

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

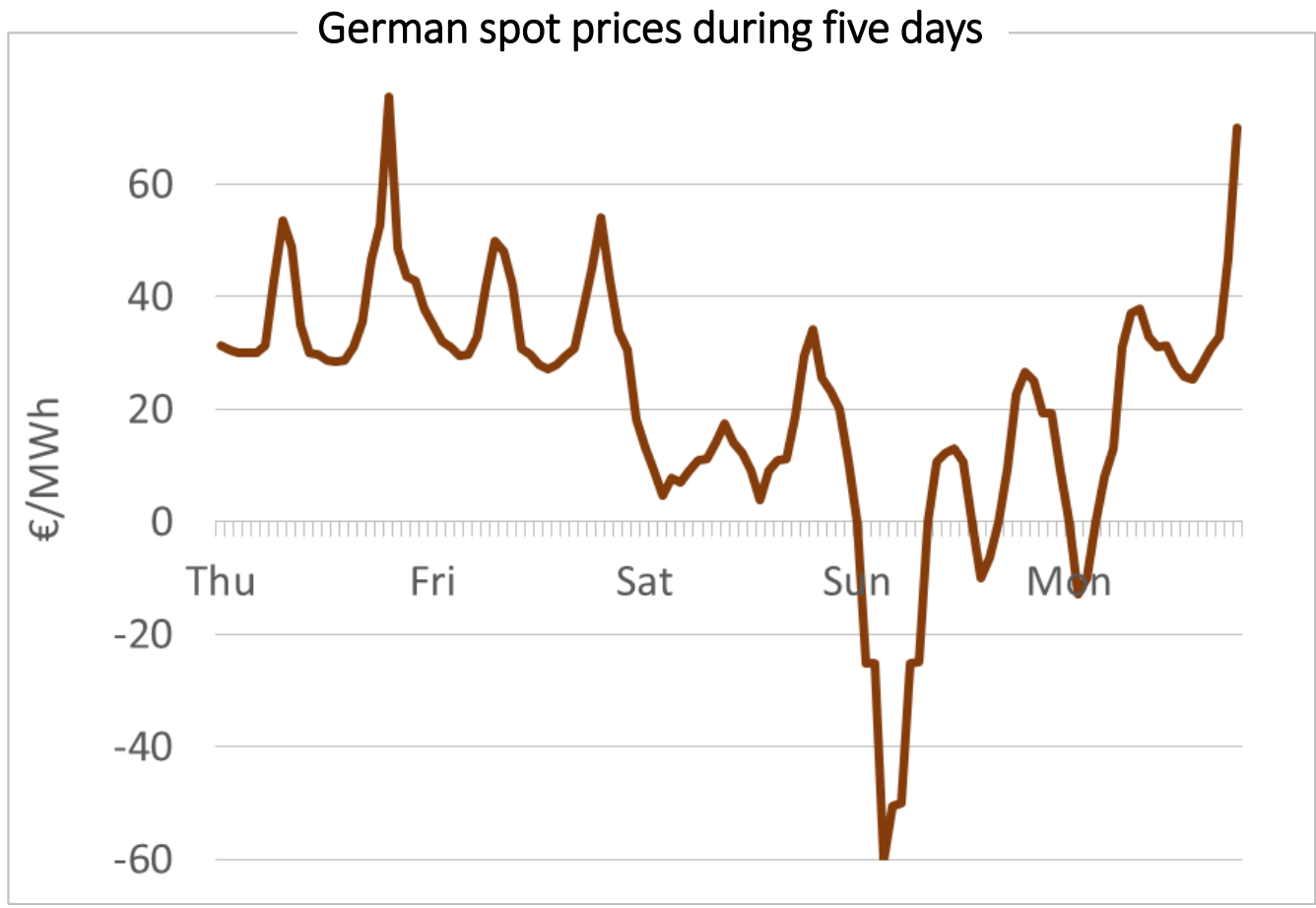
- “system costs in excess of system costs incurred by equivalent amounts of energy delivered to the system on firm, fixed schedules” (Dragon & Milligan 2003)
- “an increase in power system operating costs” (Milligan & Kirby 2009)
- “the additional cost of accommodating wind and solar” (Milligan et al. 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



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

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

$g_{i,t}$	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

$$\text{Value factor}_i = \frac{\text{market value}_i}{\text{base price}}$$

<i>base price</i>	Average electricity price during one year
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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 disproportionately at times of low prices have a value factor below 1 (“low value electricity”)

