System Integration Costs

Falko Ueckerdt & Lion Hirth

ESIG Webinar | 25 May 2021

System integration costs (SIC)

The claim

- Renewables give rise to all kind of costs across the power system, beyond the asset

System integration costs come by many names

- (System) integration costs
- System-level / grid-level costs
- Whole system costs
- Hidden costs

Defining system integration costs

- “system costs in excess of system costs incurred by equivalent amounts of energy delivered to the system on firm, fixed schedules” (Dragon & Milligan 2003)
- “an increase in power system operating costs” (Milligan & Kirby 2009)
- “the additional cost of accommodating wind and solar” (Milligan et al. 2011)
- “the extra investment and operational cost of the nonwind part of the power system when wind power is integrated” (Holttinen et al. 2011)
- “the cost of managing the delivery of wind energy” (EnerNex Corporation 2011)
- “comprising variability costs and uncertainty costs” (Katzenstein & Apt 2012)
- “the total costs above plant-level costs” (NEA 2012)
- “additional costs that are required in the power system to keep customer requirement (voltage, frequency) at an acceptable reliability level” (Holttinen et al. 2013)
- “all additional costs in the non-VRE part (residual system) of the power system when VRE are introduced” (Ueckerdt et al. 2013)

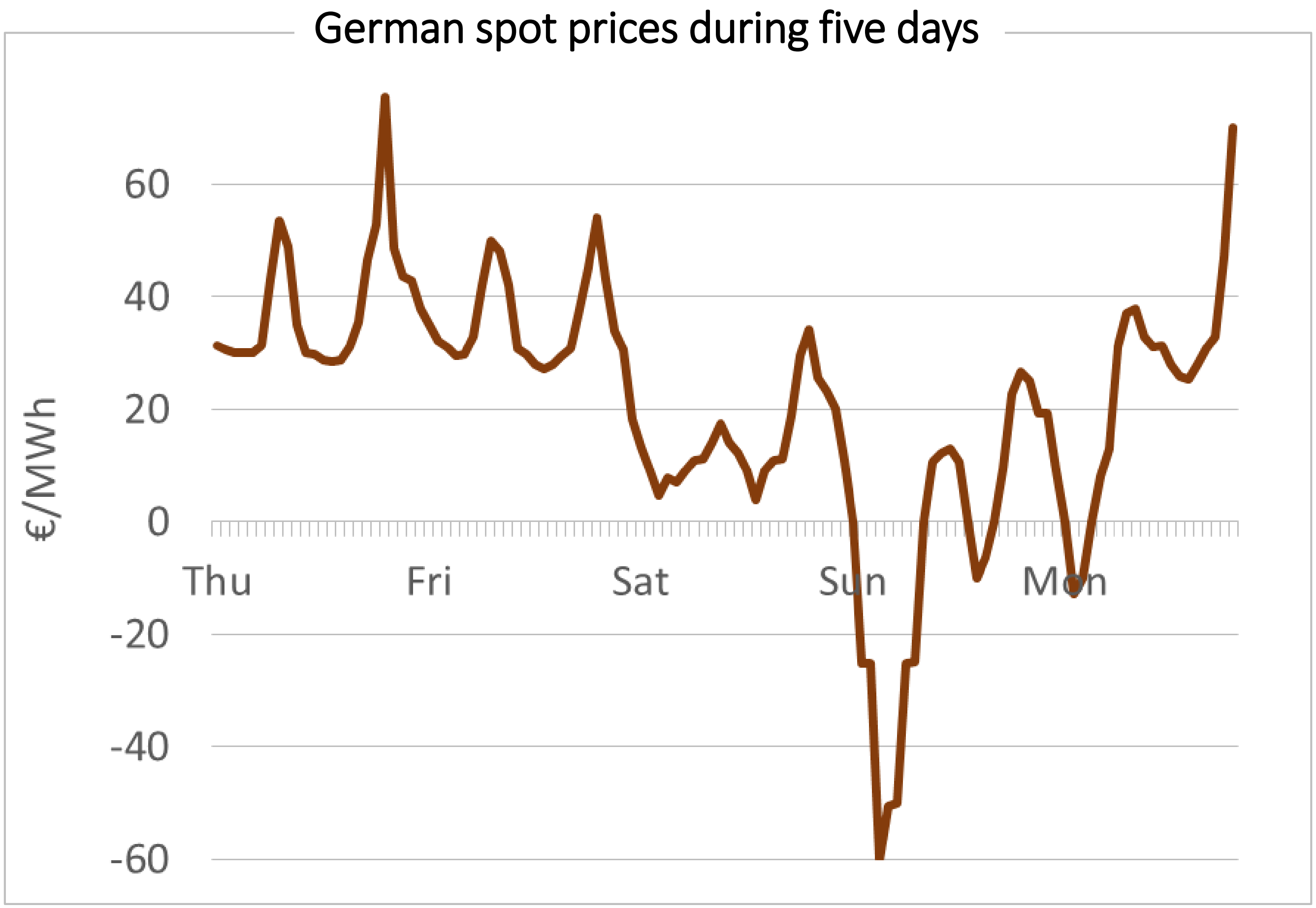
Agenda

1. Value perspective (market value)
2. Cost perspective (system integration costs)
3. Equivalence of cost and value
4. Profile cost and the utilization effect
5. The components of system integration costs
6. Quantifying system integration costs
7. Outlook

Value perspective

For economics, it matters *when* electricity is produced

market data



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

Market value: average wholesale revenue per MWh

$$Market\ value_i = \frac{\sum_{t=1}^{T} g_{i,t} \cdot p_t}{\sum_{t=1}^{T} g_{i,t}}$$

$g_{i,t}$	Generation (MWh)
i	Technology *i*
t	Hour *t*
p_t	Price (EUR per MWh)
T	Time steps per year

The market value is also…

- … the average revenue per unit of generation (€/MWh)
- … the "capture price" or "realized price"
- … the production-weighted average electricity price ("wind-weighted")
- … the price of electricity produced by generator type i

Absent market failures, the market value corresponds to economic value

- … the marginal economic value of electricity produced by generator type i
- … the "levelized value of energy" (LVOE)

Value factor

$$Value\ factor_i = \frac{market\ value_i}{base\ price}$$

$base\ price$	Average electricity price during one year

The value factor is …

- … the *relative* price of electricity of a certain source
- … also: “capture rate”

Value factor depends on dispatch

- Base load plants have a value factor of 1 (“average value electricity”)
- Peakers have a value factor (way) above 1 (“high value electricity”)
- Plants that produce disproportionally at times of low prices have a value factor below 1 (“low value electricity”)

Value factor: the relative price of wind energy

market data

Wind on land in Germany			
	Base price (€/MWh)	Market Value (Capture Price) (€/MWh)	Value Factor (Capture Rate) (1)
2001	23.1	22.7	0.96
…	…	…	…
2018	45	42	0.86
	↑ Simple average price	↑ Wind-weighted price	↑ Ratio

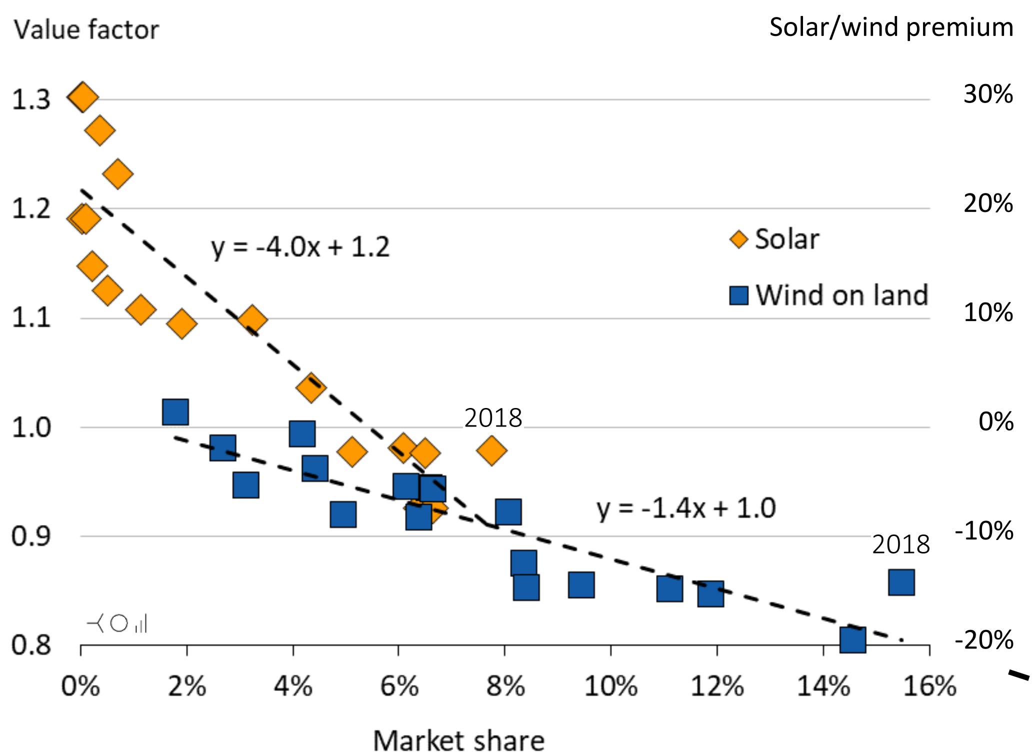
$$\bar{P} = \frac{\sum_{t=1}^{T} P_t}{T}$$

