The Decreasing Market Value of Variable Renewables

Integration Options and Deadlocks

Lion Hirth & Falko Ueckerdt

hirth@neon-energie.de

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The Decreasing Market Value of Variable Renewables: Integration Options and Deadlocks

*Lion Hirth**# and *Falko Ueckerdt**

* Potsdam-Institute for Climate Impact Research
# Vattenfall GmbH

Abstract

Wind and solar power are variable renewable energy sources (VRE) in the sense that their output is variable, subject to forecast errors, and that they are bound to certain sites. These three inherent properties reduce the income that VRE generators earn on markets (market value), especially at high penetration rates. The resulting lack of competitiveness could become a major barrier for the transition to renewable energy systems. This chapter explains the mechanisms that cause the decreasing market value, provides quantifications from model and market data, and discusses options to mitigate this value drop. Such integration options can be technological innovations, such as new storage technologies, based on investments of existing technologies, such as a shift in the generation mix from base load to peak load generators, or institutional, such as an appropriate design of spot and control power markets. We also indicate a few deadlocks, decisions that could turn out costly once high VRE penetration is reached.

Keywords: Variable renewables, market value, integration costs, integration options

1 The Decreasing Market Value of Variable Renewables

Electricity generation from renewables has been growing rapidly during the last years, driven by technological progress, economies of scale, and deployment subsidies. Renewables are one of the major options to mitigate greenhouse gas emissions and are expected to grow significantly in importance throughout the coming decades, [1]–[3]. As hydro power 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 and solar power. Wind and solar are variable[2] renewable energy sources (VRE) in the sense that their output is determined by weather, in contrast to "dispatchable" generators that adjust output as a reaction to economic incentives. Following [4], we define the market value of VRE as the revenue that

The findings, interpretations, and conclusions expressed herein are those of the author and do not necessarily reflect the views of Vattenfall or the Potsdam-Institute. Corresponding author: Lion Hirth, Vattenfall GmbH, Chausseestraße 23, 10115 Berlin, lion.hirth@vattenfall.com, +49 30 81824032.

[2] Variable renewables have been also termed intermittent, fluctuating, or non-dispatchable.

generators can earn on markets, without income from subsidies. The market value of VRE is affected by three intrinsic technological properties:

- The supply of VRE is *variable*. Due to storage constraints and supply and demand variability, electricity is a time-heterogeneous good. Thus the value of electricity depends on *when* it is produced. In the case of VRE, weather determines *when* electricity is generated, which affects their market value.
- The output of VRE is *uncertain* until realization. Electricity trading takes place, production decisions are made, and power plants are committed the day before delivery. *Forecast errors* of VRE generation need to be balanced at short notice, which is costly. These costs reduce the market value.
- The primary resource is bound to certain *locations*. Transmission constraints cause electricity to be a heterogeneous good across space. Hence, the value of electricity depends on *where* it is generated. Since good wind sites are often located far from load centers, this reduces the value of wind power (but might increase the value of solar, if located close to loads).[3]

At high penetration rates, these three properties reduce the market value of VRE. We compare the market income of a VRE generator to the system base price (Figure 1). The system base price is the average wholesale electricity price during one year. The effect of variability is called "profile costs", the effect of uncertainty "balancing costs" and the effect of locations "grid-related costs". The sum of all three are "integration costs" [6].

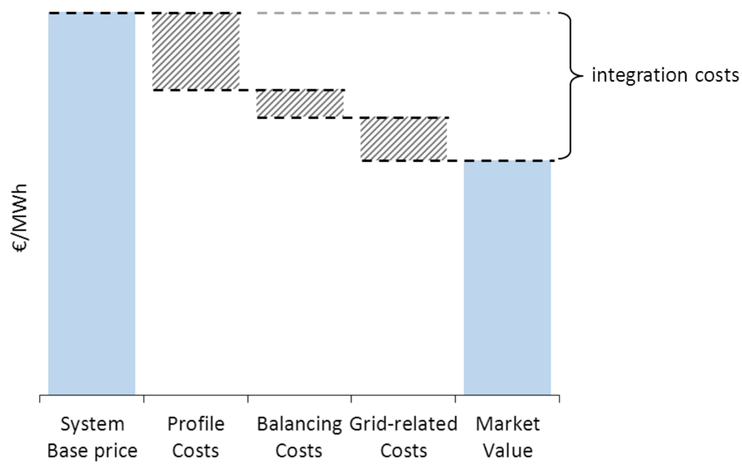


Figure 1: The system base price and the market value of wind power. The difference between those two can be decomposed into profile, balancing, and grid-related costs.

[3] Of course all types of generation are to some extend subject to expected and unexpected outages and are bound to certain sites, but vRES generation is much more uncertain, location-specific, and variable than thermal generation. Also, while weather conditions limit the generation of wind and solar power, they can be always downward adjusted and are in this sense partially dispatchable. The fourth typical property of VRE that is sometimes mentioned [5], low variable costs, does not impact the value of electricity.

