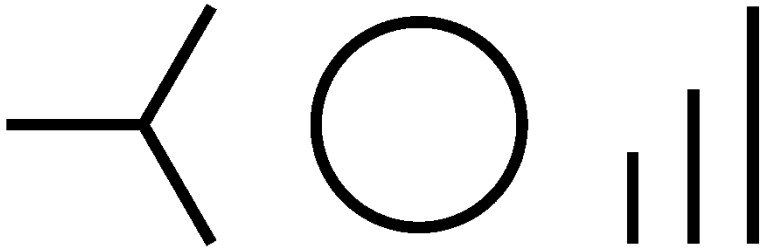
The Optimal Share of Variable Renewables

How the Variability of Wind and Solar Power affects their Welfare-optimal Deployment

Lion Hirth

Paris-Dauphine | 8 July 2015 | hirth@neon-energie.de

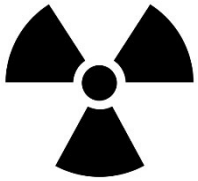
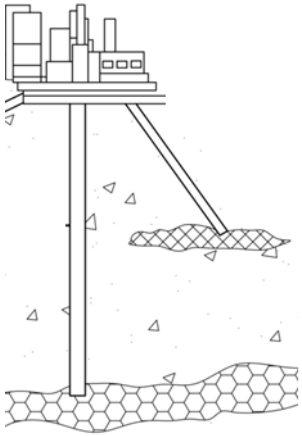
neon neue energieökonomik

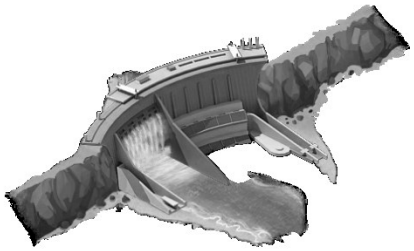
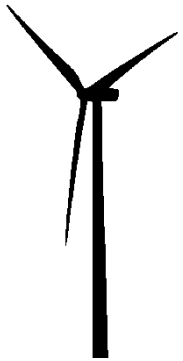


Seeking advice on power markets? Neon Neue Energieökonomik is a Berlin-based boutique consulting firm for energy economics. Neon conducts model-based studies of power markets, provides electricity price forecasts, and organizes workshops. www.neon-energie.com

Lion Hirth
hirth@neon-energie.de
+49 1 57 55 199 715

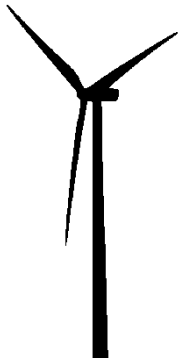
Six options for low-carbon electricity generation

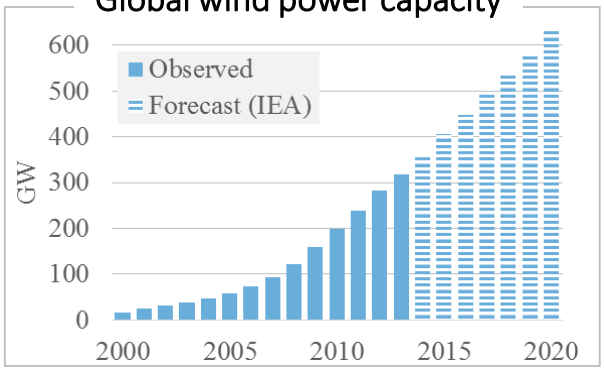

“the Energiewende is all about wind and solar power”

(Agora Energiewende 2013)

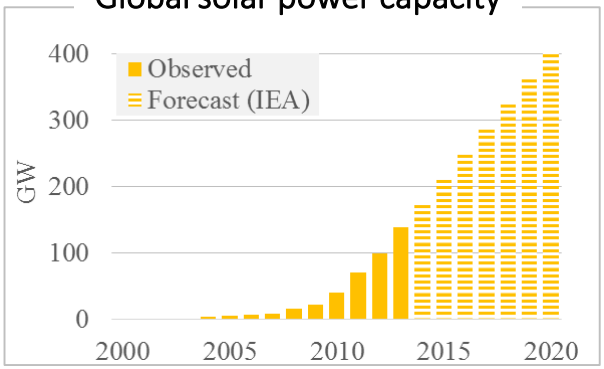


Wind & sun deliver 15+% of electricity in some regions

Global wind power capacity



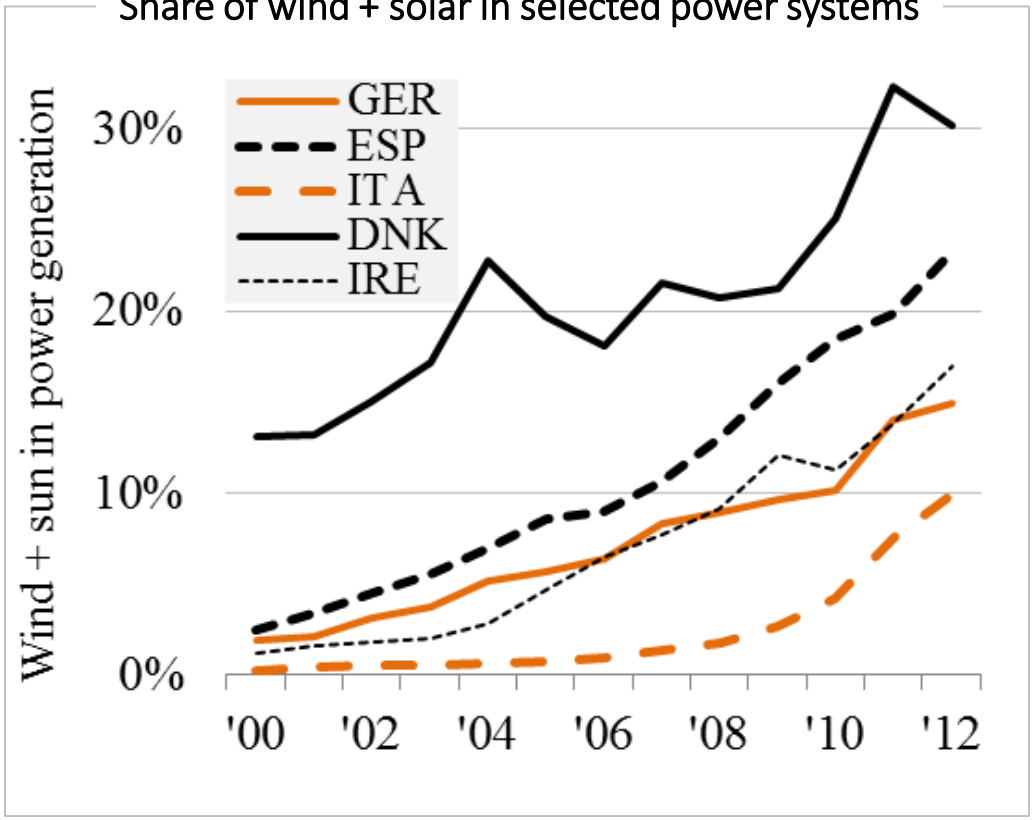
Global solar power capacity



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

Wind and solar power have been growing strongly, and are expected to continue to grow.

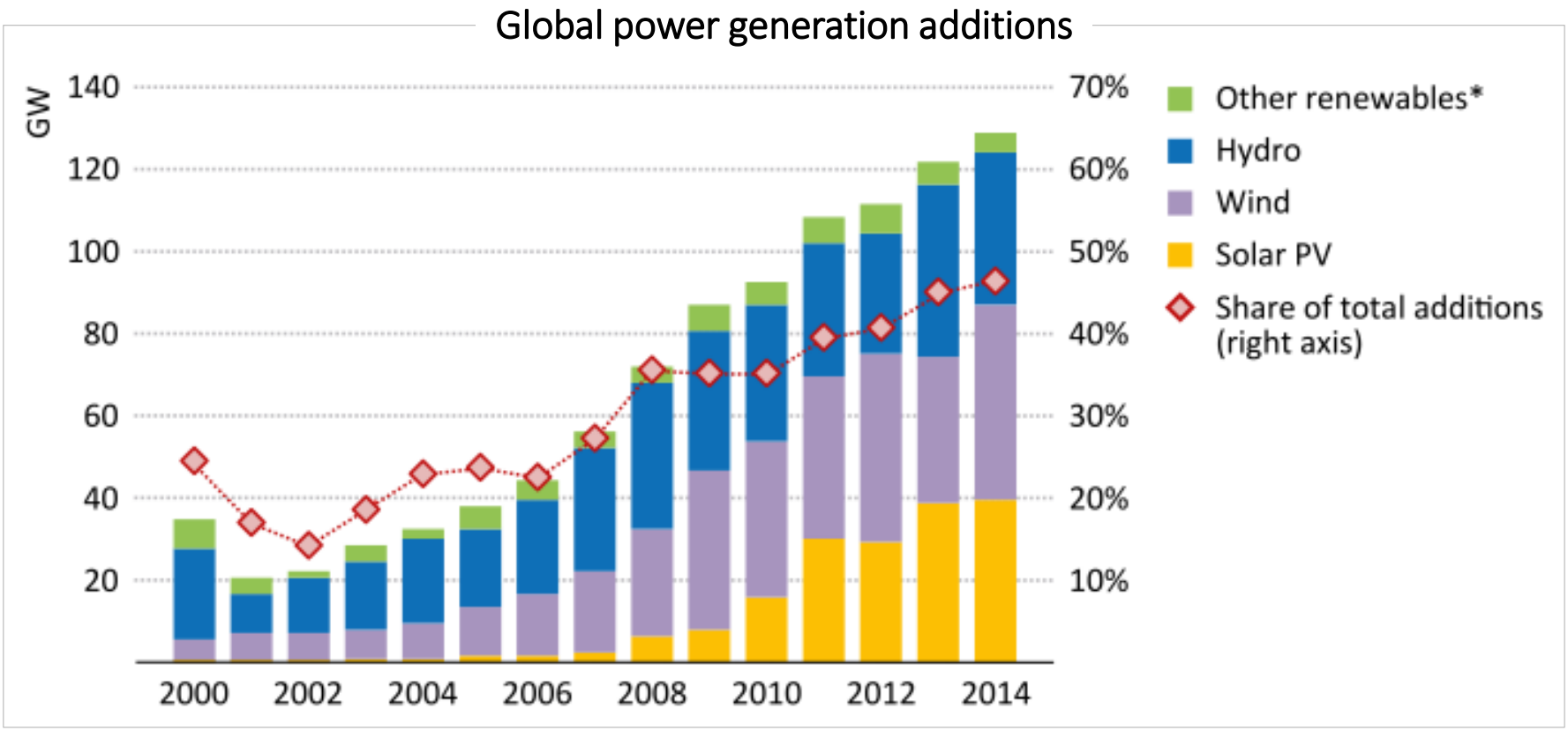
Share of wind + solar in selected power systems



Data source: IHS (2013)

Wind and solar power combined now supply more than 15% of electricity in several power systems – they become mainstream technologies.

50% of globally added capacity is renewable

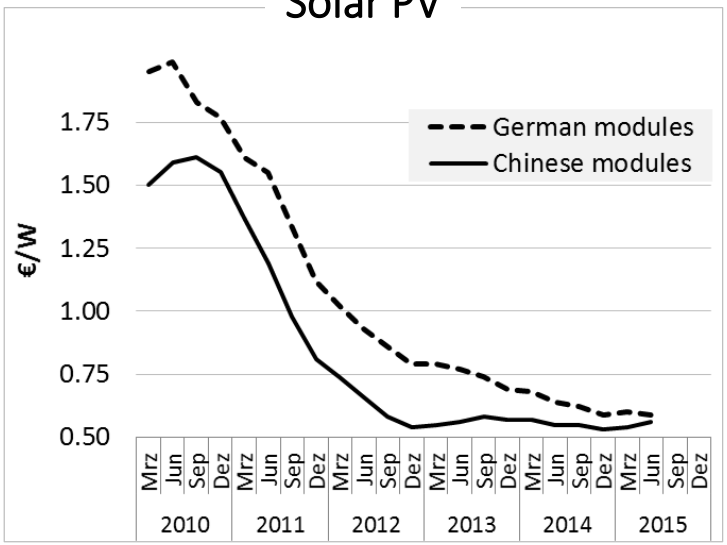


Source: IEA (2015): WEO special report

In 2014, almost half of all new power generation capacity globally was based on renewables – of which wind and solar power captured the lion's share of 70%.