$$\bar{P}_{wind} = \frac{\sum_{t=1}^{T} W_t \cdot P_t}{\sum_{t=1}^{T} W_t}$$

$$VF_{wind} = \frac{\bar{P}_{wind}}{\bar{P}}$$

market data

The value drop of wind and solar energy



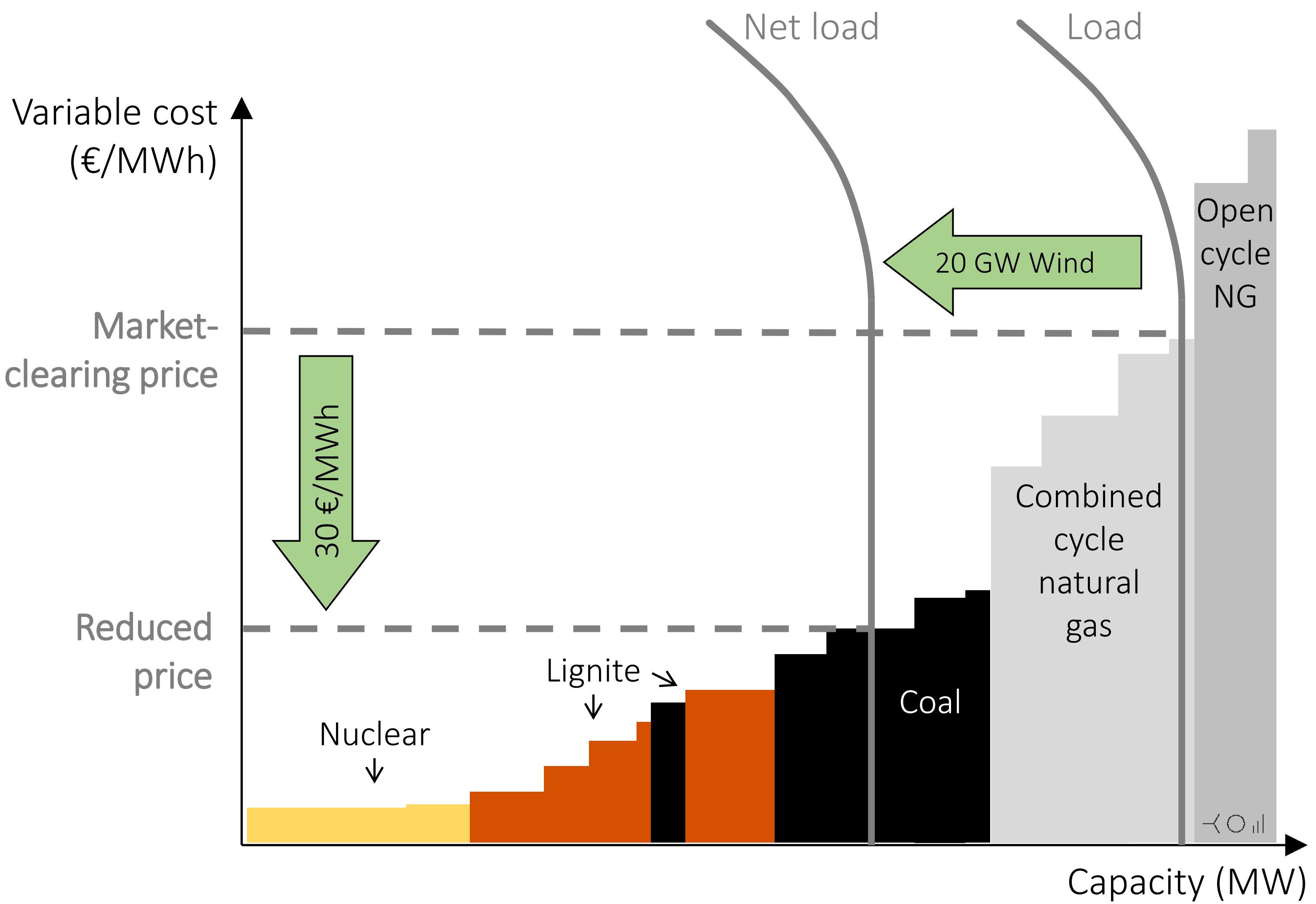
Value Factor = Market value / base price. Each symbol represents one year. Extrapolation suggests that at 30% wind share its value factors is 0.5; at 15% solar its value is 0.56.. Updated from Hirth (2013): Market value.

Relative value of wind and solar energy diminishes with market share

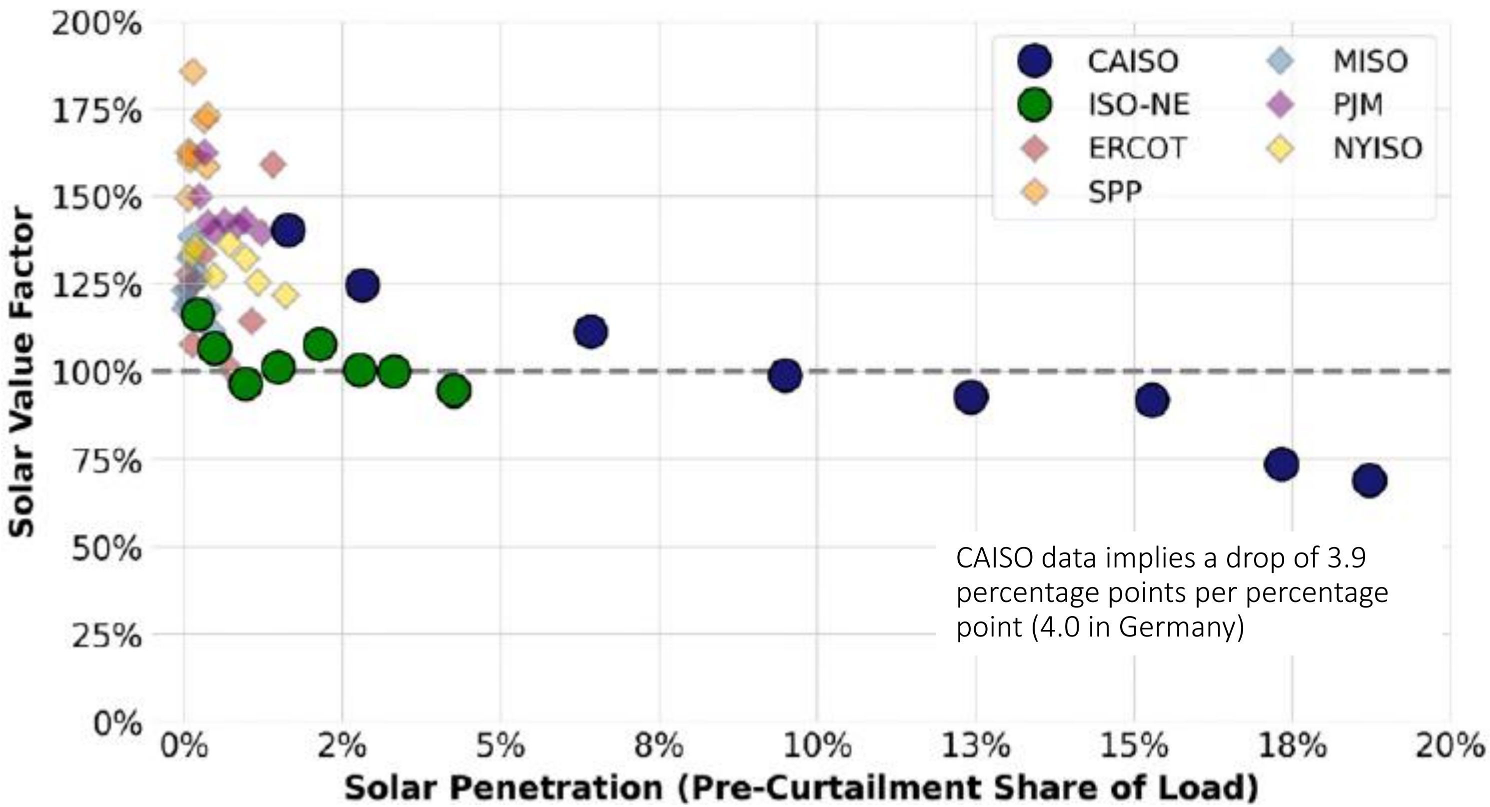
"Self-cannibalization effect", or simply: decreasing returns

For climate policy and power system transformation, it is of utmost relevance to understand how far the market value will drop

The mechanics behind the value drop



The US picture



CAISO data implies a drop of 3.9 percentage points per percentage point (4.0 in Germany)

LBNL / Mills et al. (2021): Solar-to-Grid: Trends in System Impacts, Reliability, and Market Value in the United States with Data Through 2019 (Link)

Three limitations of empirical data on market value

Is “market value” really “marginal economic value”?

- Of course it is not
- Market value: observed data
- Marginal economic value: true social marginal value

Electricity markets are incomplete

- Germany: Zonal pricing, i.e. network constraints are not priced
- Distribution network constraints are nowhere price properly

Externalities are not priced

- Climate change and others

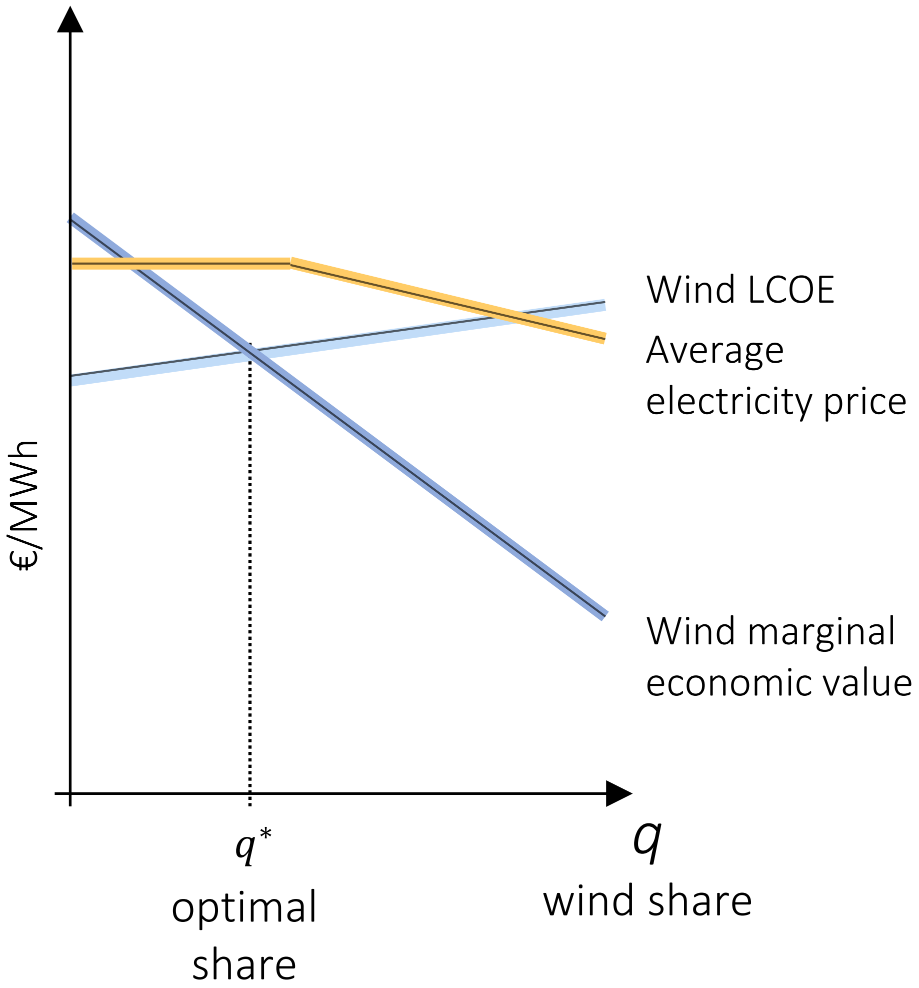
Electricity markets are out of equilibrium