Profile, balancing, and grid-related costs are not constant, but depend on a large number of factors and parameters. Most importantly, they are a function of the VRE penetration rate. The market value of wind and solar decreases with the penetration rate. Equivalently, one can say that integration costs of wind and solar increase with penetration (Figure 2).

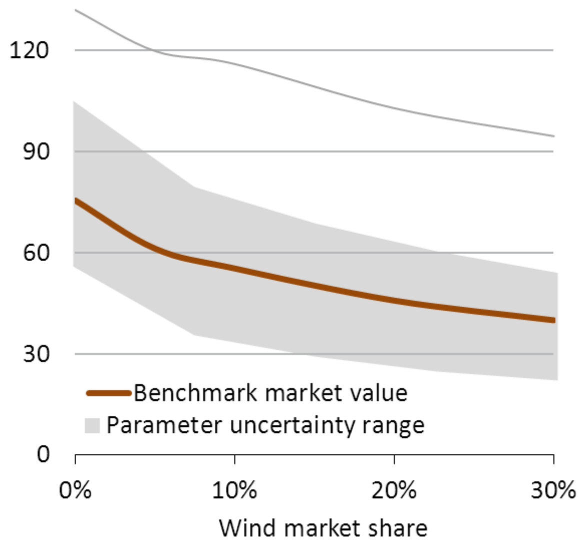


Figure 2: The market value of wind decreases with higher penetration. According to EMMA model results [7], wind power is worth 75 €/MWh at low penetration, but only 40 €/MWh at 30% market share. In all but one scenarios the value is between 20 €/MWh and 50 €/MWh.

This chapter is based on [6]–[8]. The techno-economic mechanisms that cause integration costs are discussed in section 2. Moreover, quantifications from the literature, market data, and model results are presented. Section 3 extends this work by discussing integration options. We use the term "integration options" as an umbrella term that encompasses all measures that help mitigating the value drop. While the principle mechanisms we discuss apply for all power systems, most examples taken from the European context.

2 Mechanisms and Quantification

This section discusses the economic mechanisms and the underlying technological constraints that cause the market value to decrease. We complement that with quantifications from previously published studies, model results, and market data.

There are two branches of literature that we build on. On the one hand, there is economic literature on the market value of VRE, such as [4], [9]–[15]. On the other hand, there is the “integration cost” literature, often found in engineering journals. Good overviews of this branch of the literature are given by [16]–[18]. In [8] we have tried to translate the findings of these two schools into a common terminology.

For the analysis, we sometimes report the market value not in absolute (€/MWh) terms, but relative to the system base price. We call this relative price the “value factor”.

Profile, balancing, and grid-related costs can be quantified from models or from market data. For example, profile costs can be either estimated from dispatch models, or from observed spot prices. Figure 3 summarizes VRE properties, respective costs, and quantification strategies. Results of quantification exercises are discussed in the following subsections. Because of their large size, we will discuss profile costs in most detail.

