Flexibility options in power systems: A benefit analysis on the market value of variable renewable energy

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Abstract

The market value of variable renewable energy sources (VRE) such as wind and solar decreases at increasing shares of the respective generation type. The hypothesis of the present contribution is that this effect can be mitigated by increasing the flexibility of the underlying power system. To verify and quantify this hypothesis, a MILP market model is used to assess the impact of different flexibility options, namely energy storage, international network transfer capacities (NTC) and increased flexibilities in the conventional power plant fleet, on the market value of renewables in Central and Northern Europe.

Keywords: Market Value of renewable energies, Storage, Network, Power market design

1 Introduction

To comply with the emission reduction target under the Paris Agreement, high shares of renewable energy sources will be introduced into the power system in future. Increasing the share of VRE cost efficiently is one crucial precondition to maintain societal and political support. However, under the current market design, self-cannibalization of renewables will decrease their market value at increasing VRE shares and thereby increase the integration costs [1]. Understanding the mechanisms and the magnitude of the impact of flexibilities on preventing this value drop is at the centre of this contribution. It thereby helps to realistically assess the thread of increased market value drops.

The approach of this study is to analyse the market value decline in different power systems taking into account various degrees of storage availability and international network capacities. For this aim, the market value (MV in € / MWh) of a generation type i is used according to the common definition:

$$MV_i = \frac{\int_{t=0}^{T} P_{\mathrm{gen},i}(t) \cdot p_{\mathrm{m}}(t)\,\mathrm{d}t}{\int_{t=0}^{T} P_{\mathrm{gen},i}(t)\,\mathrm{d}t}$$

It represents the average remuneration a generator can expect from the electricity generated. The ratio of market value and the load weighted average wholesale electricity price is called market value factor (MVF) and is an indicator of how valuable the generated electricity is. If generation occurs at times of low electricity prices, the market value factor is low and vice versa.

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Various authors already analysed the impact of VRE shares one the market values (e.g. [2–6]). Hirth [3] presents an overview of empirical past developments and analytical future developments of the VRE market values. His findings show a severe value decline. With the help of a greenfield investment model, he compares various central European countries and briefly discusses the impact of storage and transmission development. However, in the used model called EMMA the storage operation is strongly simplified and technical constraints on power plant flexibility are not considered. The resulting electricity price profile fluctuates little. This shows that with a strongly simplified linear programming (LP) model, storage operation can intrinsically have only minor effects. This modelling only allows for a rough estimation of general trends but will always underestimate the value of storage. Consequently, the presented findings of a weak impact of storage and transmission capacities on the market value decline represent only the lower boundary.

Most other studies also use LP optimization and therefore show similar weaknesses when assess the role of storage and to a lesser degree that of transmission [6–8]. The question whether storage is systematically underestimated is even more important since many of these studies stated generally that both storage and transmission have only minor impacts on reducing the value decline of VRE [4, 9, 10]. Only when interconnecting thermal and hydro power regions absolute market values increase in all regions involved whereas market value factors in hydro based regions decline [6, 11].

However, the existing literature gives only a rough estimate on the issue. Assessing the impact of storage and interconnection requires a more detailed modelling with high variances of the resulting electricity price.

Building on top of existing research, this paper contributes mainly in the following two aspects:

i. Compared to previous research on market values, a more sophisticated description of energy storages and modelling of plant (in-)flexibilities is used by applying a mixed-integer linear programming (MILP) model formulation. This results in a more realistic electricity price profile, which fluctuates throughout the day, and consequently the use-rates of storage and interconnections are higher.
ii. ENTSO-E’s TYNDP scenario for the development of the power plant fleet including politically agreed renewable targets is used instead of a market-based investment model. A second aim of this contribution is therefore not only to obtain general findings but also to access the impact of flexibility option in the years to come when following the European renewable targets.

In the present contribution, the influence of storage, interconnection and power plant fleet are analysed. Nevertheless, many other aspects could have an impact on the renewable market value as well. The most relevant factors are (1) larger hub heights and decreasing specific power ratings which smooth the wind generation [8, 10]; (2) east-west orientation of solar panels to increase solar output in the morning and evenings [7]; (3) reducing the must-run requirements and ramping times of conventional capacities; (4) demand side flexibility, (5) fuel prices, (6) market design like nodal pricing or the market power of few market participants. In the following analysis these parameters are kept constant and are not assessed.