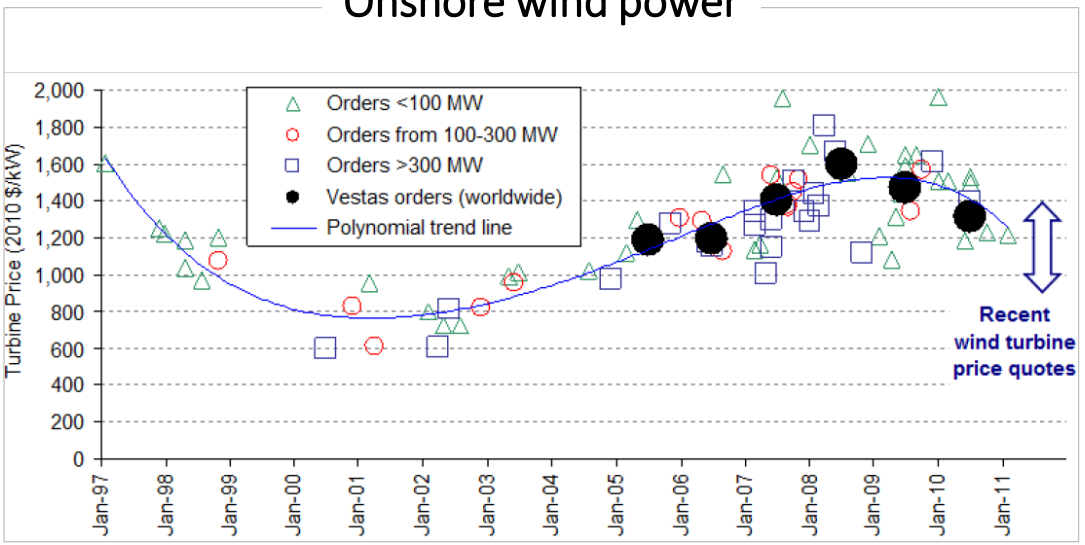
Wind and solar power become cheaper (not always)

Solar PV



Data source: pvxchange.org (2015)

Onshore wind power

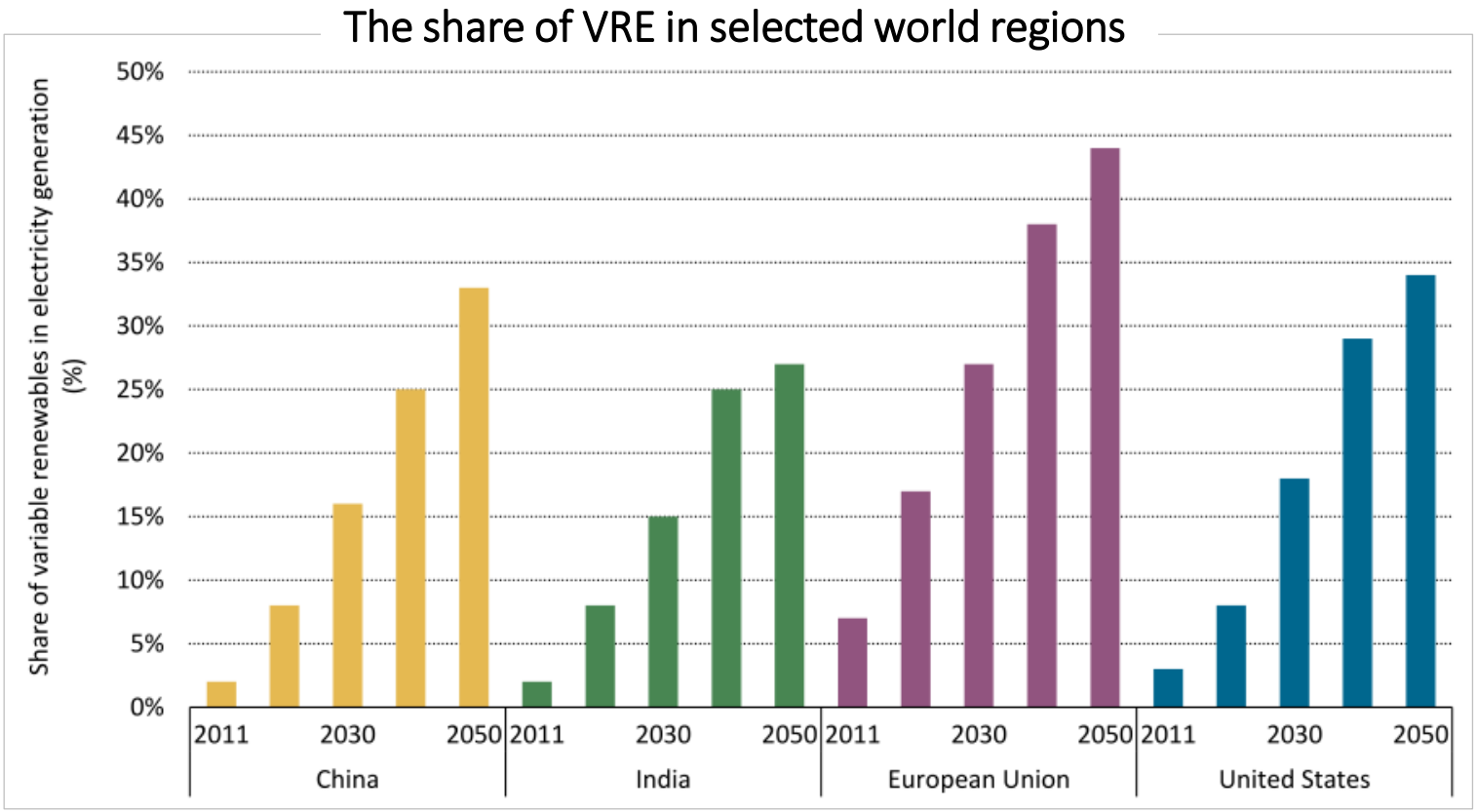


Source: IEA (2012): The past and future cost of wind energy

Solar PV module price stagnate since 2012 – after a hefty price drop 2012-12.

Wind turbine prices have been falling – after a decade of rising prices during the 2000s.

Variable renewables will supply a large share of power



IEA (2014): Energy technology perspectives

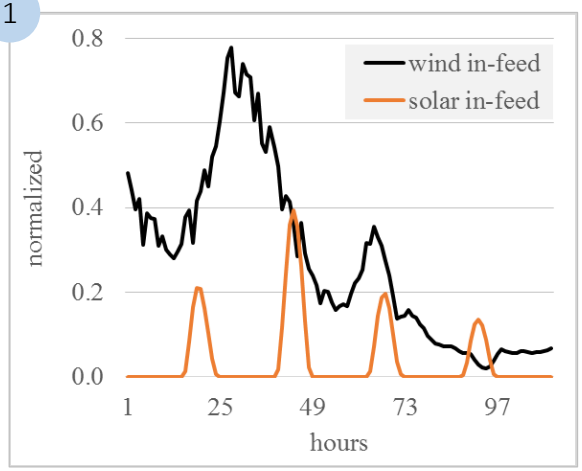
IEA's *Energy Technology Perspectives* projects that in most major world regions, variable renewables will capture at least 25% market share in energy terms by the mid of this century – up from single digit numbers today.

The intermittency challenge

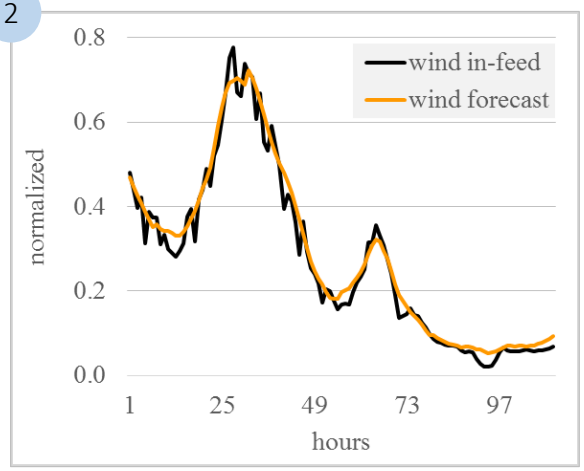
Why Wind is not Coal: On the Economics of Electricity, *The Energy Journal* (forthcoming).

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

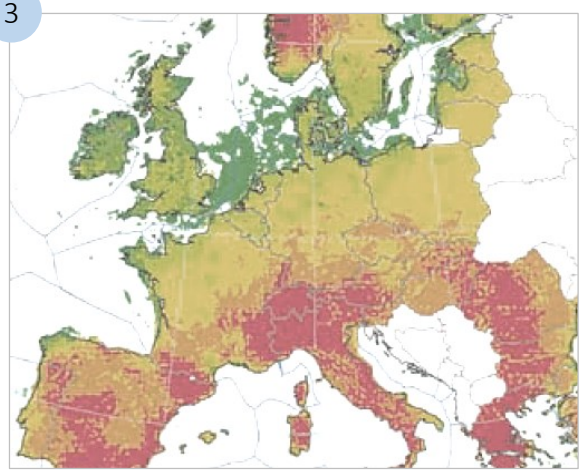
1



2



3



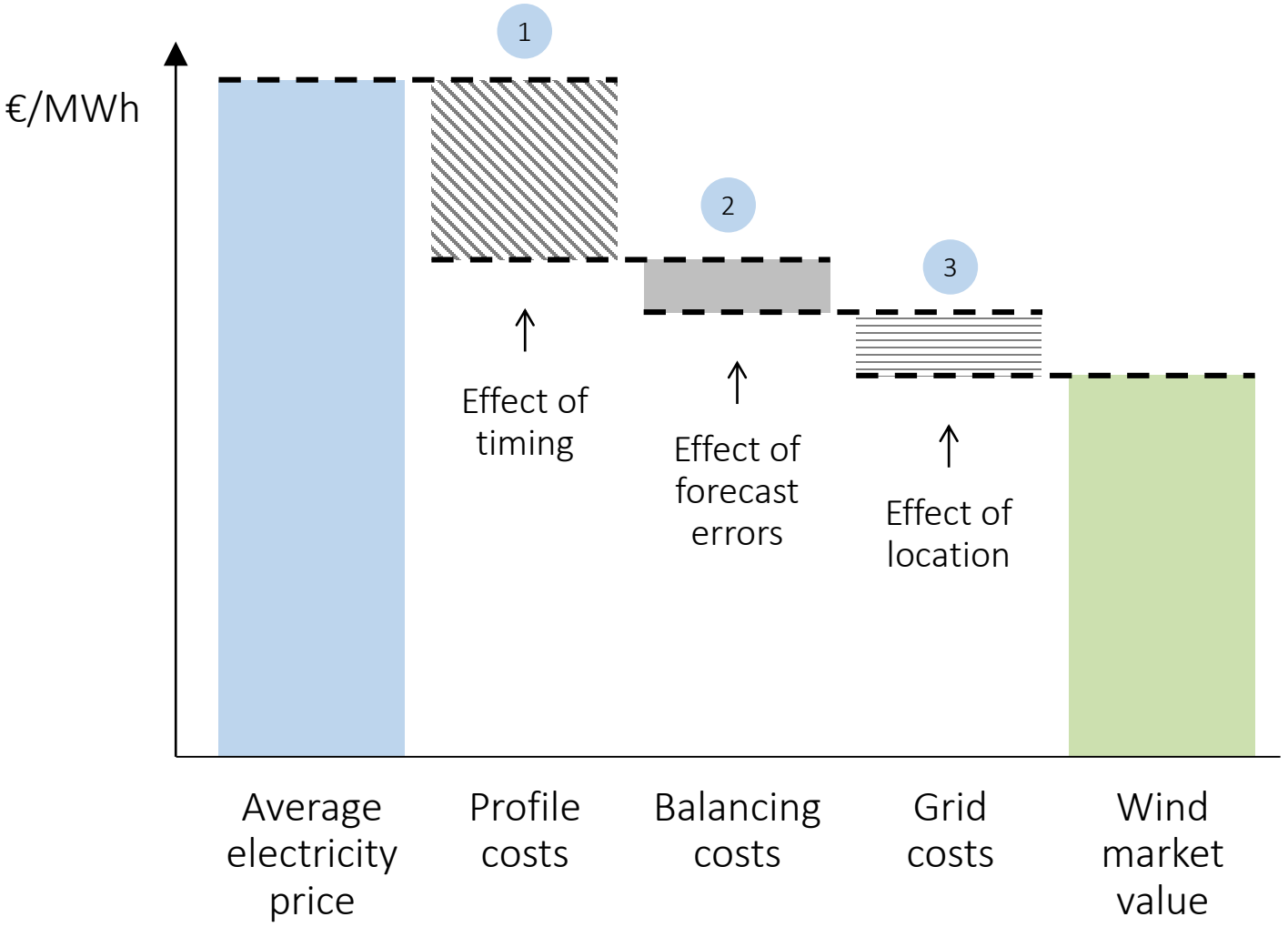
Wind does not always blow

Difficult to predict

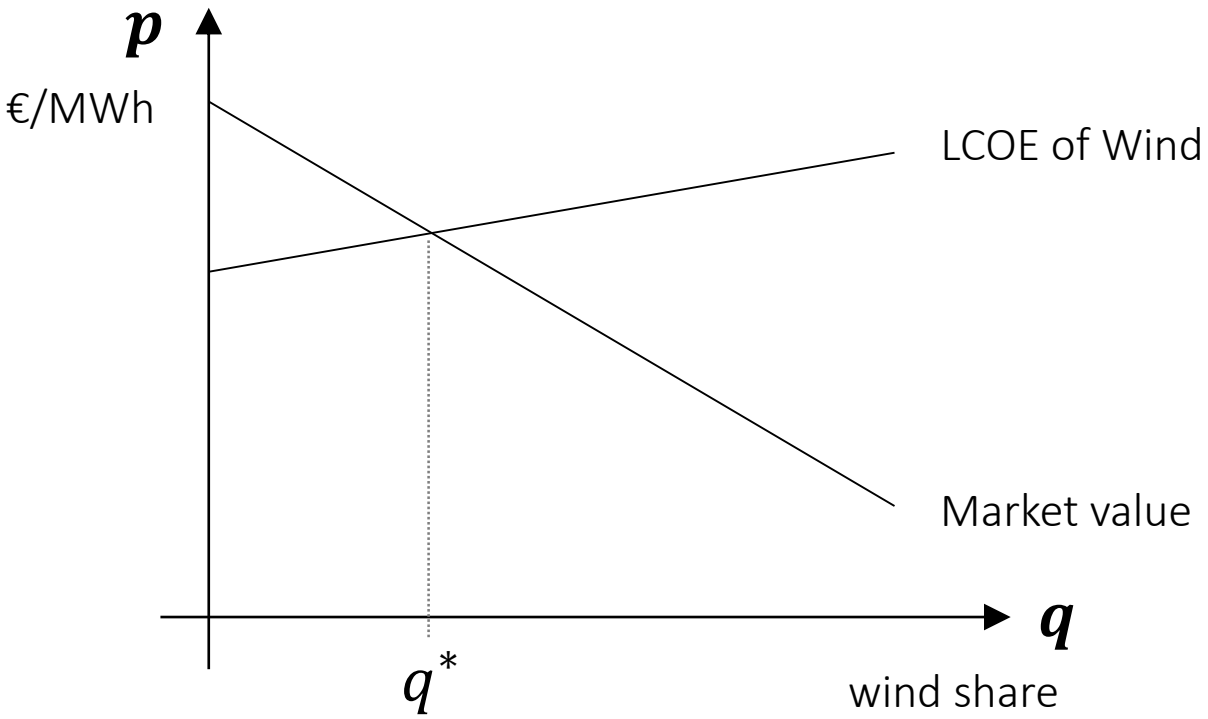
Good sites are distant from load centers

