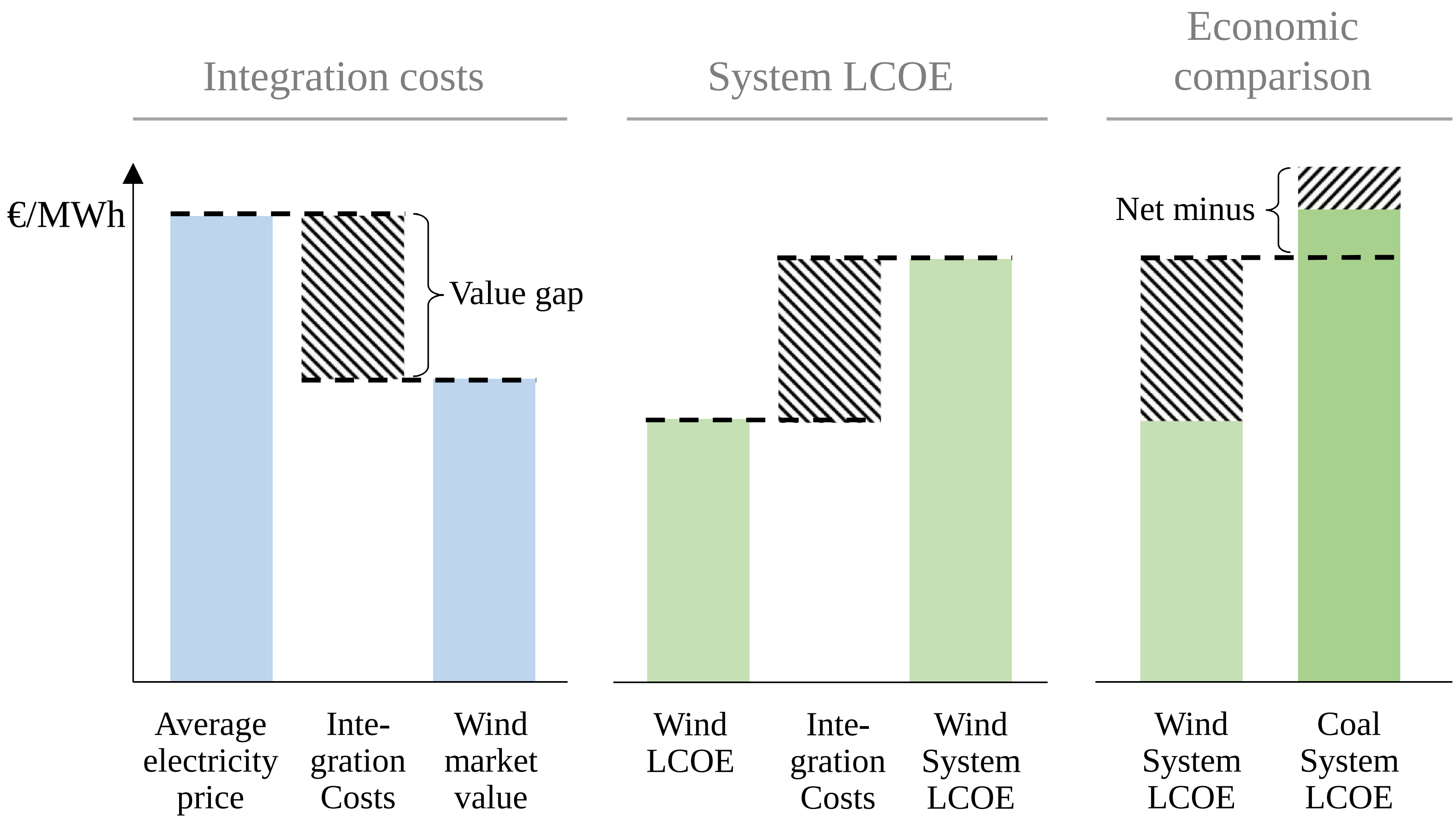
- ignoring value differences (erroneously) favors low value technologies
- → base-load generators are favored relative to peak-load generators ("base load bias")
- → at high penetration rates, VRE technologies are favored relative to dispatchable generators ("VRE bias")



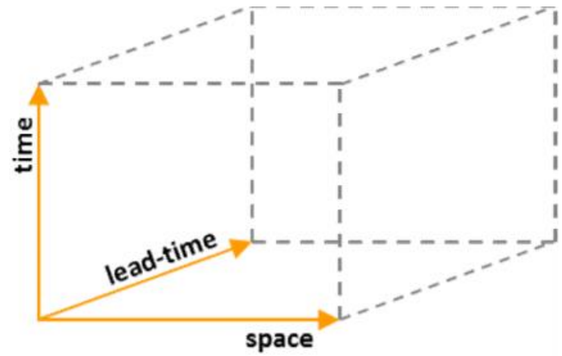
Source: updated from Hirth et al. (2014): Economics of electricity

Base-load and high-penetration VRE are the technologies with relatively low-value output.

System LCOE: one metric for cost *and* value



Concluding: Economics of electricity



Electricity is a peculiar economic good

- paradox: homogeneous *and* heterogeneous
- value difference between generators
- “a MWh is not a MWh” and ”wind is not coal“
- economic assessments need to account for these value differences

Common tools ignore the value difference

- LCOE
- grid parity
- (simple) multi-sector models

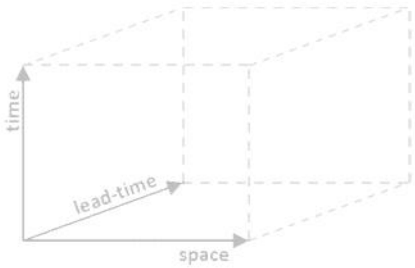
This introduces two biases

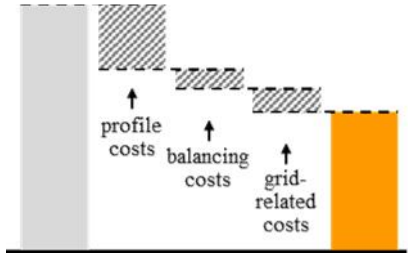
- base load bias: nuclear & CCS look better than they are
- VRE bias: wind and solar power look better than they are (at high penetration)

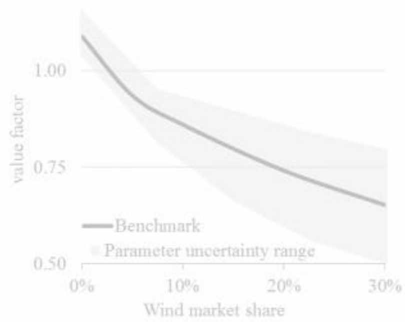
→ *a closer look at the economic value of wind and solar power generation*

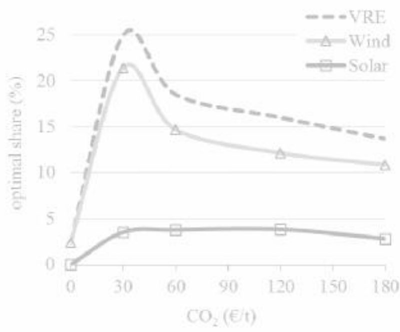
2.

Integration costs









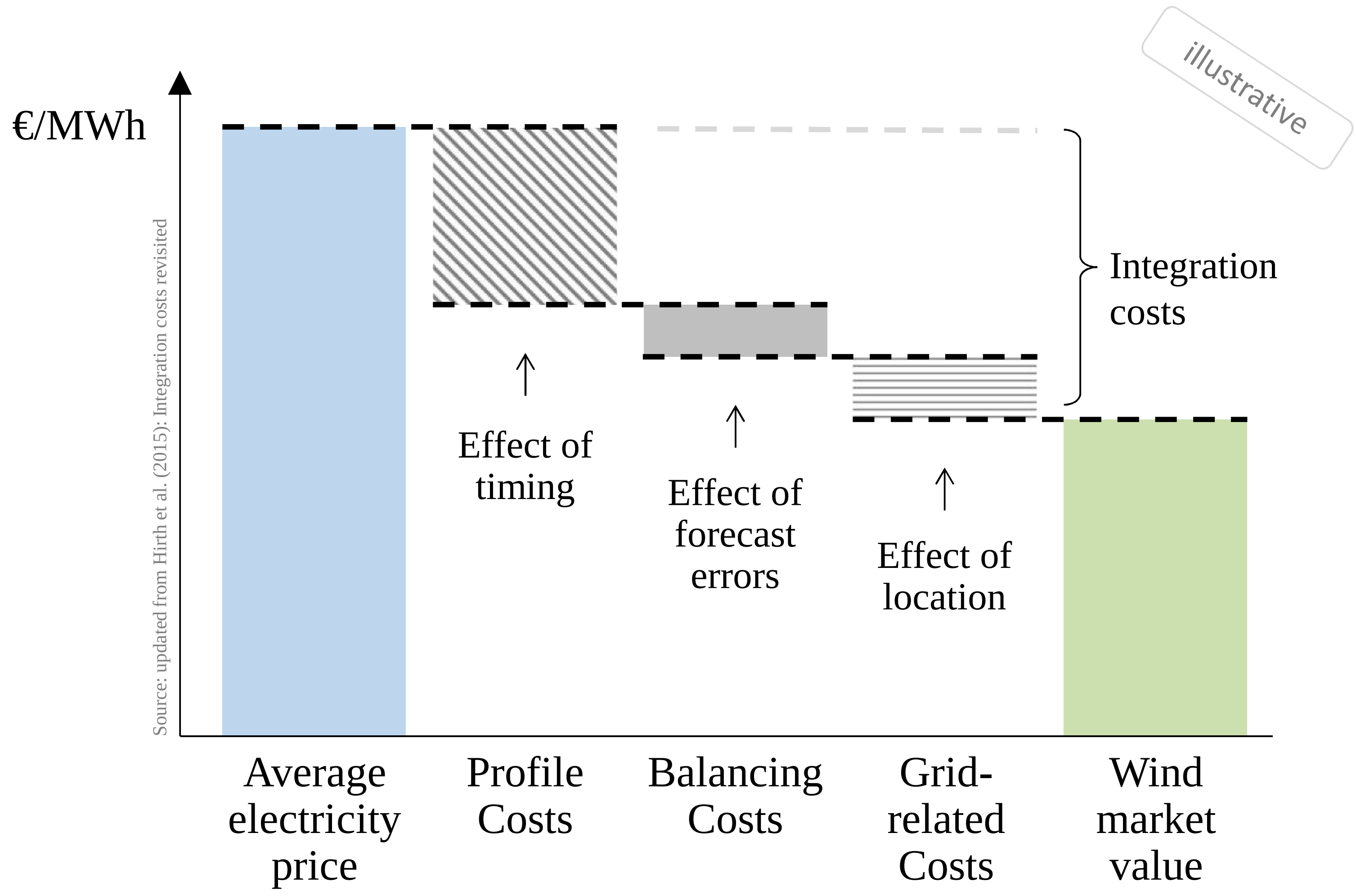
Three intrinsic properties of variable renewables

Milligan et al. 2011, Borenstein 2012, Sims et al. 2011, ...