- Business cycles, structural change, system transformation

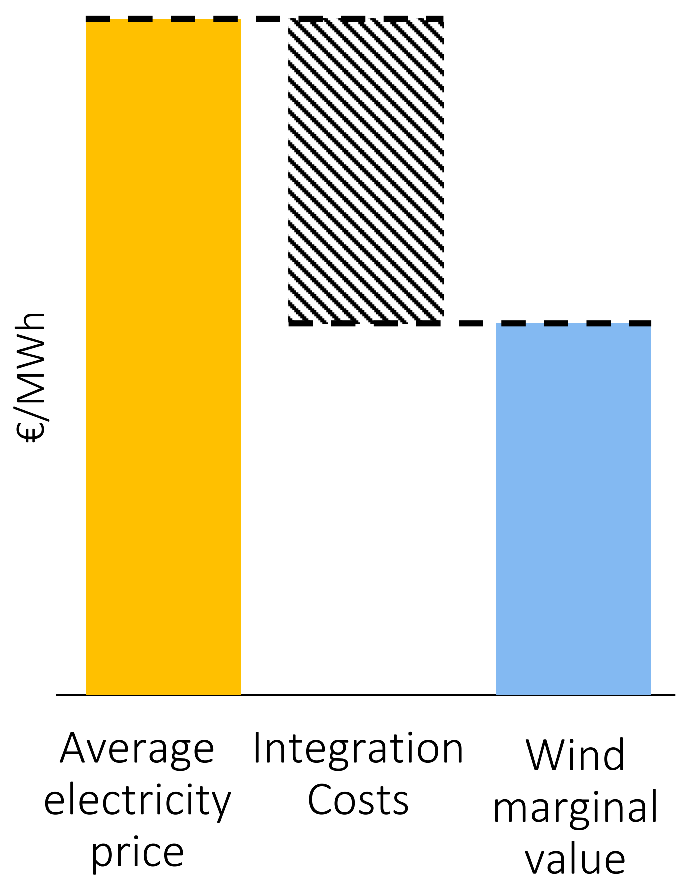
Implications for the optimal and cost-competitive market share

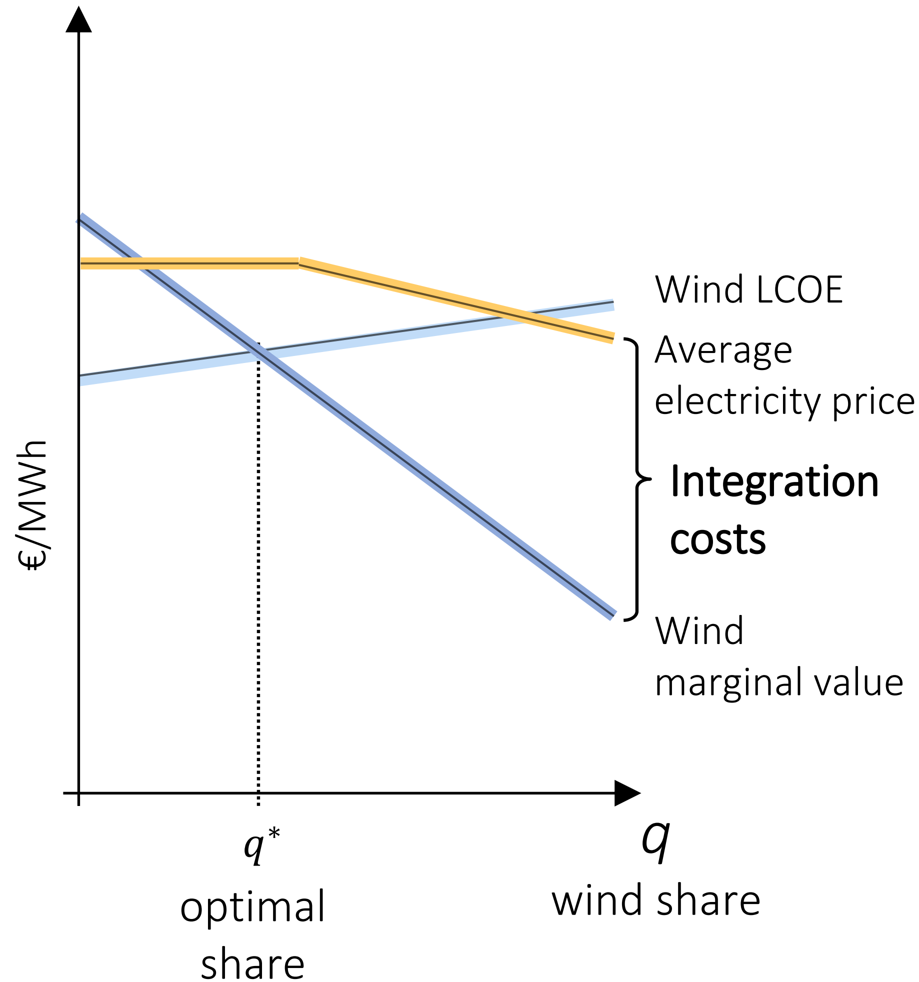
Cost and value determine deployment

- Optimal deployment (wind share) is determined by the intersection of marginal long-term cost (LCOE) and marginal economic value
- (This is a static perspective)



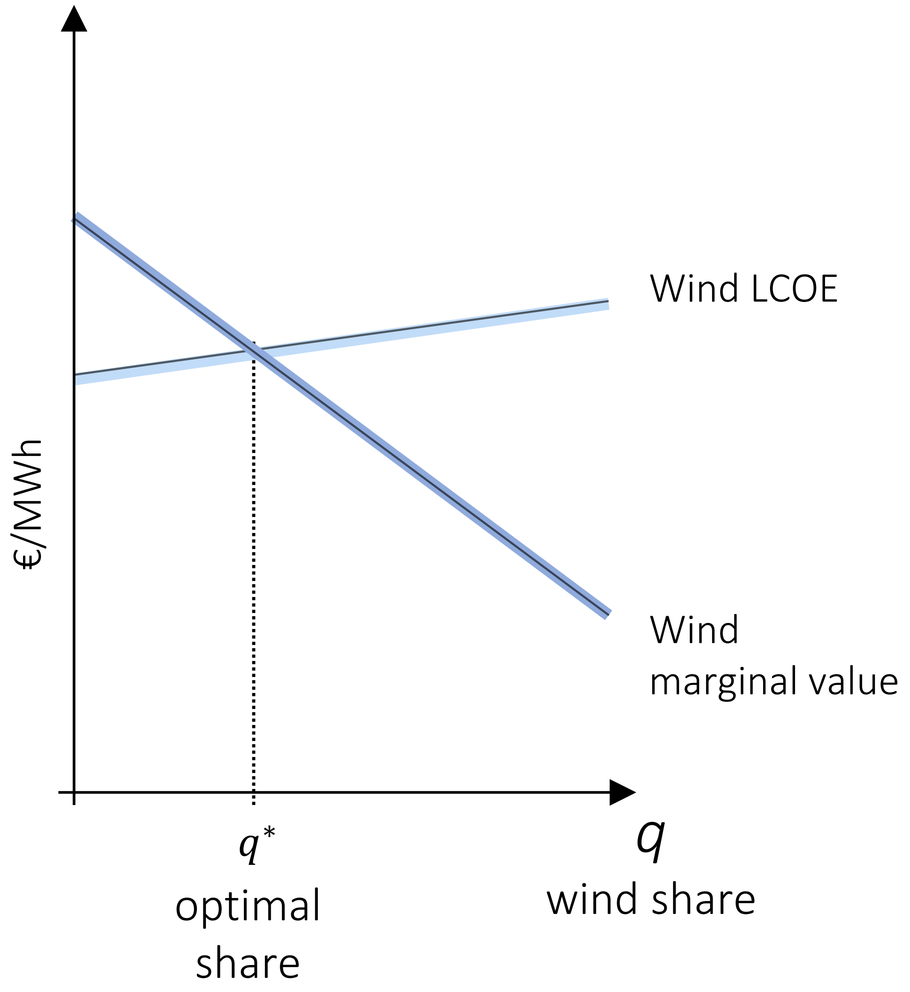
Defining system integration costs from a value perspective