“Variable“ renewable energy source (VRE)

The market value of wind power

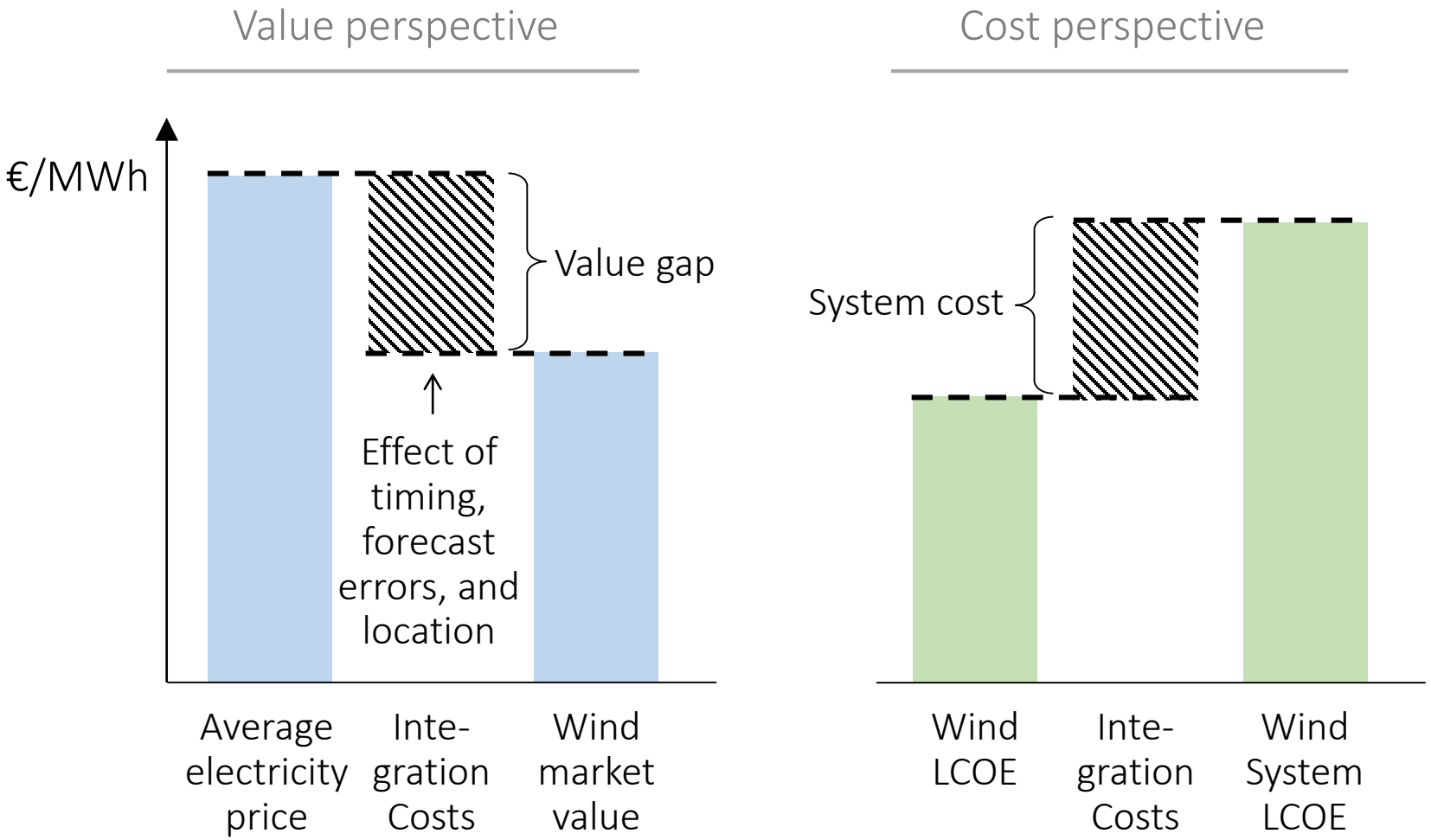


Long-term market equilibrium

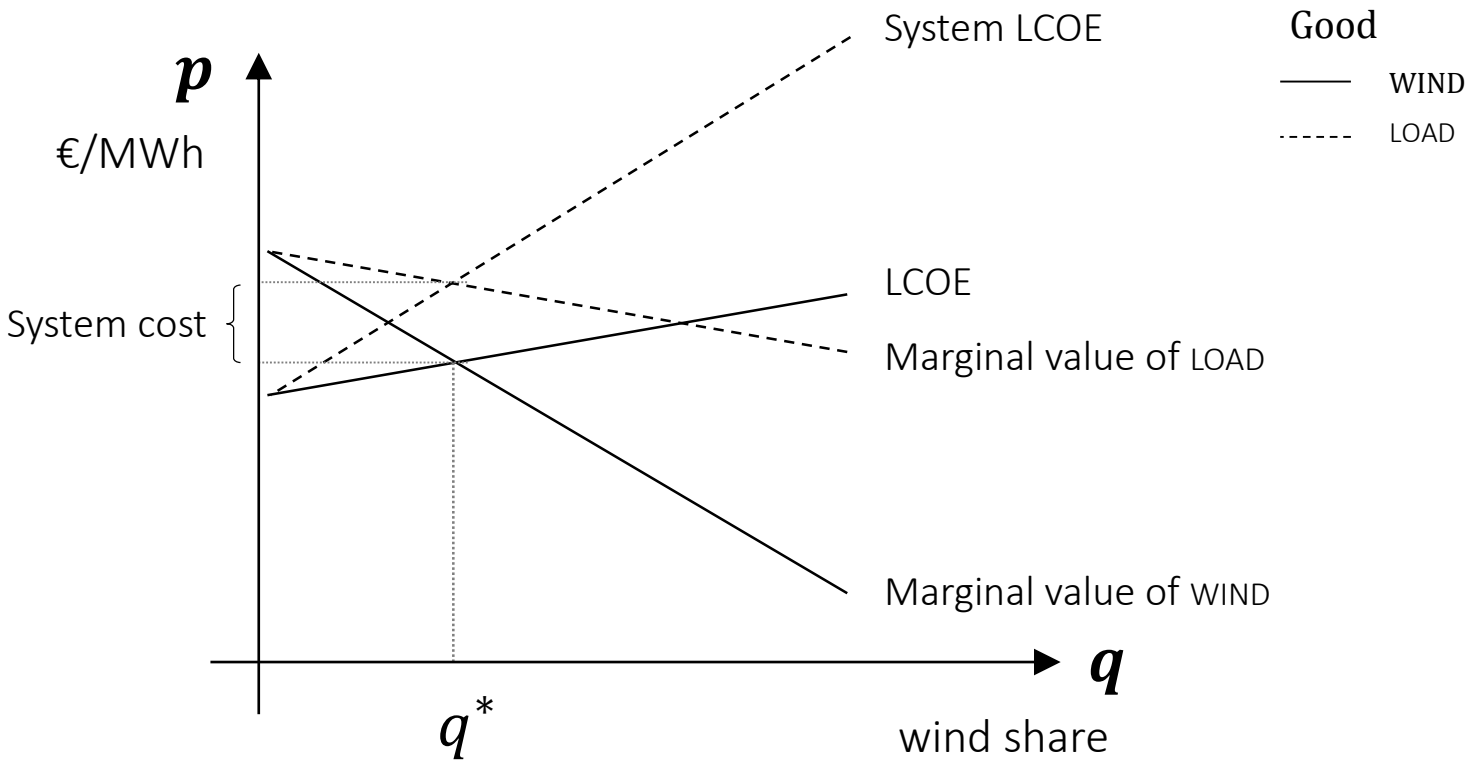


The intersection of LCOE (long-term marginal costs) and market value (long-term marginal value) defines the long-term equilibrium (optimum).

Value and costs: two perspectives



LT equilibrium: value and cost perspective



The intersection of LCOE (long-term marginal costs) and market value (long-term marginal value) defines the long-term equilibrium (optimum).

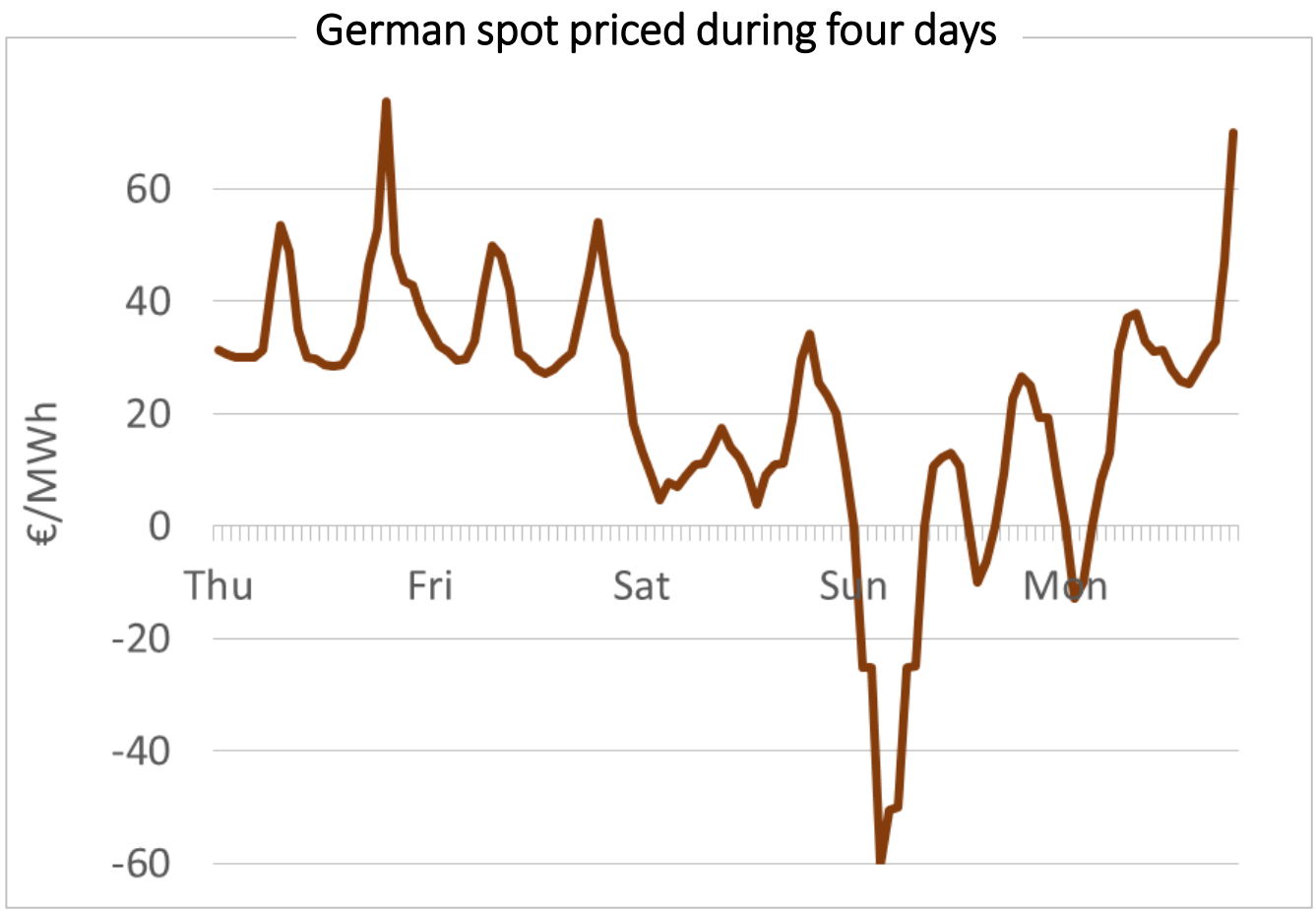
The wind and solar power value drop

The Market Value of Variable Renewables, *Energy Economics*, 2013.

The Market Value of Solar Photovoltaics: Is solar power cost-competitive?, *IET Renewable Power Generation,* 2015.

Integration Options and Deadlocks, in: Stolten/Scherer, 2013.

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%.

Value factor: the relative price of wind power

market data

Wind in Germany

	Base price (€/MWh)	Wind Revenue (€/MWh)	Value Factor (1)
2001	24	25*	1.02
…	…	…	…
2014	35	30	.86