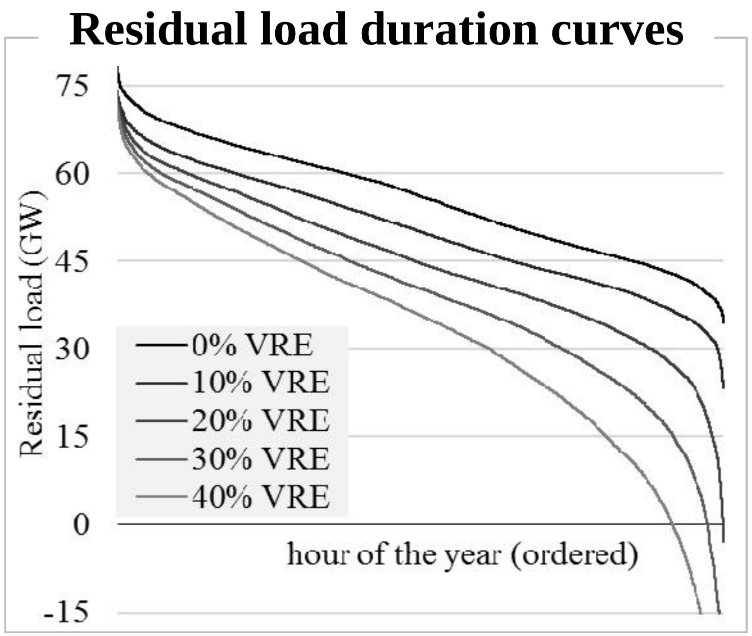
	1	2	3
Property	Output is fluctuating	Forecast errors	Bound to certain locations
	+	+	+
Electricity heterogeneity	Time (price differs between hours)	Lead-time (prices differs w.r.t. to lead-time btw contract & delivery)	Space (price differs btw locations)
	↓	↓	↓
“Costs” due to properties	“Profile costs“ (“shaping costs“)	“Balancing costs“ (“imbalance costs“)	“Grid-related costs“ (“locational / infrastructure costs“)

→ it is the *interaction* of VRE variability and price heterogeneity that is costly

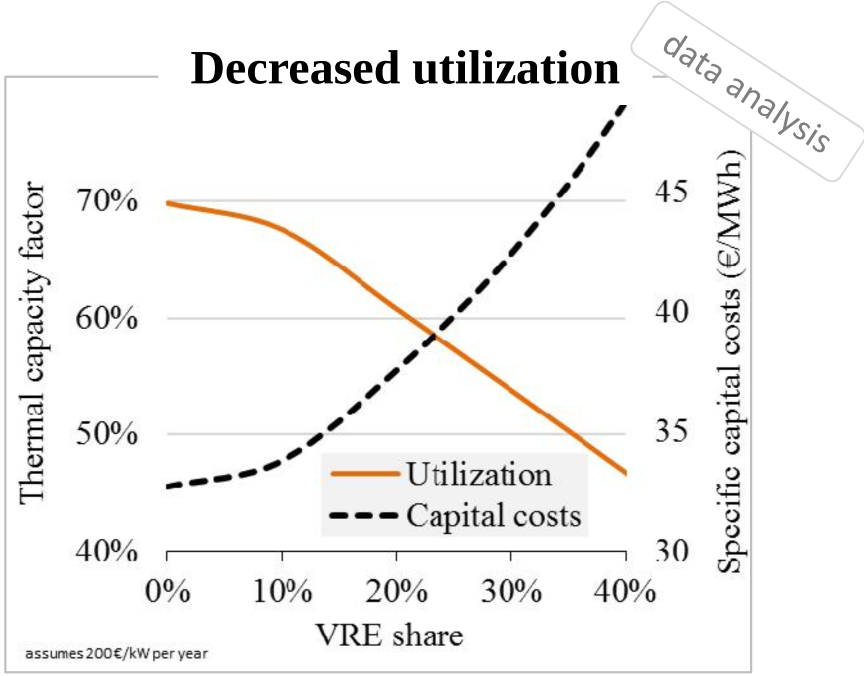
The properties (often) reduce the value of VRE output



Profile costs: driven by reduced utilization of capital



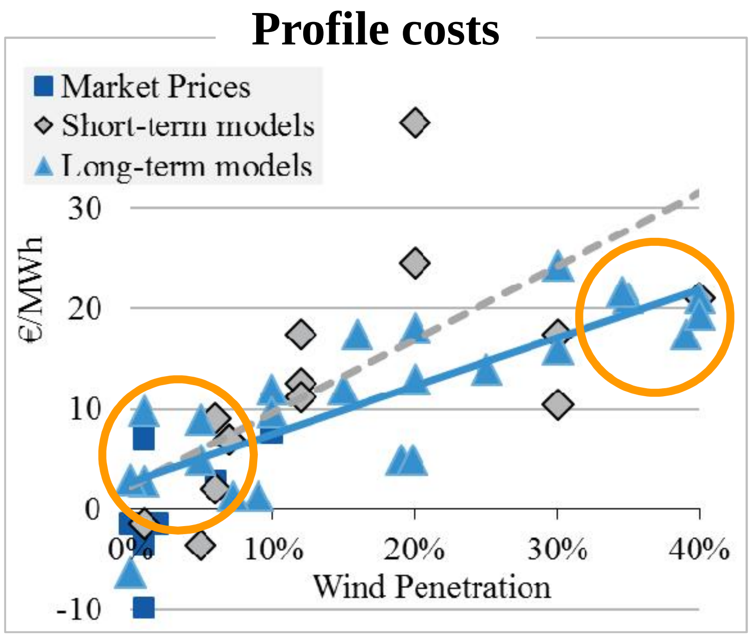
Source: updated from Hirth et al. (2015): Integration costs revisited



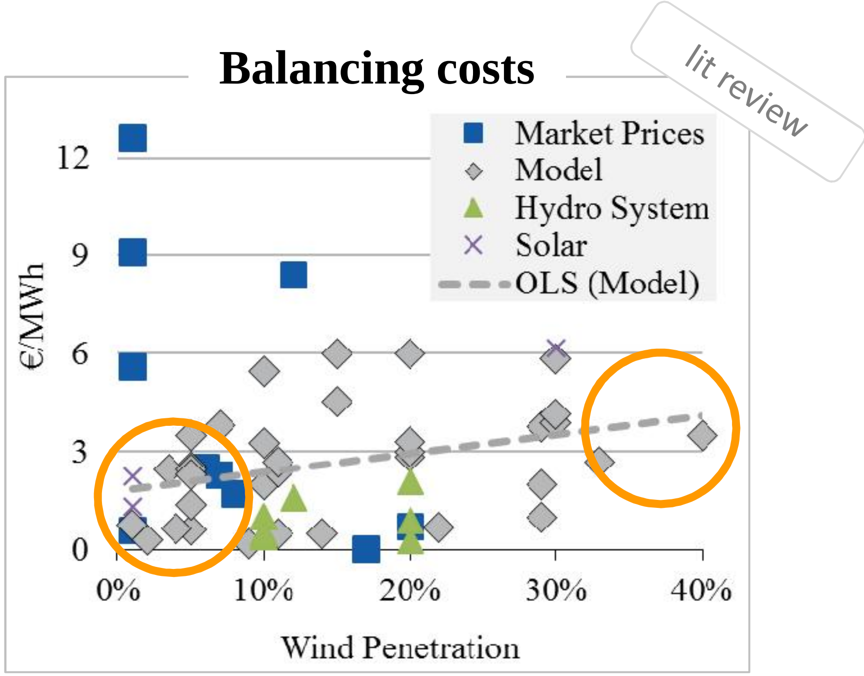
Source: updated from Hirth et al. (2015): Integration costs revisited

Lit review: profile costs are the largest component

(in thermal power systems at high penetration rates)

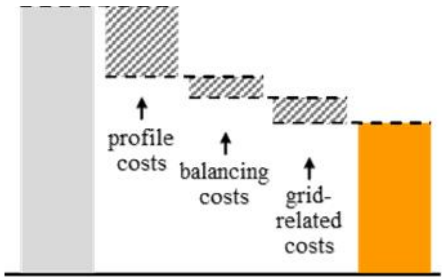


Source: updated from Hirth et al. (2015): Integration costs revisited



Source: updated from Hirth et al. (2015): Integration costs revisited

Concluding: Integration costs



The value of VRE is affect by variability

- it is the *interaction* between VRE variability and electricity price heterogeneity that is costly
- at low penetration, these costs can be negative (increase the value)
- at high penetration rates, they are usually positive and can become high: 25 – 35 €/MWh at 30 – 40% wind penetration

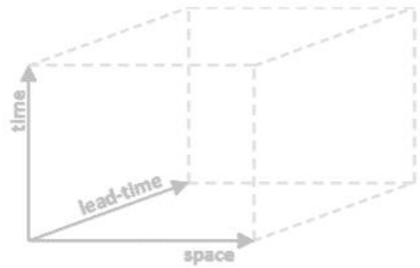
Profile costs are largest component

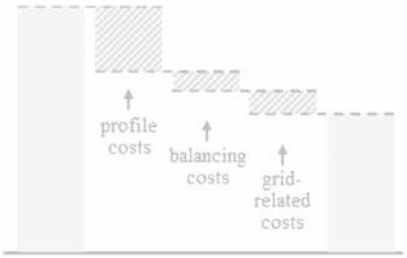
- profile costs are ~ 5 times larger than balancing cost and increase ~ 10 times faster
- profile costs are mostly driven by reduced utilization of physical capital – not cycling or ramping of power plants
- much of the existing literature looks at second-order cost drivers

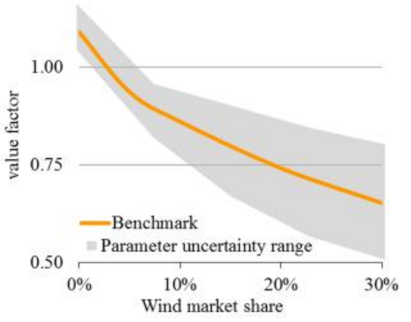
→ *a closer look at profile costs*

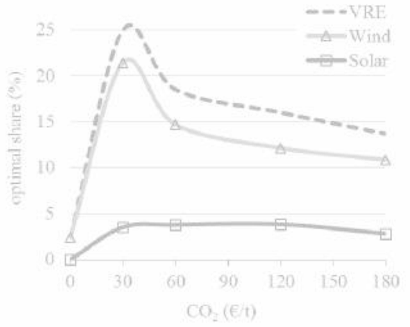
3.