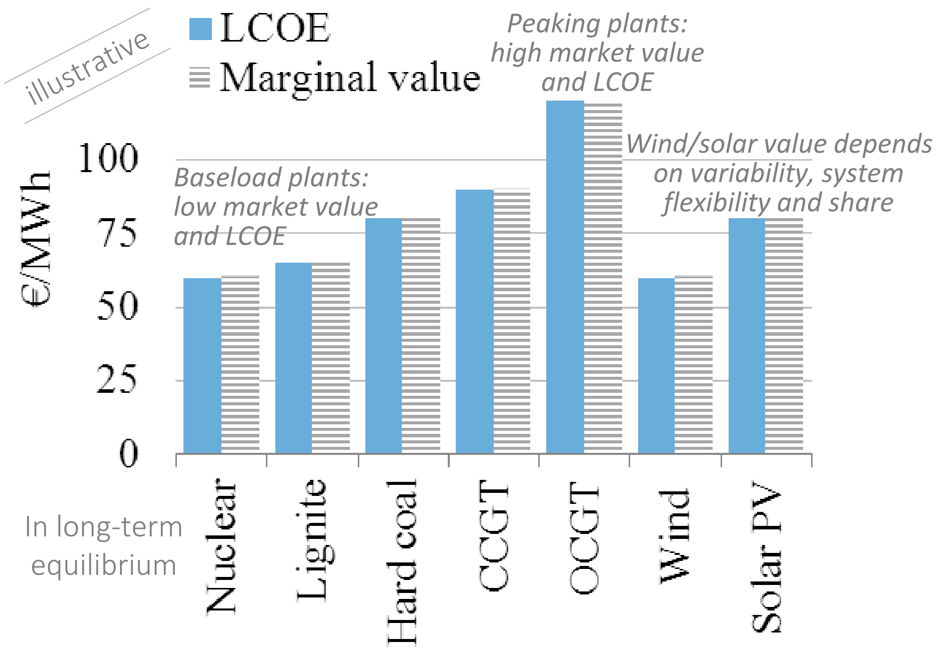


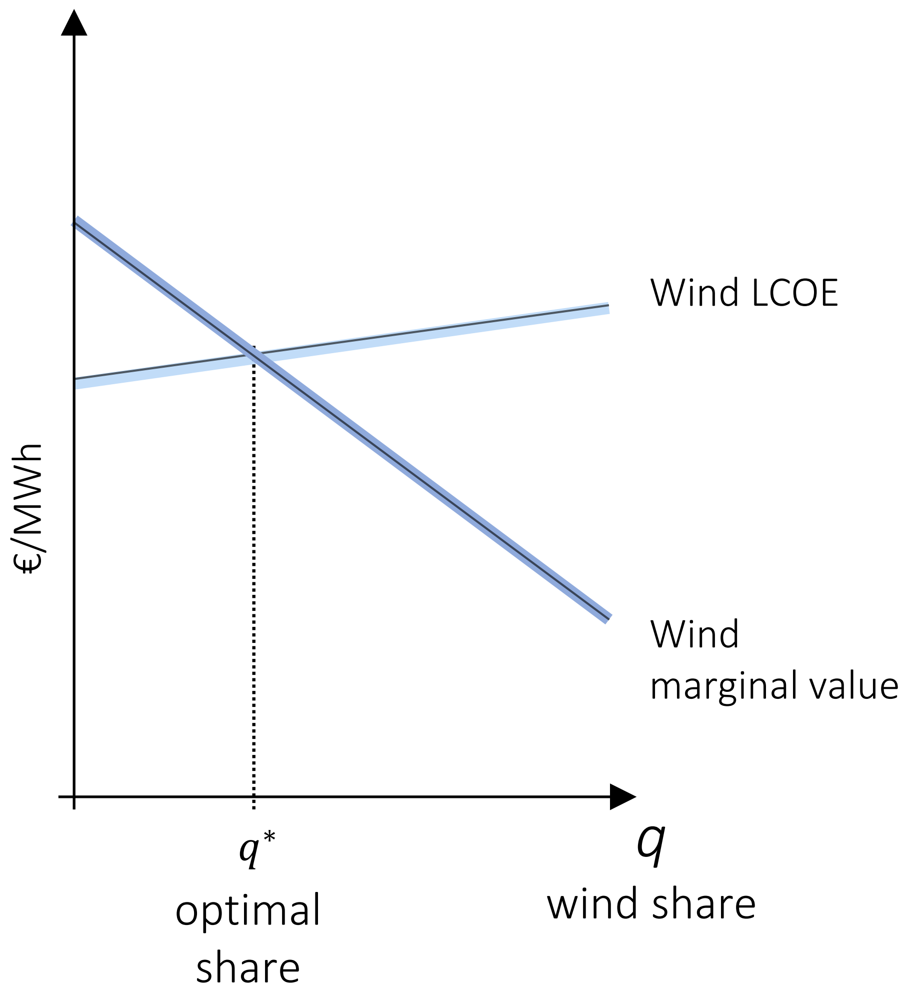
Cost perspective

This is why the LCOE metric is incomplete



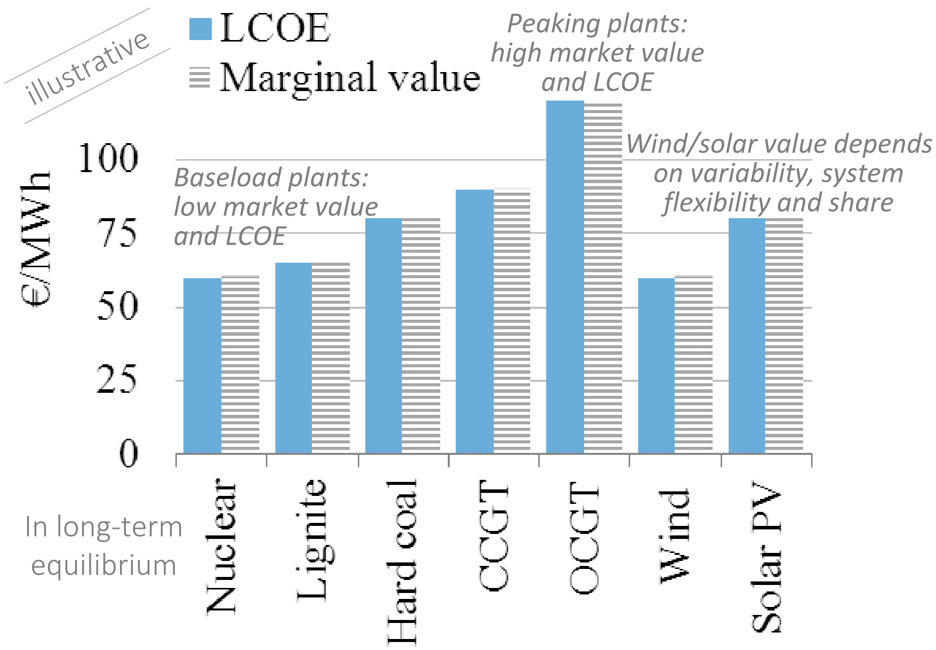
This is why the LCOE metric is incomplete





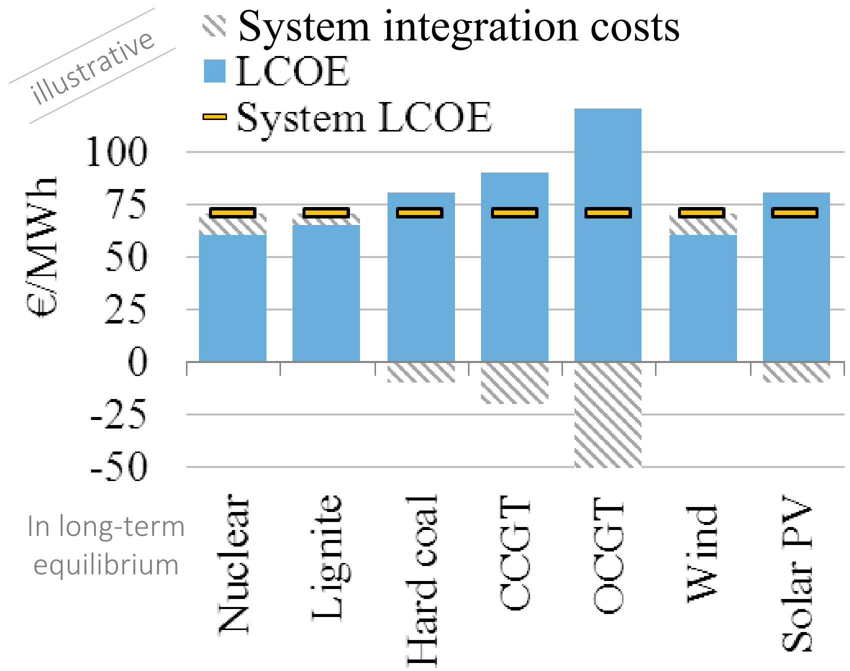
- Electricity from one tech has a *different value* than that produced by another tech
- Comparing LCOE across technologies and expecting them to be equal is misleading
- More theoretically: Technologies produce *different economic goods*

This is why the LCOE metric is incomplete



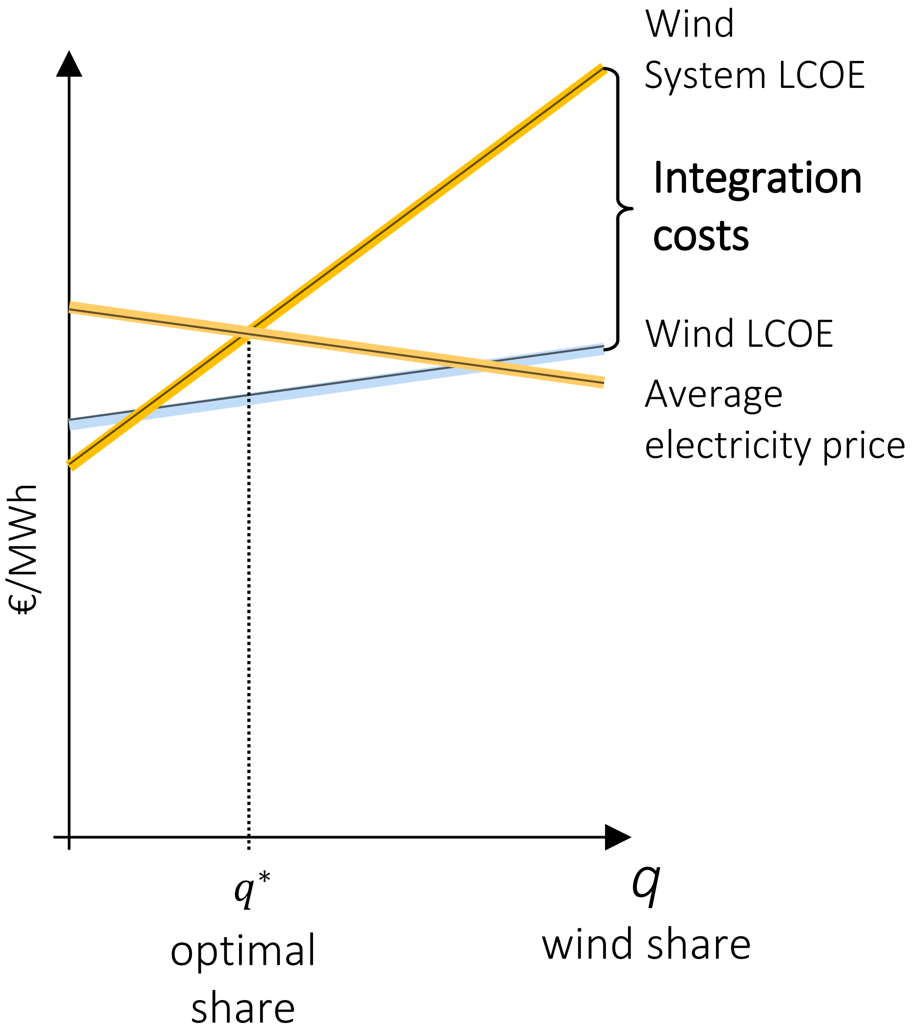
- Electricity from one tech has a *different value* than that produced by another tech
- Comparing LCOE across technologies and expecting them to be equal is misleading
- More theoretically: Technologies produce *different economic goods*

If "you" insist on comparing with a single metric: "System LCOE"



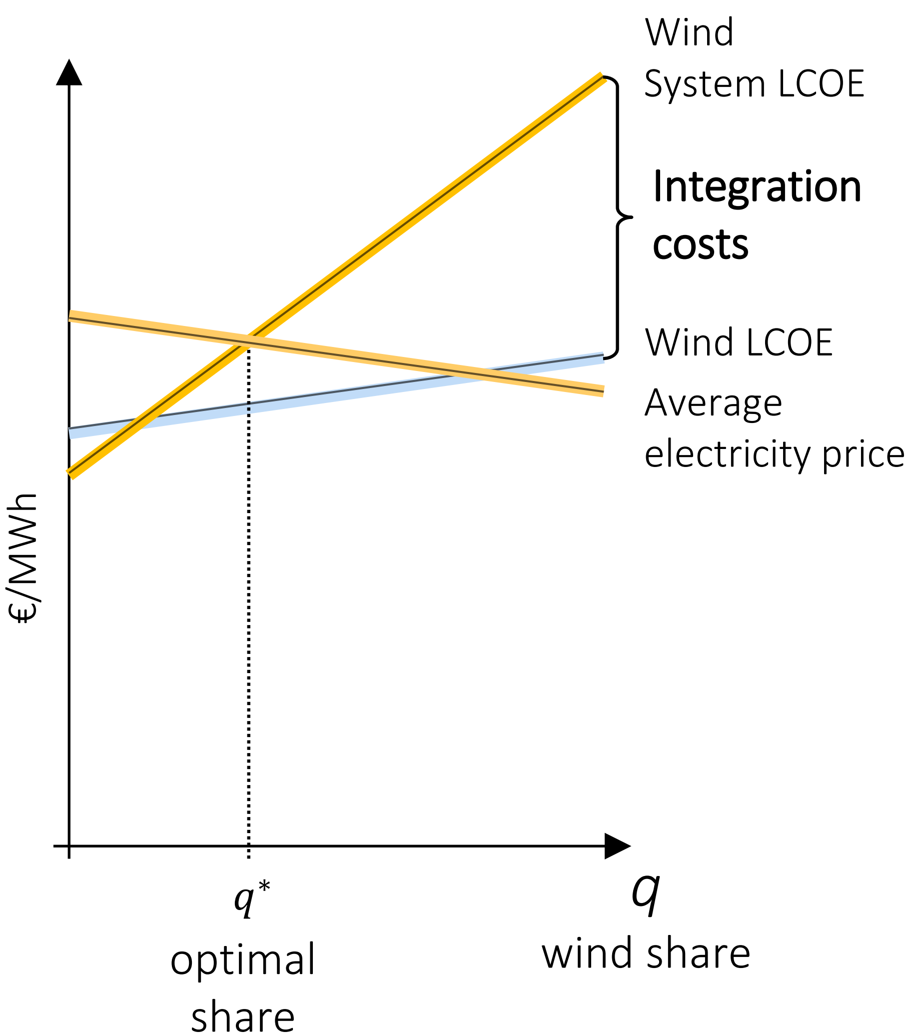
- System LCOE = LCOE + integration costs; in equilibrium: techs have equal *system LCOE*
- *System integration costs:* the *additional* costs that a technology causes on the system level (compared to a benchmark technology)
- Link to value: market value is the reduction in total costs when adding a unit of a tech