↑ Simple average of all hours of the year

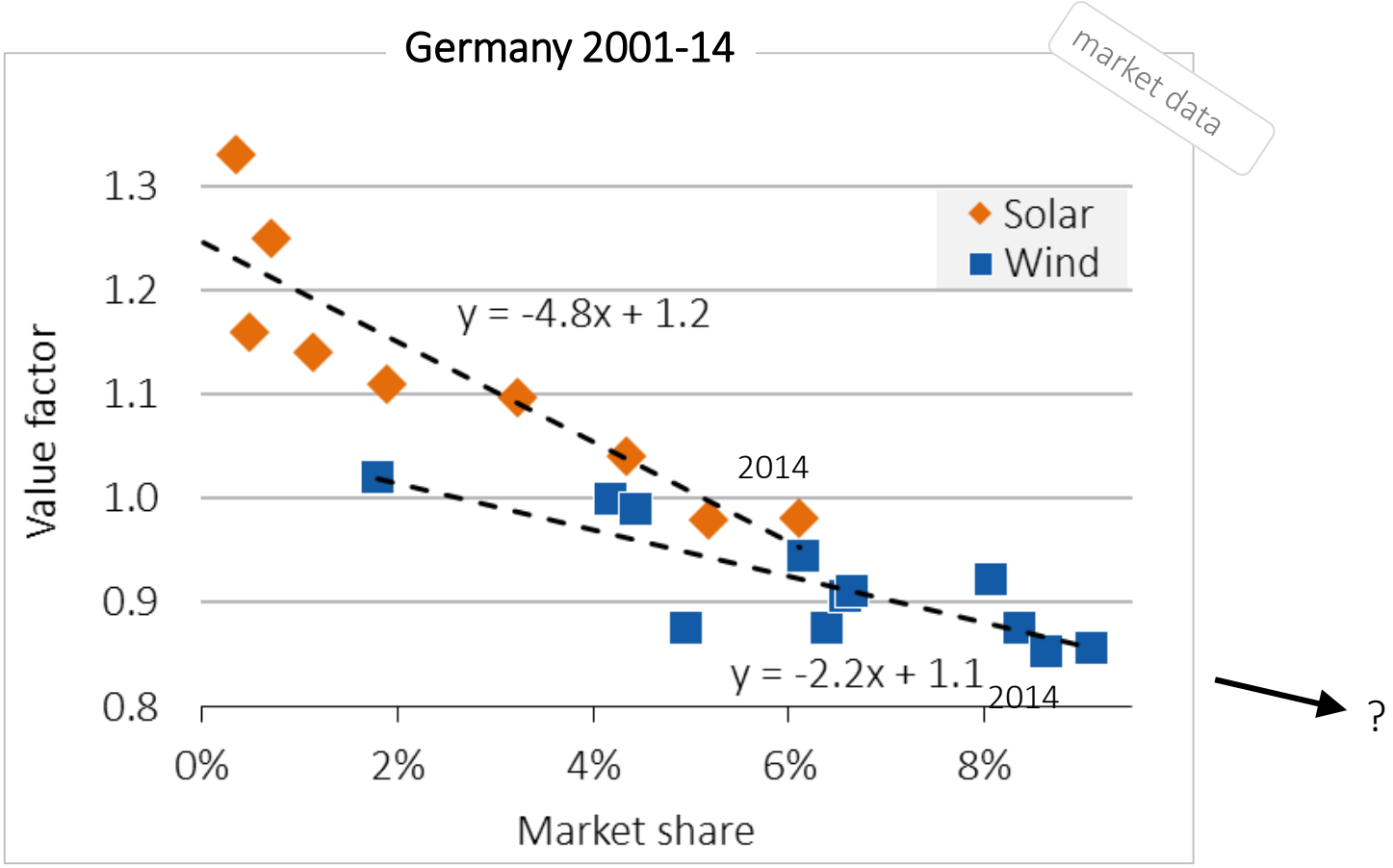
↑ Wind-weighted average

↑ Ratio of these two

The wind and solar value drop

Value Factor = Market value / base price

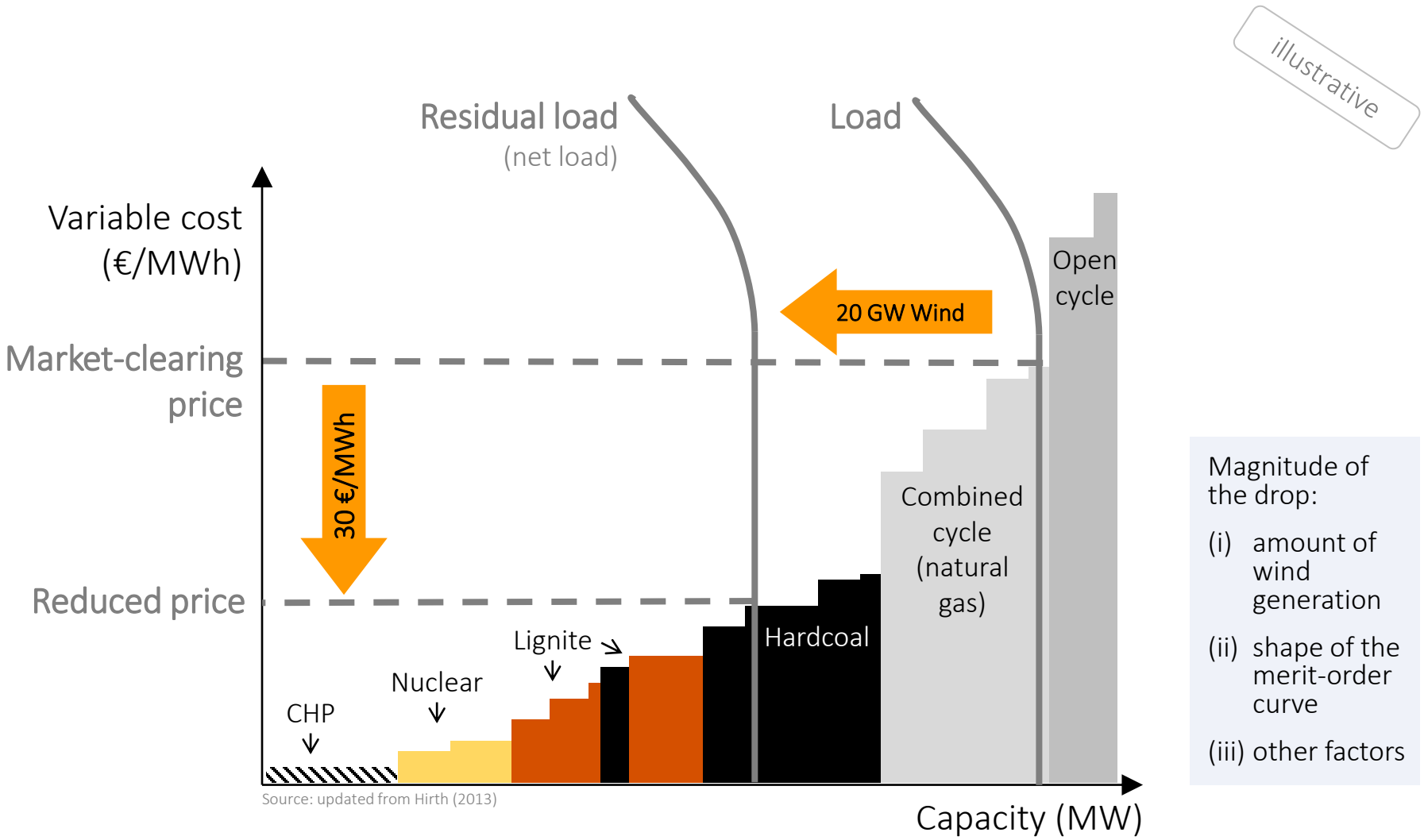
Each dot represents one year



Source: updated from Hirth (2013). Based on German day-ahead spot-price data 2001 – 2014

The relative value of electricity from wind and solar power is reduced as their market share grows. For solar power, the value drop is more pronounced.

The mechanics behind the value drop



Magnitude of the drop:

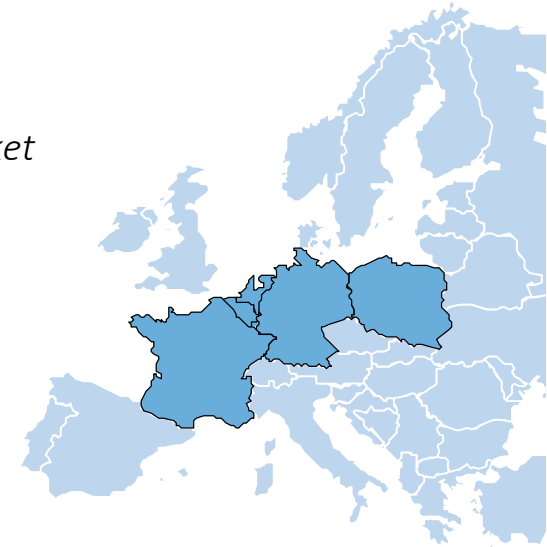
(i) amount of wind generation

(ii) shape of the merit-order curve

(iii) other factors

The Electricity Market Model EMMA

Numerical partial-equilibrium model of the European interconnected power market



Objective: minimize total system costs

- capital costs
- fuel and CO_2 costs
- fixed and and variable O&M costs
- ... of power plants, storage, interconnectors

Decision variables

- hourly plant dispatch and trade of electricity
- investment in plants, storage, interconnectors

Constraints

- energy balance
- capacity constraints
- volume constraints of storage
- balancing reserve requirement
- CHP generation
- (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 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”)

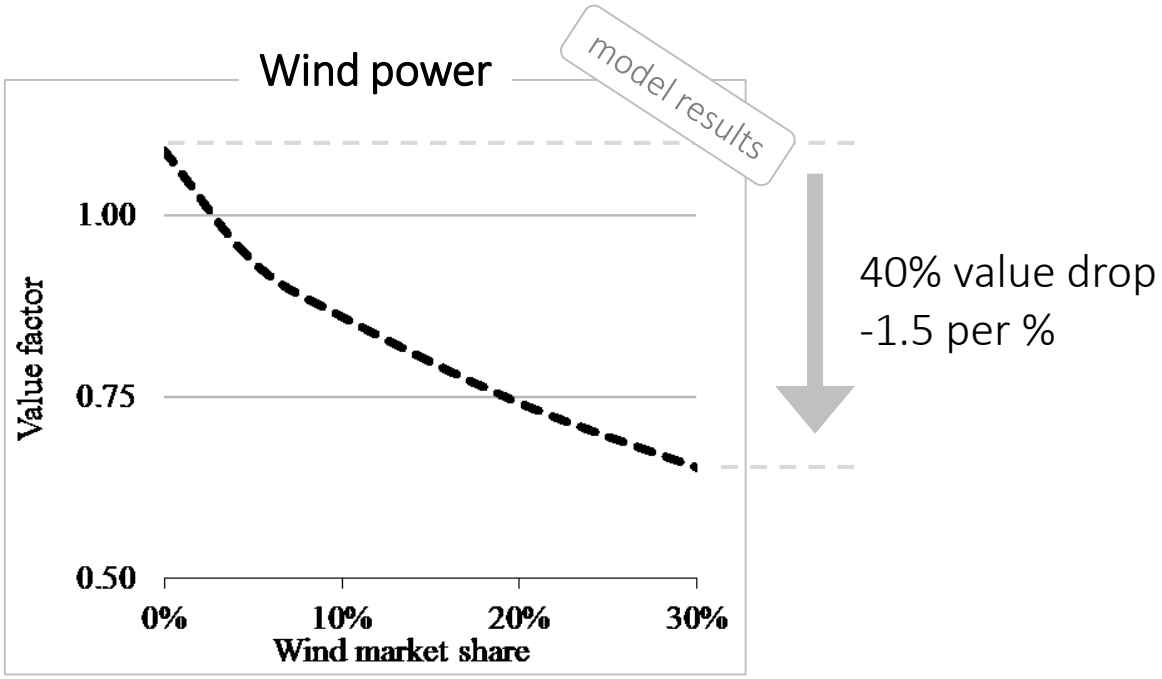
Implementation

- linear program
- GAMS / cplex

Open source

$$P^*(Q,\cdot)$$

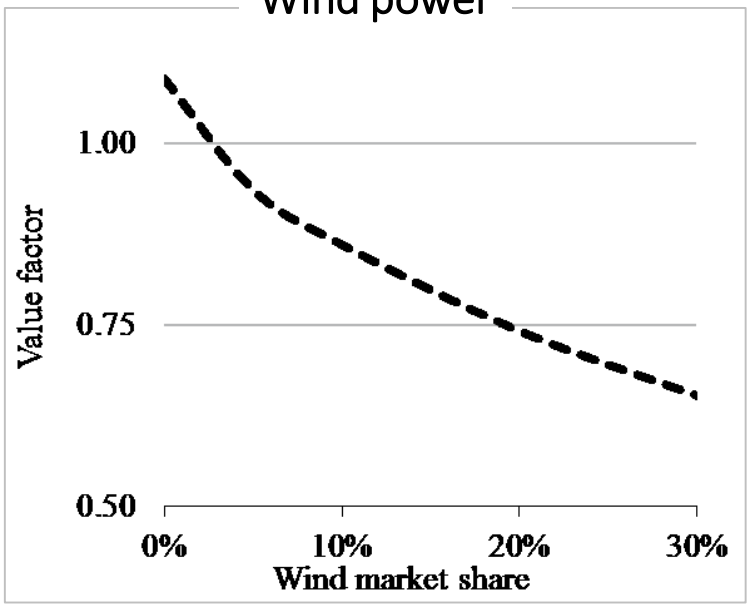
The value drop continues: model results



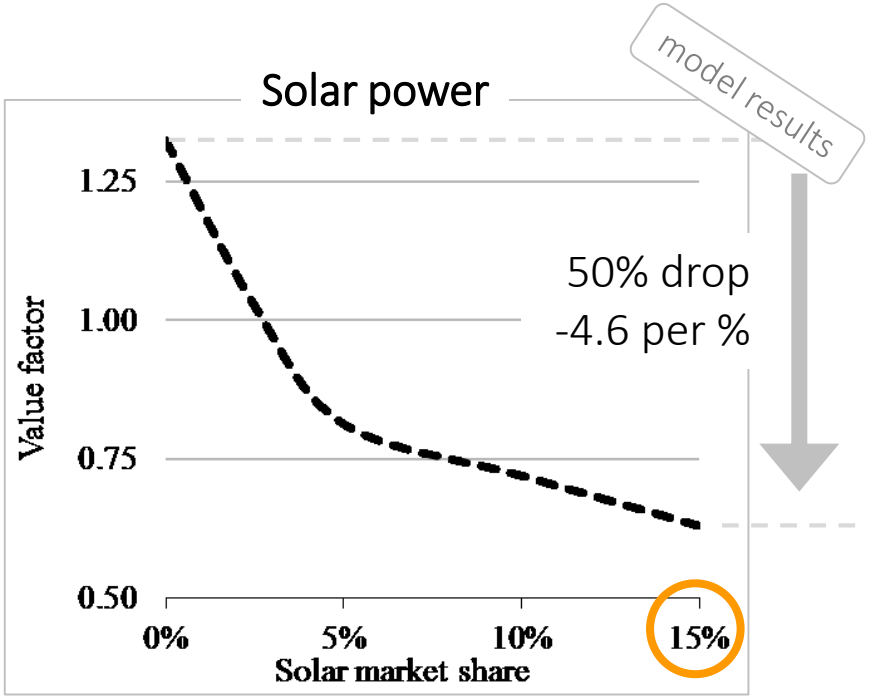
Source: updated from Hirth (2013): Market value

The value factor of wind power decreases from ~1.1 at low penetration to ~0.65 at 30% market share (1.5 points per point market share).