Market value







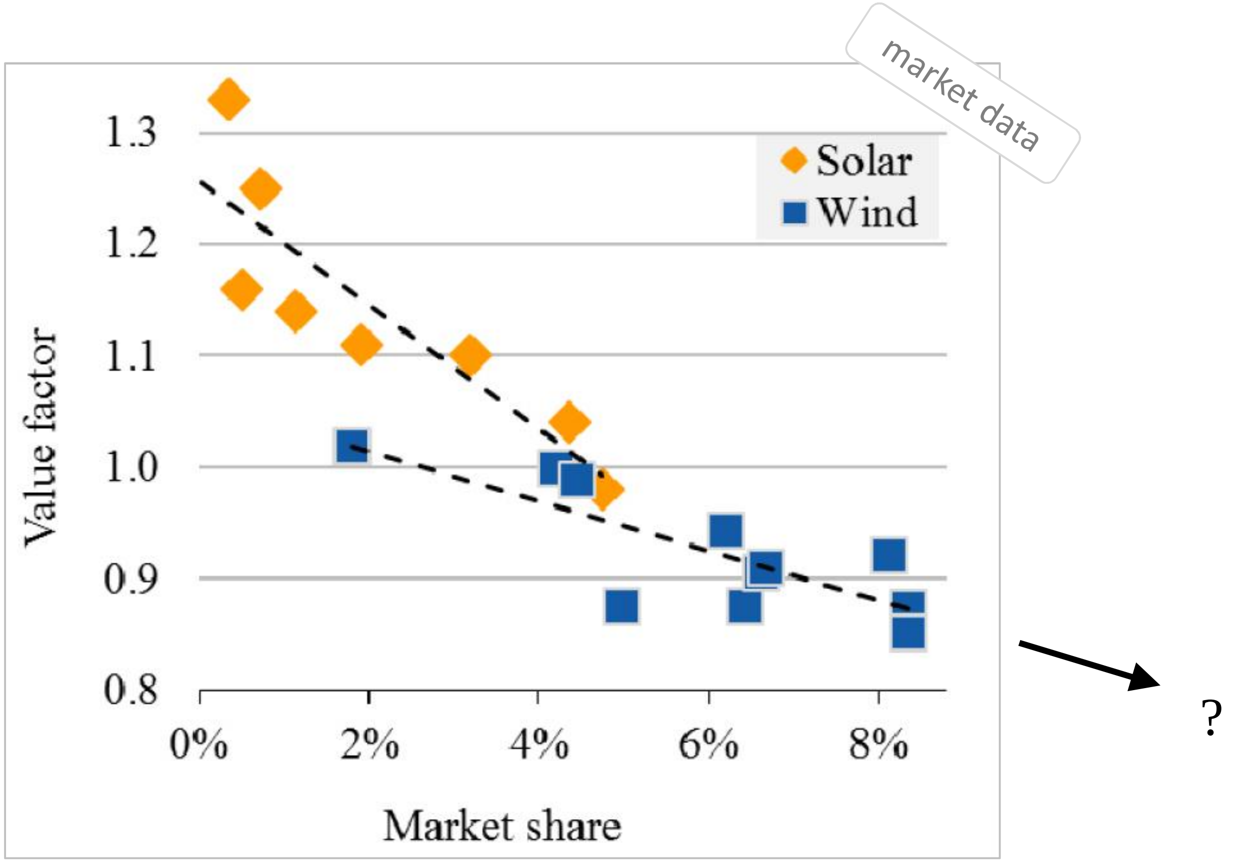


Value factor: the relative price of wind power

Wind in Germany			
	Base price (€/MWh)	Wind Revenue (€/MWh)	Value Factor (1)
2001	24	25*	1.02
...	...	...	...
2013	38	32	.85
	↑ Simple average	↑ Wind-weighted average	↑ Ratio of these two

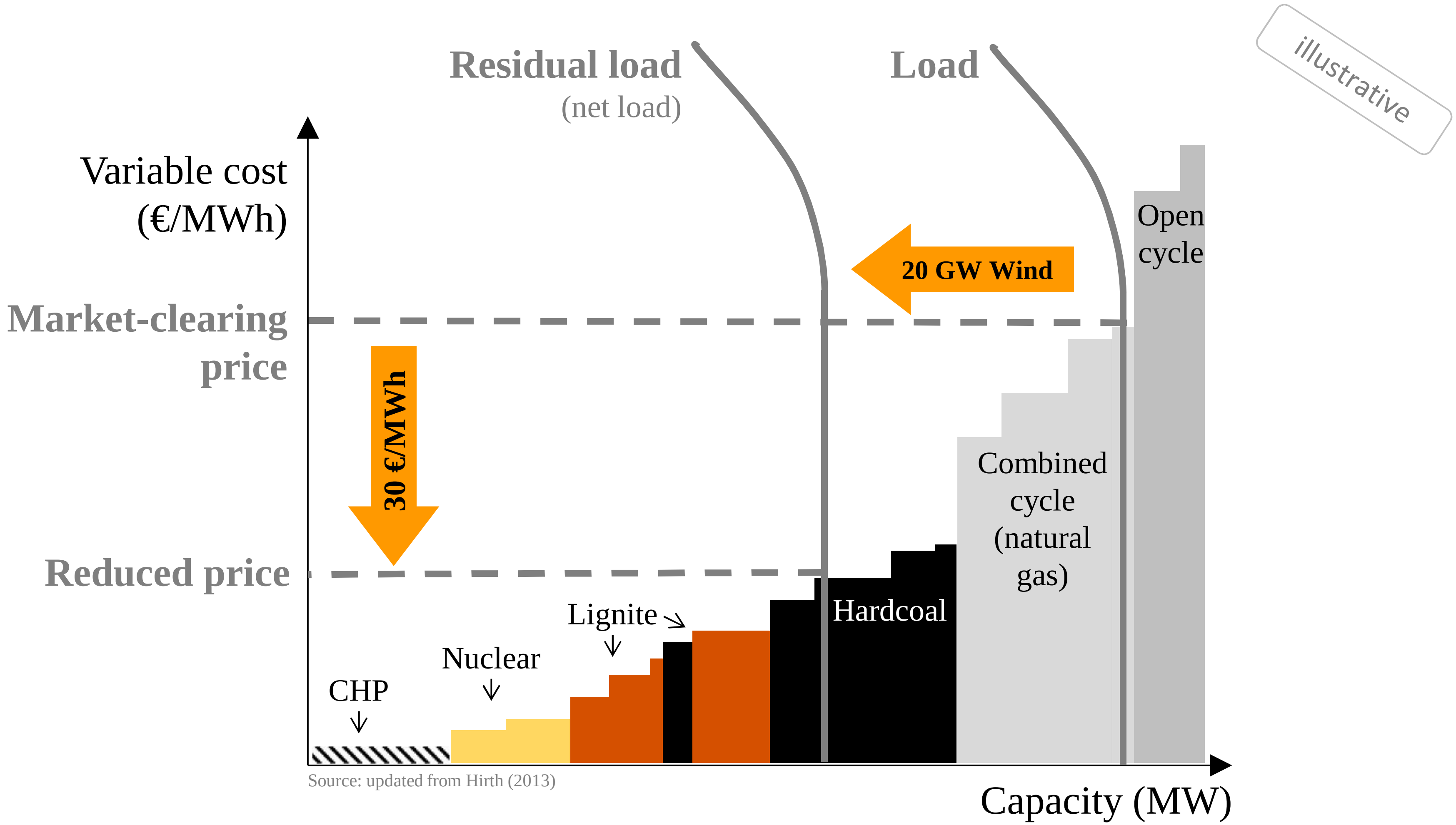
The value drop

Value Factor =
Market value /
base price



Source: updated from Hirth (2013). Based on German day-ahead spot-price data 2001 – 2013

The mechanics behind the value drop

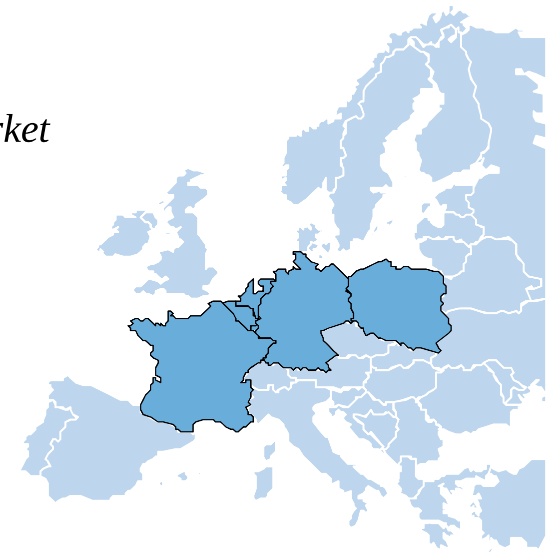


Source: updated from Hirth (2013)

$$P(Q,\cdot)$$

The Electricity Market Model EMMA

Numerical partial-equilibrium model of the European interconnected power market



Objective: minimize total system costs
- capital cost of generation, storage, interconnectors
- fuel and CO_2 costs
- fixed and and variable O&M

Decision variables
- hourly generation and trade of electricity
- investment in generation, storage, interconnectors

Constraints
- capacity constraints of plants, storage, interconnectors
- volume constraints of storage
- must-run: balancing reserve requirement, CHP plants
- no unit commitment