2 Model

For a meaningful analysis of the described research question, a detailed model of inherent flexibilities and inflexibilities of the power system is necessary. For this purpose, the open source model DISPA SET from the Joint Research Centre of the European Commission is employed [12]. The model is formulated as MILP which enables simulating individual plant commitment. The goal of the unit commitment problem is to minimize the short-term costs of electricity generation by simulating the hourly dispatch of generation units. Each generation facility is considered with inherent constraints on ramping rates, up and down times and minimum partial load. Additionally, the model considers decreasing efficiencies at reduced load and costs for starting and ramping of plants. The storage operation includes perfect foresight for one day. Thereby, the potential of short-term storage is evaluated. Transmission restrictions within the studied countries are not part of the investigation due to the considered spatial resolution. However, interconnection between countries as a means of offsetting diverging VRE generation in different geographic areas is considered. Hence, the simulation is run for all included countries simultaneously to optimize the use of network transfer capacities and to prevent unrealistic assumptions for import and export availabilities. The following European countries are included in the assessment and selected because their rather strong interconnection: Germany, France, Poland, Czech Republic, Austria, Switzerland, Netherlands, Belgium, Luxemburg, Denmark, Sweden and Norway. For further information on the model formulation please refer to the detailed model description of DISPA SET [13].

2.1 Input data

Input data of the model influence the quality of the simulation results. Table 1 summarizes the most important time-series. Other parameters are given in Table 2 as well as in the Annex. Since many parameters vary for distinct generation units, the variable costs for different plants differ from each other. This leads to a Merit Order curve which is much less simplified than in a LP formulation.

Table 1: Input time series data and source

Data	technology	source
Availability factors	Photovoltaic, On- and Offshore wind	*2015 historical data from Open Power System Data [14]*
	Bioenergy	*Own calculation based on historical generation from Open Power System Data [14]*
Outage factors	Nuclear, Lignite, Hard Coal, Gas turbines	*EEX Transparency, data for Germany 2015, data processing by Philip Beran [15]*
Inflow data	Hydro run-of-the-river	*Own calculation based on historical generation from Open Power System Data [14]*
	Hydro dam	*Own calculation based on historical generation from Open Power System Data [14]*
Electricity demand		*ENTSO-E, TYNDP 2018 dataset* [16]

Table 2: Overview of additional data

Data	Source
Installed capacities	*ENTSO-E Transparency Platform [17] and IRENA database [18] for historical data, ENTSO-E TYNDP for future years [16]*
Network transfer capacities (NTC)	*2010: ENTSO-E NTC Summer Values 2010 [19]* *2020, 2030: ENTSO-E Transparency Platform [17] [17, 19]*
Power plant data	*Data collection from various papers and studies [20–22], detailed overview in the A*
Storage data	*Currently installed storage capacities (in MWh) taken from an assessment by the JRC of the EU Commission [18]; Maximal generation (in MW) taken from ENTSO-E [17]*
Fuel Prices	*ENTSO-E TYNDP data for 2020 [16]*

2.2 Output data

Based on the input data and given constraints, the model optimizes the dispatch of all power plants and the use of energy storages. As a result, the marginal costs of electricity in each country can be deducted as shadow price of electricity production. Moreover, the amount of curtailed renewable generation and the resulting cross border flows result from a model run.

3 Results

Within the analysis, the market values are compared for different scenarios to assess the impact of the flexibility options. As a reference case, installed capacities for the Sustainable Transition Scenario are taken from the Ten Year Network Development Plan 2018 (TYNDP 2018). It was developed by the European Network of Transmission System Operators (ENTSO-E) for their network planning and evaluation. This scenario describes a possible pathway from today until 2040 which reaches European GHG emission goals through national regulation, emission trading schemes and subsidies by maximising the use of existing infrastructure [16]. In all, it is a realistic and at the same time ambitious trajectory for VRE expansion in Europe.