The value drop continues: model results



Source: updated from Hirth (2013): Market value

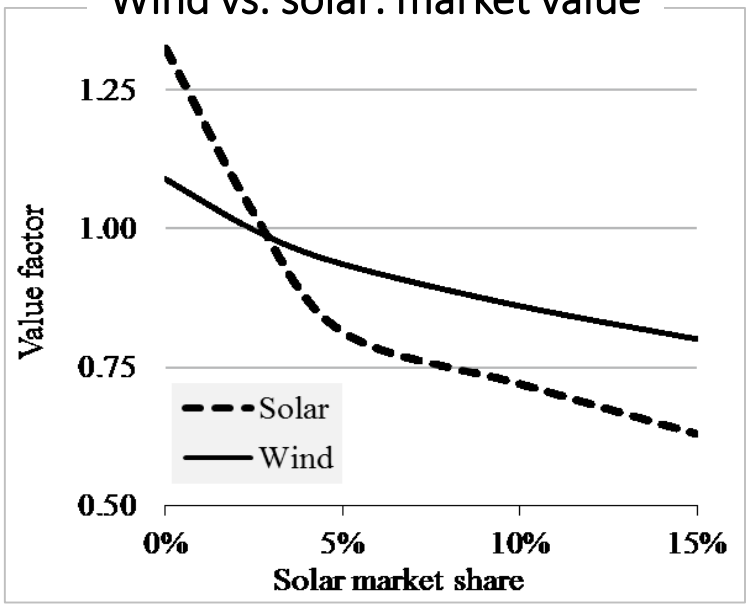


Source: updated from Hirth (2015): Market value of solar

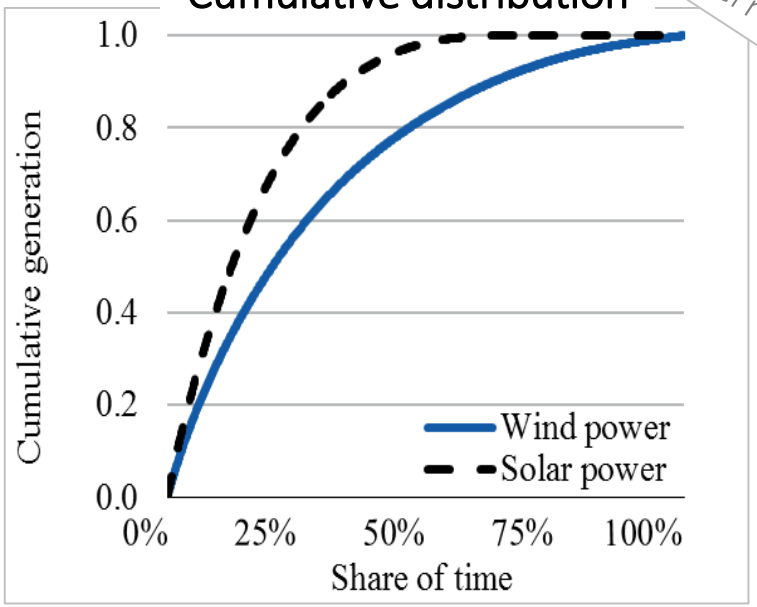
The value factor of wind power decreases from ~1.1 at low penetration to ~0.65 at 30% market share (1.5 points per point market share).

The value factor of solar power decreases from ~ 1.3 at low penetration to ~ 0.6 at 15% market share: (4.6 points per point market share).

Solar generation is concentrated in very few hours



Source: updated from Hirth (2013): Market value

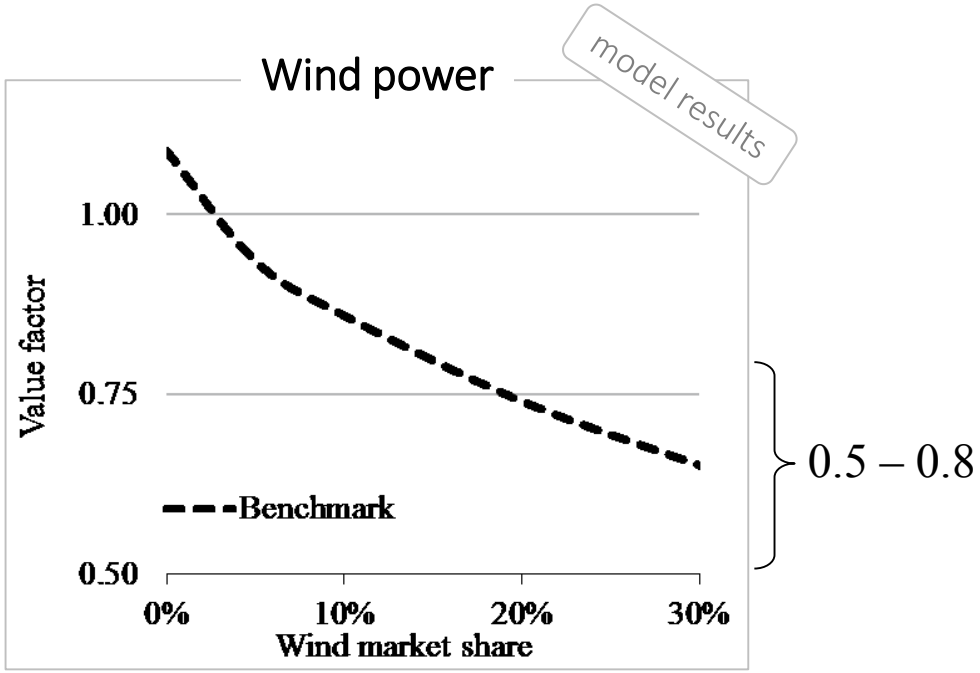


Source: updated from Hirth (2015): Market value of solar

Solar power's market value is higher than wind power's at low penetration, but drops quicker.

Solar generation is concentrated in fewer hours than wind power. The fundamental reason is earth's rotation: at night, the sun never shines.

The value drop continues: model results



Source: updated from Hirth (2013): Market value

The wind value factor falls to 0.5 to 0.8 at 30% penetration.

CO2 price between 0 – 100 €/t, Flexible ancillary services provision, Zero / double interconnector capacity, Flexible CHP plants, Zero / double storage capacity, Double fuel price, …

The value drop jeopardized…

… profitability

… phase-out of support schemes

… decarbonization of the power system

… renewables targets

… which is bad news for …

… investors in renewables

… finance ministers

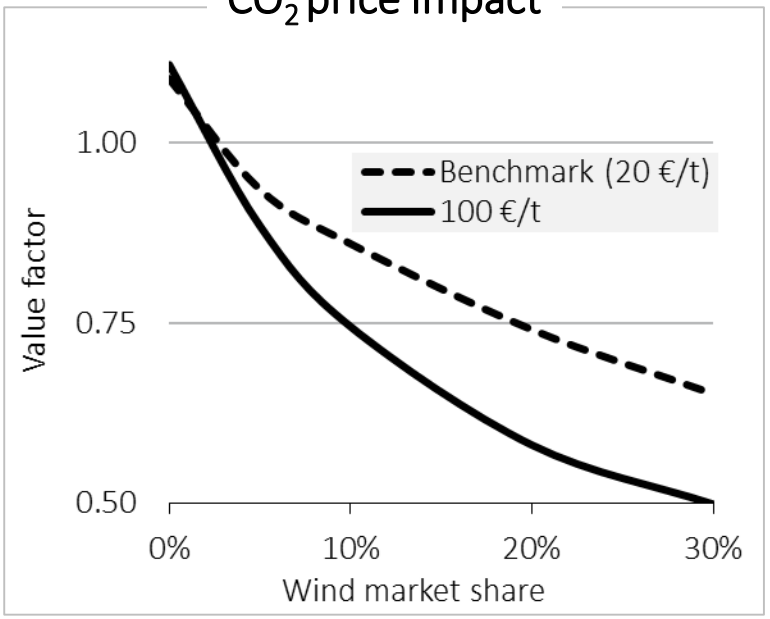
… the climate

… the renewable industry

The surprising impact of carbon pricing

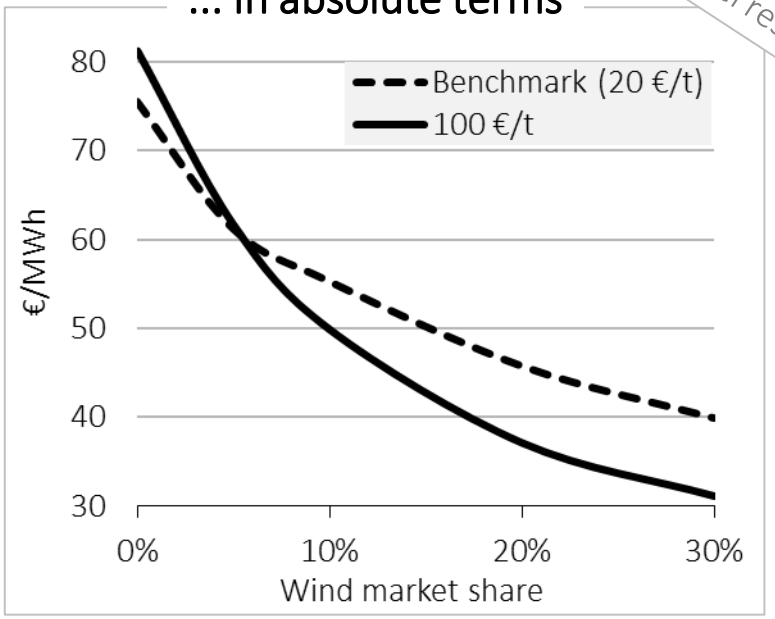
model results

CO_2 price impact



Source: updated from Hirth (2013): Market value

... in absolute terms

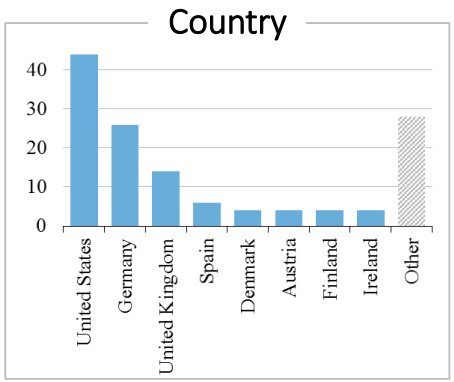


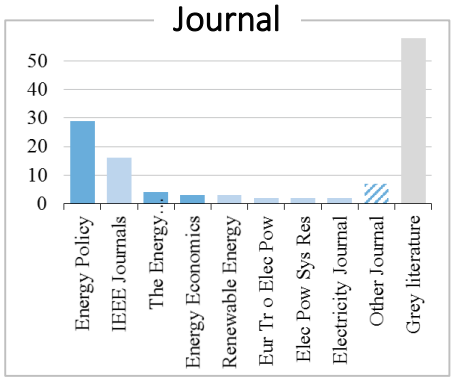
Source: updated from Hirth (2013): Market value

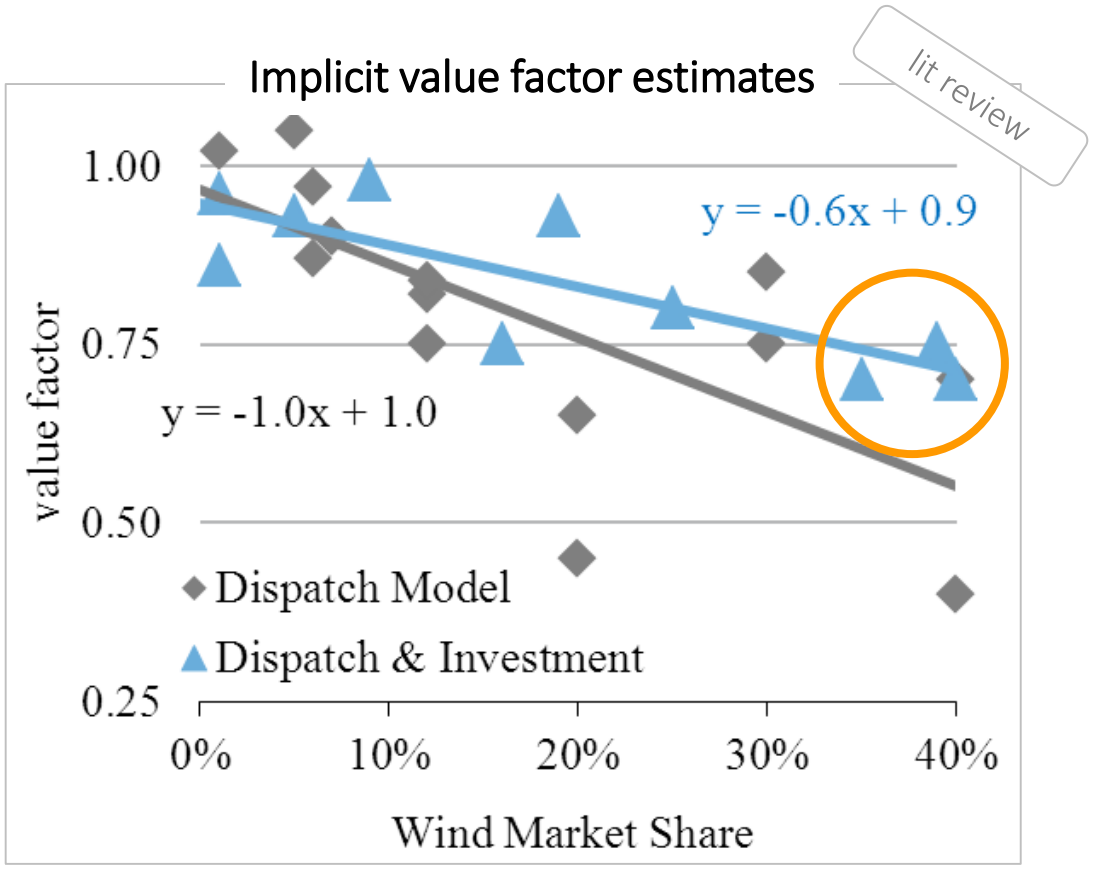
At a high CO_2 price, the value factor of wind power is *lowered* ...

... and even the absolute market value is reduced! The reason behind this is investments in capital-intensive base load plants.