Resolution
- temporal: hours
- spatial: bidding areas (countries) – no load flow
- technologies: eleven plant types

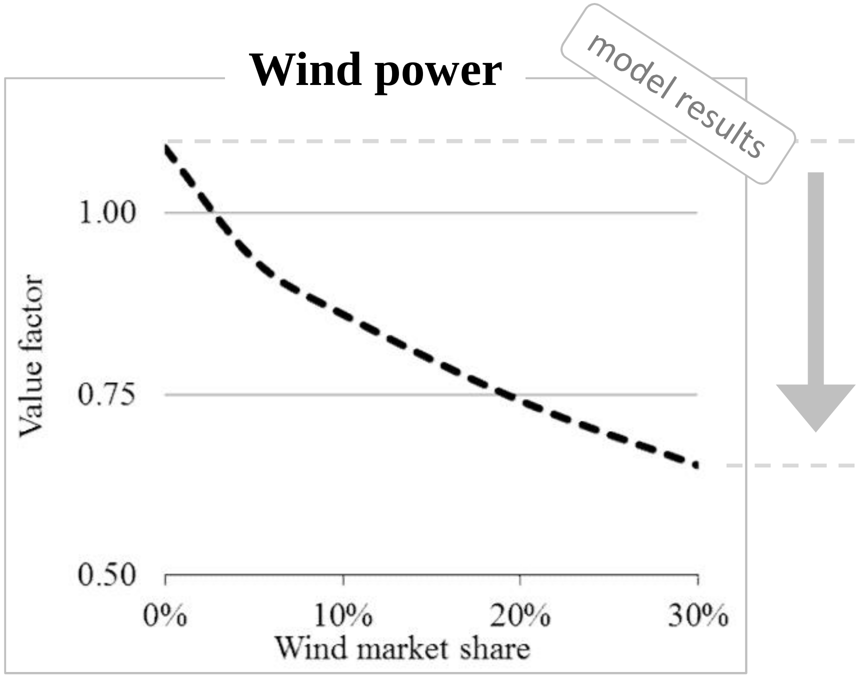
Input data
- wind, solar and load data from the same historical year
- existing plant stack

Economic assumptions
- price-inelastic demand
- no market power

Equilibrium
- short- / mid- / long-term equilibrium ("one year")
- no transition path ("up to 2030")

Implementation
- linear program
- GAMS / cplex

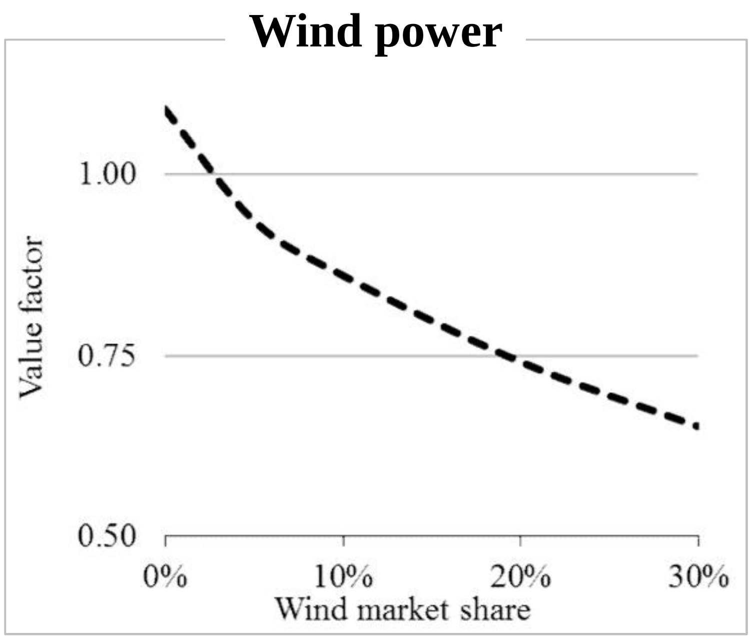
Estimating the value drop (long-term equilibirum)



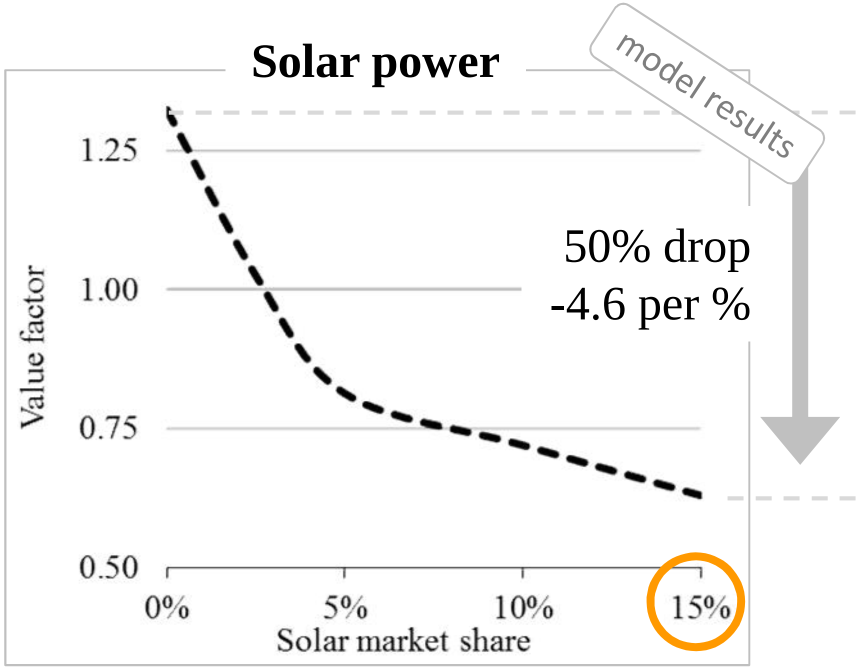
Source: updated from Hirth (2013): Market value

40% value drop
-1.5 per %

Estimating the value drop (long-term equilibirum)