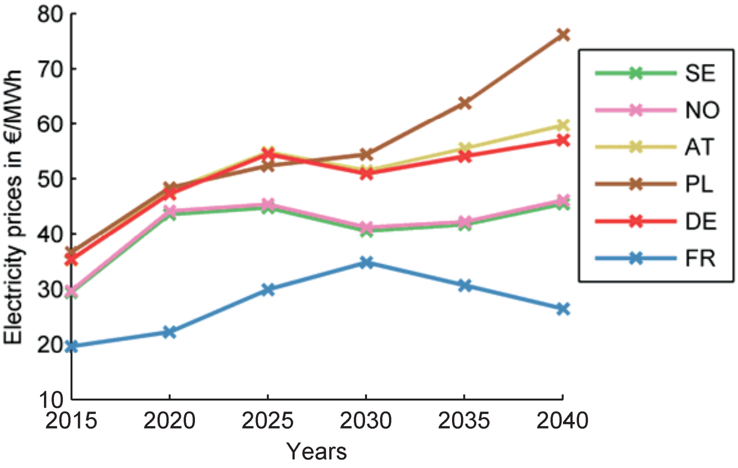

Figure 1: Development of averaged electricity prices

The modelled averaged wholesale prices for selected countries are shown in Figure 1. For details regarding the resulting share of technologies on power generation confer to Figure 4 in the Annex.

The effect of the nuclear phase out in Germany in 2022 can be seen. The generated power is mainly compensated for by natural gas and renewables. This translates into rising wholesale prices – in Germany but also in neighbouring countries, especially Austria. Also note the remarkable discrepancies in wholesale power price levels. Most striking, electricity prices in France are significantly lower than in countries dominated by coal and gas fired power generation due to the high amount of nuclear power with relatively low short-term costs. Derived from this reference scenario, alternative scenarios are modelled and the variation of the market value of renewables is compared. The results are presented in this chapter.

3.1 Intrinsic flexibility of the power system

First, some quantitative findings on the impact of flexibilities within the power system are presented. The development of the MVF in the reference scenario for selected countries is shown in Figure 2. In accordance to literature, the correlation of high wind shares on total generation (shown by the pie charts) and declining market value factors can be clearly seen. Equally, the fact that large hydro availability lowers the MVF drop can be retraced. Comparing Sweden, Austria (modelled as uncoupled power market from Germany), France and Germany with each other, one can see that similar shares of wind generation correspond to very different market value factors. Out of these countries, Austria has the highest hydro shares and a rather flexible remaining generation capacity mainly comprising gas fired power plants (Figure 4). Sweden differs from France by a much higher hydro share; beyond that both countries rely mostly on nuclear. The inflexibility of nuclear power plants to quickly adapt their power generation, leads to a strong market value decline of renewables once total wind generation surpass the buffer of hydro generation: Figure 2 shows that this flexibility offered by hydro is much larger in Sweden than in France. Germany shows the strongest decline of market value factors. Its inflexible strongly coal reliant power generation leads to strong market value declines in times of significant renewable generation. Norway appears to be a counterexample, since its system is almost entirely based on hydro power. However, the declining MVF depicted is exclusively due to the interconnection with Sweden and the

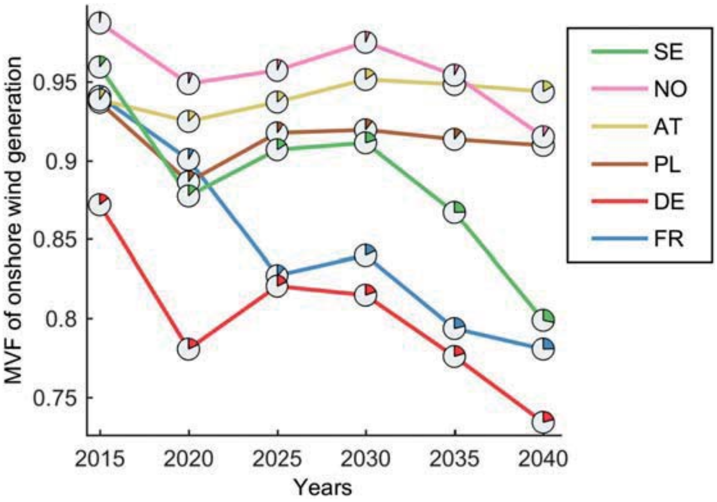

Figure 2: Development of the MVF in selected European countries Onshore wind shares of total power generation are shown in the pie charts)

correlation of wind availability factors[3]. When modelling Norway isolated, the market value factor for onshore wind remains constant over time (not shown here).