Value factor: the relative price of wind energy

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

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

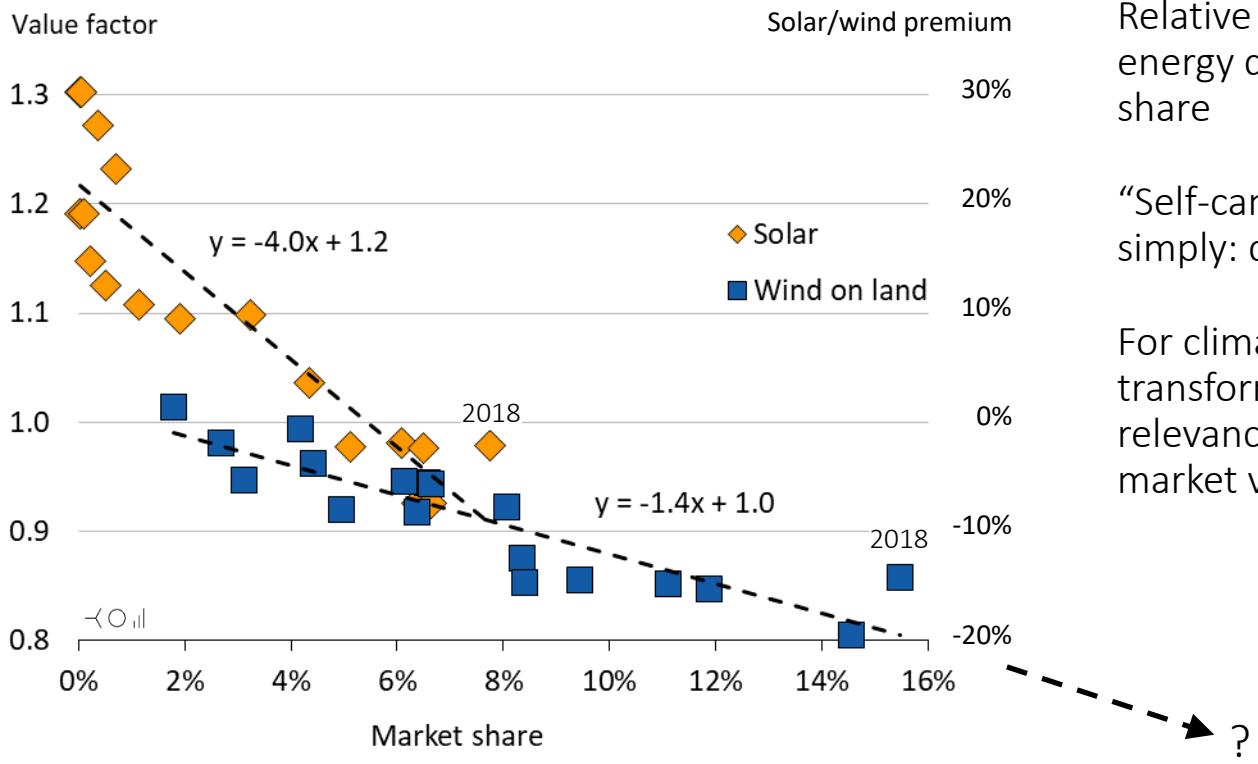
↑
Wind-weighted
price

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

↑
Ratio

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

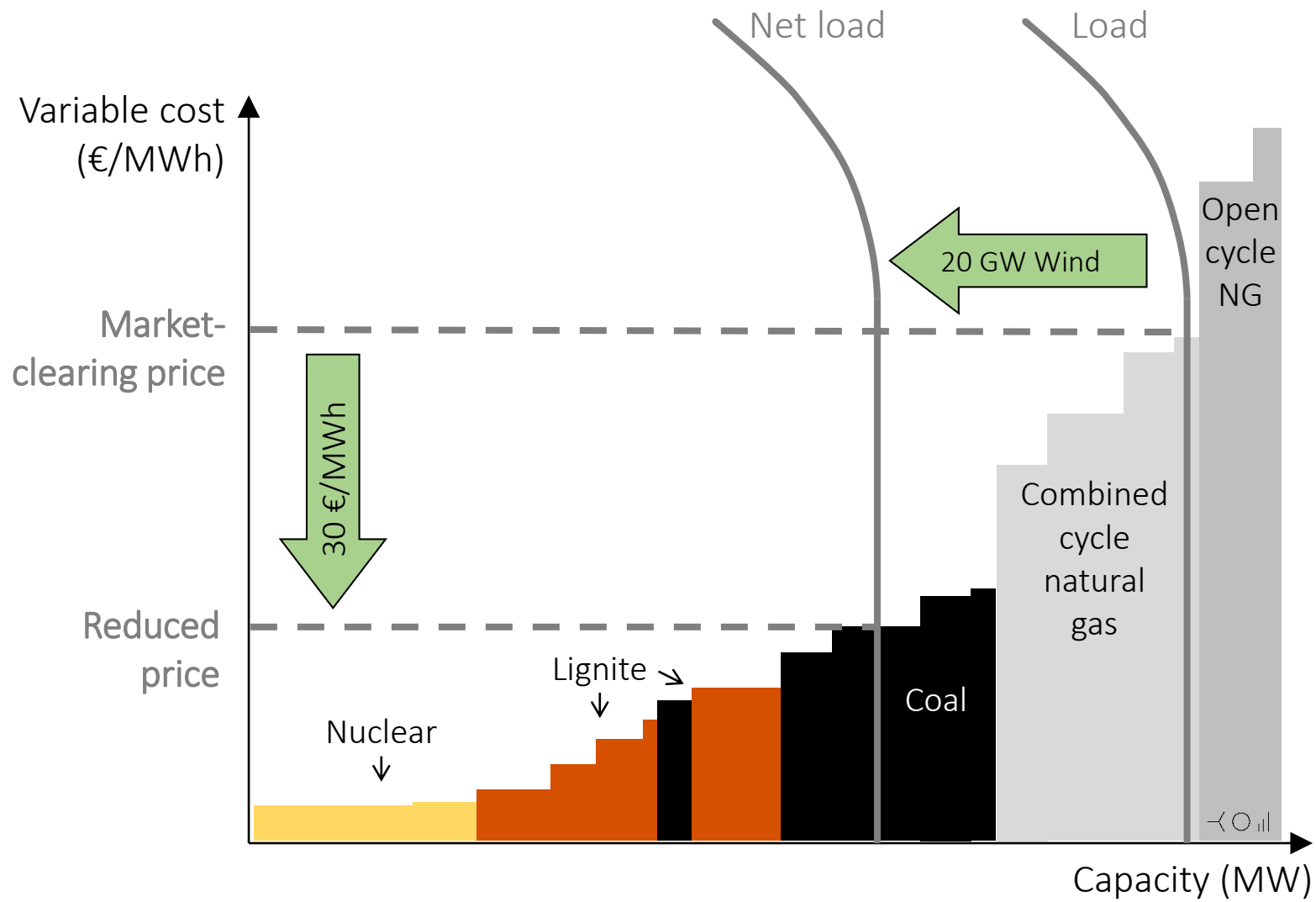
The value drop of wind and solar energy



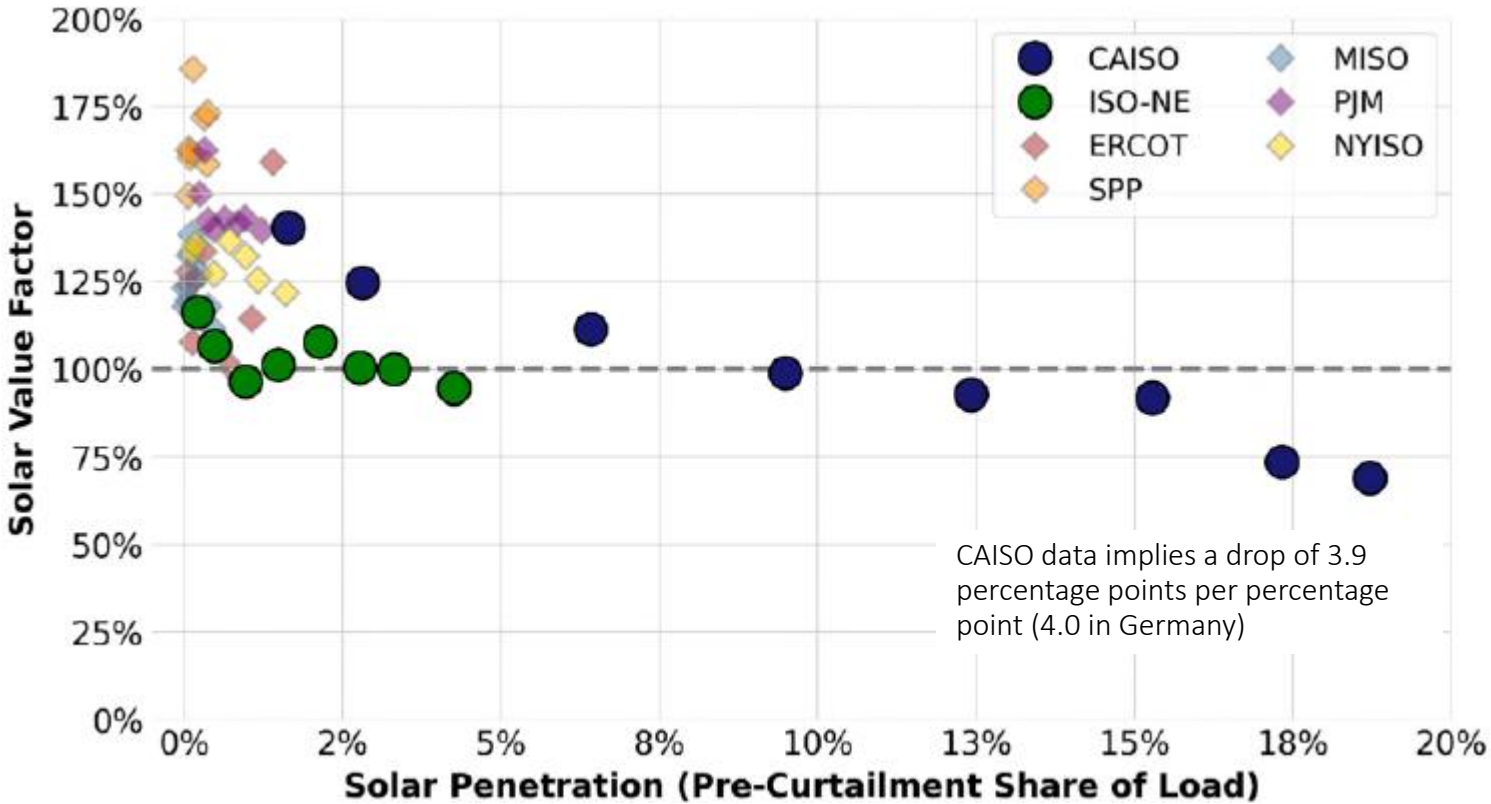
Value Factor = Market value / base price. Each symbol represents one year. Extrapolation suggests that at 30% wind share its value factors is 0.5; at 15% solar its value is 0.56.. Updated from Hirth (2013): Market value.

illustrative

The mechanics behind the value drop



The US picture



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

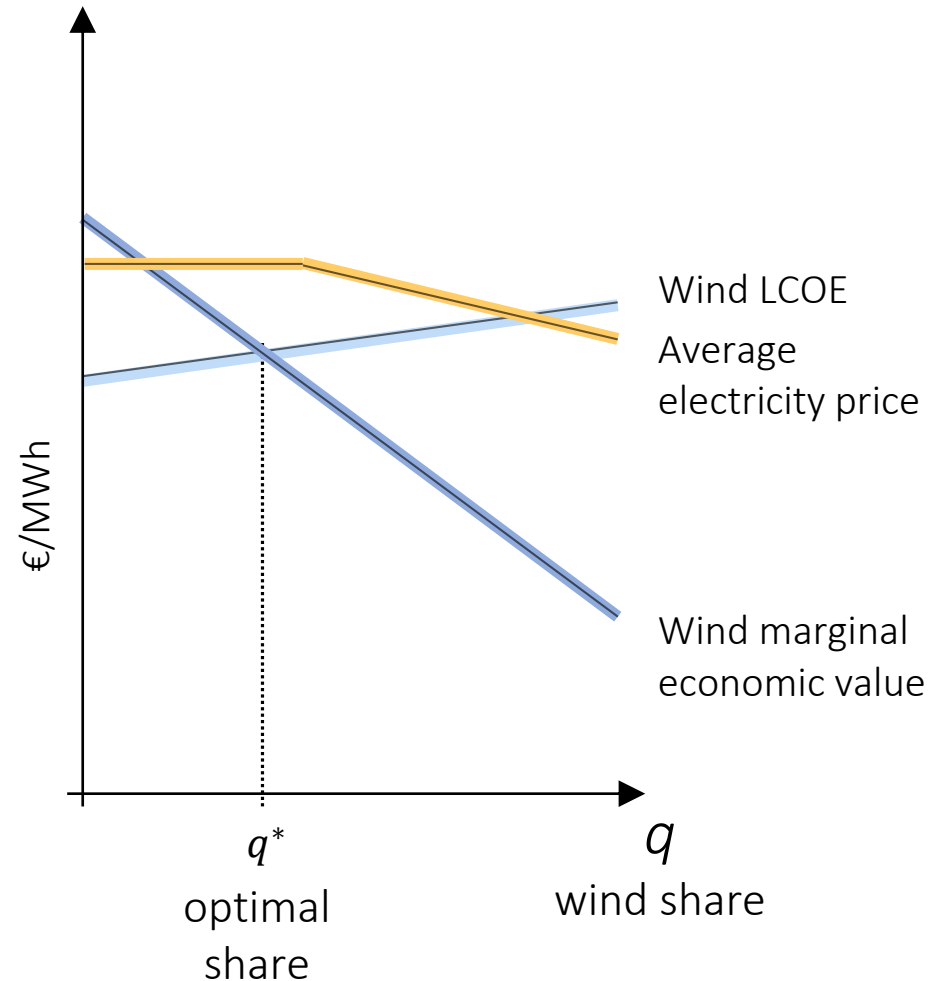
Electricity markets are out of equilibrium

- Business cycles, structural change, system transformation

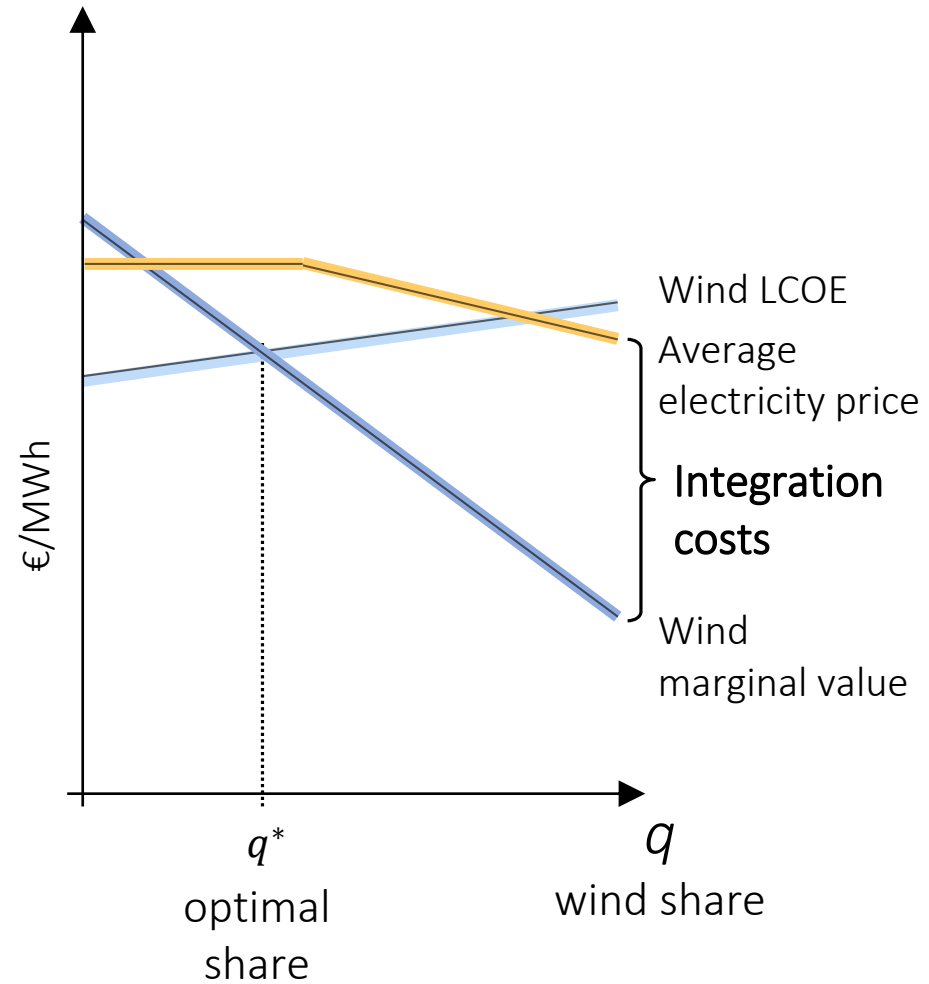
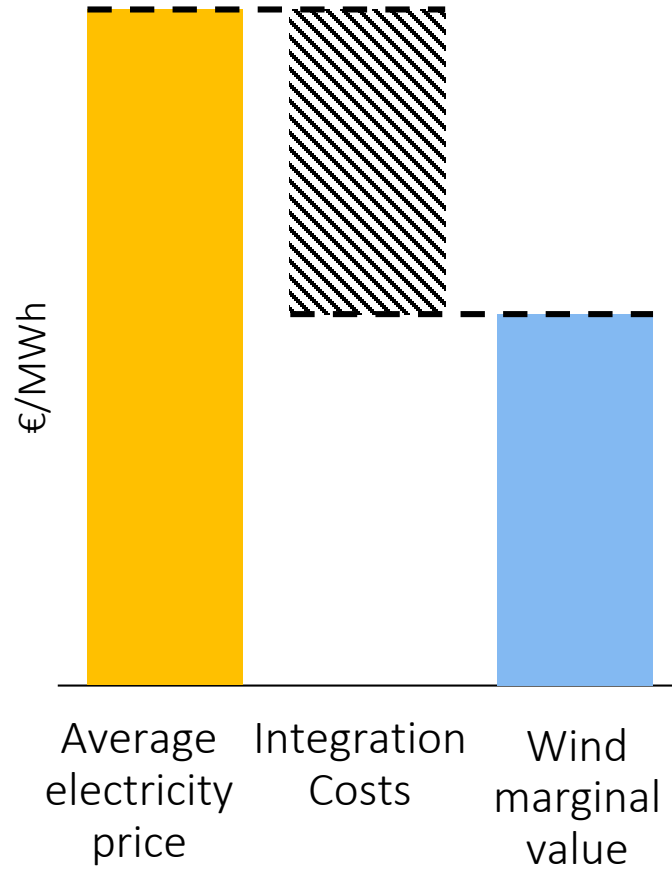
Implications for the optimal and cost-competitive market share