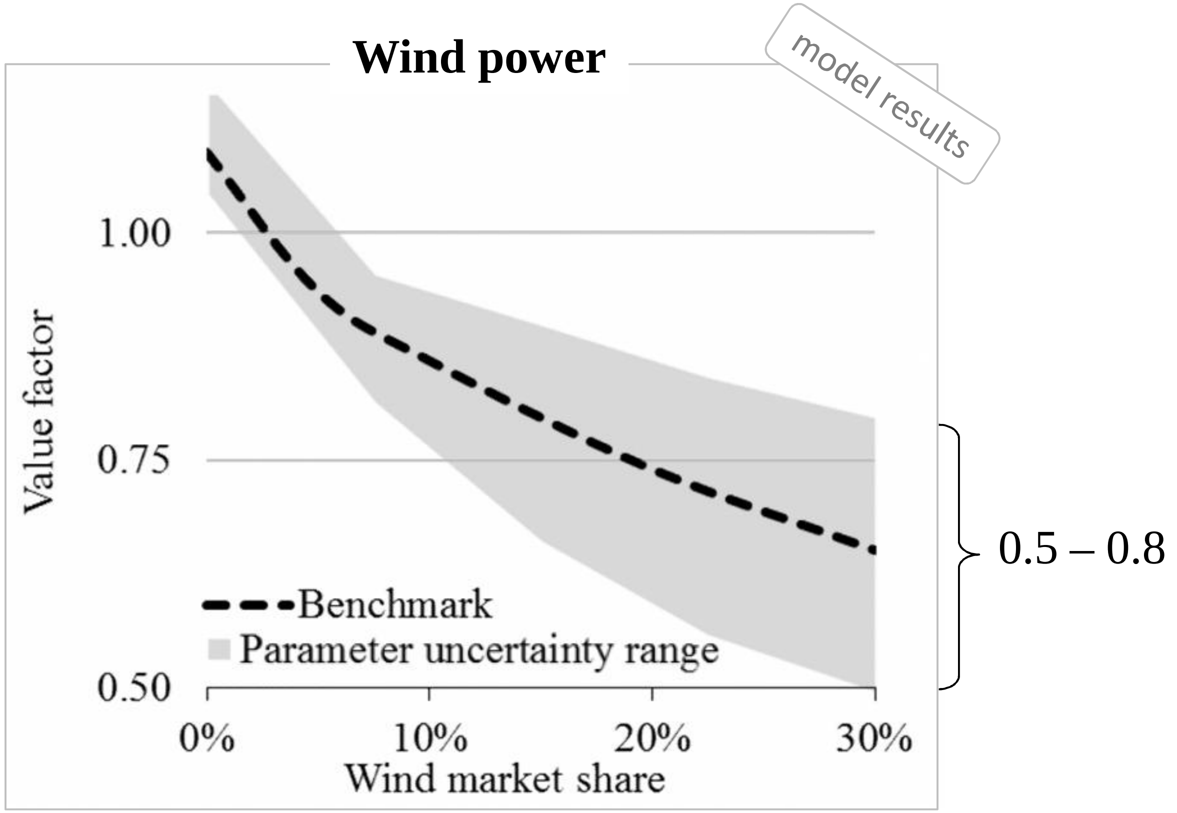


Source: updated from Hirth (2013): Market value



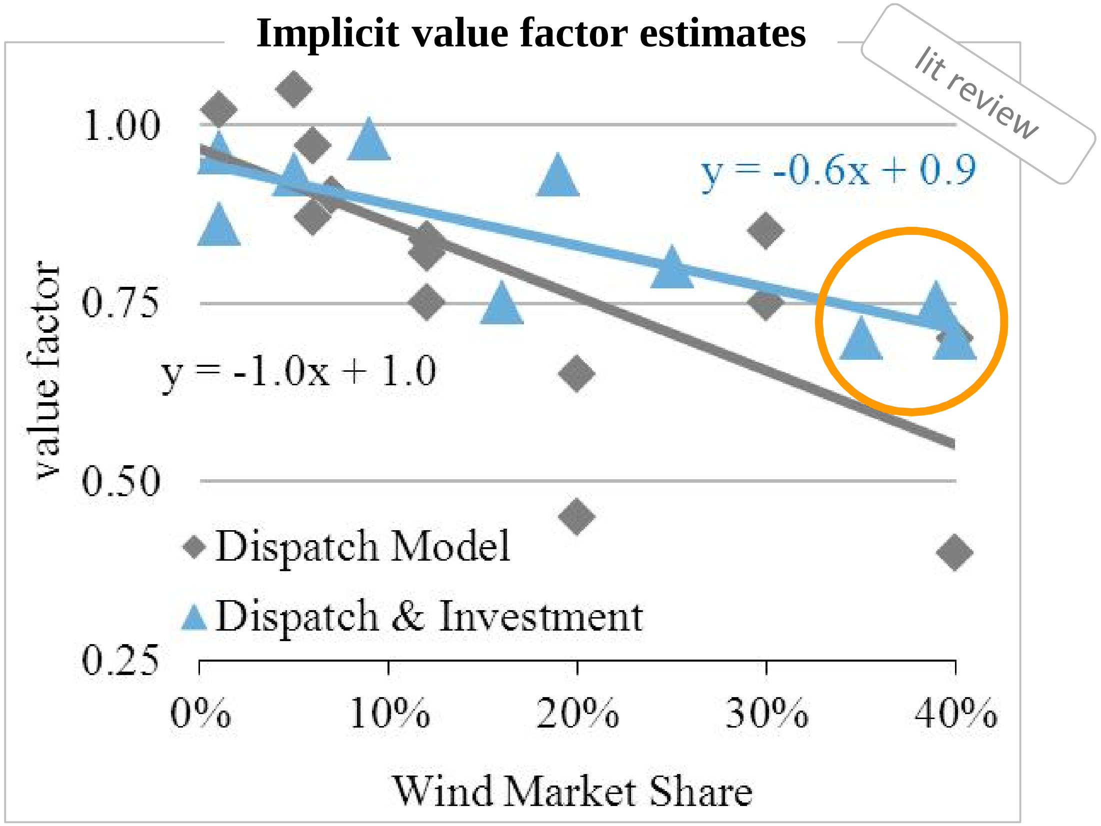
Source: updated from Hirth (2013): Market value

Assessing parameter uncertainty: 0.5 – 0.8 at 30% wind

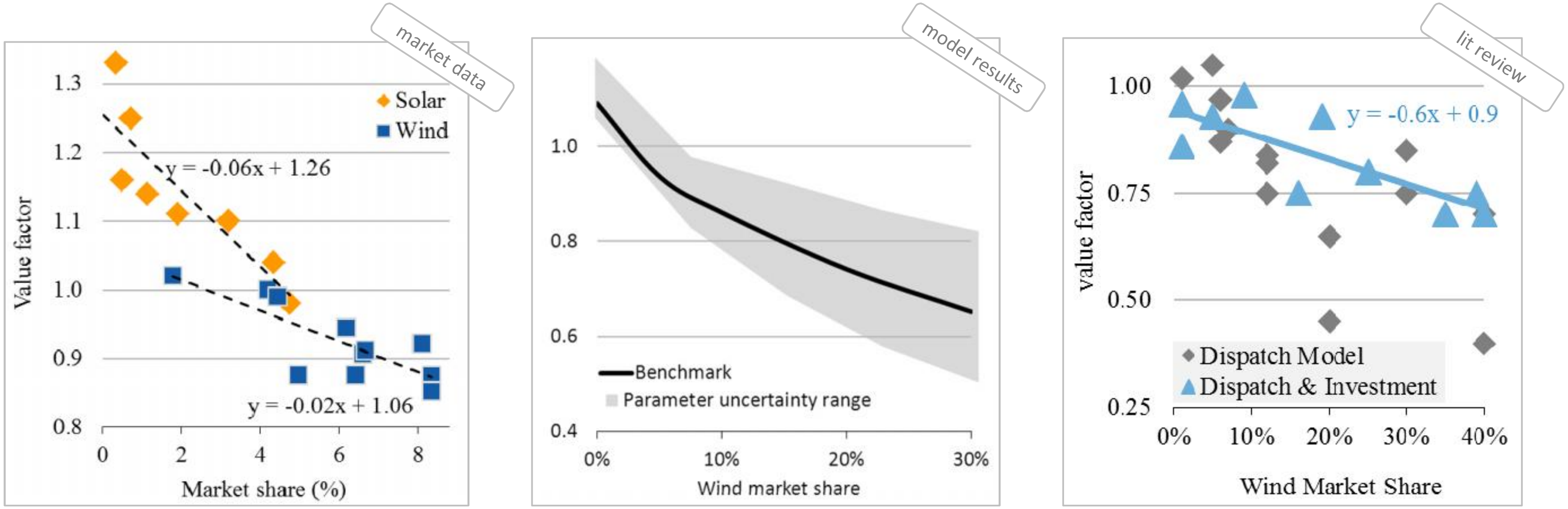


Source: updated from Hirth (2013): Market value. Parameters considered: CO_2 price between 0 – 100 €/t, Flexible ancillary services provision, Zero / double interconnector capacity, Flexible CHP plants, Zero / double storage capacity, Double fuel price, ...

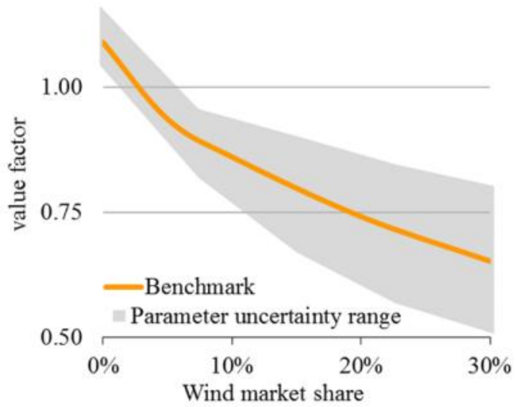
Literature review: consistent with model results



Source: updated from Hirth (2013): Market value


market data
Solar
Wind
y = -0.06x + 1.26
y = -0.02x + 1.06
Value factor
Market share (%)
model results
Benchmark
Parameter uncertainty range
Wind market share
lit review
y = -0.6x + 0.9
value factor
Dispatch Model
Dispatch & Investment
Wind Market Share

Concluding: Market value



Relatively low value of VRE at high penetration

- compared to value of other generators
- compared to today‘s value of VRE

Value drop is large

- ~40% value drop for wind
- massive shift in relative prices
- drop is larger for solar than for wind
- potentially large ‘VRE bias’ towards optimism

Robust results

- w.r.t. parameter uncertainty
- w.r.t. model uncertainty

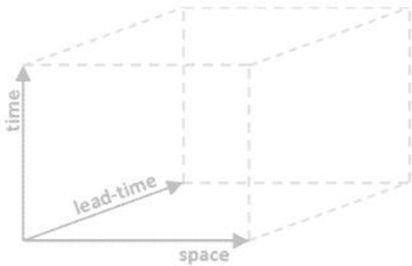
Profitability in questions

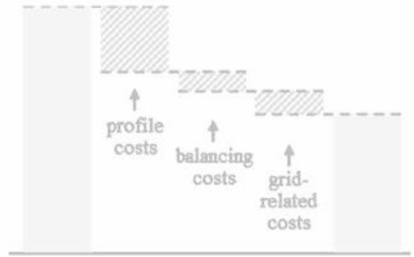
- difficult to become profitable at high penetration rate
- puts into question ambitious renewables targets without subsidies

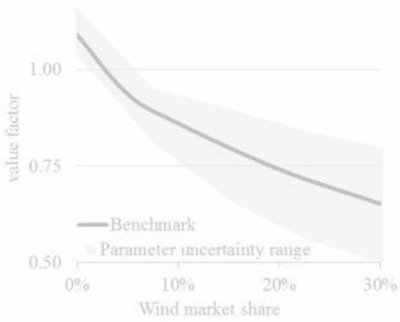
→ *does this mean there is no role for wind and sun in the future power system?*

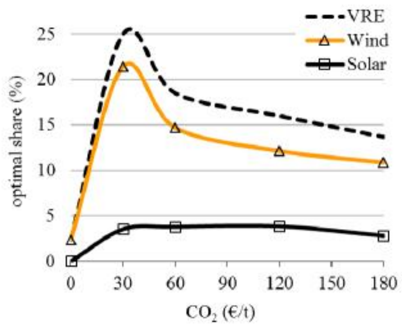
4.