The particularly low MVF in several countries in 2020 is eye-catching. In the following, two explanations are given for Germany[4]. First, a strong increase of VRE capacities into a relatively inflexible power system leads to a strong MVF decline from 2015 to 2020. An only slightly increasing national demand (+2%) stands in contrast to a significant national generation increase (+5%). However, average electricity prices are rising (cf. Figure 1) and above the level of most neighbouring countries (except for Denmark, not shown in the figure). Consequently, surplus electricity is increasingly exported at times of high VRE generation and low prices. Rising averaged prices and declining MV of wind lead to this strong decline of the MVF. Additionally, curtailed power increases drastically from 4 000 MWh in 2015 to 200 000 MWh in 2020. Note that the model does not take into account remuneration schemes; curtailed power in the model occurs therefore already at market prices of zero. Since curtailed power is accounted for generation at the calculation of the MVF but has a zero price, it contributes strongly to a decreasing market value.

Second, by 2025, the overgeneration is reduced via the nuclear phase out. Additionally, the share of more flexible power generation from gas fired power plants increases strongly. Subsequently, curtailment remains at a constant level, despite rising wind shares. This is another indicator of how a flexible power system reduces the MVF decline. On this basis, further research will be made on the effects of very inflexible generation types such as nuclear and coal power plants.

Generally spoken, the composition of the power generation fleet has a strong impact on the market value decline. However, LP optimization models which cannot consider individual plant constraints mainly investigate on the form of the merit order curve. They find for countries with a flat merit order on the usual price setting technologies, that the volatility of electricity prices is low; this results in a positive effect on the MVF. In contrary to that, a steep merit order fosters more price fluctuation which leads to declining MVF at increasing VRE shares [23]. With the use of a MILP model, constraints on ramping rates and start-up times can be assessed as well. The full value of the availability of flexible power generation facilities such as hydro dams and gas fired plants can thereby be assessed. Comparing the merit order curves for Sweden and France for the year 2025 shows an example of this issue. In the model results, both countries will generate power in 2025 from variable renewables, hydro and nuclear power. However, the shares of nuclear and hydro vary: Sweden has relatively seen a higher hydro generation capacity,

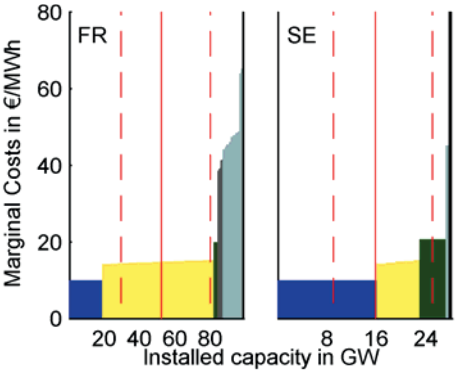

Figure 3: Merit order for France and Sweden in 2025. The red lines mark maximal, minimal and average demand

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[3] Medium Pearson correlation coefficient of onshore wind availability factors between Norway and Sweden r = 0.58. The strong interconnection between both countries can also be seen in the very similar price development

[4] Germany explained in detail since it has strong effects on its neighbouring countries. Especially the polish MVF decline can be explained through Germany due to a high correlation of onshore wind availability factors (Pearson correlation coefficient r = 0.72). The correlation between German and Swedish wind availability is lower (r = 0.32).

whereas France has a higher share of nuclear power. Still, the merit order for both countries is relatively flat. The demand average and extreme values show that nuclear and water are theoretically always sufficient to meet supply (compare Figure 3). In a LP model, the electricity price would in that case only vary between the marginal costs for hydro and the marginal costs for nuclear. Since the difference of variable costs for both technologies is rather small, a LP model will show a small decline of MVF. In contrast, the MILP model shows a significant value drop (compare Figure 2). This is caused by inflexibilities of nuclear power plants to ramp down fast enough. Instead, renewable energy is curtailed causing a cost which is lower than the ramping costs for nuclear implying electricity prices of zero. This example shows that a MILP model has strong advantages when modelling plant inflexibilities compare to LP models and that the impact of the power plant fleet is often underestimated in literature.