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)

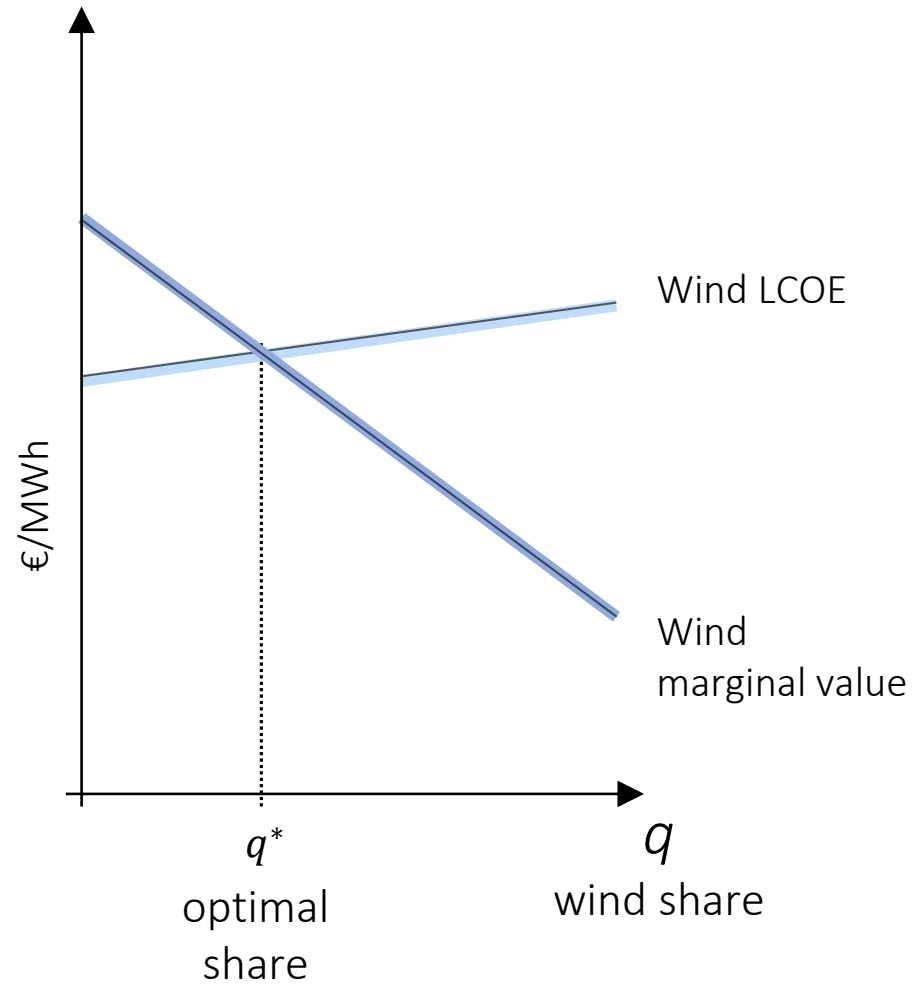


Defining system integration costs from a value perspective

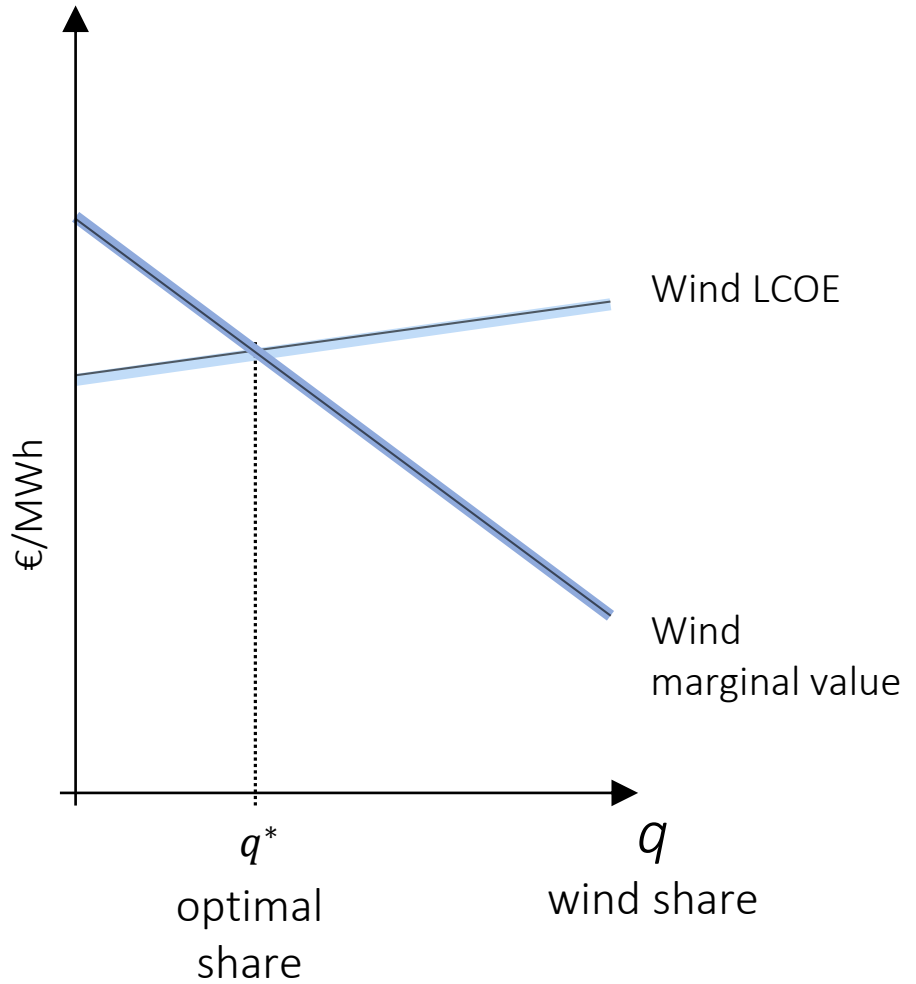
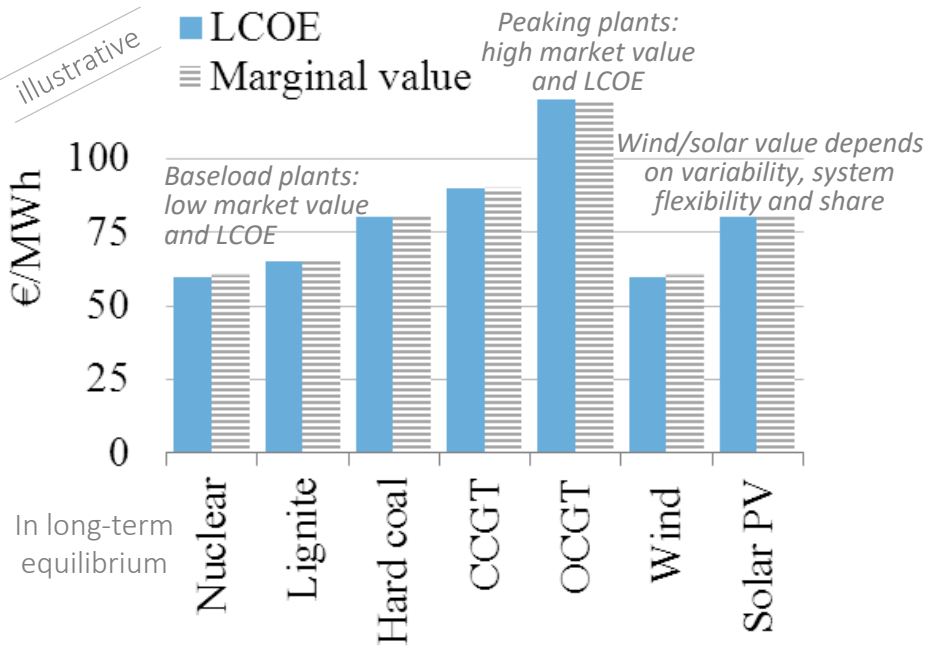


Cost perspective

This is why the LCOE metric is incomplete



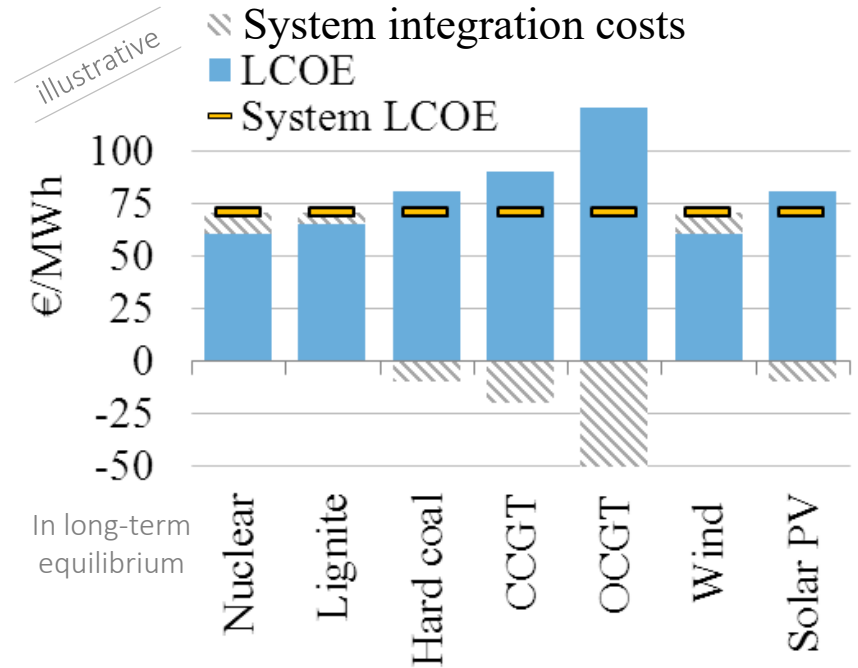
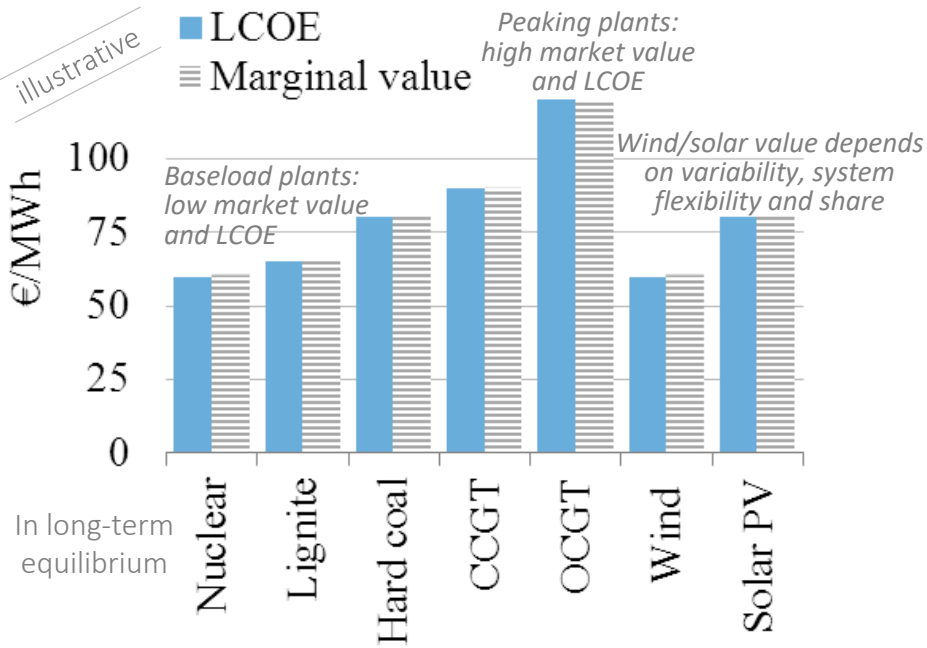
This is why the LCOE metric is incomplete