Literature review: consistent with model results



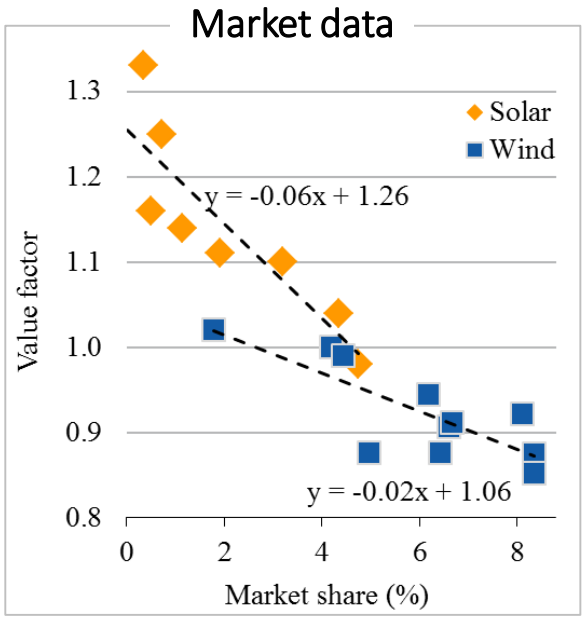


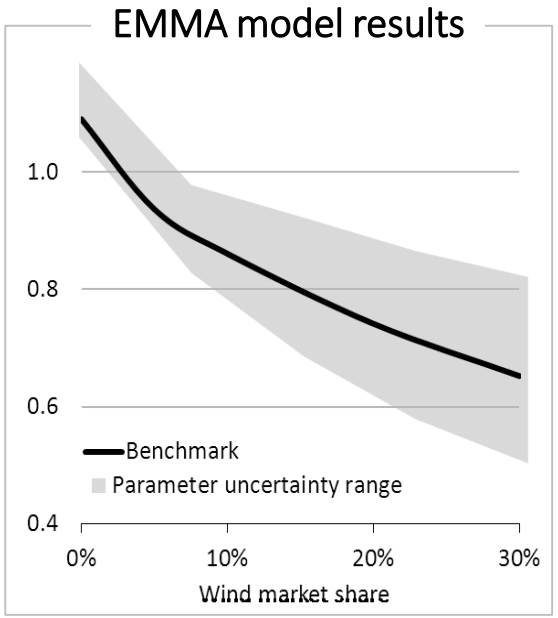


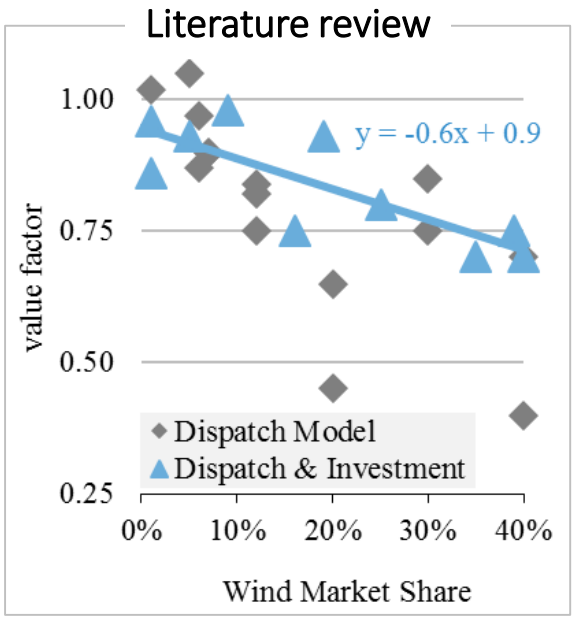
Source: updated from Hirth (2013): Market value

Translating the results of previous studies into value factors shows: consistency.

Different methodologies – robust finding: value drops







At 30% penetration, the value factor of wind falls to 0.5 – 0.8 of the base price. In Germany, it has already fallen from 1.02 to 0.89 as penetration increased from 2% to 8%. The value drop jeopardizes power system decarbonization and transformation.

Summing up: Market value

Relatively low value of wind and solar power at high penetration

- Compared to value of other generators
- Compared to today‘s value of wind and solar power

Value drop is large

- ~40% value drop for wind
- In other words: a massive shift in relative prices
- Drop is at least twice as steep for solar compared to wind

Robust results

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

Profitability in questions

- Difficult to archive profitability at high penetration rate
- Puts into question ambitious renewables targets without subsidies
- High carbon prices can *reduce* the market value of VRE – if investments in low-carbon base load technologies are accounted for (nuclear, CCS)

Balancing

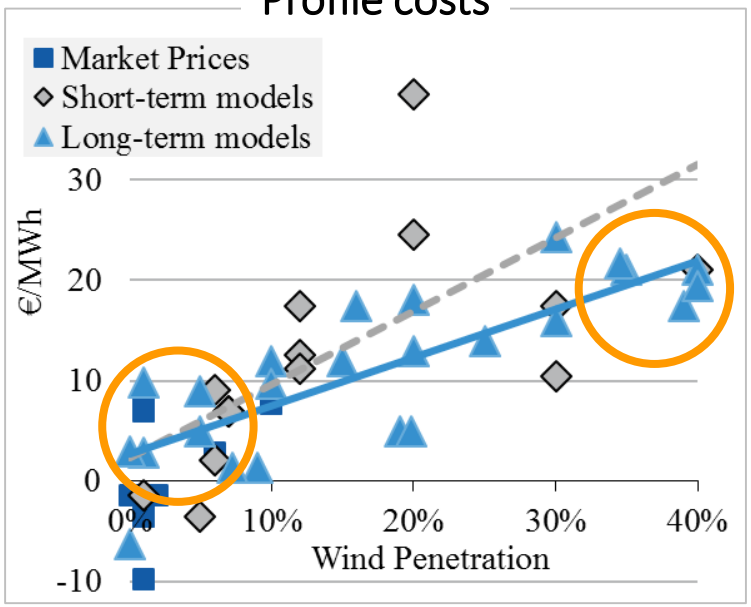
Integration costs revisited – An economic framework of wind and solar variability, *Renewable Energy*, 2015.

Integration costs, *study for Agora Energiewende* (forthcoming).

Balancing power and variable renewables: Three links, *Renewable & Sustainable Energy Reviews*, 2015.

Balancing is a minor issue – compared to profile costs

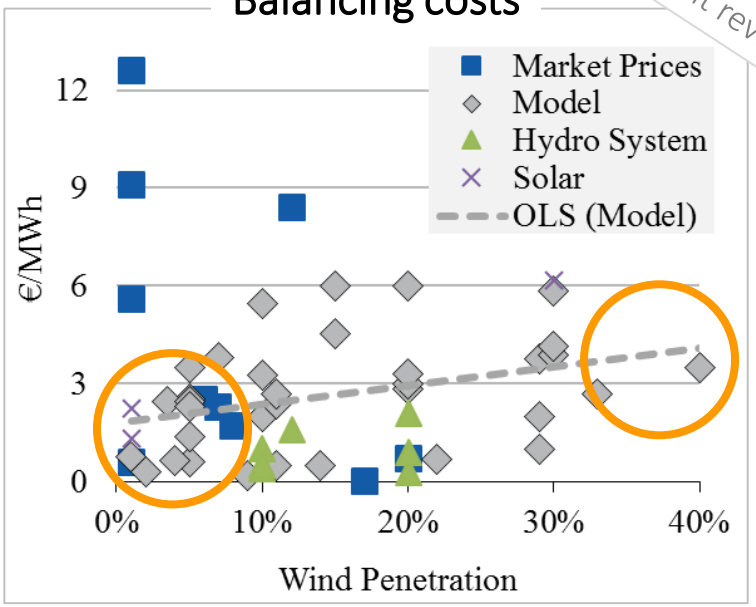
Profile costs



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

Balancing costs

lit review



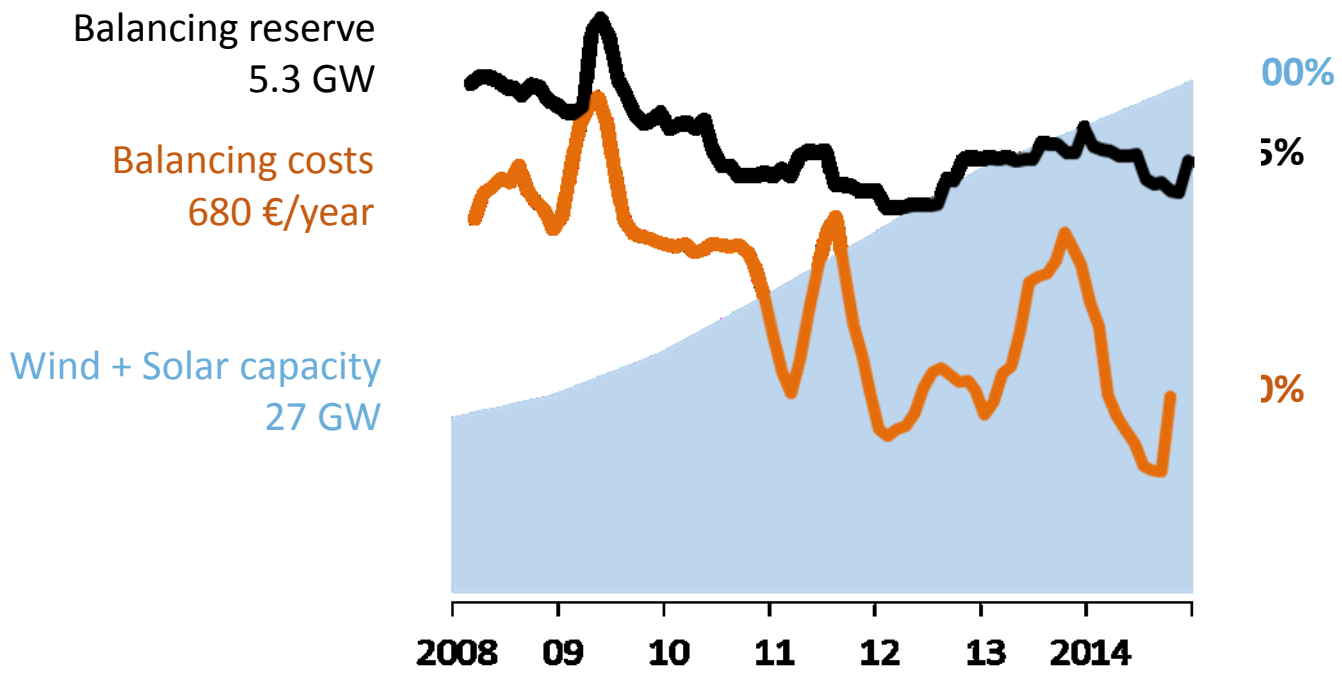
Source: updated from Hirth et al. (2015): Integration costs revisited

Profile costs (spot market value loss) reach ~20 €/MWh at 30 – 40% penetration rate. They grow at *0.5 €/MWh* per percentage-point.

Balancing costs reach ~ 4 €/MWh at 30 – 40% penetration rate, growing at *0.04 €/MWh* per percentage-point – a tenth of profile costs.

The German balancing paradox

German reserve requirement vs. VRE deployment



Source: Hirth & Ziegenhagen (2015): Balancing power

Since 2008, German VRE capacity tripled. At the same time, balancing reserves could be *reduced* by 15%. The reasons: better forecasts, more liquid intra-day markets, TSO cooperation.

Summing up: Balancing

Balancing is of secondary economic importance

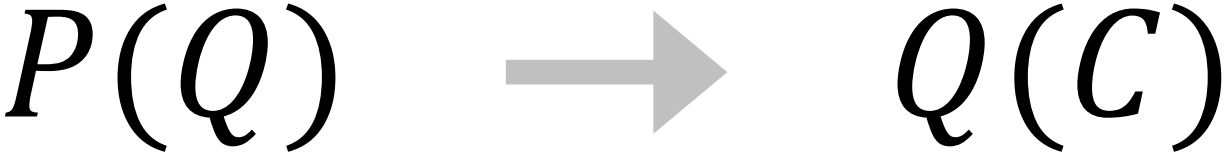
- At high penetration rate, profile costs (the impact of producing during low-price hours) are much larger than balancing costs (the impact of forecast errors)
- Balancing costs are likely to be below 6 €/MWh for wind power, even at very high penetrations

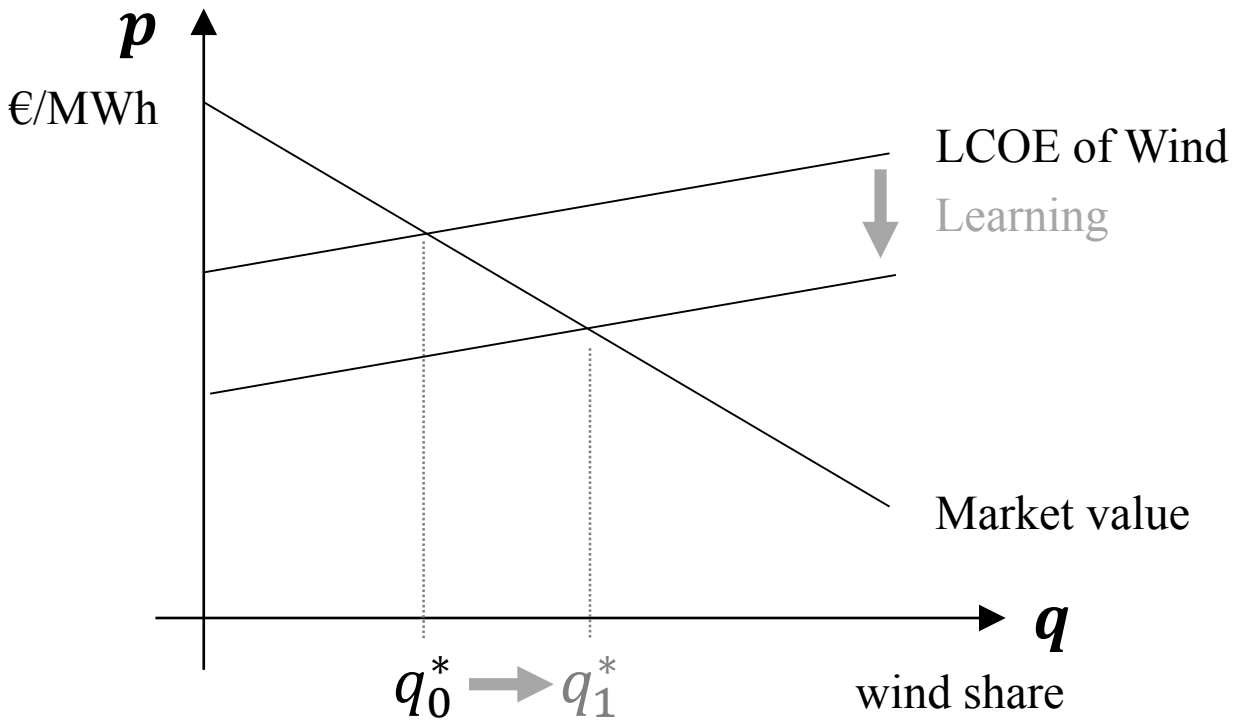
Balancing can become cheaper even during times of booming VRE