3.2 Flexibility of storage

The impact of additional storage capacity on the market value development shall be analysed. To get qualitative results on the potential to reduce the market value decline, the reference scenario is modified by adding storage capacity of one Megawatt installed power and one Megawatthour installed storage capacity with an efficiency of 90% in a chosen country. By doing so, it will be analysed whether a marginal impact of storage can be found. It will be interesting to compare these results over the course of time and throughout different countries.

Additionally, the impact of a large-scale role out of PV and storage systems in Germany will be analysed and its potential impact on the market value decline of PV generation assessed. To do so, an alternative scenario is designed. For half of the installed PV capacity, additional storage is installed. For the year 2020, first findings reveal that these additional storages lead to a decrease of the wholesale price levels by around 2%. As expected, the additional storage has a stronger impact on solar generation than on wind. For Germany, the solar market value factor increases slightly from 0.90 to 0.92 at a solar share of 10% on total power generation.

3.3 Flexibility of transmission capacities

To get a magnitude of the benefit of additional transmission capacities on the market value of renewables, the transmission grid is expanded on its forecasted level of 2030. For the year 2020, the reference scenario adapted by this grid expansion is compared to the calculation based on the original grid levels from 2015. The MVF of these two scenarios will then be compared. First findings reveal an expected decline for wholesale prices in Germany. Although absolute market values decline, MVF increase slightly by 0.7 percentage points for the case of solar, by 1.2 percentage points for onshore wind and by 1.1 percentage points for offshore wind. Further research shall give more insights on the impact grid expansion has in different countries.

4 Conclusion

This contribution used a MILP model to give a qualitative overview of the impact of selected flexibility options on the market value decline of variable renewable energy sources. First, the selected countries were analysed and differences resulting from inherent (in-) flexibilities of the underlying power systems were pointed out. The qualitative review showed that the composition of the power sector has a significant impact on the market value decline of renewables. Moreover, the use of a more complex MILP optimisation model was justified. Second, the role of storage on the market value decline was briefly assessed on the example of PV storage in Germany. Third, transmission capacities were evaluated based on further network enhancement. Further research will need be conducted on the latter two aspects. An interesting question is how the benefit of additional transmission and storage capacities evolves over time. It is likely that the role of these flexibility options will increase when VRE shares rise.

Finally, one last commend on the results shall be made. Although this paper shows how flexibility options affect the market value of VRE, this should not be read as recommendation for further subsidies. Absent of externalities, an economic equilibrium of storage capacities and VRE shares results from a fixed amount of VRE subsidies. The promotion of storage capacities shifts the market equilibrium towards slightly higher renewable shares since they economically benefit from the additional flexibility as shown in this contribution. Yet, since additional storage is not a target per se, regulators should not subsidise them to promote renewables indirectly. On the other side, this contribution shows that reducing barriers for storage operation – such as double taxation or difficulties to access the market – may indirectly impact market conditions for renewables.

Acknowledgements

The results presented here are based on calculations carried out on the cluster system at the Leibniz University of Hannover, Germany.

5 Annex

Table 3 Parameterisation of power plant

Technology	**Efficiency range** *in %*	**Min. up time** *in h*	**Min down time** *in h*	**Ramping rate** in % of P_{non} / min	**Starting Costs** in € / MW	**Ramping Cost** in € / MW_{ramp} MW_{nom}	**Min. partial load** *in %*	**Efficiency at partial load** in % of η_{nom}	**CO_2 Intensity** in t_{CO_2}/MWh_{el}	**O & M Costs** in € / MWh_{el}	**Max. Plant size** *in MW*
Lignite	29 - 44	8	8	7	260	0.5	55	86	0.9	4	1200
Hard Coal	32 - 45	6	6	1	251	0.7	45	90	0.81	4	600
Gas – Simple Cy.	50 - 58	3	4	1.5	44	0	70	85	0.36	4	550
Gas – Combined Cy.	35 - 40	1	0	10	33	0	40	78	0.55	5	400
Nuclear	30 - 35	12	12	1	850	2	60	95	0	8	1500
Oil	37 - 42	1	0	7	45	0	20	78	0.79	4	300
Photovoltaics	100	0	0	100	0	0	0	100	0	0	-
Offshore Wind	100	0	0	100	0	0	0	100	0	0	-
Onshore Wind	100	0	0	100	0	0	0	100	0	0	-