- 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

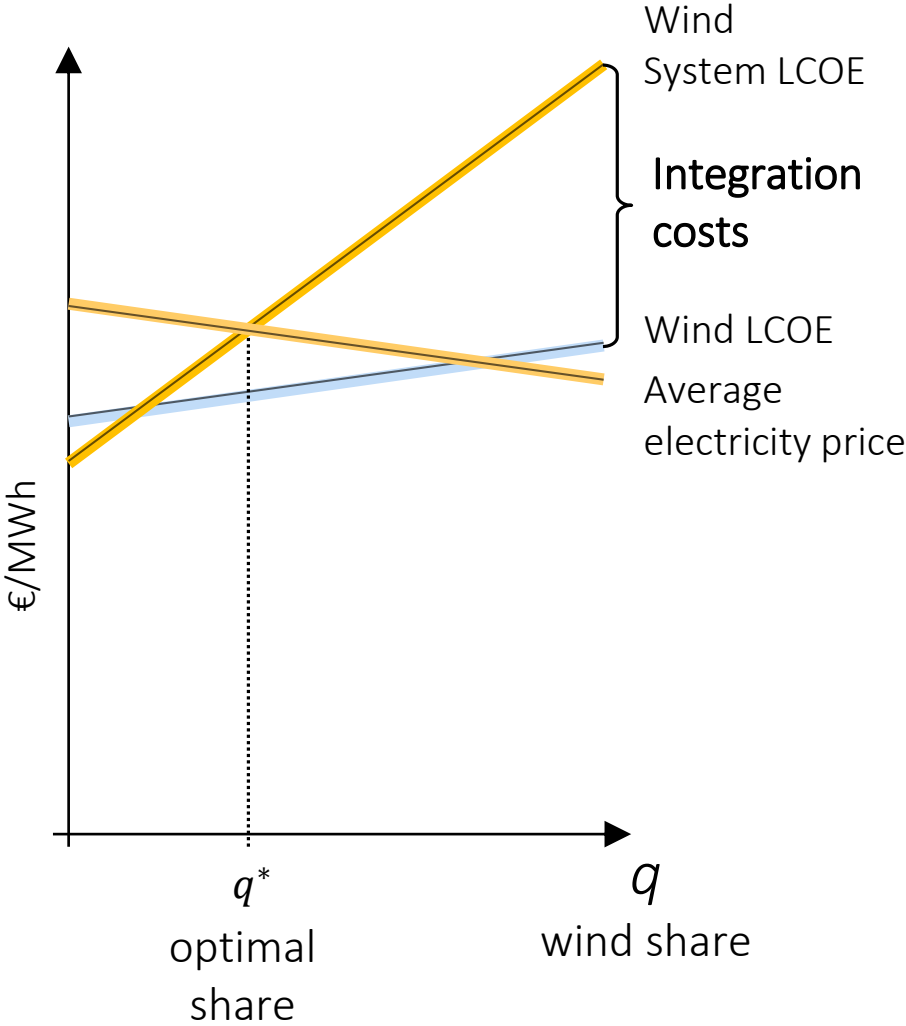
If “you” insist on comparing with a single metric: “System LCOE”



- 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*

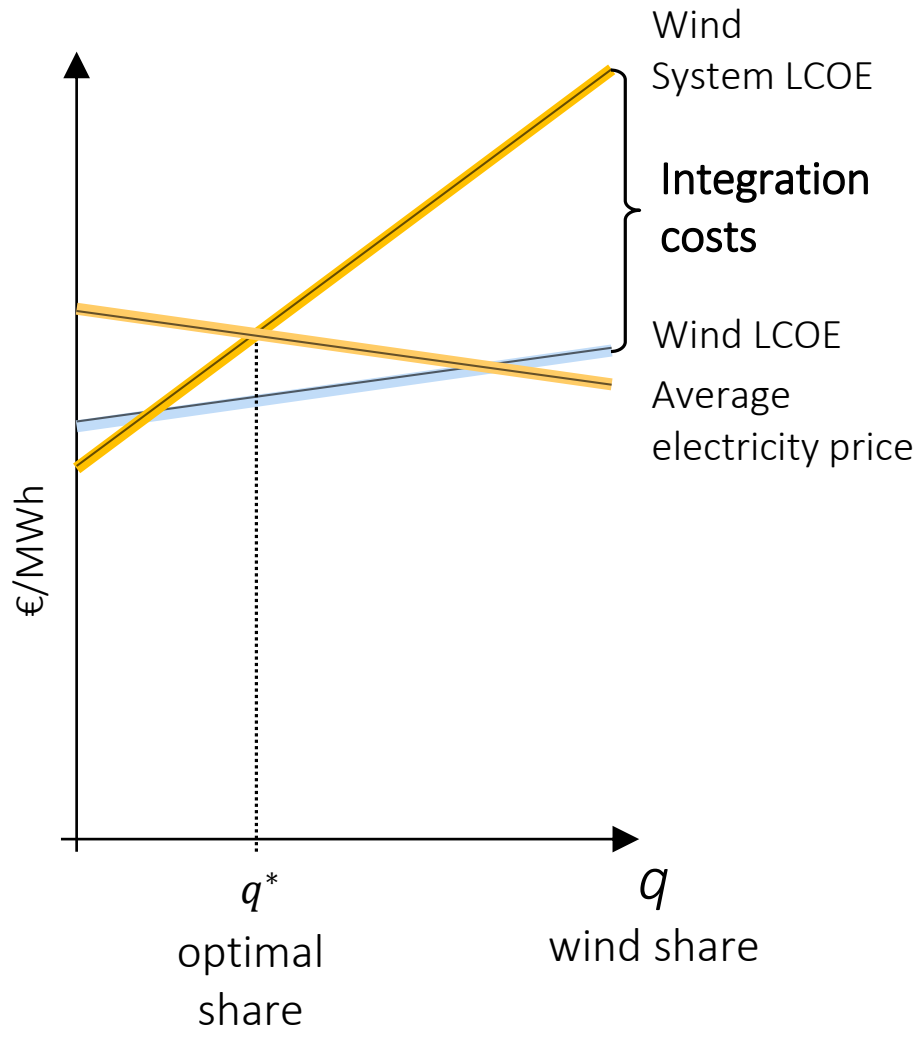
- System LCOE = LCOE + integration costs; in equilibrium: techs have equal *system LCOE*
- *System integration costs*: the *additional* costs that a technology causes on the system level (compared to a benchmark technology)
- Link to value: market value is the reduction in total costs when adding a unit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