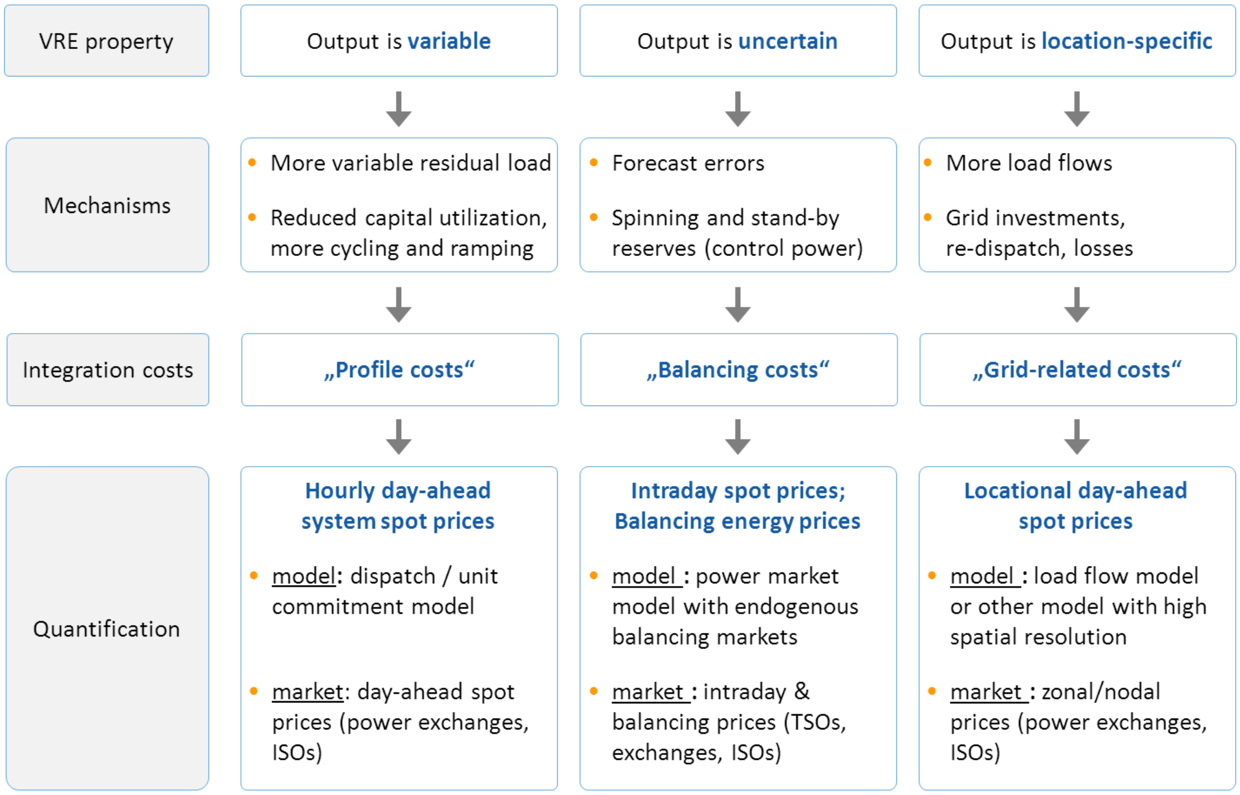


Figure 3: The three inherent properties of VRE, the corresponding costs, and possibilities for quantification from model and market data.

2.1 Profile Costs

Wind and solar power have variable costs of close to zero. They produce when the wind is blowing and the sun is shining – independently of the power price. In times of high wind speeds or solar radiation, VRE generate so much electricity that they reduce the electricity price. As a consequence, VRE "cannibalizes itself". The more VRE capacity is installed, the stronger is this effect.

Figure 4 displays the average price paid for electricity from wind and solar power in Germany relative to the base price (value factor) for the years 2001-12. As the wind penetration rate grew from two percent to eight percent, the price of wind power fell from 1.02 to 0.89 of the base price. As the solar penetration grew from zero to four percent, the solar value factor dropped from 1.3 to 1.05. These historical market prices confirm the model results presented in Figure 2.

The impact of solar power can be easily seen in the daily price structure (Figure 5). While historically, prices used to be high around noon due to high demand, now they are much reduced, because of the solar in-feed during those hours. In that way VRE reduce their own revenues and thus the market value decreases.

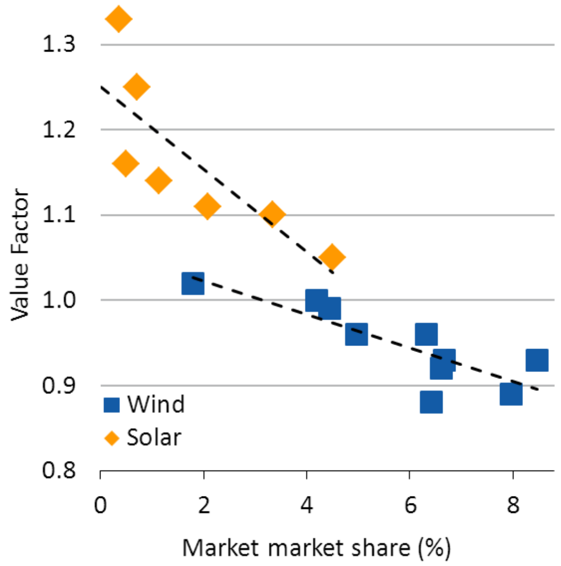


Figure 4: Historical wind and solar value factors in Germany. Data sources and methodology is discussed in [7].

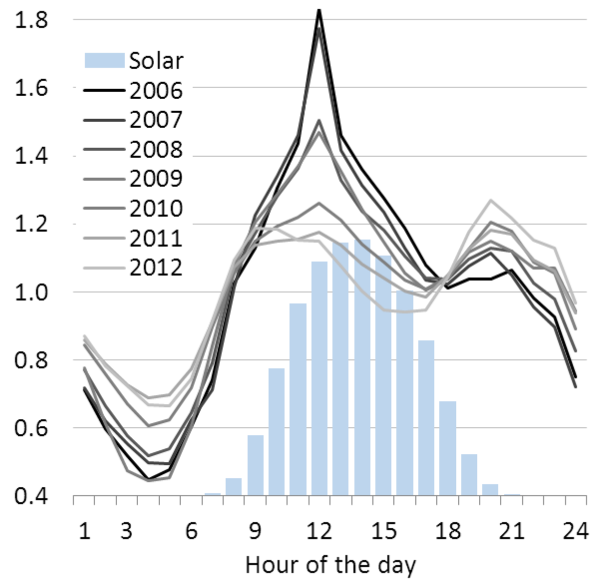


Figure 5: The daily price structure in Germany during summers from 2006 – 2012. The bars display the distribution of solar generation over the day, [7].