Run-of-the-Ricer	85	0	0	100	0	0	0	100	0	10	-
Hydro dam	80	0	0	100	0	0	0	100	0	10	-
Hydro pump storage	75 - 80	0	0	100	0	0	0	100	0	0	-
Biomass	42 - 50	0	12	2	251	0	40	93	0	5	-
PV Storage	100	0	0	100	0	0	0	100	0	0	-

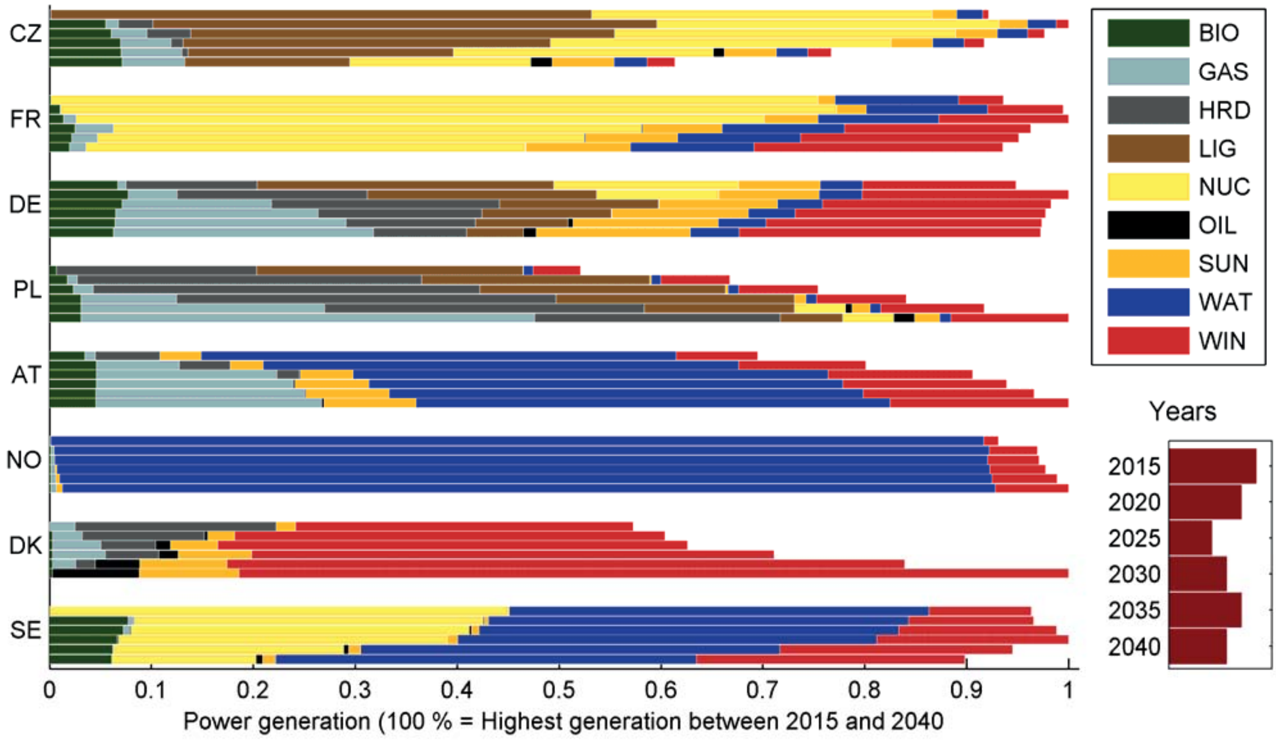

Figure 4: Simulated power generation by fuel type in the reference scenario (selected countries)

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