- Other factors have a significant impact on balancing power

The Optimal Share of Wind and Solar Power

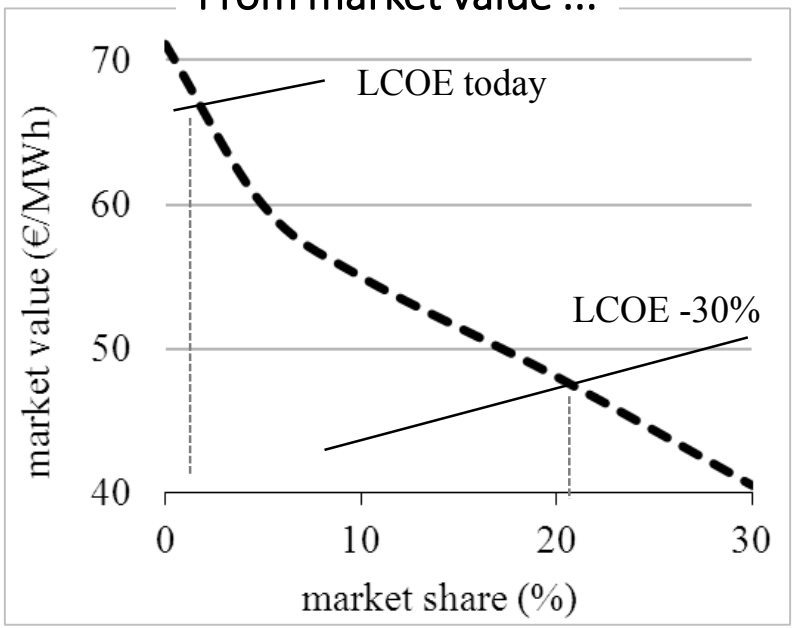
The Optimal Share of Variable Renewables, *The Energy Journal,* 2015.


P(Q)
Q(C)


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

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

From market value …

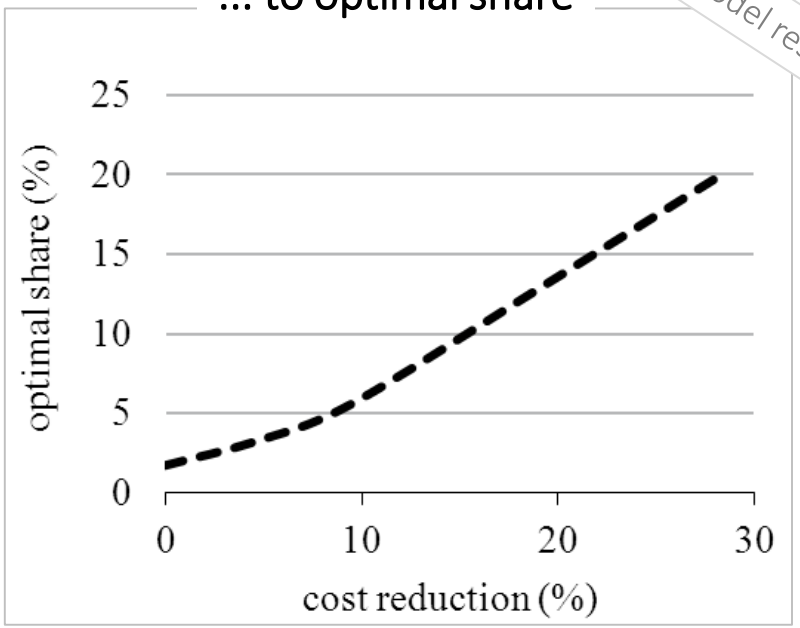


Source: Hirth (2015): Optimal Share of Variable Renewables

The market value of wind power falls from ~70 €/MWh to ~40 €/MWh as its penetration rate rises from zero to 30%

… to optimal share

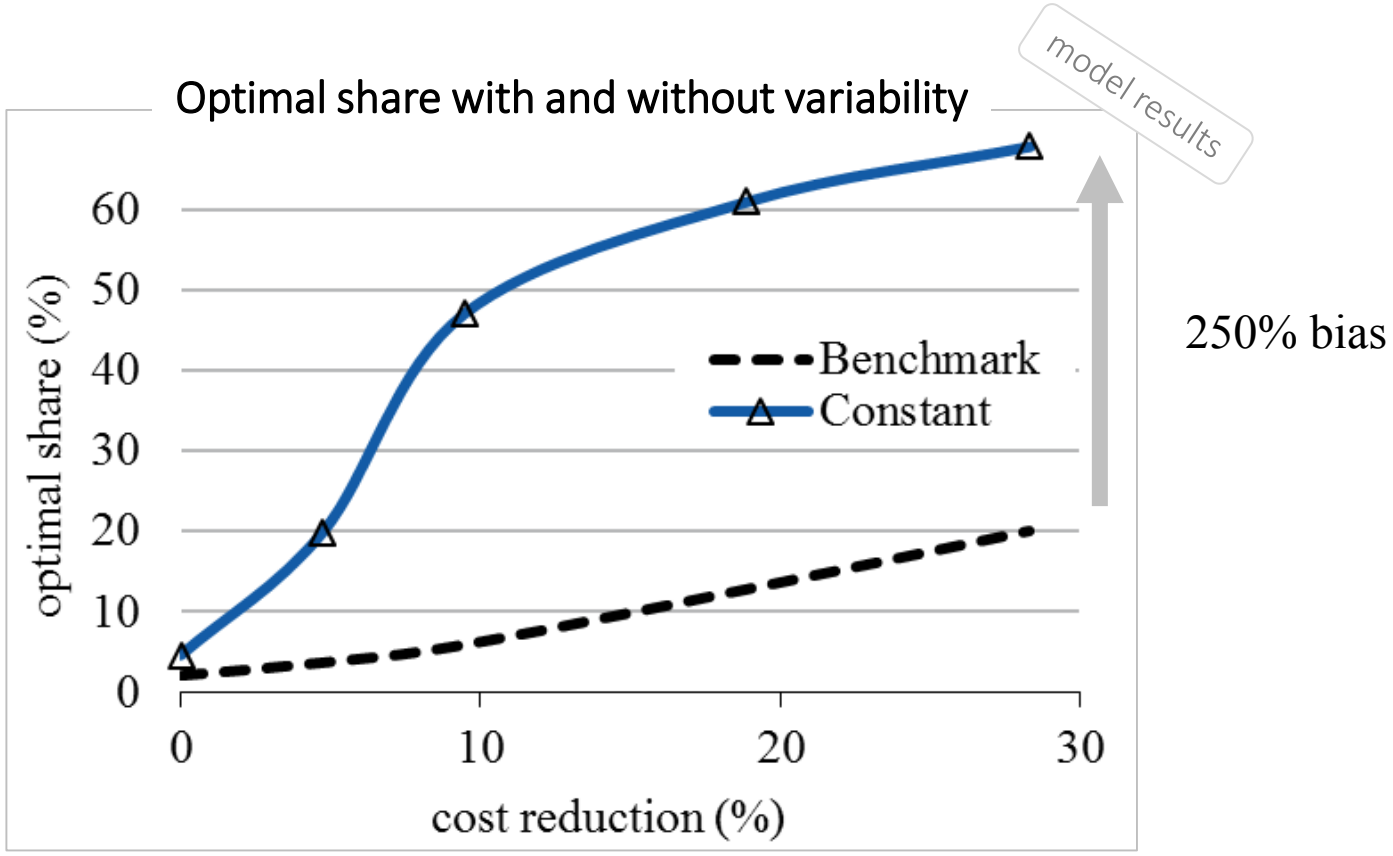
model results



Source: Hirth (2015): Optimal Share of Variable Renewables

This implies an cost-optimal wind market share of 2% at current cost, and of 20% if turbine costs fall by 30%.

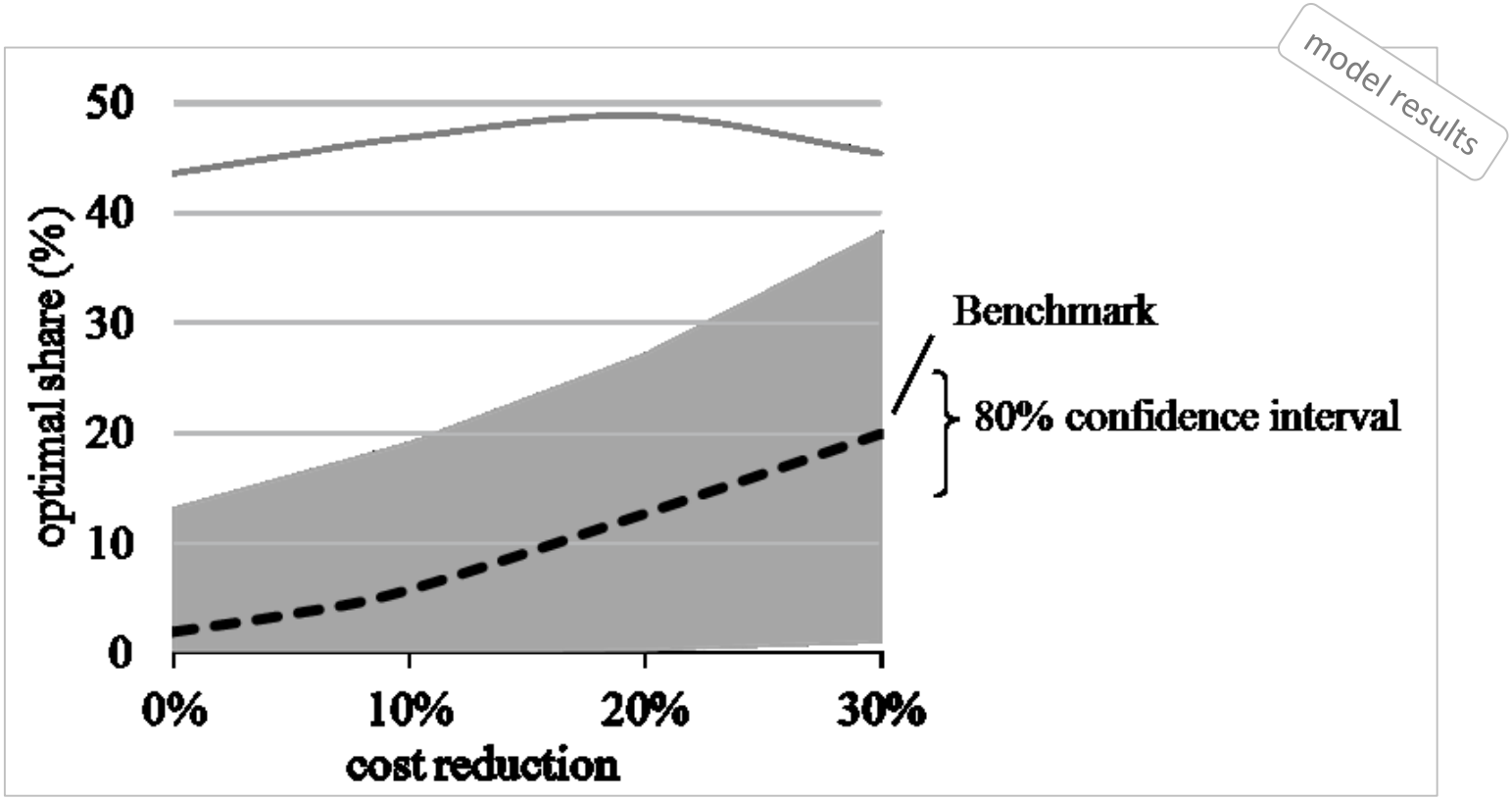
Ignoring variability dramatically alters results



Source: Updated from Hirth (2015): Optimal Share of Variable Renewables

Without variability, the estimated optimal share is 250% larger. In other words: ignoring variability introduces a 250% bias.