The value drop can be explained by the way the equilibrium price of electricity is determined. The price settles where the merit-order curve (short-term supply curve) intersects with residual demand (demand net of VRE generation). During windy and sunny hours the residual load curve is shifted to the left and the equilibrium price is reduced, which we call the "merit-order effect" (Figure 6). The more capacity is installed, the larger the price drop will be. This implies that the market value of VRE falls with higher penetration (Figure 7).[4]

At low penetration rates, before the merit-order effect comes into place, the value of wind and solar power is above the base price (at least in Europe). The reason is that VRE and demand are positively correlated, wind on seasonal time scales and solar on diurnal scales.

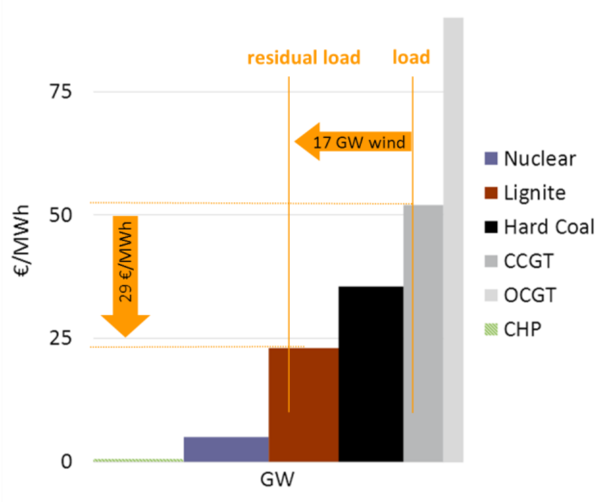


Figure 6: Merit-order effect during a windy hour: VRE in-feed reduces the equilibrium price (numbers are illustrative). This is the case in thermal[5] power systems.

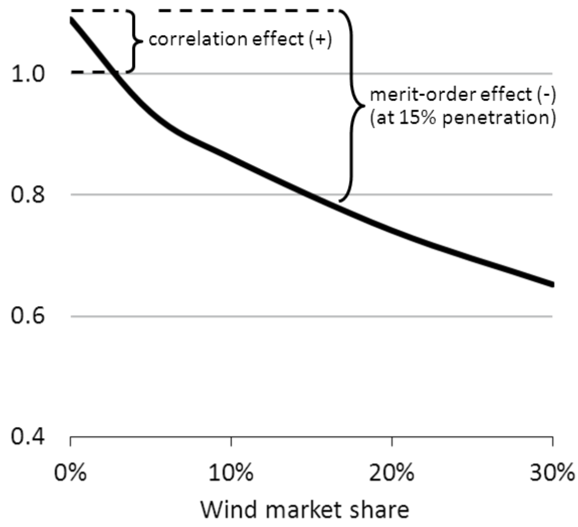


Figure 7: The wind value factor. The positive seasonal correlation increases the value of wind at low penetration rate. The merit-order effect reduces it at higher penetration rate.

Looking at profile costs from a system cost perspective, there are two underlying techno-economic mechanisms that cause these costs to arise. Intuitively, more variability causes more ramping and cycling of thermal plants ("flexibility effect"). This is costly because of part-load efficiency losses, start-up fuel costs, and increased wear and tear.

However, there is a less obvious, but economically more important mechanism: high VRE shares reduce the average utilization of plants ("utilization effect", [14]). This is costly, because the capital embodied in these plants is costly. Table 1 provides illustrative calculations based

[4] In economic terms, the equilibrium price clears the market by equalizing demand and supply. This mechanism is a universal principle and not confined to power markets. However, because electricity is very costly to store, its price varies strongly on short time scales (minutes to hours).

[5] "Thermal" (capacity-constrained) power systems are systems with predominantly thermal generators. These systems offer limited possibility to store energy. In contrast, (energy-constrained) "hydro" systems have significant amounts of hydro reservoirs that allow storing energy in the form of water.

on German load and in-feed data. As the market share of VRE increases from zero to 50%, the average utilization of thermal capacity is reduced from 70% to 39%.

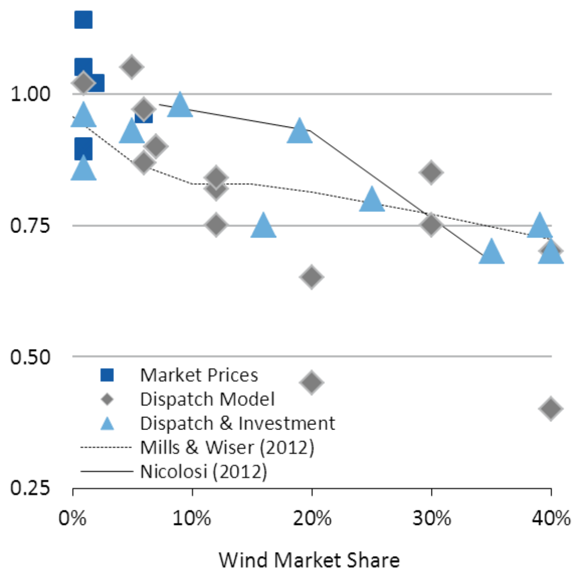
They are also the fundamental reasons why prices fall if residual demand decreases.