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

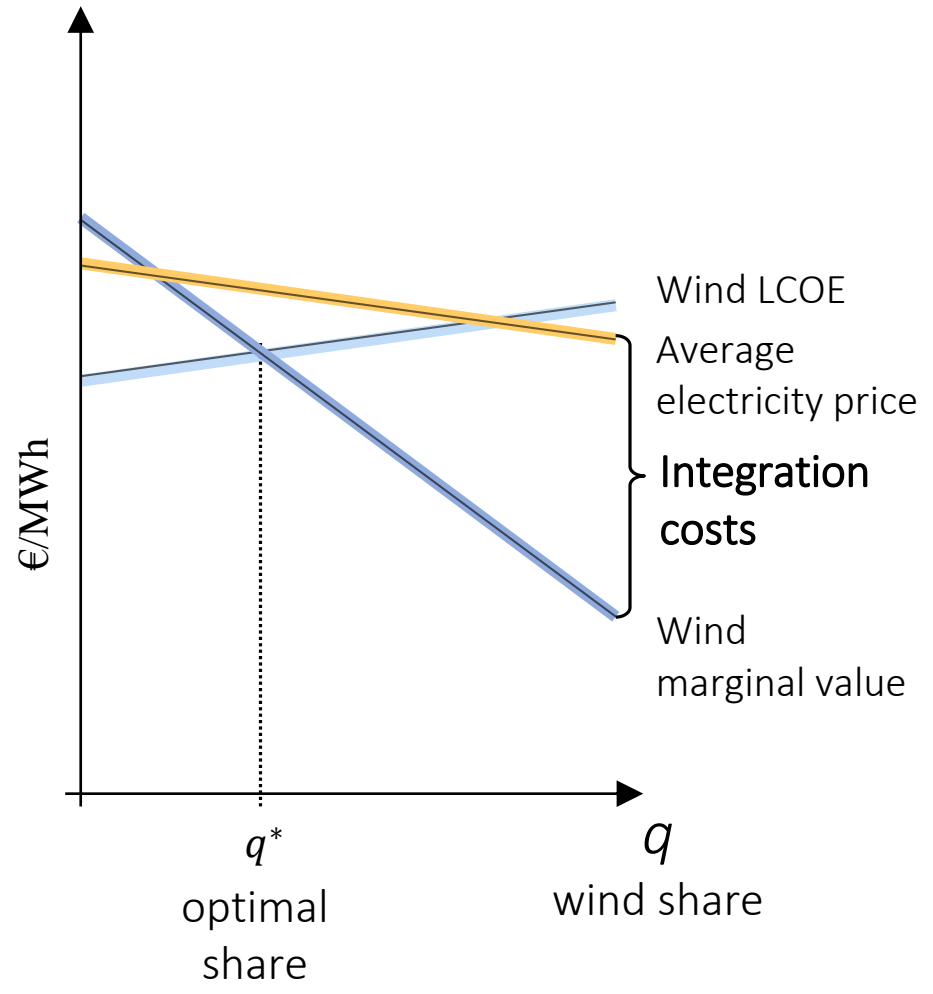


Two perspectives on integration costs and optimality are *equivalent*

Cost perspective



Value perspective



Profile cost

A thought experiment

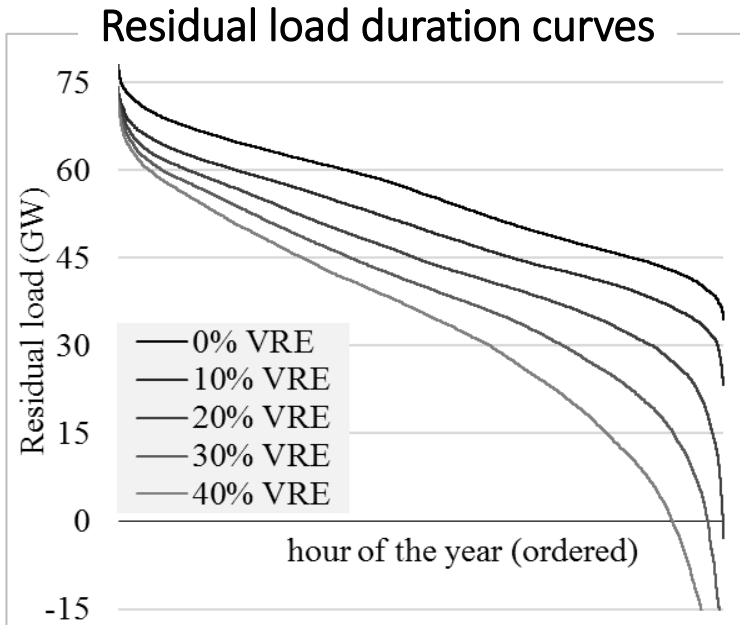
Compare two power systems

- “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

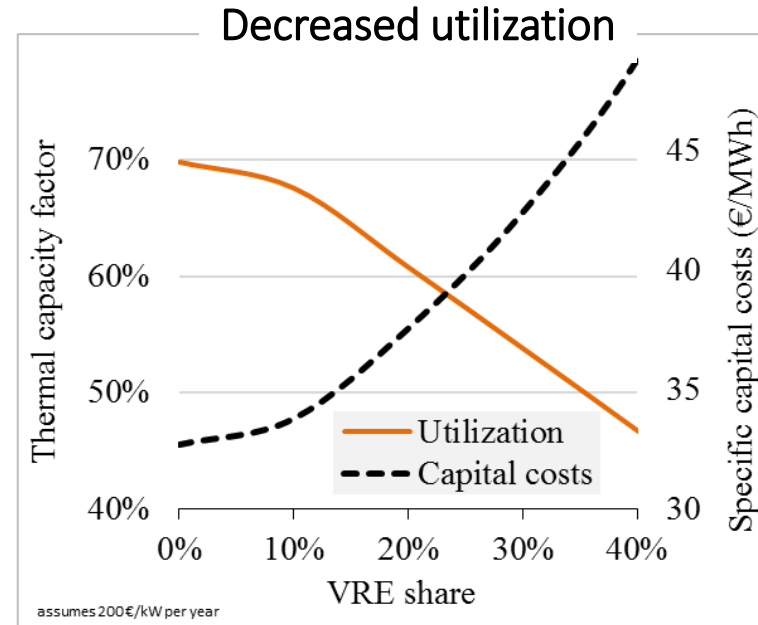
- Without RE, utilization of thermal generators averages round 70%
- With 40% wind and solar, utilization of thermal generators is around 45%
- As a consequence, the “levelized” capital cost per $\text{MWh}_{\text{thermal}}$ is higher (even though the thermal mix shifts towards less CAPEX-intensive technologies)

Reduced utilization of residual power plants



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

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



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

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 $\text{MWh}_{\text{thermal}}$)

Renewables utilization effect

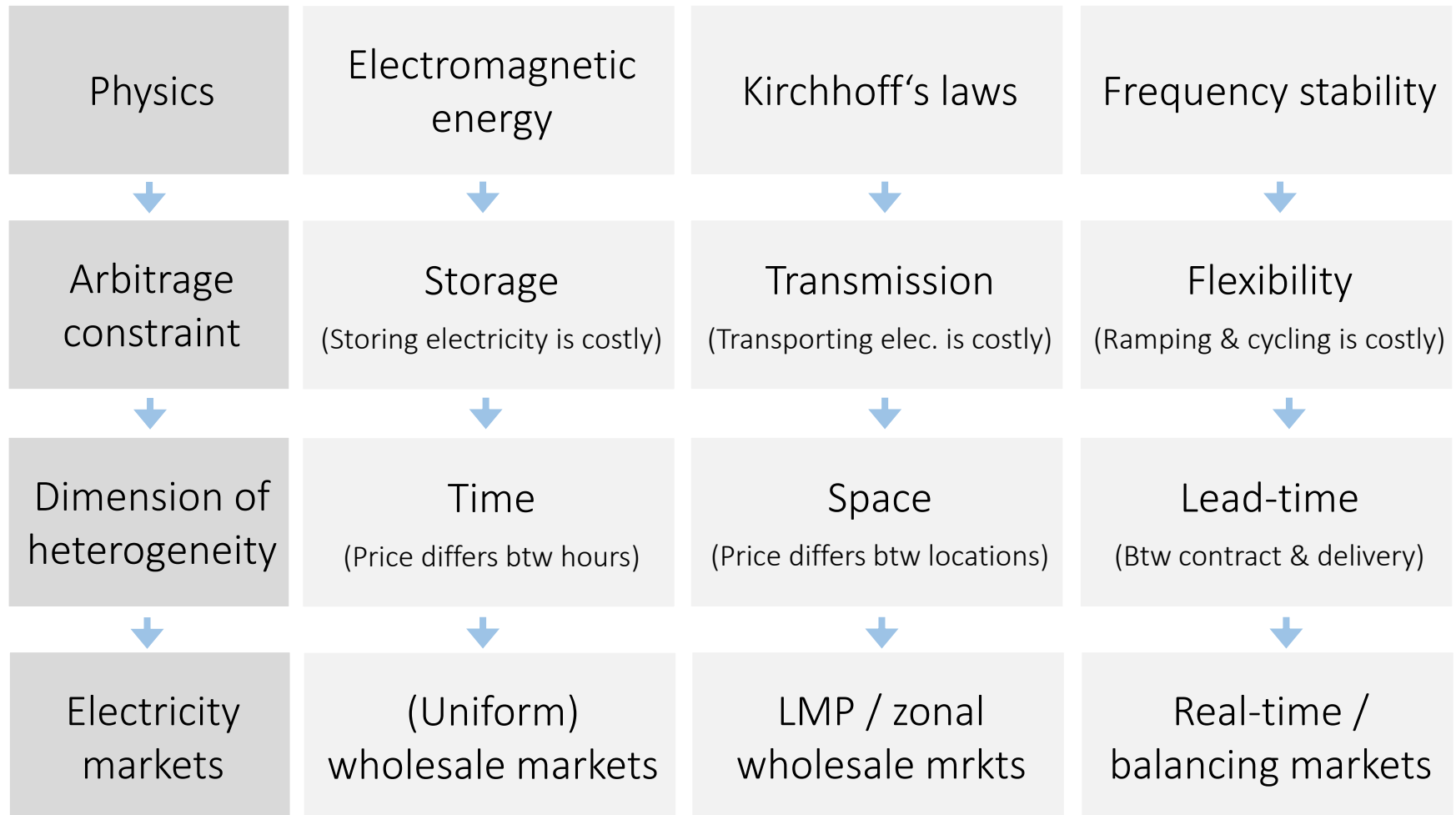
- Curtailment as a consequence of oversupply (remember: no network constraints)
- Increases the levelized capital cost of renewable generation (per MWh_{RE})

Flexibility effect

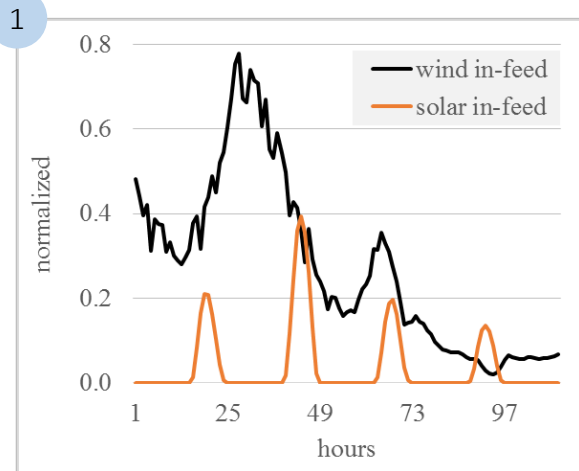
- Ramping and cycling of thermal plants (start-up costs)
- But: shifting the mix towards mid/peak load reduces start-up costs

Cost components

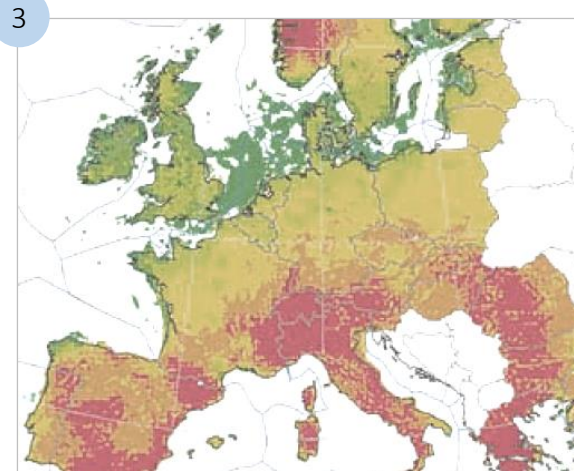
Electricity is a heterogeneous good along 3 dimensions



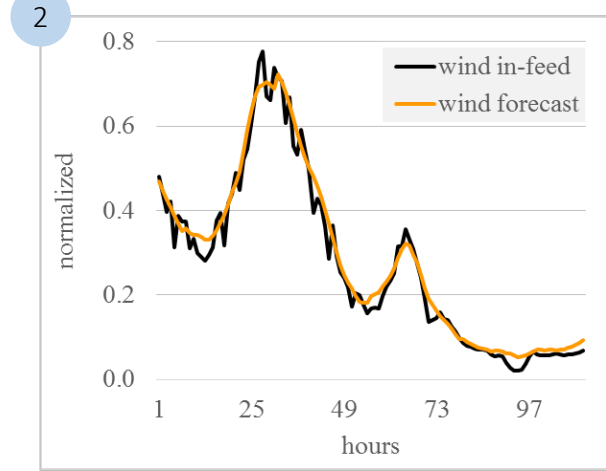
Wind and sun: “intermittent” or “variable” sources