Optimal deployment (e.g. wind share) is determined by the intersection of system LCOE and average electricity price

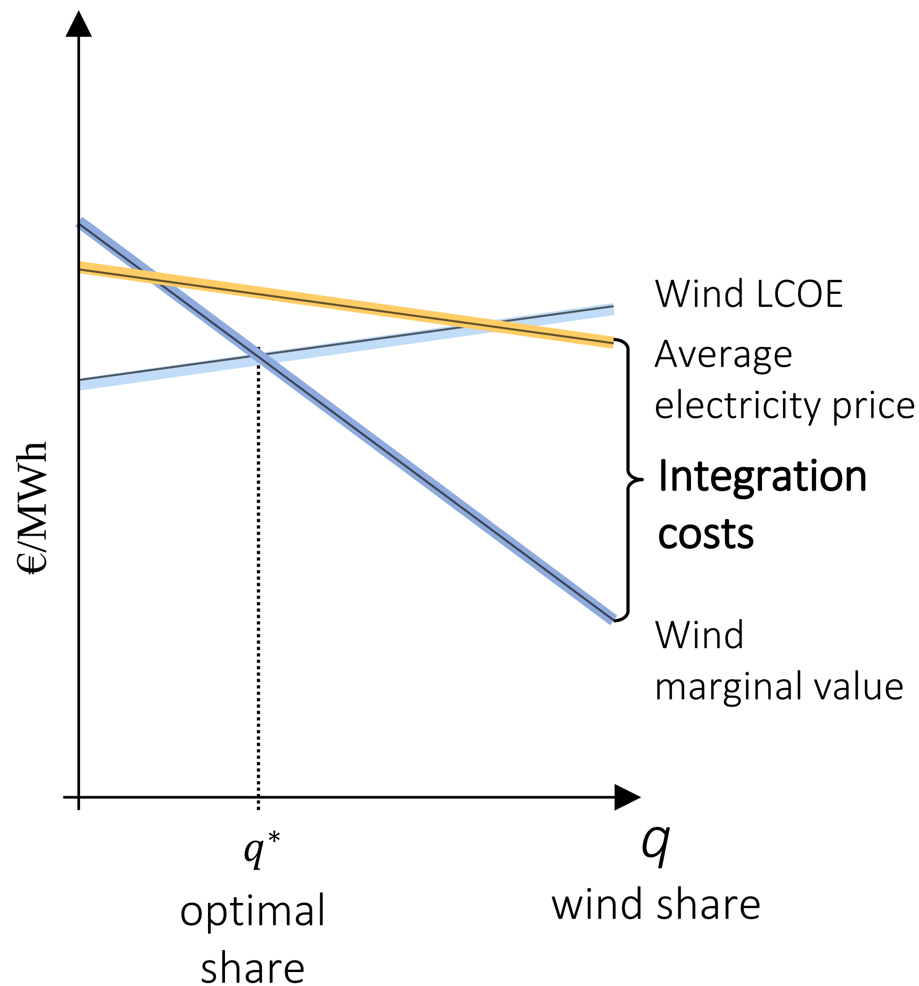


Two perspectives on integration costs and optimality are *equivalent*

Cost perspective



Value perspective



Profile cost

A thought experiment

Compare two power systems

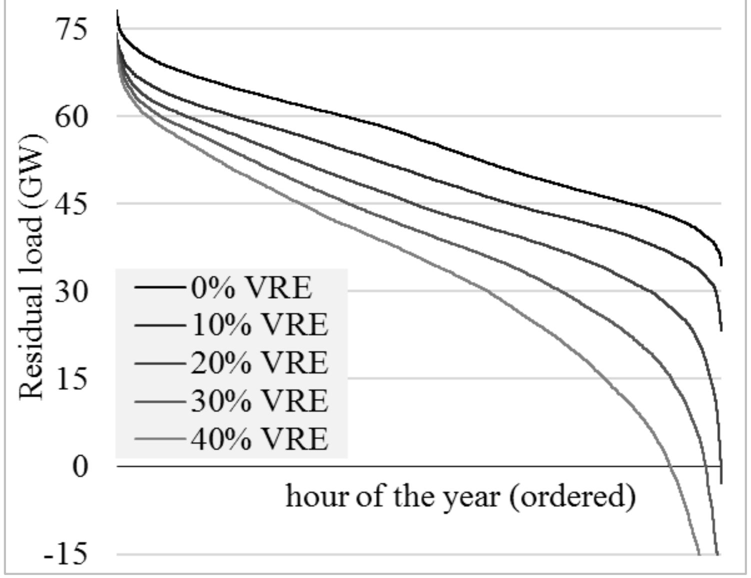
- "No RE system": little wind and solar, optimal thermal mix
- "40% RE system": a lot of wind and solar, optimal thermal mix (more mid, peak load)
- Otherwise identical (country-size system, same load level and pattern, copperplate, electrical island, no storage, inflexible demand)

Thermal utilization differs

- Without RE, utilization of thermal generators averages round 70%
- With 40% wind and solar, utilization of thermal generators is around 45%
- As a consequence, the "levelized" capital cost per $MWh_{thermal}$ is higher (even though the thermal mix shifts towards less CAPEX-intensive technologies)

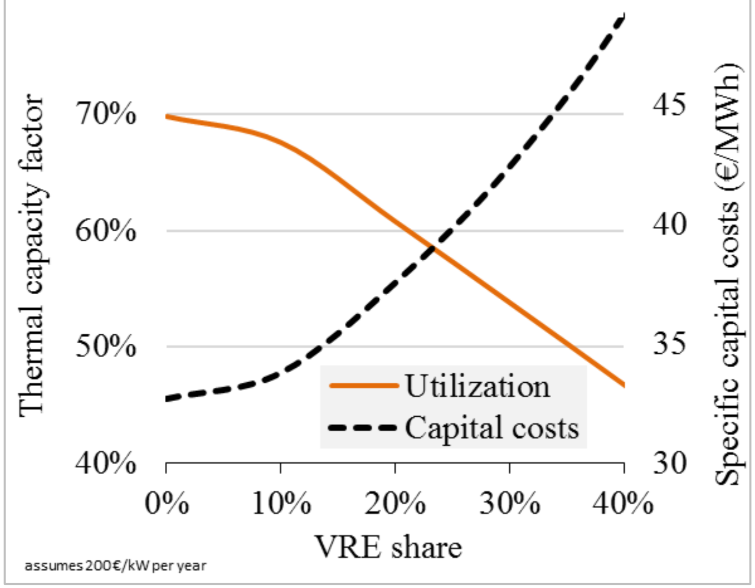
Reduced utilization of residual power plants

Residual load duration curves



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

Decreased utilization



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

With increasing RE shares, the other power plants are utilized less.

Lower utilization implies higher per-MWh capital costs (€/$MWh_{thermal}$). This is the “utilization effect“.

Profile costs

"Profile costs" are the results of the time pattern of RE generation ("profile")

- Excludes: costs that are a result of grids or uncertainty

Thermal utilization effect

- See above
- Increases the levelized capital cost of thermal generation (per $MWh_{thermal}$)

Renewables utilization effect

- Curtailment as a consequence of oversupply (remember: no network constraints)
- Increases the levelized capital cost of renewable generation (per MWh_{RE})

Flexibility effect

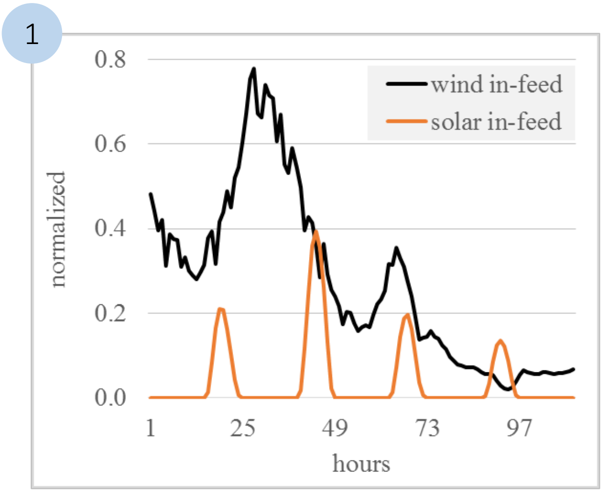
- Ramping and cycling of thermal plants (start-up costs)
- But: shifting the mix towards mid/peak load reduces start-up costs

Cost components

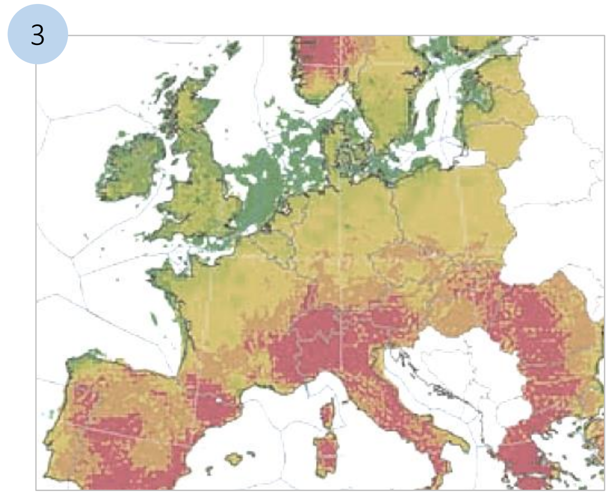
Electricity is a heterogeneous good along 3 dimensions