Table 1: Utilization of the residual generation capacity at increasing shares of VRE.

VRE share (% of consumption)	No RES	10% RES	20% RES	30% RES	40% RES	50% RES
Peak residual load ($GW_{thermal}$)	80	74	73	73	72	71
Residual generation ($TWh_{residual}$)	489	440	391	342	293	244
Utilization of residual capacity (in FLH)	70% (6100)	68% (6000)	61% (5300)	54% (4700)	47% (4100)	39% (3500)
Average utilization effect (€/MWh_{VRE})*	**0**	**10**	**20**	**24**	**30**	**39**

* Assuming 80 €/MWh_{VRE}, a constant average capital costs of the residual system of 200 €/KW*a, and a ration of wind to solar of 2:1 energy terms. For details, limitations, and sources see [8].

Having discussed the mechanisms, we come to quantifications of profile costs. Wind value factor estimates of around 30 published studies are summarized in Figure 8. At low penetration rates, wind value factors are reported to be close to unity. They are estimated to drop to around 0.7 at 30% market share. Solar value factors are reported to drop faster, so they reach 0.7 at 10-15% penetration rate (not shown). Figure 9 display model results from the North-European power system model EMMA, [7]. The value factor is estimated to fall to 0.5-0.8 at a penetration rate of 30%. Model results are consistent with the reviewed literature, and also consistent with the market data shown in Figure 4.



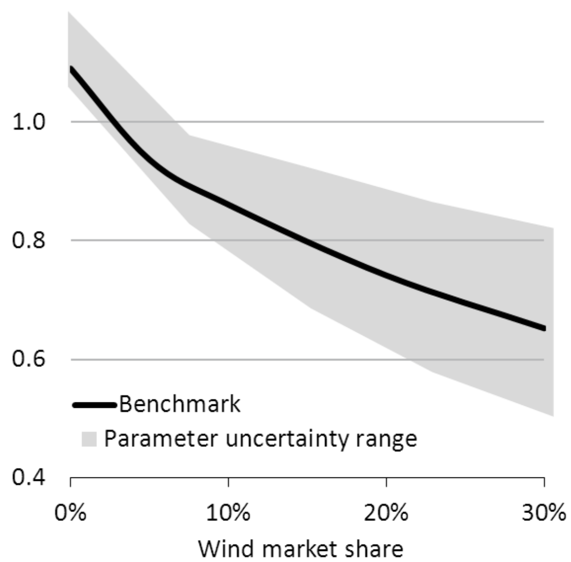


Figure 8: Wind value factors as reported in the literature. For a list of reference see [8].

Figure 9: Wind value factors as estimated with the energy system model EMMA, [7]. The benchmark run are best-guess parameter assumptions.

2.2 Balancing costs

Wind speeds and solar radiation are fundamentally stochastic processes; hence wind and solar predictability will always be limited. Realized VRE generation deviates from day-ahead forecasts. Balancing costs arise because balancing these forecast errors is costly. Those cost are caused by the capital costs of idle stand-by reserves, wear and tear due to cycling and ramping, and part-load efficiency losses.

[10] estimates balancing costs statistically to be around 3.6% of the value of electricity. [19] and [15] model balancing costs in unit commitment models and report them to be 3-5% of the base price. Surveying wind integration studies, [16], [17], [20], [21] report balancing costs below 10% of the base price, sometimes below 1 €/MWh.

Studies based on observed prices for balancing energy often find much higher balancing costs, for example [22]–[24]. However, [8], [25] report market balancing costs well below 10% of the base price.

Despite some conflicting evidence, we are quite confident to conclude that balancing costs are significant smaller than profile costs at high penetration rates.

2.3 Grid-related Costs

The quality of renewable energy resources varies across space. For example, windy sites with cheap land and little acceptance issues are typically located far away from load centers. This implies that adding large amounts of VRE to a power system increases load flows, which in turn increase network losses and tighten grid constraints. These are the reasons for “grid-related costs.” On markets, these costs are represented as locational marginal spot prices (nodal or zonal), or as geographically differentiated grid fees.

Quantifications of grid-related costs are sometimes reported in wind integration studies, [17], [26], and there are a few studies that use location prices, [27], [28]. However, results are very diverse for different power systems and methodologies. In general, grid-location costs are higher in geographically widespread power systems that can be found in the US and in Nordic countries, but lower in continental European systems that feature a more dense transmission network. In the thermal systems of continental Europe, grid-related costs are probably significantly smaller than profile costs.