Wind does not always
blow



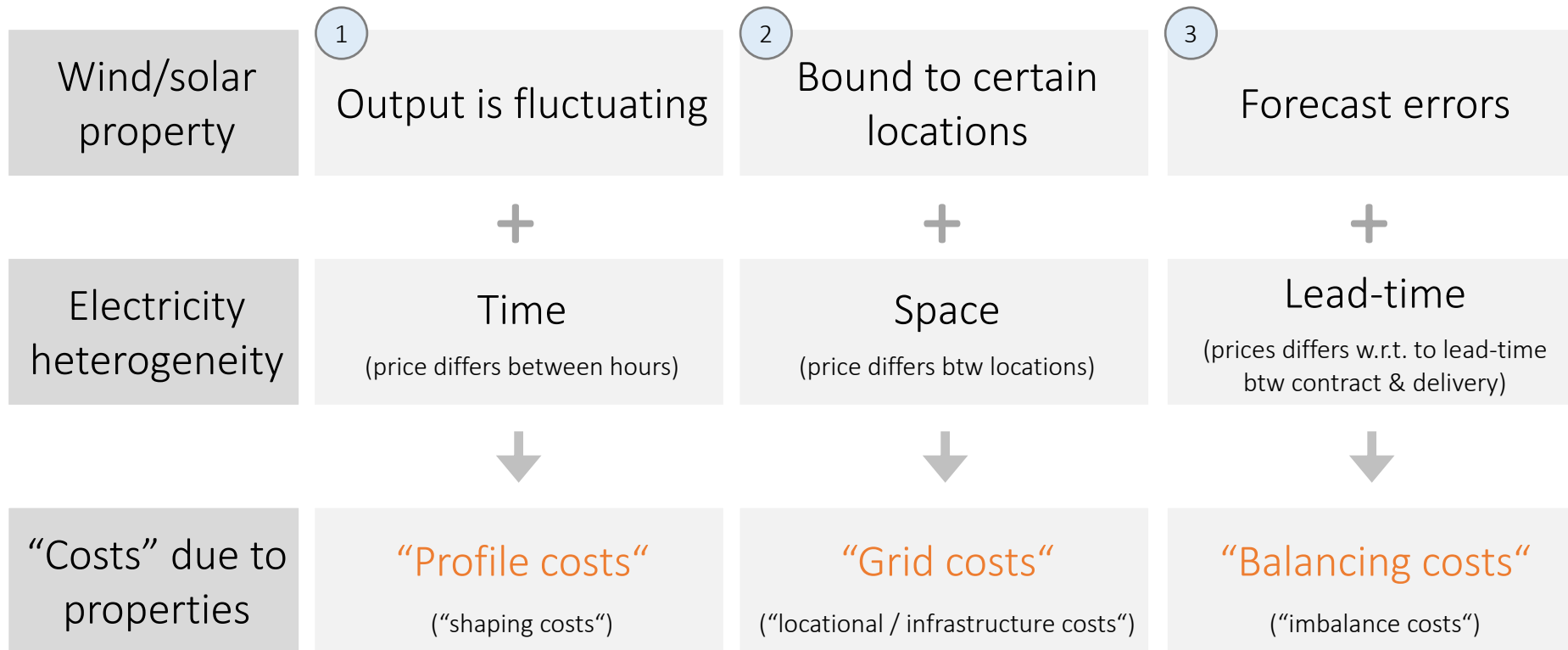
Good sites are distant from
load centers



Difficult to predict

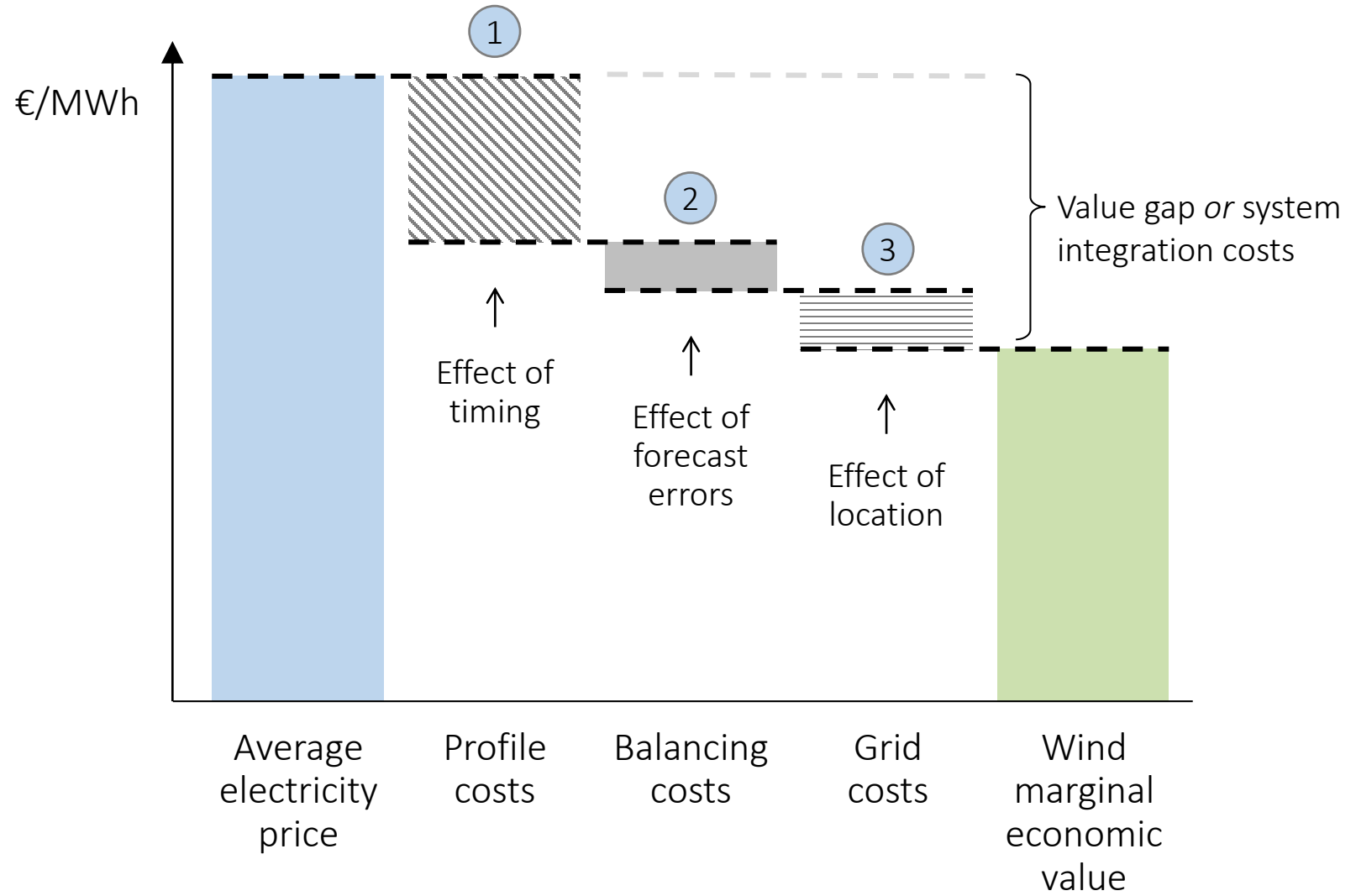
“Variable” renewable energy source (VRE)

Three properties of renewables *and* of electricity

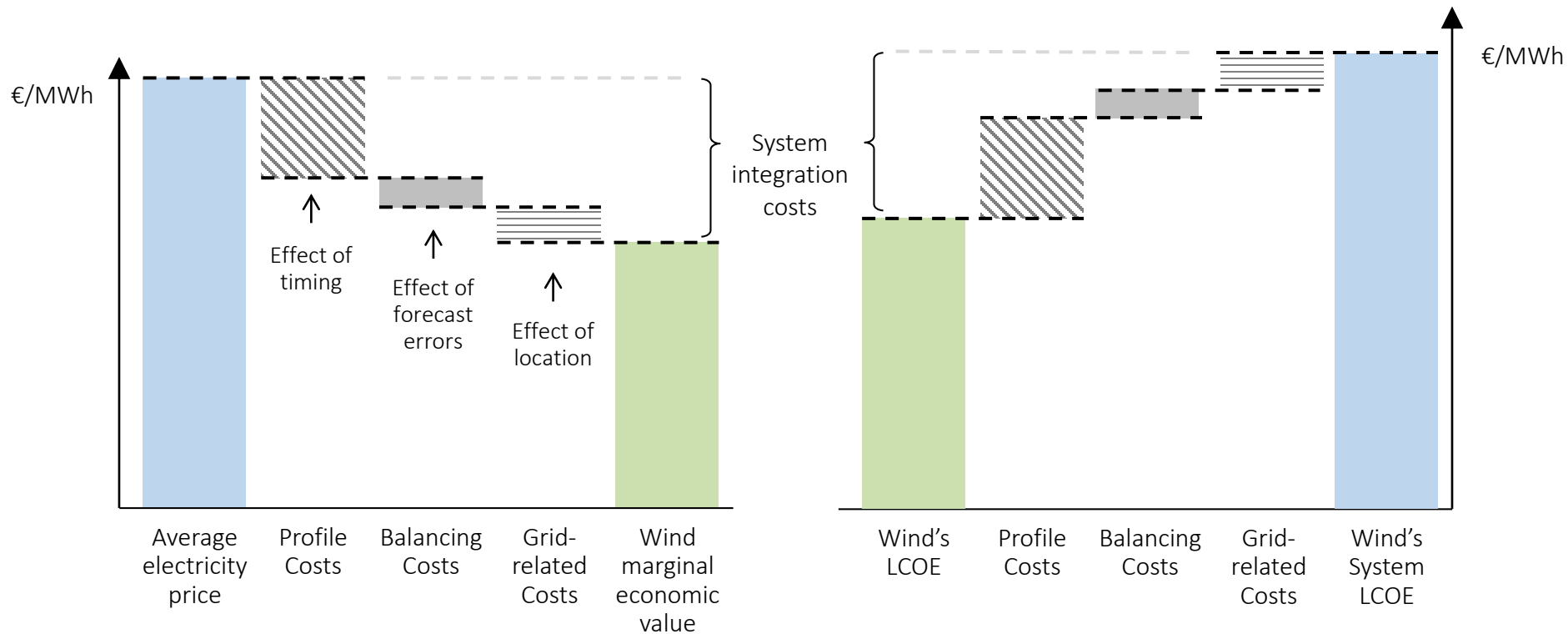


→ It is the *interaction* of VRE variability and price heterogeneity that is costly

The market value of wind energy



Value gap and system integration costs



In the long-term optimum, two equivalent optimality conditions hold:

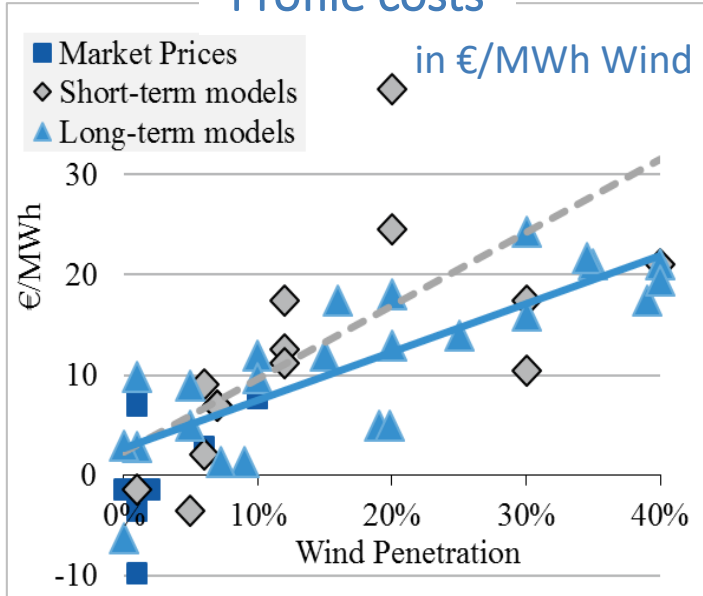
- (1) Marginal economic value = LCOE
- (2) Average Electricity Price = System LCOE

Quantification (for VRE)