Optimal share

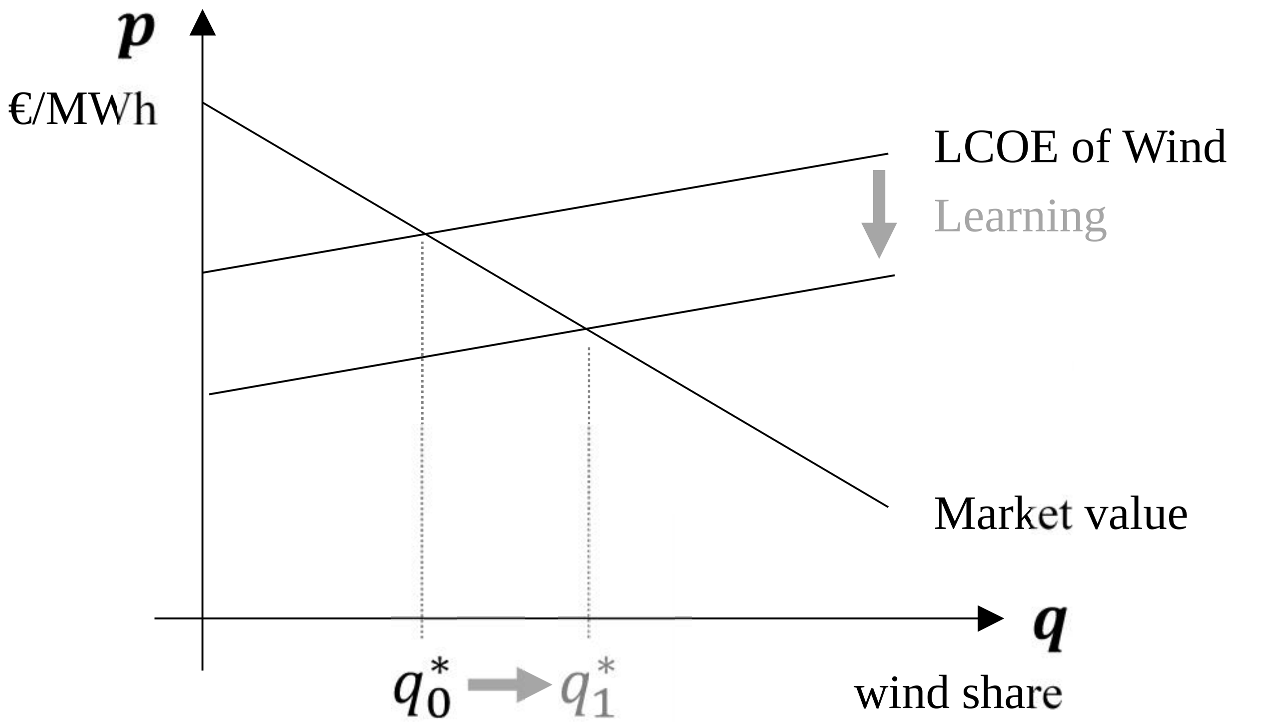




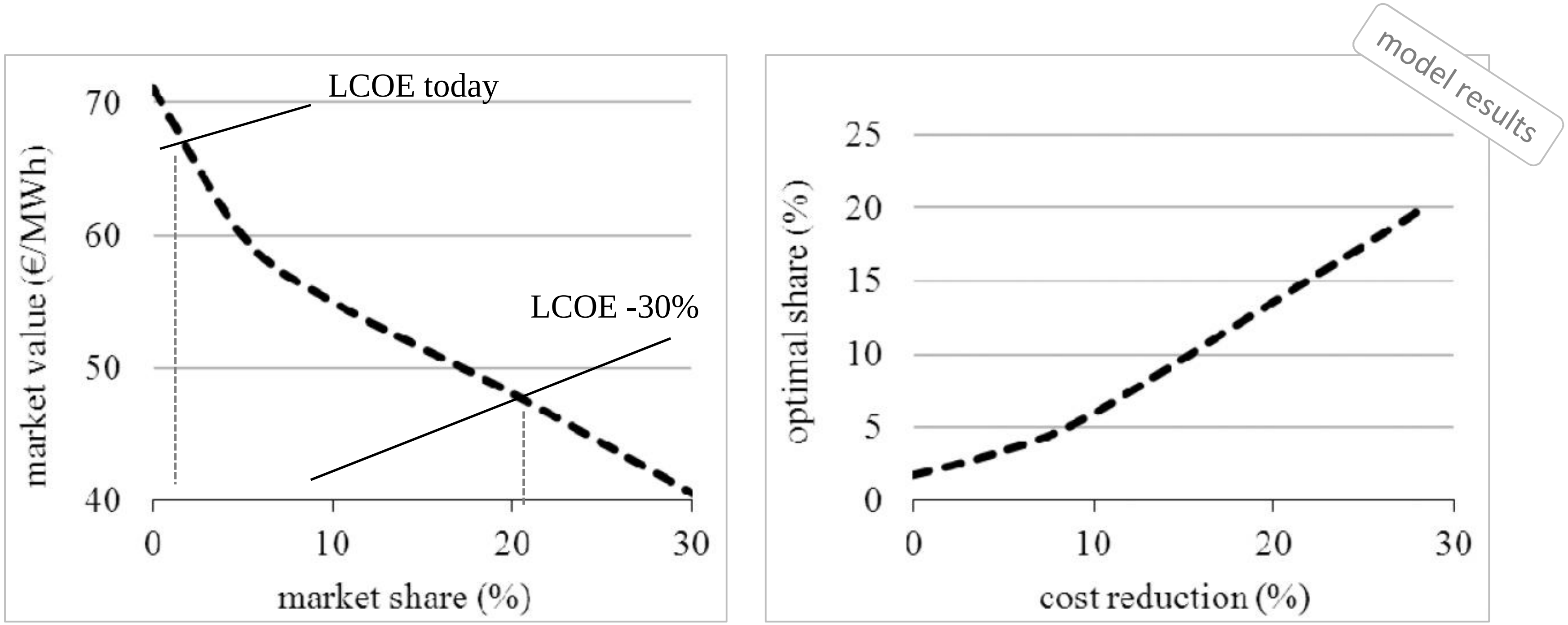




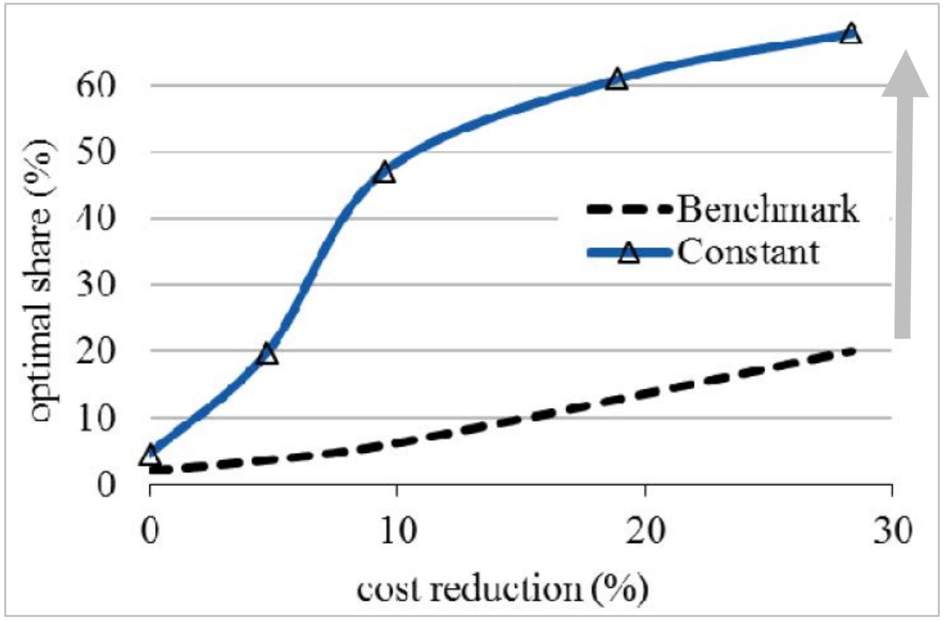
$$P(Q) \rightarrow Q(C)$$


p
€/MWh
LCOE of Wind
Learning
Market value
q
wind share
q_0^*
q_1^*

Flipping the perspective: $P(Q) \rightarrow Q(C)$

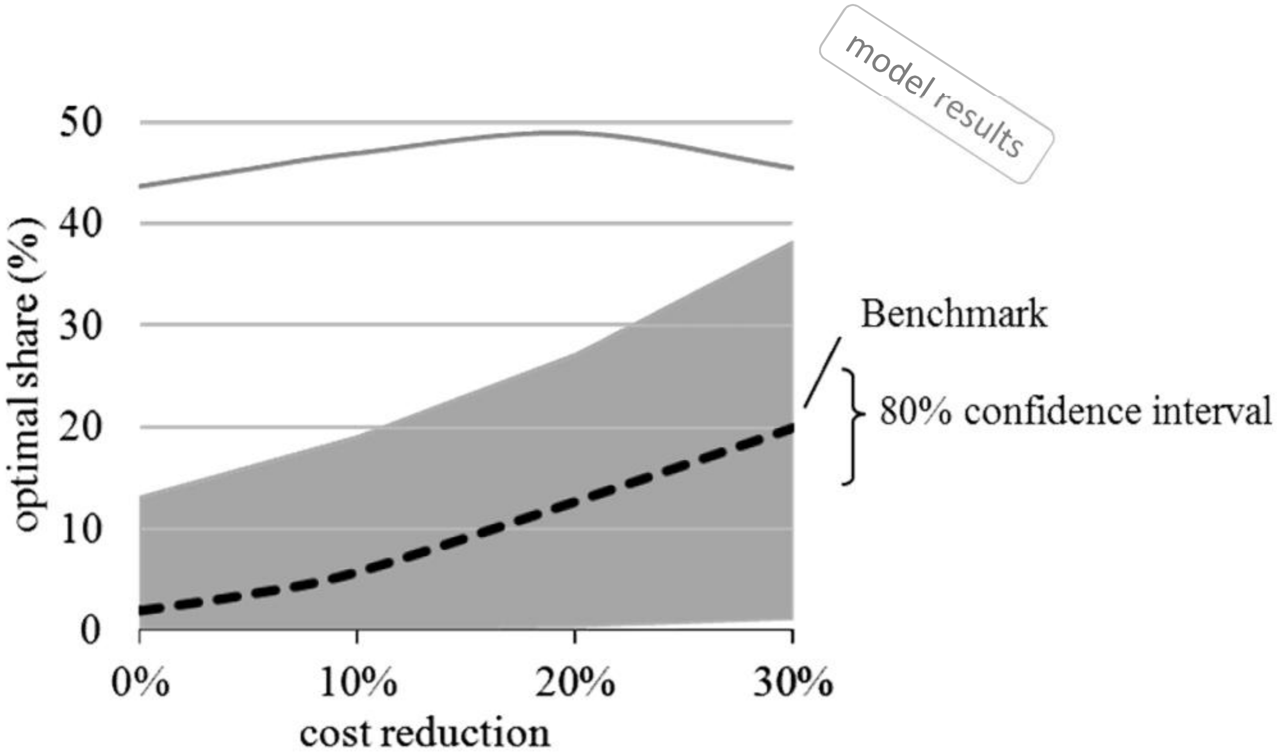


Ignoring variability dramatically alters results

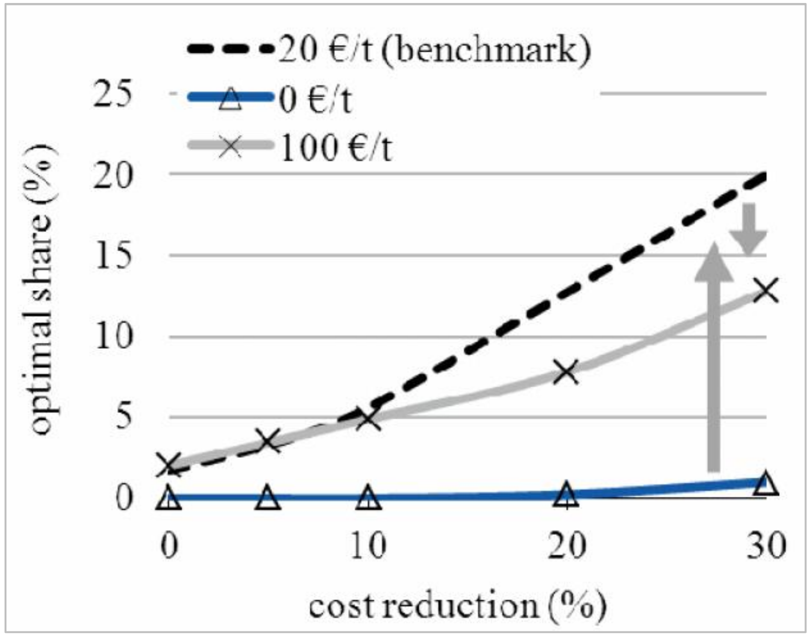


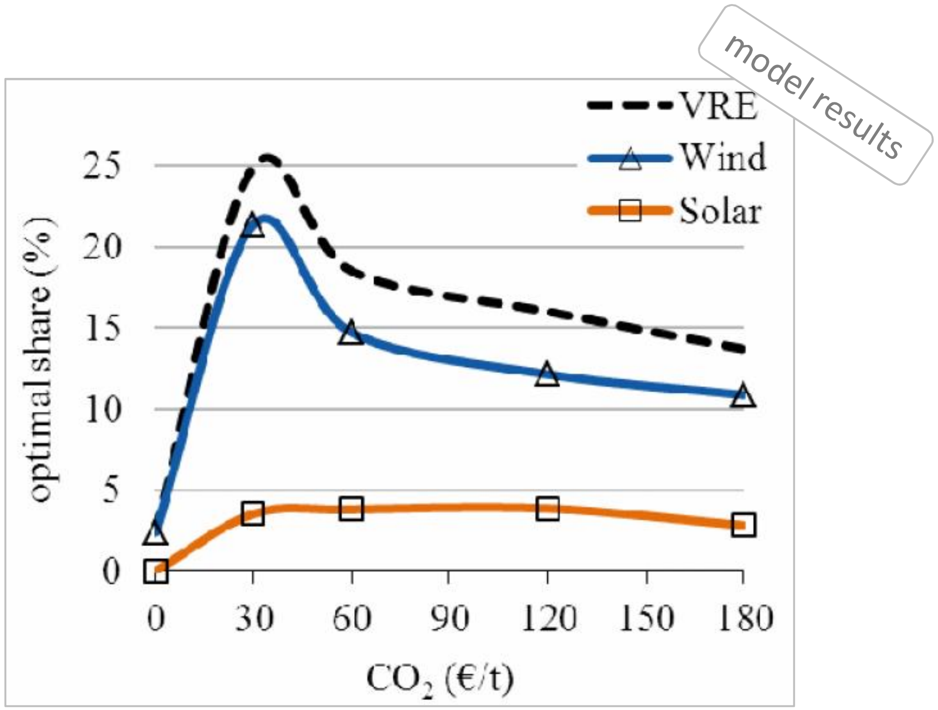
250% bias

Uncertainty range: 16% - 25% share at low cost



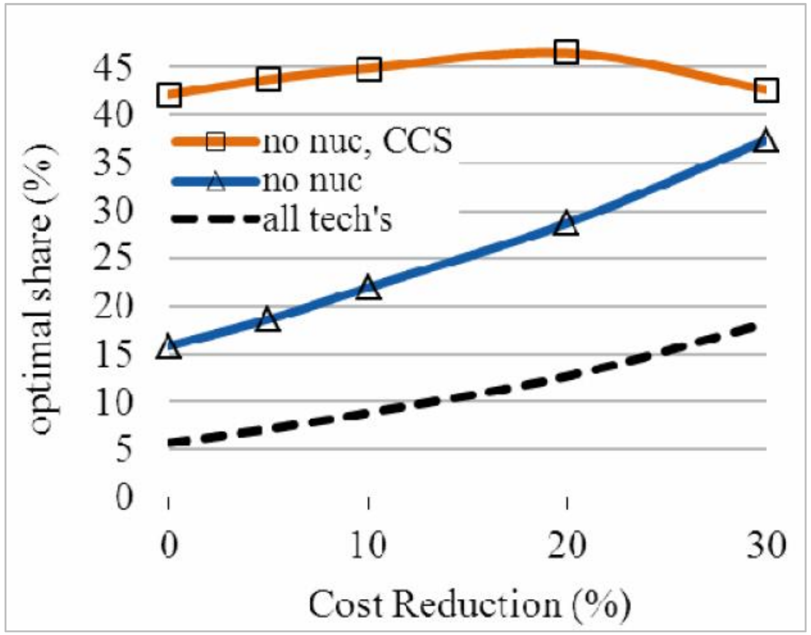
The impact of climate policy (1)



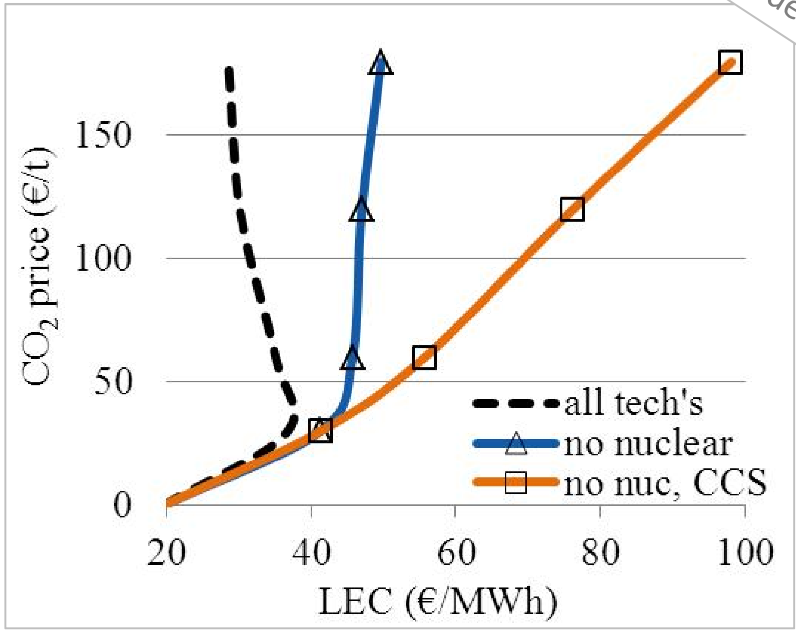


The impact of climate policy (2)

model results

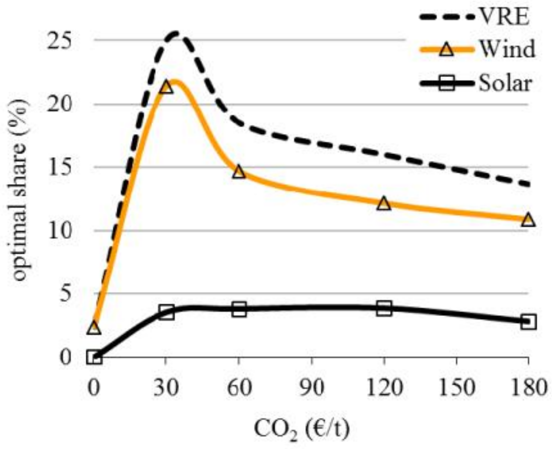


100 €/t CO_2



Contour plot: the lines represent a 40% wind share. Above / left there is a higher share.

Concluding: Optimal share



Wind power is competitive (solar isn't)

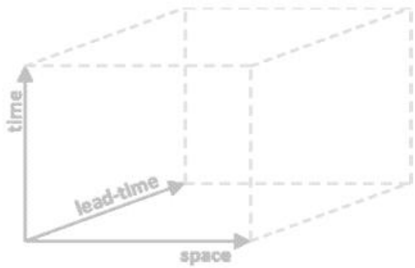