Physics	Electromagnetic energy	Kirchhoff's laws	Frequency stability
↓	↓	↓	↓
Arbitrage constraint	Storage (Storing electricity is costly)	Transmission (Transporting elec. is costly)	Flexibility (Ramping & cycling is costly)
↓	↓	↓	↓
Dimension of heterogeneity	Time (Price differs btw hours)	Space (Price differs btw locations)	Lead-time (Btw contract & delivery)
↓	↓	↓	↓
Electricity markets	(Uniform) wholesale markets	LMP / zonal wholesale mrkts	Real-time / balancing markets

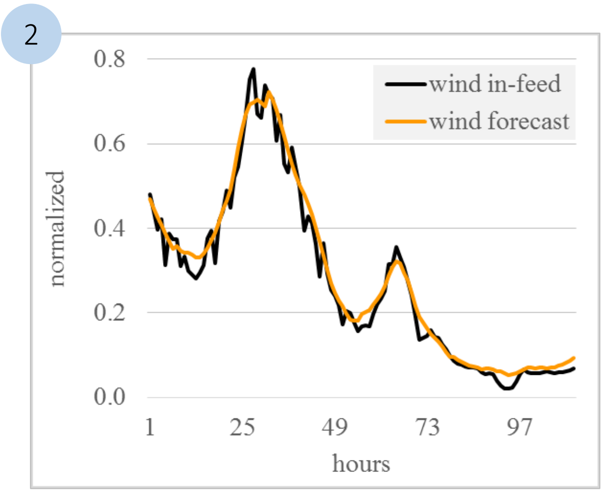
Wind and sun: “intermittent” or “variable” sources



Wind does not always blow



Good sites are distant from load centers



Difficult to predict

“Variable“ renewable energy source (VRE)

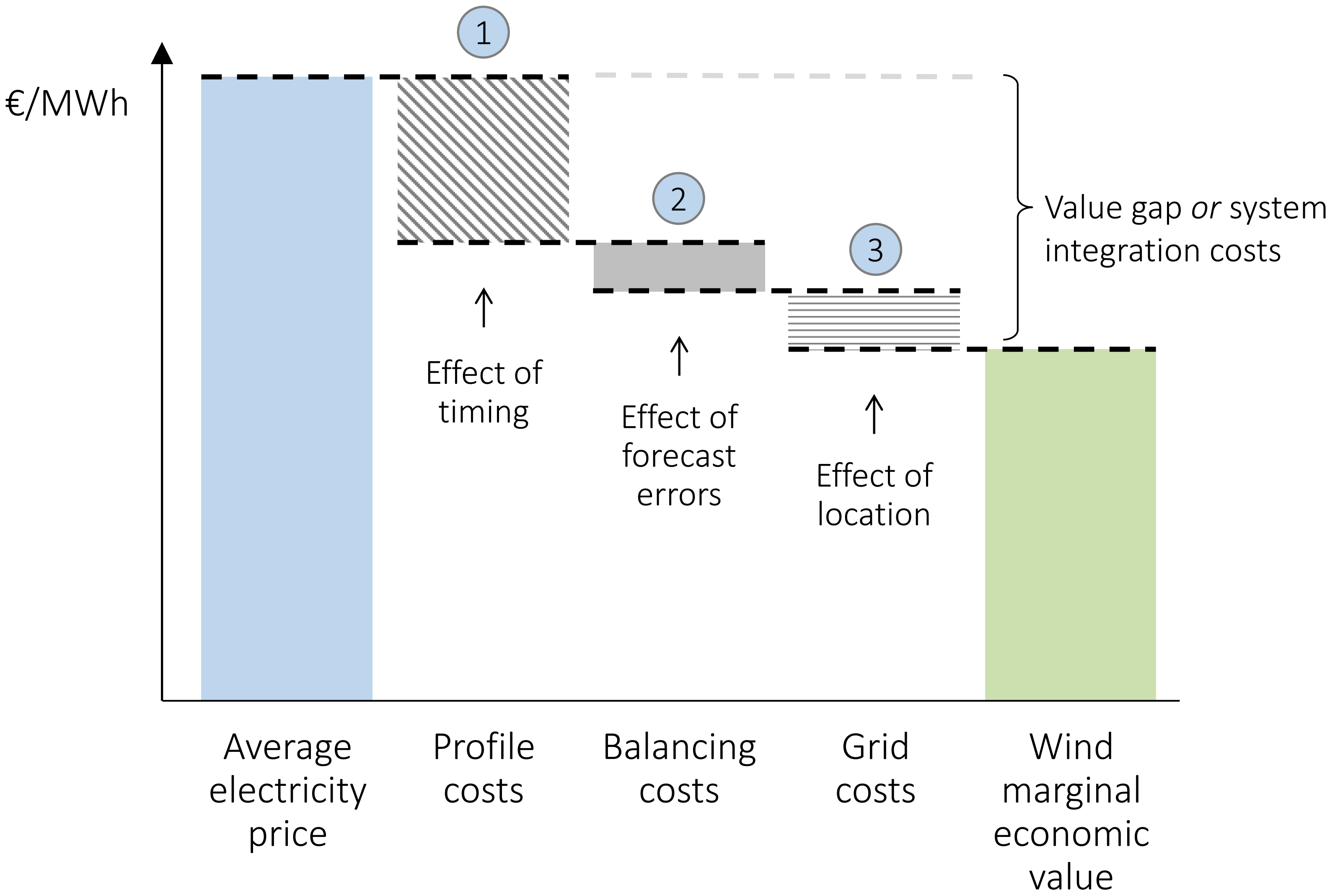
Three properties of renewables *and* of electricity

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

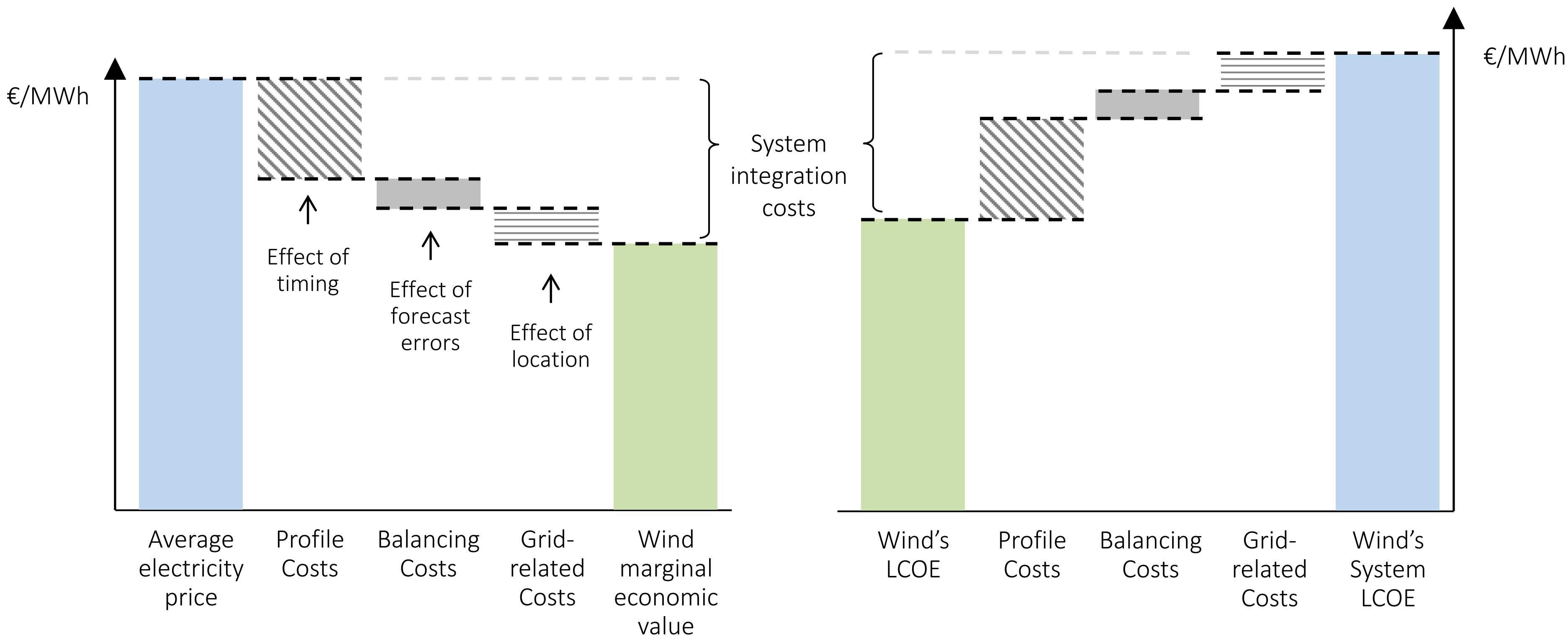
→ It is the *interaction* of VRE variability and price heterogeneity that is costly

The market value of wind energy

illustrative



Value gap and system integration costs



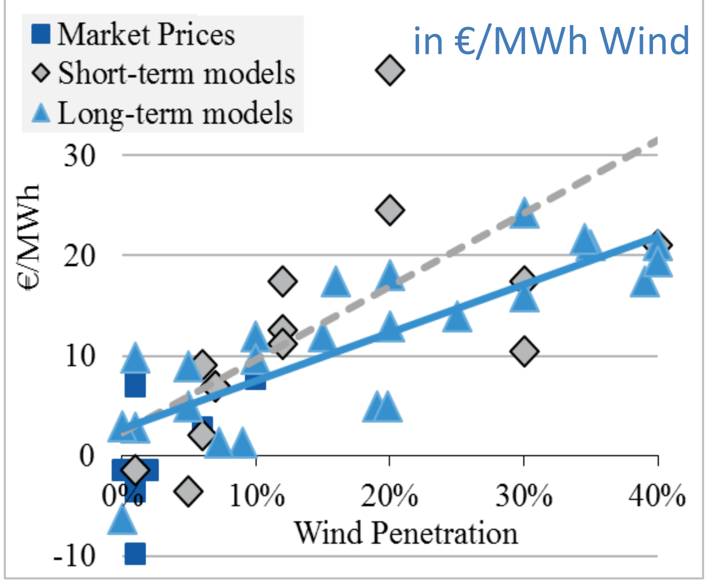
In the long-term optimum, two equivalent optimality conditions hold:
(1) Marginal economic value = LCOE
(2) Average Electricity Price = System LCOE

Quantification (for VRE)