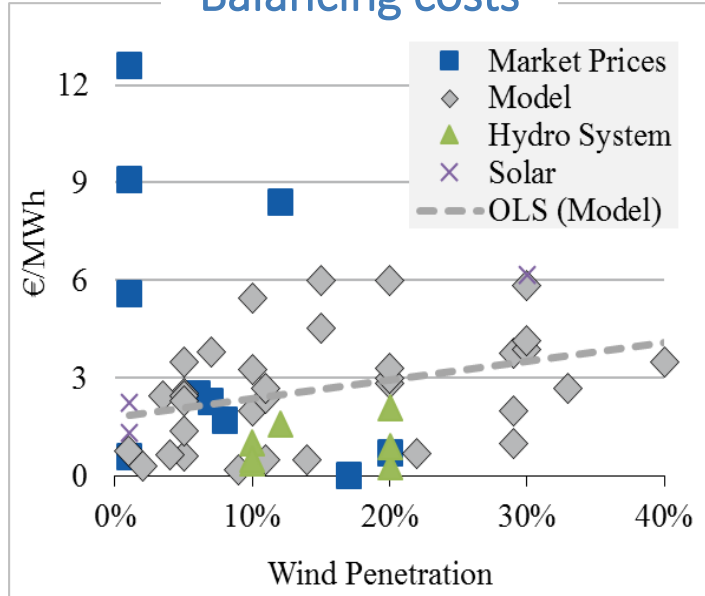
Literature review for wind from 2015

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)

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

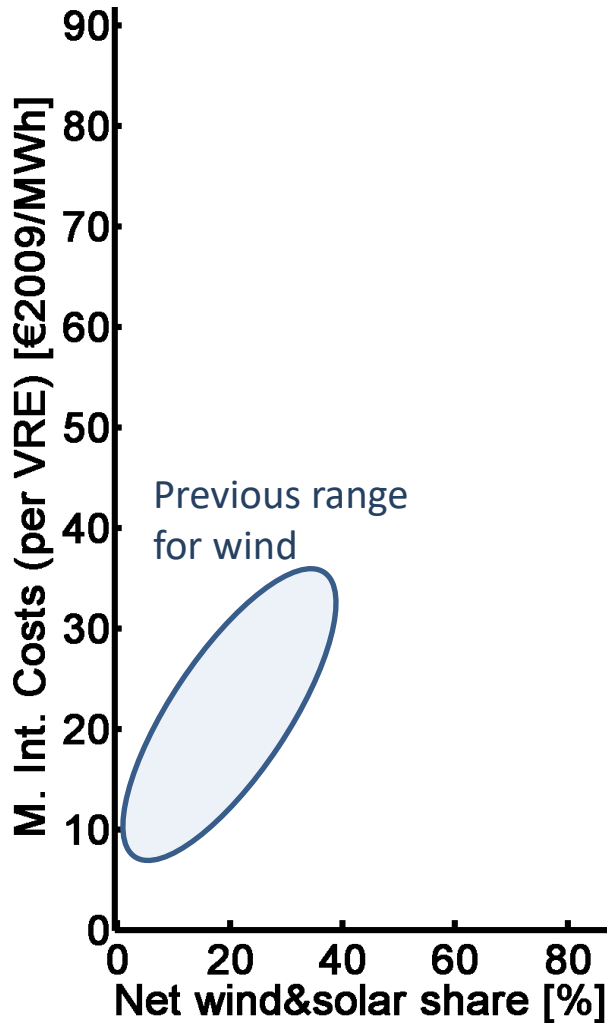
Flexibility options: EU grid expansion and ST/LT storage

No broad electrification

~2015 short-term storage cost expectations

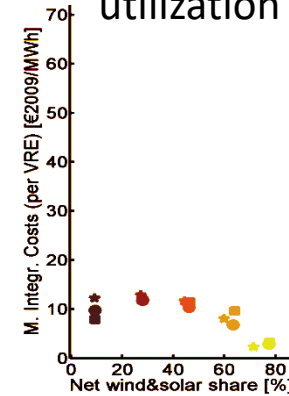
Integration costs with large grids and storage

(€/MWh VRE, marginal)

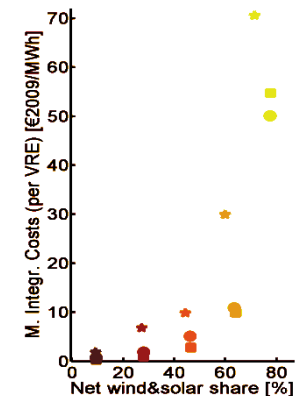


1. Profile costs

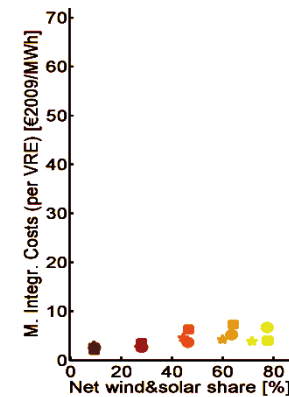
Reduced utilization



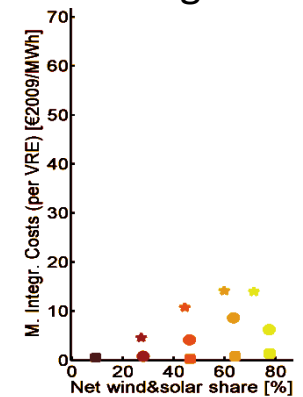
Curtailment



2. Grid costs



Storage costs



2021: literature review

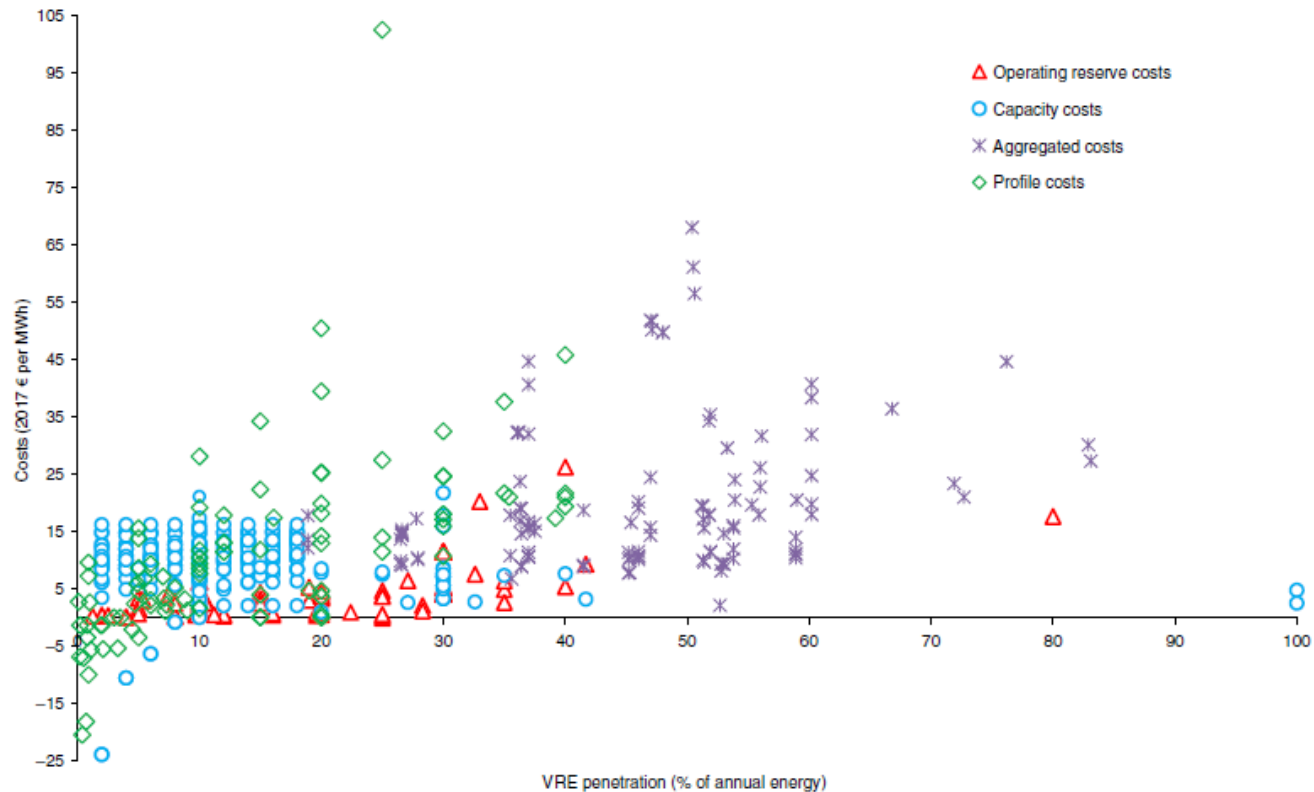


Fig. 2 | Data for operating reserve, capacity adequacy, aggregated and profile costs. Costs are normalized to 2017 Euro. The VRE penetration level is expressed using the most common metric found in the literature, that is, the percentage of annual electricity demand met by VRE. Approximately three-quarters 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. ^{16,37,24,33,37,44,49,74-86}. 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.

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)

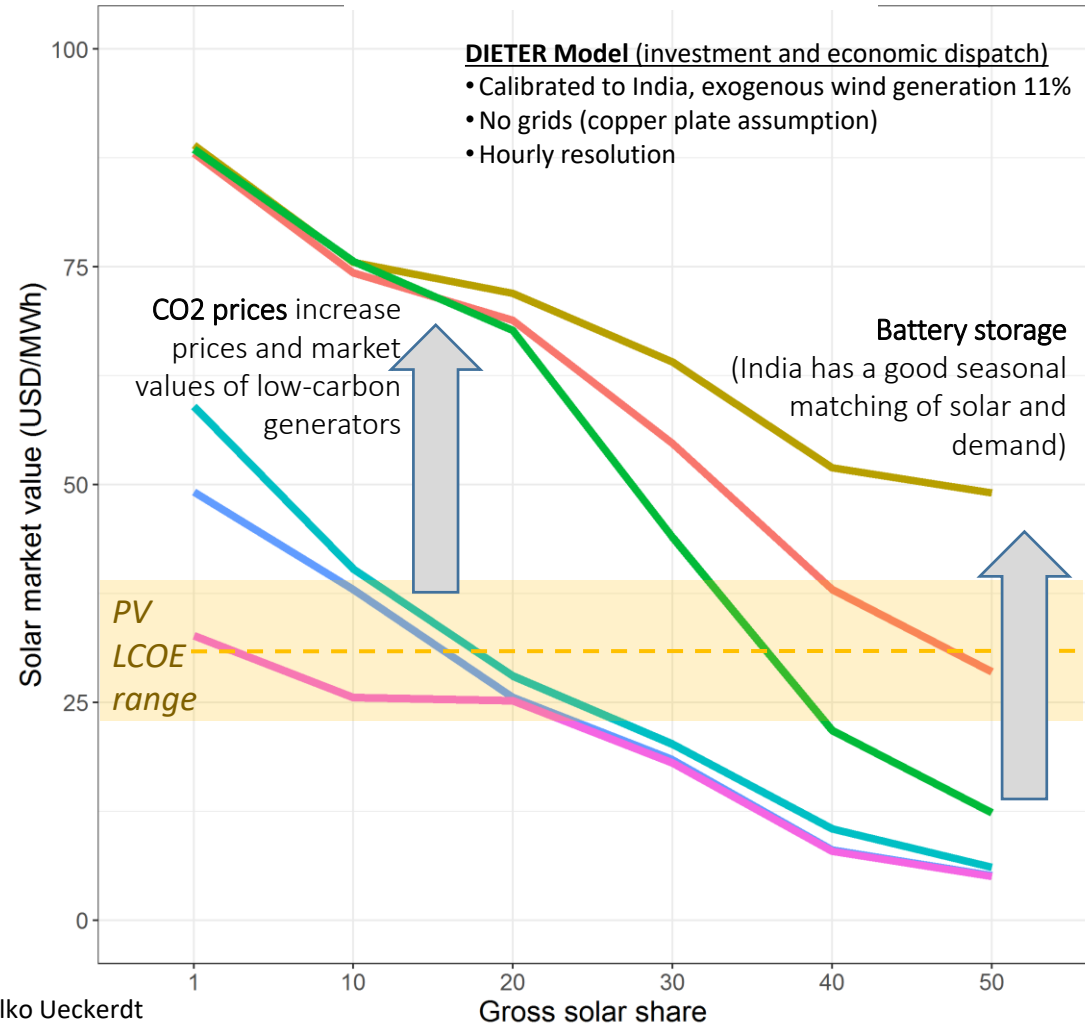
„Coal lock-in as in IEA-NPS“ (quasi BROWNFIELD)