Three robust findings emerge from this review. Firstly, integration costs are high. They can reduce the market value of wind and solar power to half of the system base price or less. Secondly, the market value decreases with penetration. Finally, profile costs are under most conditions larger than balancing costs, despite the latter seems to attract much more attention. Within profile costs, the utilization effect is more important than the flexibility effect.

An important consequence of the decreasing market value is that it is unlikely that wind and solar power will become competitive if deployed at large scale. However, there are a multitude of options that increase the market value of VRE.

3 Integration Options

The previous section explained why the value of wind and solar power decreases with penetration, and showed that this value drop can be very significant. However, there are a number of options to mitigate this. We call these options collectively "integration options." In this section, we first introduce a new taxonomy of integration options. Then, we will discuss options to tackle profile, balancing, and grid-related costs one by one.

During that discussion, it should be kept in mind that increasing the VRE market value is not an end in itself. Most (but not all) integration options are costly, and it is not clear if and to what extend these options are economically efficient. Only an integrated welfare analysis of the power system can reveal which integration options should be pursued.

Moreover, absent of externalities, market prices will incentivize all efficient integration options. Hence this section should *not* be read as a list of things policy should subsidize, but rather as a starting point for further research.

3.1 A Taxonomy

Integration options can be classified at least along three dimensions.

1. *Which* integration challenge is addressed: variability, uncertainty, locational specificity
2. *How* the challenge is addressed: the challenge itself is mitigated; or its economic impact reduced
3. The *type* of integration option: technological innovation, investments, market design

Table 2 summarizes this taxonomy as a matrix along the first two dimensions. Take the example of profile costs (first column). Profile costs arise because VRE variability increases the variability of residual load, thereby increasing specific (€/MWh) capital costs and cycling of plants. Some integration options, such as increased long-distance transmission, or a different wind turbine design with more even output, reduce the variability of VRE. Other integration options, such as a shift of the thermal generation mix from capital-intensive base load to peak load generators does not change VRE variability itself, but reduces the economic impact by reducing capital costs.

Table 2. A Taxonomy of Integration Options

	Profile Costs	Balancing Costs	Grid-related Costs
Challenge	*Variability*: residual load becomes more unevenly distributed and more volatile	*Uncertainty*: Forecast errors increase in absolute terms	*Locational specificity*: geographical distance between generation and consumption increases
Economic Impact (Cost Driver)	Reduced capital utilization (utilization effect) and more ramping and cycling of plants (flexibility effect)	Reservation and activation of fast-reacting reserves, for example control power	Grid congestion
Mitigate the Challenge	*Increase utilization of capital:* storage, transmission, DSM, different turbine layout, reduce must-run	*Make forecast errors smaller:* Improve weather forecasts, joint load-VRE forecasts, transmission	*Reduce mismatch*: move generation closer to loads, e.g. via technology shift from offshore wind to solar PV
Reduce Economic Impact	*Reduced capital intensity:* shift generation mix from base to peak load	*Provide quickly responding capacity:* more flexible thermal plants, improve spot market design, change control power market design, integrate control areas	*Reduce congestion:* grid investments, introduce locational price signals on spot markets

3.2 Profile Costs

The important driver of profile costs is the reduced utilization of the capital stock embodied in the power system, especially in thermal plants. To reduce specific (per MWh) capital costs, on the one hand, utilization can be increased. On the other hand, the capital intensity of the system can be reduced.

The by far most important mean to reduce capital intensity is a shift in the thermal generation mix from capital-intensive base load technologies such as nuclear power, but also lignite and lignite CCS to less capital intensive mid and base load generators such as open cycle and combined cycle gas turbines. Simple back-of-the envelope calculations indicate that at a VRE penetration rate of 50% no thermal plant will run more than 7000 full load hours, hence base load technologies are not needed at all (Figure 10). Turned around, investing today in long-living base load plants creates a barrier to high VRE deployment. This might be the most important potential deadlock for the transition to renewable energy systems.

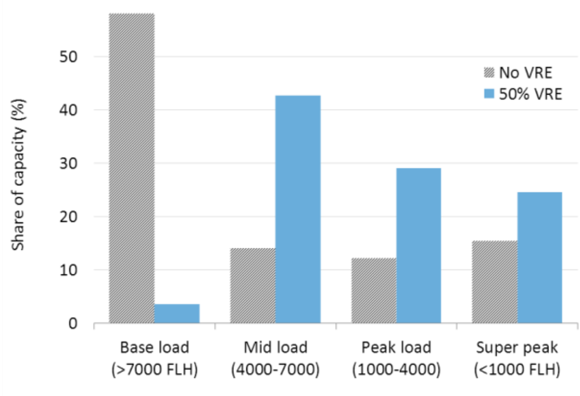


Figure 10: The cost-optimal distribution of thermal capacity without VRE and at a VRE share of 50%, [8].