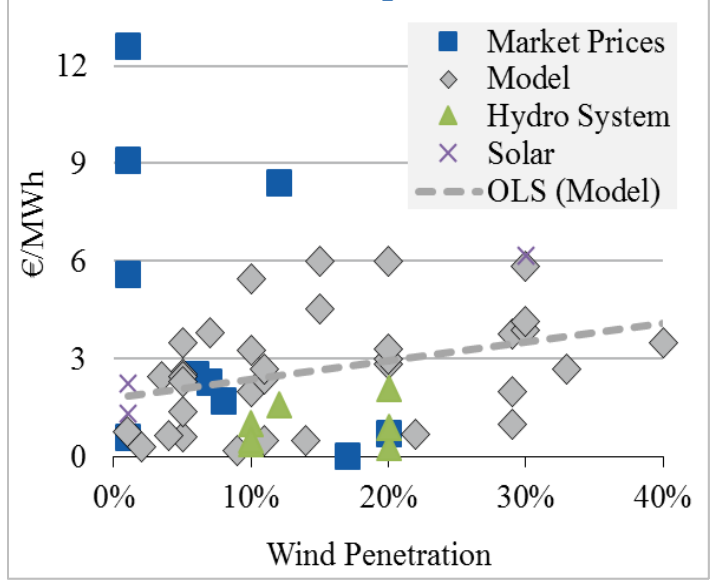
Literature review for wind from 2015

Hardly flexibility options considered

Profile costs



Balancing costs



Grid costs

- **2-13 €/MWh wind** (at 15-40% wind,)
- Scarce and partly inconclusive data

- Integration costs increase with VRE and can become high (~30€/MWh VRE at 40% wind)
- Profile costs are the largest cost component (at high shares in thermal power systems)

Model estimation (REMix/DLR for Europe) (2016)

Flexibility options: EU grid expansion and ST/LT storage

No broad electrification

~2015 short-term storage cost expectations

REMix model

(German Aerospace Centre, DLR)

- Minimizes total system costs
- Linear optimization of hourly dispatch and investment (based on annuities)
- Represents Europe in 15 regions
- Endogenous DC transmission grid and storage (redox flow battery, pumped hydro and hydrogen storage)

Scholz, Y., Gils, H.C., Pietzcker, R. (2016): "*Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares*". Energy Economics. 10.1016/j.eneco.2016.06.021

Model estimation (REMix/DLR for Europe) (2016)

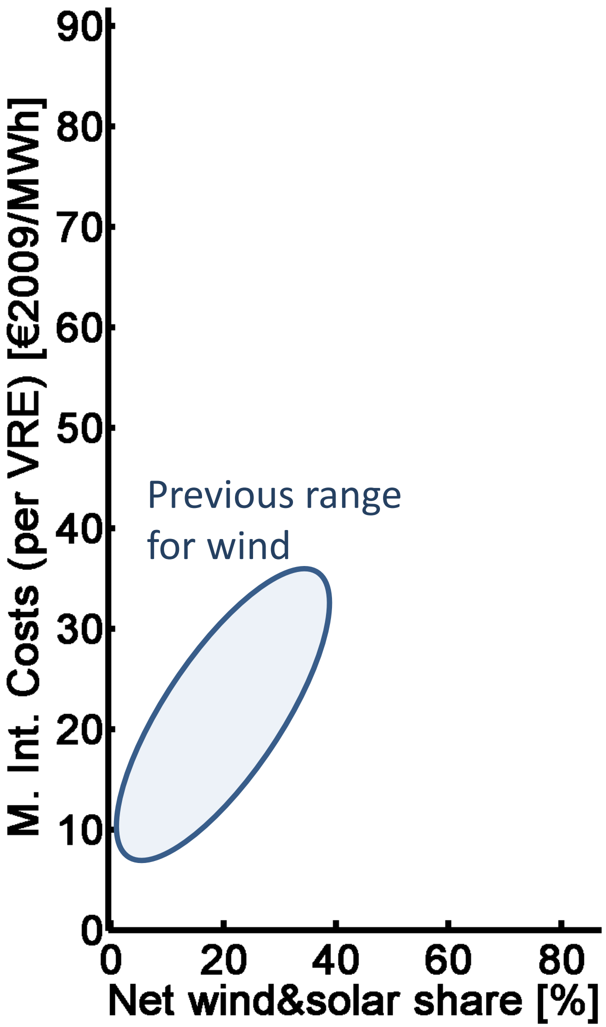
Flexibility options: EU grid expansion and ST/LT storage

No broad electrification

~2015 short-term storage cost expectations

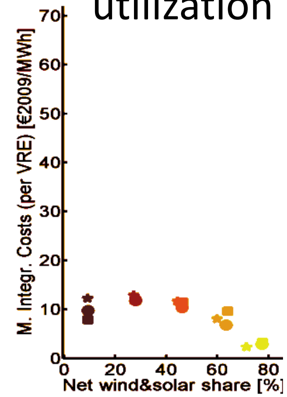
Integration costs with large grids and storage

(€/MWh VRE, marginal)

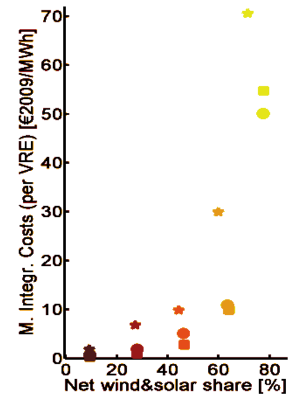


1. Profile costs

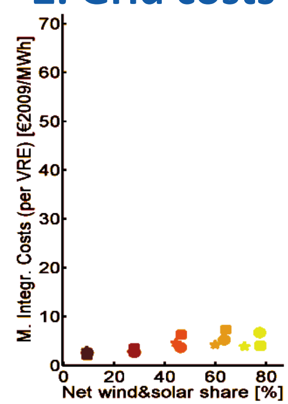
Reduced utilization



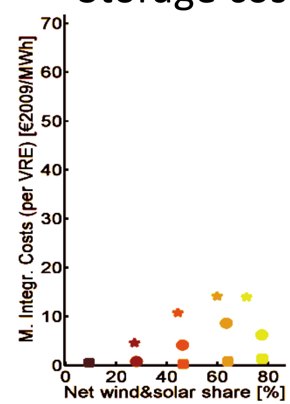
Curtailment



2. Grid costs



Storage costs



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2021: literature review

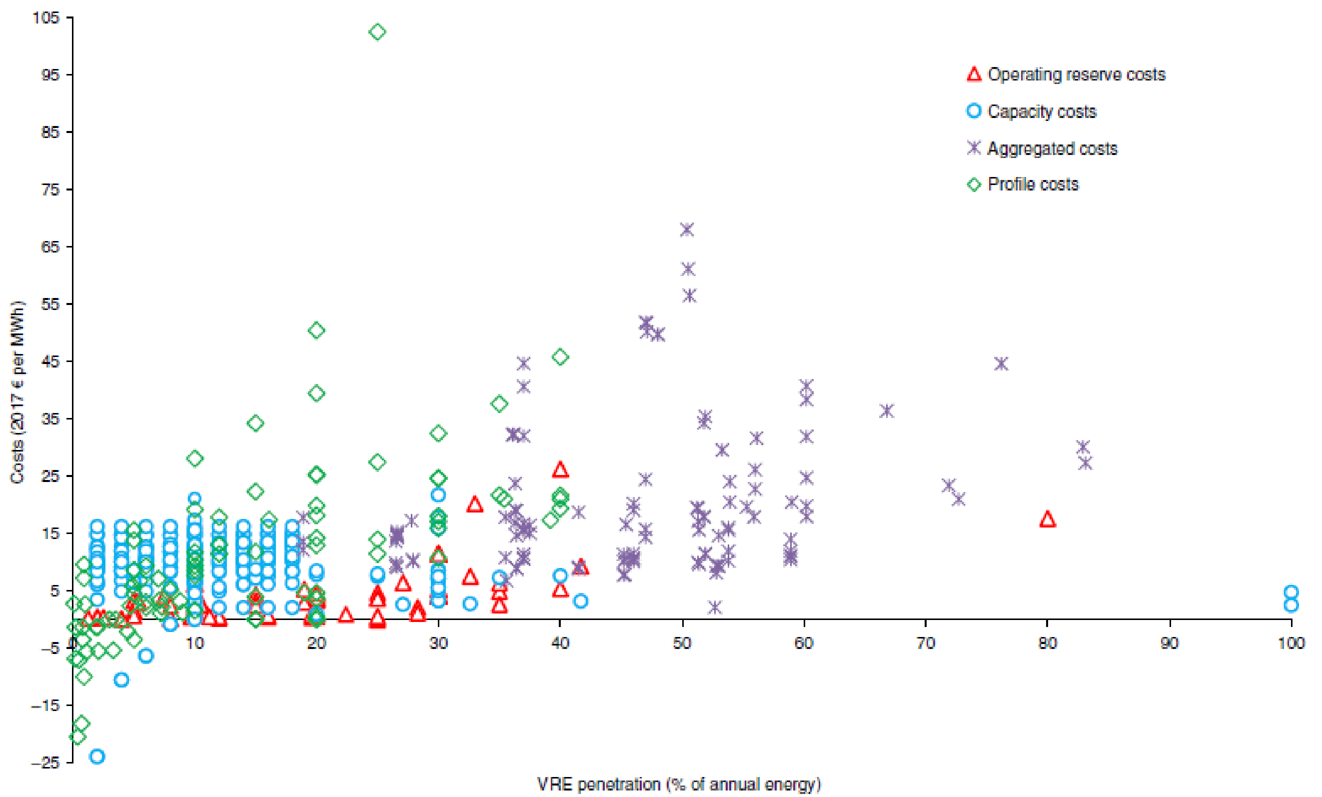


Fig. 2 | Data for operating reserve, capacity adequacy, aggregated and profile costs. Costs are normalized to 2017 Euro. The VRE penetration level is expressed using the most common metric found in the literature, that is, the percentage of annual electricity demand met by VRE. Approximately three-quarters of the entire dataset used this metric. Less common metrics for assessing VRE penetration levels include the percentage of total system installed capacity and the percentage of peak system load. Findings that used these metrics are not included in the figures in this paper as the data are not directly comparable. Data sources for this figure are from refs. [16,17,24,33,37,44,49,74–86]. The operating reserve data were drawn from 11 studies with no single study dominating the results. Capacity cost data were drawn from seven studies, with ref. [49] contributing approximately 75% of the total number of data points. Aggregated cost data were drawn from three studies, with ref. [24] contributing over 60% of the data. Profile costs data were drawn from five studies, with ref. [17] contributing slightly less than half of the data points. This data are available in the Supplementary Data.