- 20% wind market share without subsidies – if costs decrease by a third
- 16% – 25% market share in 80% of runs
- optimal solar deployment is very small – even if costs decrease by another 60%

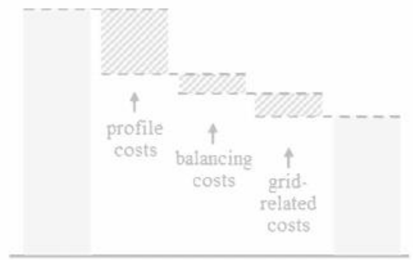
Flexibility helps

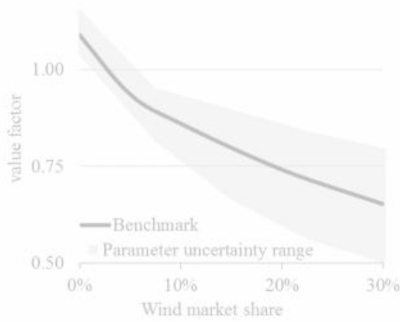
- system: interconnectors, electricity storage
- thermal plants: co-generation of heat and ancillary services
- wind power: low wind-speed turbines

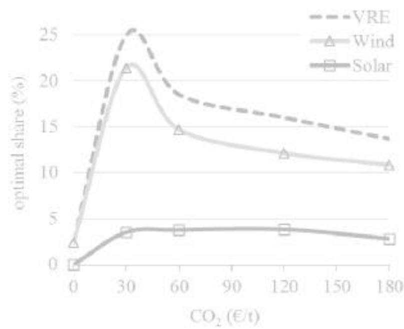
Surprising results

- seemingly counter-intuitive results, driven by investments into base load plants
- use quantitative models and model investments – don‘t rely on intuition (only)

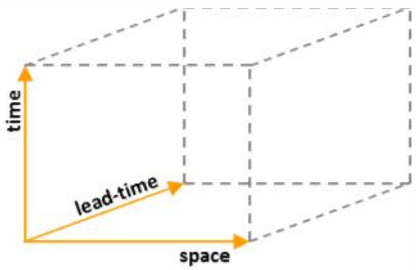

time
lead-time
space

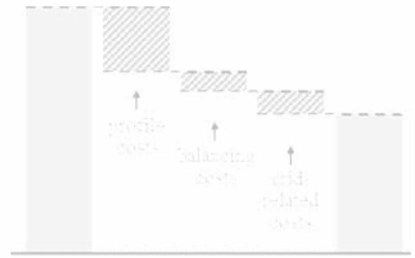

profile costs
balancing costs
grid-related costs

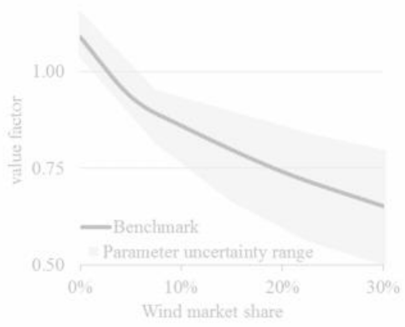

value factor
1.00
0.75
0.50
0%
10%
20%
30%
Wind market share
Benchmark
Parameter uncertainty range