A wide range of options exist to increase the utilization of capital in thermal plants and the rest of the power system:

- electricity storage
- demand response
- market integration of different thermal power systems
- market integration of thermal and hydro power systems
- options at the electricity-heat interface
- unconventional ancillary service provision
- different wind turbine design
- a more balanced mix of variable renewables

A discussion of technological characteristics, cost structures, or learning potentials of these options is beyond the scope of this paper. Instead, we focus on the qualitative impact that each option has on the market value of wind and solar power.

Very intuitively, *electricity storage* and *demand response* even out fluctuations of renewables and load and increase the utilization of thermal plants. Solar power fluctuates mainly on daily time scales, such that daily storage helps integrating solar, as do demand response activities that shift demand for a few hours. Wind power fluctuates more irregularly over a wide range of time scales; hence it requires more long-term storage. Since long-term storage is costly, electricity storage and demand response could be a more important option for solar power than for wind.

Integrating different thermal power systems via transmission investments and/or market design changes such as (flow-based) market coupling helps to keep up the market value, because fluctuations are smoothened over a larger geographic area, [29]. However, weather systems in Europe typically have a size of 1000-1500 km, such that transmission grids have to cover quite long distances for effective smoothening. For example, model results in [7] indicate that doubling the interconnector capacity between Northwestern European countries (not including

Nordic) would increase the value of wind by less than 1 €/MWh at a penetration rate of 30%. The impact on solar power is even less, since solar generation is better correlated than wind.

Integrating thermal with hydro systems is more promising. Reservoir hydro power can offer intertemporal flexibility and can readily attenuate VRE fluctuations. In Europe, flexible hydro plants are located in the Nordic countries, the Alps, but also in France and Spain. Making existing hydro flexibility in Norway and Sweden available to the European power system could be one of the crucial options to stem the value drop of VRE. Hydro power is an important integration options both for wind and solar power.

A failure integrate markets in Europe could produce an important deadlock. National solutions for market rules, capacity markets, and balancing settlement as well as sluggish interconnector capacity expansion would create a long-lasting barrier for VRE integration.

The *interface between heat and electricity* offers a number of flexibility options (which might be also classified as storage or demand response). A prominent example is the application of heat storages at combined heat and power (CHP) plants which has been pioneered in Denmark. Model results in [7] indicate that the impact on both solar and wind market value could be very large in systems with significant CHP generation. Other possibilities is to include heat pumps or direct electrical heating in heating grids, or combine heat storages with heat pumps of micro-CHP in small scale heating systems. However, some of these measures are opposed to the ambition to increase energy efficiency.

Ancillary services such as control power and voltage support are today usually provided by synchronized generators. During the time they provide these services, generators typically have to be dispatched ("must-run"). As an alternative, control power can also be provided by loads, variable renewables, or storage units. Voltage support can be provided by phase-shift transformers or power electronics such as the converters that are already installed in wind turbines and photovoltaic systems. It is important that grid codes and market design does not prevent the entry of these unconventional technologies intro ancillary service markets.

The *design of wind turbines* has a large impact on the variability of their output. By increasing hub heights and the ration of swept area to electrical capacity wind turbines are able to provide more stable output. Modern wind turbines are already designed to run about 3000 FLH, while historically they have often delivered only 2000 FLH or less.

Finally, *the renewables mix* could be adjusted to reduce overall VRE variability. Wind and solar output combined is less variable than the output of each technology separately. Future technologies that are variable, but uncorrelated or even anticorrelated to wind and solar generation could improve the mix further. However, potential technologies such as wave power are quite far away from being commercially deployed.

Some have argued that because of the decreasing VRE market value, the current energy-only wholesale markets should be transformed, [30], [31]. However, the value drop is *not* the consequence of a flawed market design. It efficiently reflects the economic costs of variability. We believe energy-only markets are well suited to integrate large amounts of VRE.

Figure 11 summarizes the effect of four of the discussed integration options as modeled in EMMA. All integration options increase the long-term market value of wind significantly, by 4-

7 €/MWh or 10-18%. However, while integration options can mitigate the value drop, they cannot prevent it.

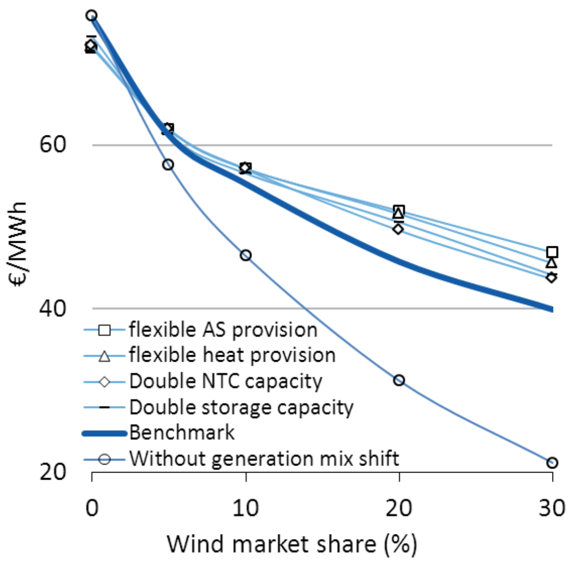


Figure 11: Some integration options modeled in EMMA. The benchmark value is the same as in Figure 2. A flexible provision of ancillary services (AS) or district heating as well as increasing interconnector (NTC) or storage capacity increases the market value. Not allowing the capital stock to adjust dramatically reduces the value.