Heptonstall, P., Gross, R. (2021): "A systematic review of the costs and impacts of integrating variable renewables into power grids". Nature energy. https://doi.org/10.1038/s41560-020-00695-4

The impact of CO2 pricing and battery storage

+ Batteries, future costs 94$/kWh (market deployment)
→ Optimal PV share >50%
(without DSM, without electrification)

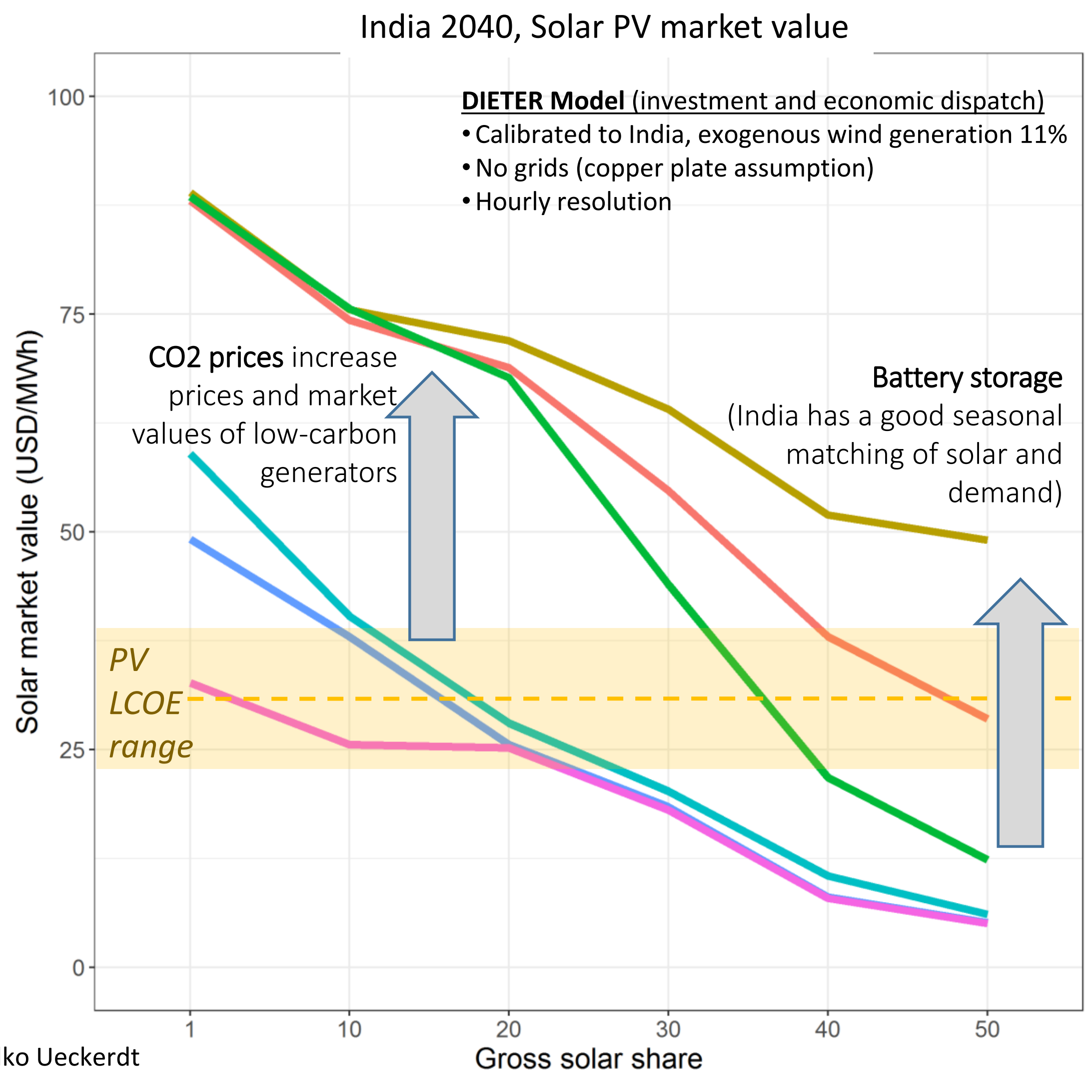
+ Batteries, 2020 costs 188$/kWh (market deployment)
→ Optimal PV share ~40-50%
(without DSM)

+ Pricing externalities (50$/tCO2)
→ Optimal PV share ~30-40%
(without batteries, DSM)

+ „Future AC demand profile“ (no flexibility)
→ Optimal PV share ~10-23%
(without: batteries, DSM, CO2 price)

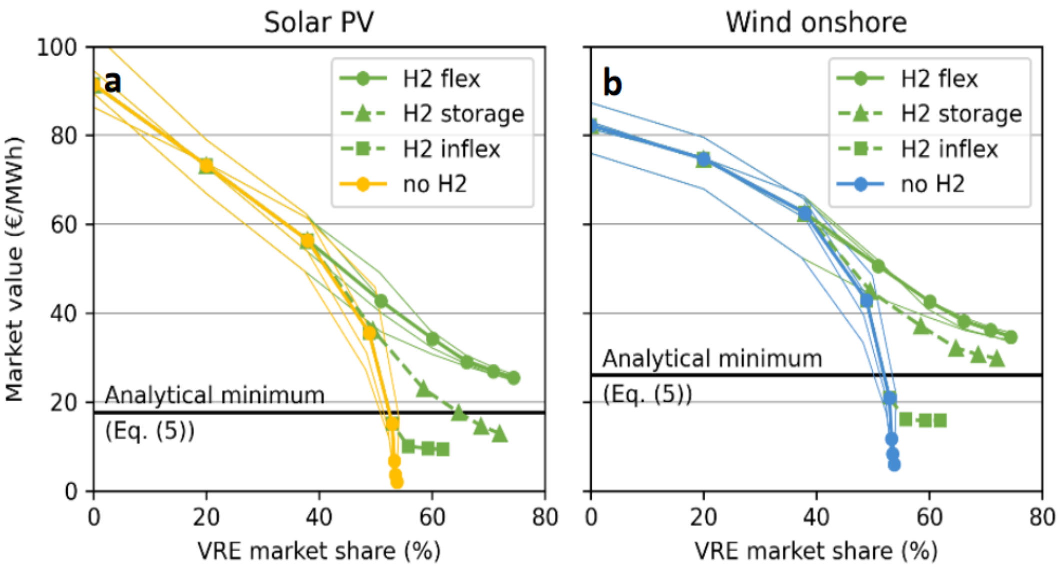
„Optimized expansion“ (quasi GREENFIELD)
(endogenous 300-400GW coal)
→ Optimal PV share → ~0-20%
(without: batteries, AC, DSM, CO2 price)

“Coal lock-in as in IEA-NPS“ (quasi BROWNFIELD)
(exogenous 421 GW coal, WEO, NPS)
→ Optimal PV share ~0-20%
(without: batteries, AC, DSM, CO2 price)

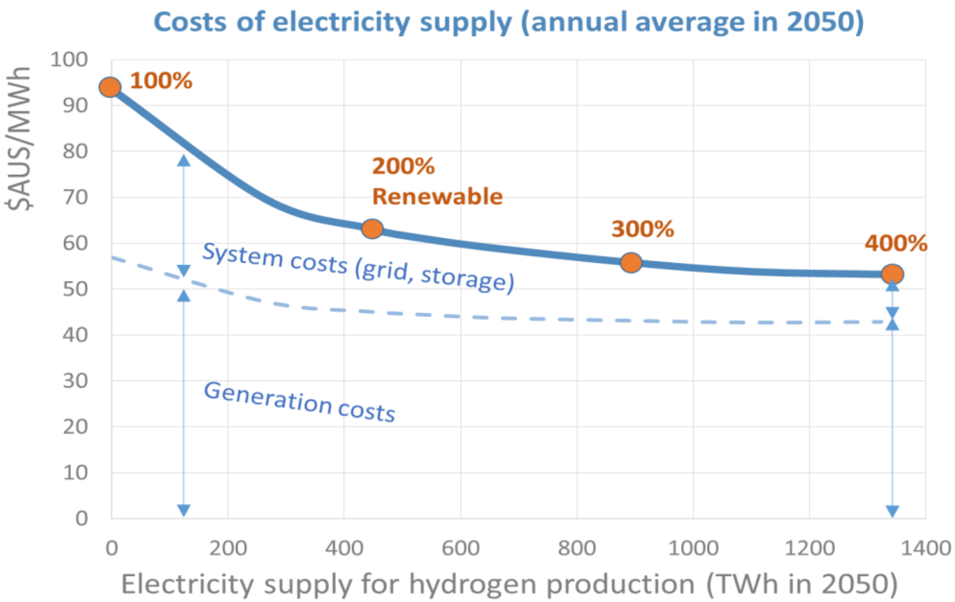


Source: PIK analysis (2019) by Murtaza Ershad, Robert Pietzcker, Falko Ueckerdt

Finally, considering electrification (direct and indirect) further decreases integration cost

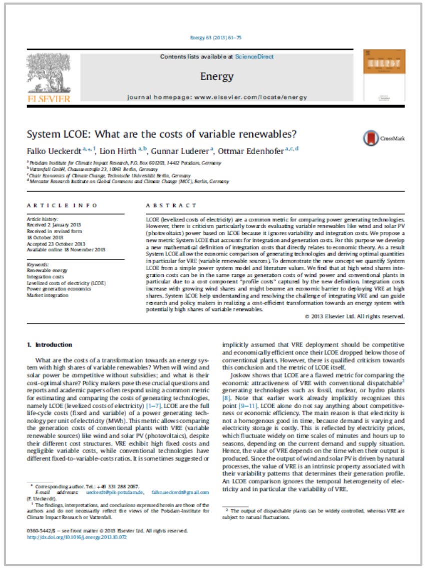


Ruhnau, Oliver (2021) : How flexible electricity demand stabilizes wind and solar market values: the case of hydrogen electrolyzers, ZBW - Leibniz Information Centre for Economics, Kiel, Hamburg



Ueckerdt F, Dargaville R, Gils H-C, et al (2019) Australia's power advantage. Energy transition and hydrogen export scenarios

The details: further readings


Energy

System LCOE: What are the costs of variable renewables?

Falko Ueckerdt, Lion Hirth, Gunnar Luderer, Ottmar Edenhofer

System LCOE

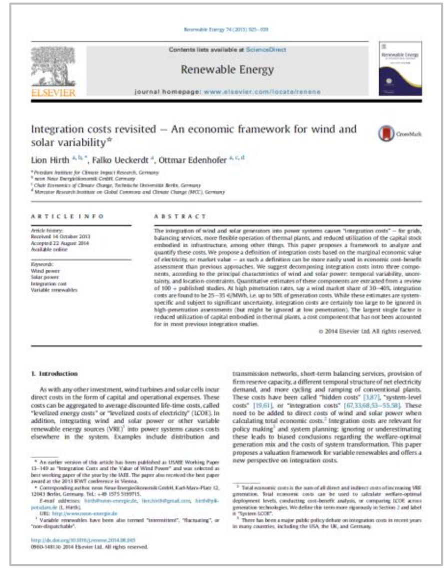

Energy Economics

The market value of variable renewables

The effect of solar wind power variability on their relative price

Lion Hirth

Market value


Renewable Energy

Integration costs revisited – An economic framework for wind and solar variability

Lion Hirth, Falko Ueckerdt, Ottmar Edenhofer

Integration cost


Why Wind Is Not Coal: On the Economics of Electricity Generation

Lion Hirth, Falko Ueckerdt and Ottmar Edenhofer

Wind not coal

Thank you for your attention!