(exogenous 421 GW coal, WEO, NPS)

→ **Optimal PV share ~0-20%**

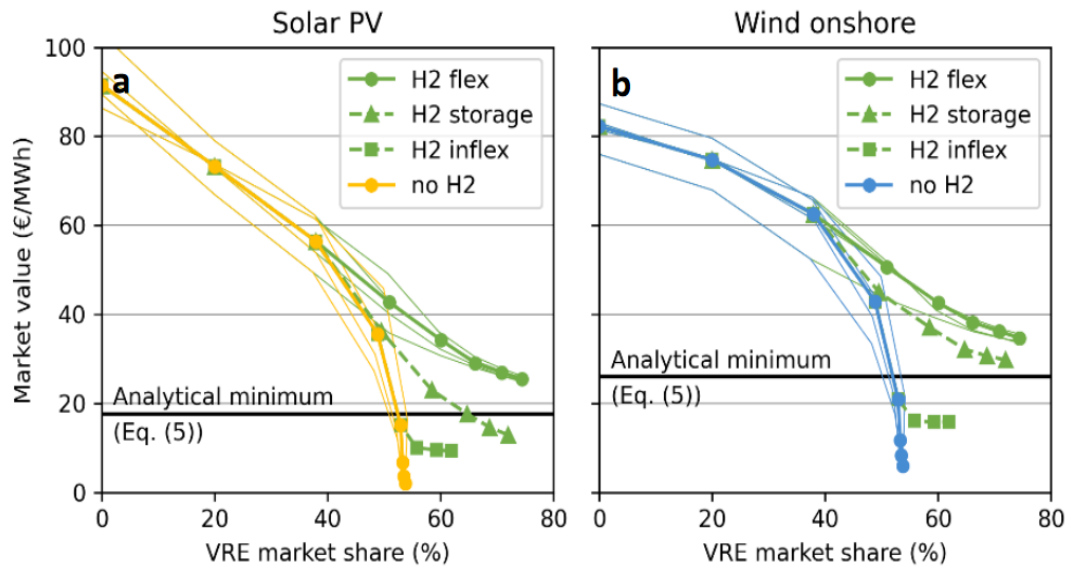
(without: batteries, AC, DSM, CO2 price)

India 2040, Solar PV market value

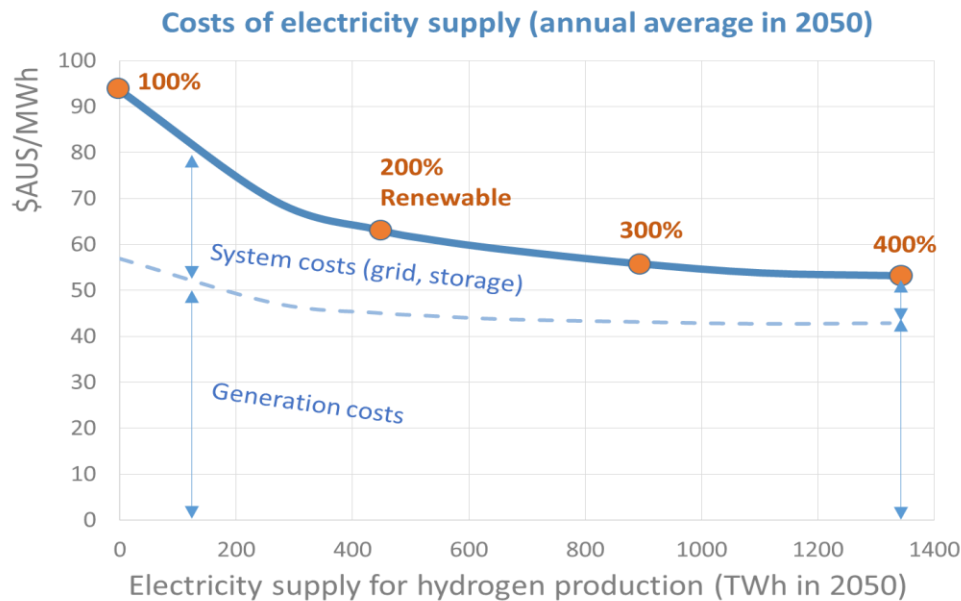


Source: PIK analysis (2019) by Murtaza Ershad, Robert Pietzcker, Falko Ueckerdt

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 10 (2015) 10–15

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Energy

journal homepage: www.elsevier.com/locate/energy

System LCOE: What are the costs of variable renewables?

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ABSTRACT

LCOE (levelized cost of electricity) are a common metric for comparing power generating technologies. However, there is a common specific focus on including variable renewables (wind and solar PV) (variable) power based on LCOE because it ignores variability and integration costs. We propose a new metric, System LCOE that accounts for integration and generation costs. In this paper we describe a new mathematical definition of integration cost that directly refers to reserves. Thus, as a result System LCOE allows for a consistent comparison of generation technologies and a consistent definition of integration cost. In this article we describe the new concept of System LCOE from a simple power system model and illustrate values. We find that at high wind shares integration costs can be in the same range as generation costs of wind power and conventional plants in particular due to a new component “variable cost” captured by the new definition. Integration costs increase with growing wind power, and might become an economic barrier to adopting VRE at high shares. System LCOE helps understanding and resolving the challenge of integrating VRE and can guide research and policy making in increasing a cost-efficient transformation towards an energy system with potentially high shares of wind and PV renewables.

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1. Introduction

Implicitly assumed that VRE deployment should be competitive and economically efficient once that LCOE dropped below those of conventional plants. However, there is qualified criticism towards this view. In particular, the fact that LCOE does not account for the cost of integration is a major concern. In particular, the fact that LCOE does not account for the cost of integration is a major concern. In particular, the fact that LCOE does not account for the cost of integration is a major concern.

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The market value of variable renewables^{a,b,c,d}

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ABSTRACT

This paper provides a comprehensive discussion of the market value of variable renewable energy (VRE). The inherent variability of wind speeds and solar radiation affects the price that VRE generators receive on the market (market value). During windy and sunny times the additional electricity simply reduces the price. Because the large wind farms have installed capacity the market value of VRE falls with higher penetration rates. This study aims to derive a better understanding on how the market value of generation and how the price of electricity affects the market value. Quantitative results are derived from a review of published studies, regression analysis of market data, and the calibrated model of the European electricity market (EMM). We find that the value of wind power is low. The value of the average power price is 30–40% as value based on a constant capacity. The value of solar power is even lower. The value of solar power is even lower than the value of wind power. The value of solar power is even lower than the value of wind power.

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1. Introduction

Electricity generation from renewables has been growing rapidly during the last years, driven by technological progress, increases of fuel, and equipment subsidies. Renewable, as one of the major power sources, is important throughout the world. The growth has been significantly in response to increasing demand and the rising cost of fossil fuels (ILO, 2012; IREC, 2013). According to official targets, the share of renewables in EU electricity consumption shall reach 35% by 2020 and 40–40% in 2050, up from 17% in 2008. As hydrogen potentials are largely exploited in many regions, and biomass growth is limited by supply constraints and sustainability concerns, much of the growth will need to come from wind, solar power, wind and solar power (renewable energy sources) (RES). In the longer term, wind and solar power (renewable energy sources) (RES) is the source that generates the most value as a result of its economic benefits. Following Hirth (2011), we define the market value of VRE as the revenue that generators can earn on markets, without income from

Renewable Energy 10 (2015) 10–15

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

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ABSTRACT

The integration of wind and solar generation into power systems causes “integration costs” – the grid, balancing services, more flexible operation of thermal plants, and reduction utilization of the capital stock. Integration costs are not flexible operation of thermal plants, and reduction utilization of the capital stock. Integration costs are not flexible operation of thermal plants, and reduction utilization of the capital stock. Integration costs are not flexible operation of thermal plants, and reduction utilization of the capital stock.

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1. Introduction

As with any other investment, wind turbines and solar cells incur direct costs in the form of capital and operational expenses. These costs have been called “hidden costs” (SIT), “system-level costs” (SIL), or “integration costs” (IC) (Hirth, 2011). These costs need to be added to direct costs of wind and solar power when calculating net economic value. Integration costs are relevant for policy making and system planning, ignoring or underestimating these costs is a bad framework regarding the welfare-optimal generation mix and the costs of system transformation. This paper proposes a balanced framework for variable renewables and offers a new perspective on integration costs.

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

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ABSTRACT

Electricity is a production economic good. It is highly homogeneous and heterogeneous at the same time. Electricity prices vary drastically between moments in time, between location, and according to lead-time between contract and delivery. This three-dimensional heterogeneity has implications for the economic assessment of power generation technologies; different technologies, such as coal-fired plants and wind turbines, produce electricity that has, on average, a different economic value. Several tools that are used to evaluate generators in practice ignore these value differences, including “levelized electricity costs”, “grid parity”, and simple macroeconomic models. This paper provides a rigorous and general discussion of heterogeneity and its implications for the economic assessment of electricity generating technologies. It shows that these tools are biased, specifically, they tend to favor wind and solar power over dispatchable generators where these renewable generators have a high market share. A literature review shows that, in a wind market share of 30–40%, the value of a megawatt-hour of electricity from a wind turbine can be 20–50% lower than the value of one megawatt-hour as demanded by consumers. We introduce “System LCOE” as one way of comparing generation technologies economically.

Keywords: power generation, electricity sector, integrated assessment modeling, wind power, solar power, variable renewables, integration costs, welfare economics, power economics, levelized electricity cost, LCOE, grid parity

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1. INTRODUCTION

In several parts of the world, it is cheaper to generate electricity from wind than from conventional power sources such as coal-fired plants, and many observers expect wind turbines costs to continue to fall. It is widely believed that this cost advantage by itself implies that wind power is profitable (in a private investment option or efficient for society). However, this is not the case. Inferring about competitiveness from a cost advantage would only be correct if electricity was a homogeneous economic good. If that was the case, one megawatt-hour of electricity generated

System LCOE Market value Integration cost Wind not coal

That will keep your attention!