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

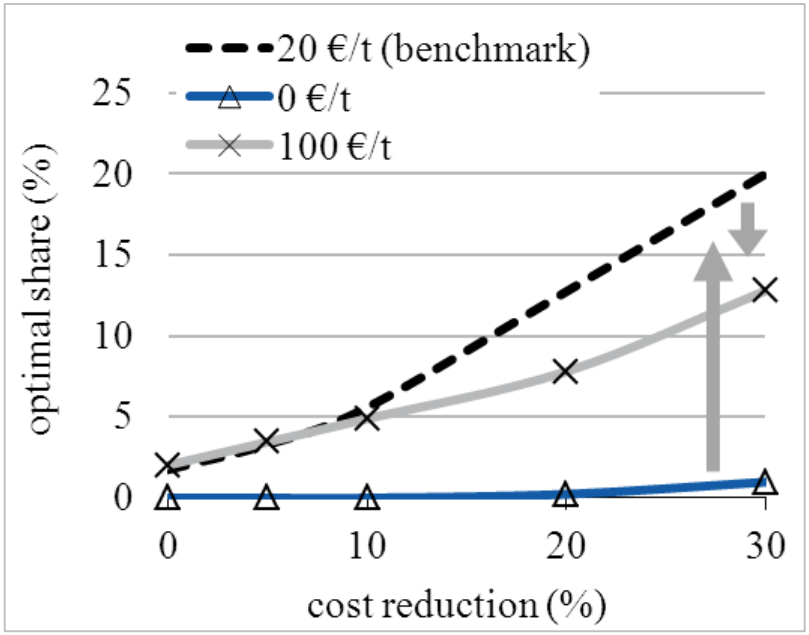


Source: Updated from Hirth (2015): Optimal Share of Variable Renewables

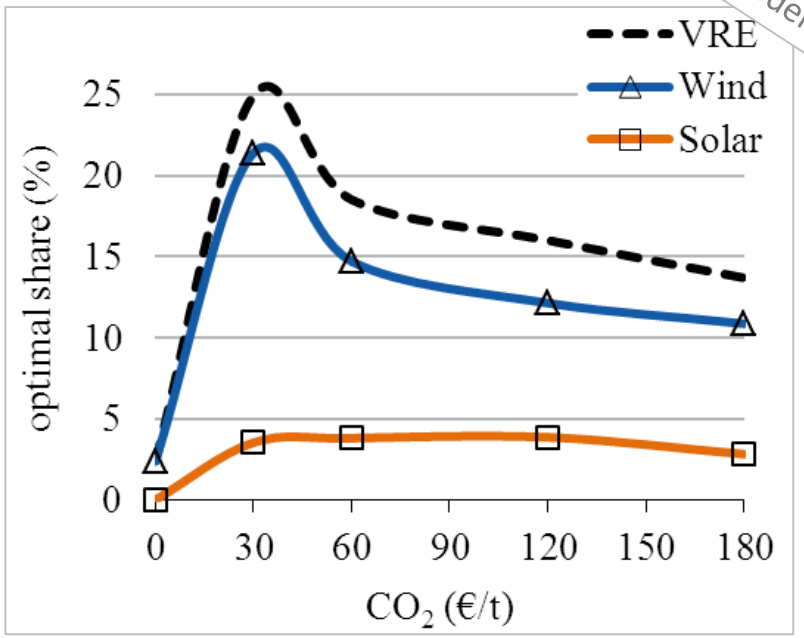
Without variability, the estimated optimal share is 250% larger. In other words: ignoring variability introduces a 250% bias.

CO2 price between 0 – 100 €/t, Flexible ancillary services provision, Zero / double interconnector capacity, Flexible CHP plants, Zero / double storage capacity, Double fuel price, …

The impact of climate policy (1)



Source: Hirth (2015): Optimal Share of Variable Renewables

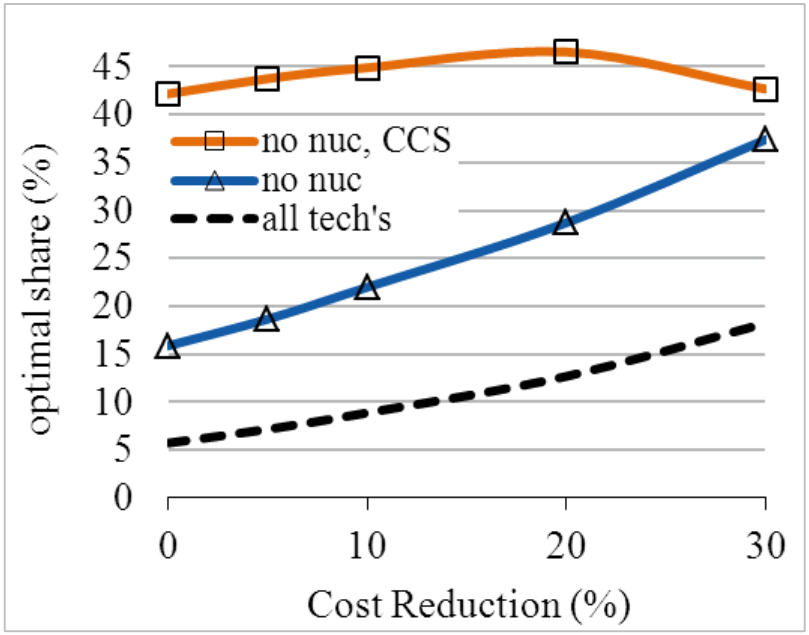


model results

Source: Hirth (2015): Optimal Share of Variable Renewables

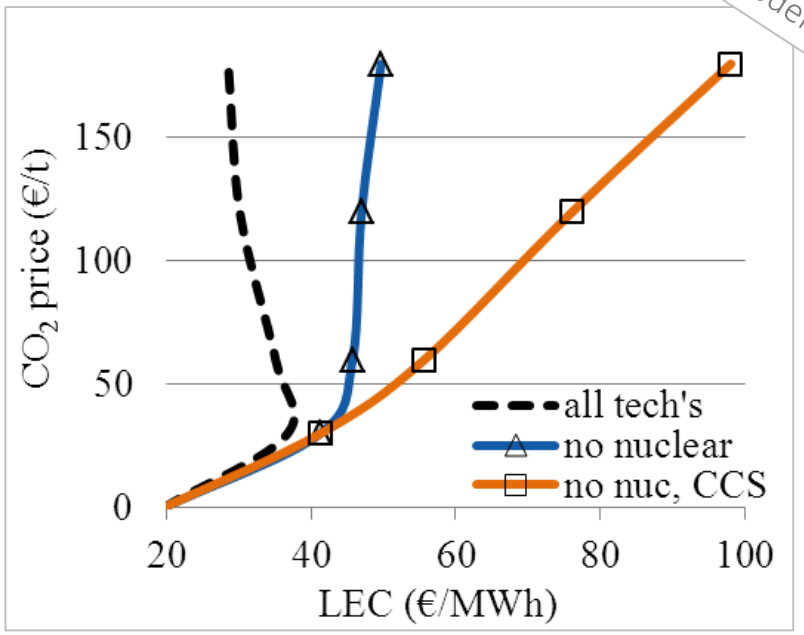
At low CO2 price levels, carbon pricing increases VRE penetration (as expected). At levels above 40 €/t, carbon pricing triggers nuclear/CCS investments; these base load technology reduce optimal wind deployment – a (surprising) non-monotonic impact

The impact of climate policy (2)



100 €/t CO_2

model results



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

Results depend on investments nuclear power and/or CCS. Without nuclear/CCS, the optimal wind share under climate policy is much higher and increases monotonically with the CO2 price.

Summing up: Optimal share

Wind power is competitive (solar isn't)

- 20% wind market share without subsidies – if costs decrease by a third to about 50 €/MWh in LCOE terms
- 16% – 25% market share in 80% of all model runs
- Optimal solar deployment is very small – even if costs decrease by another 60%

Flexibility helps

- Power system: interconnectors, electricity storage
- Thermal plants: co-generation of heat and ancillary services
- Wind power: "system-friendly" wind power (→ upcoming IEA study)

Surprising results

- Counter-intuitive results – driven by investments into base load plants
- Use quantitative models and model investments! – don't rely on intuition (only)

Summary

The market value of wind power is affected by

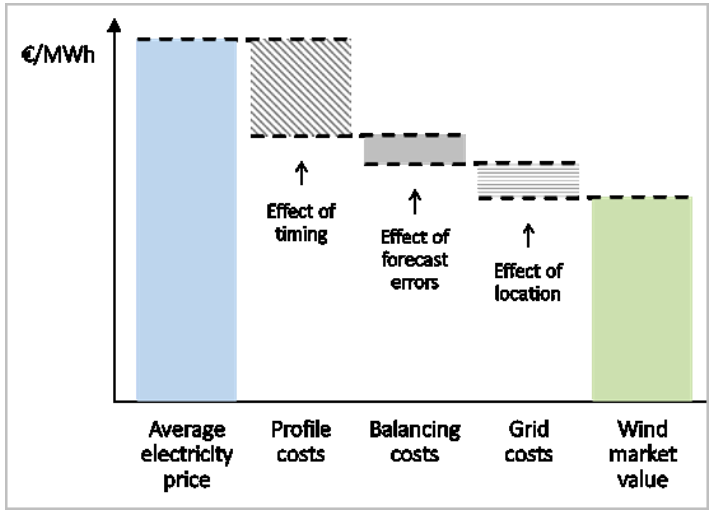
- Timing (generation profile)
- Forecast errors
- Network costs
- (True for all generators, not just VRE)

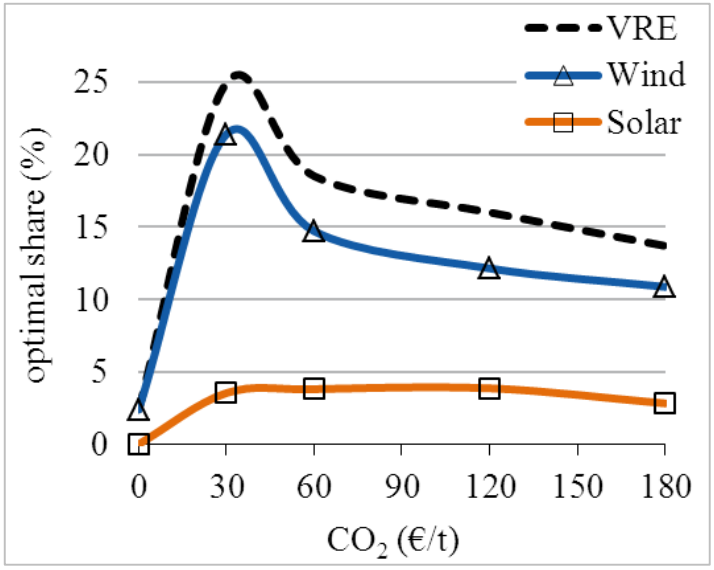
The €/MWh-value of wind and solar power declines with penetration

- By 40% as wind power reaches 30% share
- By 50% as solar power reaches 15% share

The cost minimal share of wind and solar power is likely to be 16% – 25%

- Limited by the costs of variability
- Higher carbon prices can *reduce* VRE deployment





Conclusions

1. Methodological conclusions

- Value differences among generators matter (not only for renewables) – interpret LCOE carefully, use appropriate models
- VRE variability matters – ignoring variability can lead to large bias
- Surprising results – use models, and model capital adjustments

2. Technology conclusions

- The largest economic impact of VRE is to reduce the utilization of other plants, not forecast errors or grid costs
- Base load technologies (nuclear, CCS) don‘t go well with VRE – because they are capital-intensive, not because they are inflexible
- VRE require low-capex mid and peak load plants as complementary technologies

Conclusions

3. Policy conclusions

- Variability has major economic costs at high penetration rate
- Role of VRE smaller than some hope, even at a (very) high CO2 price ...
- ... but (much) larger than today
- Very high shares of VRE are likely to require continues subsidies.
- Many options to mitigate the value drop: flexible plants, reservoir hydro power, system-friendly wind turbines are among the most promising.
- Design markets and policies properly: let prices signal scarcity!

Studies and publications

Economics of Electricity	Hirth, Lion, Falko Ueckerdt & Ottmar Edenhofer (2016): "Why Wind is not Coal: On the Economics of Electricity", *The Energy Journal* (forthcoming). 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
System LCOE	Ueckerdt, Falko, Lion Hirth, Gunnar Luderer & Ottmar Edenhofer (2013): "System LCOE: What are the costs of variable renewables?", *Energy* 63, 61-75. http://dx.doi.org/10.1016/j.energy.2013.10.072
Market Value of Solar	Hirth, Lion (2015): "The market value of solar photovoltaics: Is solar power cost-competitive?", *IET Renewable Power Generation 9(1), 37-45*. http://dx.doi.org/10.1049/iet-rpg.2014.0101
Balancing Power	Hirth, Lion & Inka Ziegenhagen (2015): "Balancing power and variable renewables: Three links", *Renewable & Sustainable Energy Reviews* 50, 1035-1051. http://dx.doi.org/10.1016/j.rser.2015.04.180
Open access	www.neon-energie.de/publications/

Neon project references

Neon Neue Energieökonomik GmbH is a Berlin-based boutique consulting firm for energy economics. We combine expertise on economic theory with advanced modelling capabilities and extensive industry experience. Neon specializes in five areas:

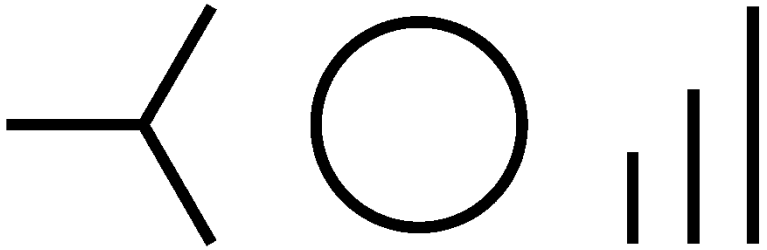
1. The economics of wind and solar power
2. Design of spot and balancing power markets
3. System costs / integration costs
4. Open-source power market modelling
5. Training seminars

System-friendly wind and solar power (IEA). Model-based study for the International Energy Agency (Paris). Neon assessed the market and system benefits of low-wind speed wind turbines and east- and west-oriented PV, conducted the underlying power market modelling with EMMA and drafted report and slides. The study has been published by the IEA.

Integration costs (Agora Energiewende). Workshops and a literature-based study for Agora Energiewende, a Berlin-based think tank. Neon advised Agora in study design, conducted workshops in Berlin and Paris, and drafted parts of the report. The study will be published by Agora.

Power market trainings (IRENA, ERRA, Vattenfall, JRC, UFZ, Swedenergy, Clean Air Task Force, among others). Neon designed and conducted a number of trainings and seminars on power markets, energy economics, and electricity policy, or more specific topics. Participants have been regulators, industry experts and analysts, as well as policy makers.

Electricity Market Design (IEA-RETD). Project on power market design under very high shares of variable renewables. Wholesale, balancing, and retail markets are covered in a range of different market prototypes, ranging from liberalized to vertically integrated. Neon is conducting the project in cooperation with FTI CompassLexecon Energy.



Seeking advice on power markets? Neon Neue Energieökonomik is a Berlin-based boutique consulting firm for energy economics. Neon conducts model-based studies of power markets, provides electricity price forecasts, and organizes workshops. www.neon-energie.com

Lion Hirth
hirth@neon-energie.de
+49 1 57 55 199 715