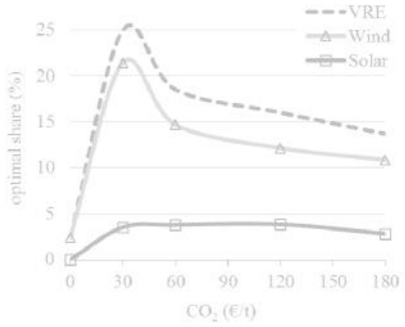

VRE
Wind
Solar
optimal share (%)
25
20
15
10
5
0
0
30
60
90
120
150
180
CO2 (€/t)

1. Electricity is a heterogeneous good
   → prices vary over time, space, lead-time



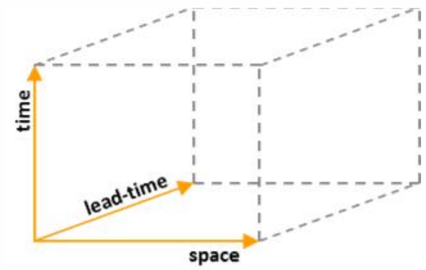


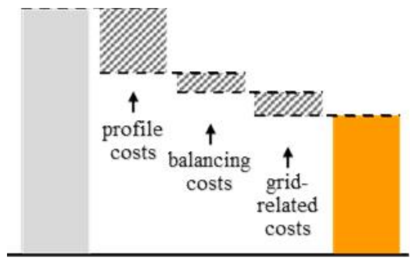


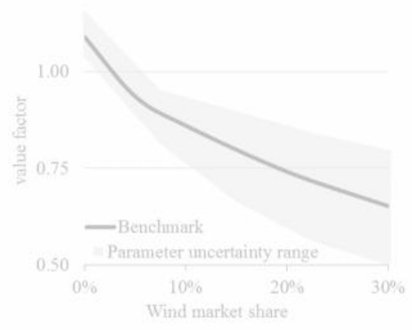


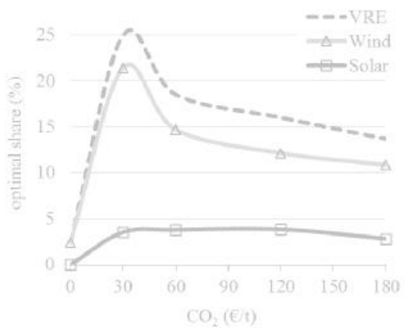
1. Electricity is a heterogeneous good
   → prices vary over time, space, lead-time

2. Profile, balancing, grid-related costs
   → profile costs largest





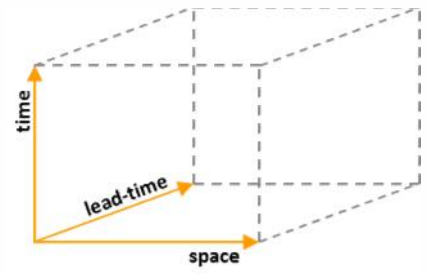


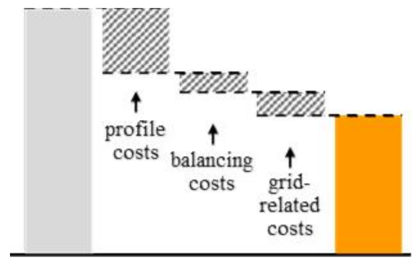


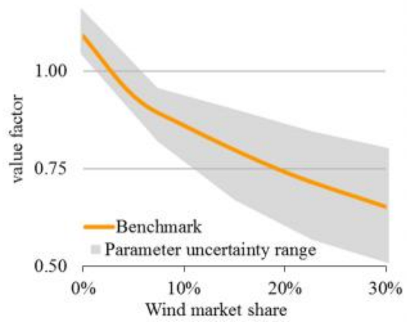
1. Electricity is a heterogeneous good
   → prices vary over time, space, lead-time

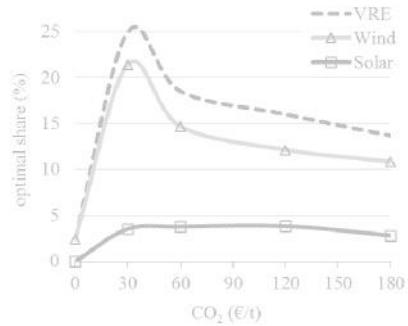
2. Profile, balancing, grid-related costs
   → profile costs largest

3. Value of wind and solar power decreases with penetration
   → large bias if ignored







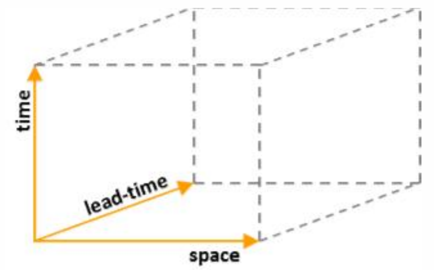


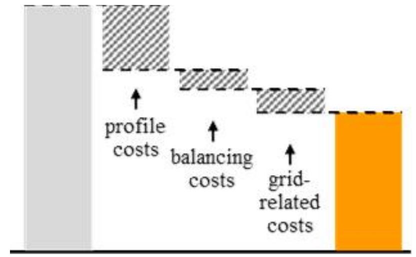
1. Electricity is a heterogeneous good
   → prices vary over time, space, lead-time

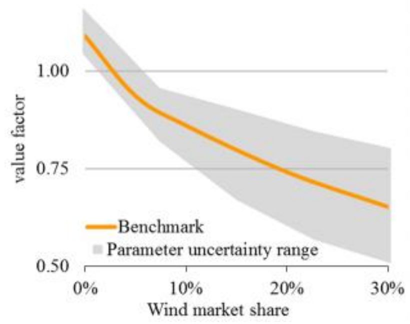
2. Profile, balancing, grid-related costs
   → profile costs largest

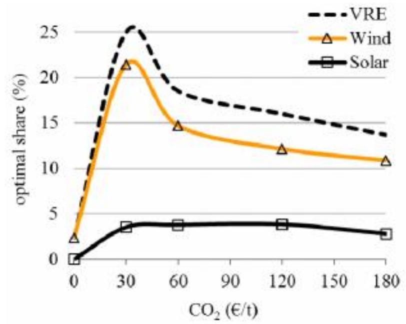
3. Value of wind and solar power decreases with penetration
   → large bias if ignored

4. Still, onshore wind power is likely to become competitive









What are the economic implications of wind and solar power variability?

... in terms of costs?

... in terms of value?

... in terms of optimal deployment?

It depends. For wind power at 30%:

... integration costs of 20 – 35 €/MWh

... value reduced by 30 – 50% relative to constant source

... deployment reduced from 70% to 20%

Conclusions

Methodological conclusions

- value differences matter → use LCOE, multi-sector models carefully
- VRE variability matters → ignoring variability can lead to large VRE bias
- surprising results → use models, and model capital adjustments

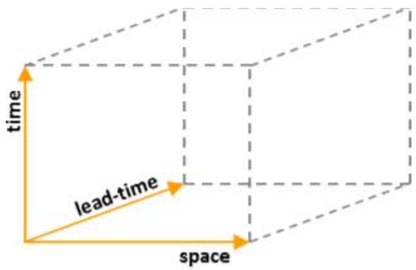
Economic conclusions

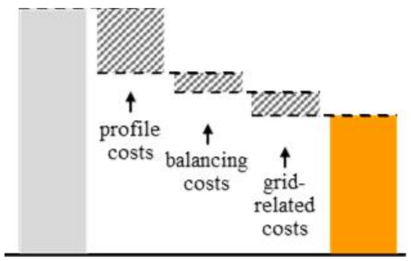
- the largest economic impact of VRE is to reduce the utilization of other plants
- base load technologies (nuclear, CCS) don‘t go well with VRE – because they are capital-intensive

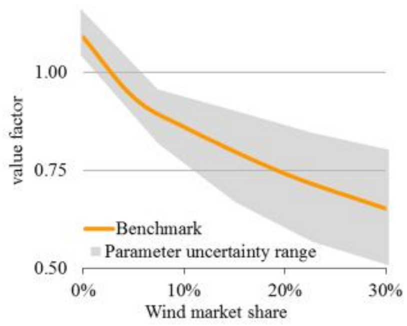
Policy conclusions

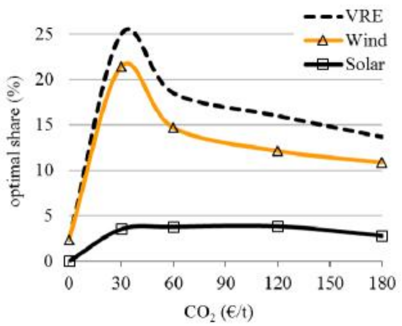
- variability has major economic costs at high penetration rate
- role of VRE smaller than some hope – but (much) larger than today
- many options to mitigate the value drop: flexible plants, advanced wind power, ...
- design markets and policies properly: let prices signal scarcity

The Economics *of* *Wind & Solar Variability*









References

Economics of Electricity	Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2014): "Why Wind is not Coal: On the Economics of Electricity", *FEEM Working Paper* 2014.039. www.feem.it/getpage.aspx?id=6308
Integration Costs	Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2015): "Integration Costs Revisited – An economic framework of wind and solar variability", *Renewable Energy* 74, 925–939. http://dx.doi.org/10.1016/j.renene.2014.08.065
Market Value	Hirth, Lion (2013): "The Market Value of Variable Renewables", *Energy Economics* 38, 218-236. http://dx.doi.org/10.1016/j.eneco.2013.02.004
Optimal Share	Hirth, Lion (2015): "The Optimal Share of Variable Renewables", *The Energy Journal* 36(1), 127-162. http://dx.doi.org/10.5547/01956574.36.1.5
Redistribution	Hirth, Lion & Falko Ueckerdt (2013): "Redistribution Effects of Energy and Climate Policy", *Energy Policy* 62, 934-947. http://dx.doi.org/10.1016/j.enpol.2013.07.055
Balancing Power	Hirth, Lion & Inka Ziegenhagen (2013): ”Balancing power and variable renewables“, *USAEE Working Paper* 13-154. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2371752