3.3 Balancing Costs

There are four broad options to reduce balancing costs: reduce forecast errors, make existing flexibilities available for provision of balancing services, create new sources of flexibility, and geographical integration of control areas. While the first option tackles the problem itself (forecast errors), the other three reduce its economic impact. Each option will be discussed in turn.

Improved meteorological models and the use of real-time generation data can help to significantly reduce forecast errors of wind and solar power, especially for short prediction horizons ("nowcasting"). In systems where VRE generation and load are negatively correlated (solar power and cooling demand; wind power and heating demand) the joint forecast of VRE generation and load can reduce overall forecast errors. Sometimes market design changes might be necessary to set the right incentives for these technological changes. As [32] emphasize, a single price balancing settlement system with marginal pricing provides efficient incentives.

Existing flexibility resources that can provide balancing services at low costs should be activated by opening the respective markets. Liquid intra-day markets with short gate-closure times (one hour and less) and short contract durations (15 min and less) allow VRE generators to use continuously improving weather forecasts. Intra-day markets could replace day-ahead auctions as the most important spot market. Lowering entrance barriers to regulating power markets is crucial to allow small generators, loads, storage facilities, and foreign suppliers to bid into the market.

In the long run, existing sources of flexibility might not be sufficient. Thermal and hydro plants with higher ramping capabilities and lower minimum load might be needed. In addition, many of the options that were listed in section 3.2 could also provide fast-responding flexibility.

Integrating a larger geographic region into one control area helps balancing VRE and other forecast errors. Since 2009, the four German TSOs cooperate closely, which helped to bring down the need for regulating power provision despite a strong growth of VRE capacity.

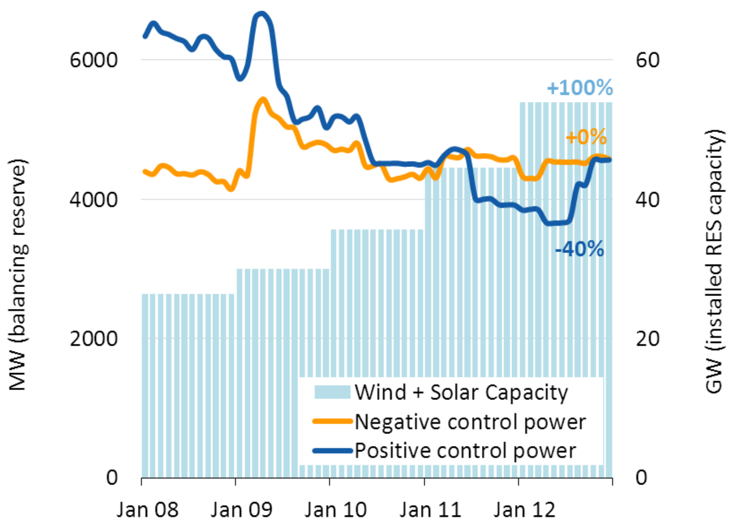


Figure 12: Reserved control power capacity could be reduced by 20% despite a doubling of VRE capacity in Germany. The main reason for this is a cooperation of TSOs. Figure from [33].

3.4 Grid-related Costs

Probably there is only one sensible measure to reduce grid-related costs: investments in transmission grids. Back-of-the envelope calculations suggest that relocating generators or even loads is almost always more expensive than building transmission lines. Model results confirm this [34].

4 Concluding remarks

This chapter has discussed the decreasing market value of wind and solar power as a barrier for the transition to renewable energy systems. VRE feature three distinct properties, variability, uncertainty, and locational specificity. These characteristics cause the market value of electricity from wind and solar power to decrease with higher penetration. Equivalent, one can say that "integration costs increase." In many cases, the market value drop is so strong that it probably overcompensates learning effects and cost decrease. Hence, without changes in the energy system, wind and solar power will never become competitive at large scale and subsidies would be needed to reach ambitious policy targets.

We propose a taxonomy to structure "integration options" and discuss a number of them. Integration options are measures that increase the market value of VRE at high penetration rates. However, increasing the market value is not an end in itself, and without a cost-benefit analysis we cannot say if these options make sense from a welfare perspective. Having said that, we believe there are a number of "no regret options" that should be done independently of renewable deployment: transmission investments, making intra-day markets more liquid, lowering entrance barriers to control power markets, market coupling of spot and control power markets.

On the other hand, there are a few actions that decrease the market value of variable renewables. Important deadlocks are large investments in base load generation technologies, or national solutions instead of European market integration.

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