THE MERIT-ORDER AND CANNIBALIZATION EFFECT OF THE VARIABLE RENEWABLE ENERGY SOURCES AND ITS MITIGATION MEASURES

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Abstract

Over the past two decades, global efforts to reduce carbon emissions have driven a shift in electricity generation from traditional fossil-based sources, such as coal and gas, to variable renewable energy (VRE) sources, including wind and photovoltaic power. However, because these sources often generate power simultaneously, they can cause oversupply, which—when coupled with the way electricity prices are determined in the market—depresses electricity prices. This phenomenon is known as the merit-order effect. Furthermore, as more VRE capacity is installed, the resulting decline in prices reduces the revenues of these producers, thereby undermining the market value of additional renewables. This direct consequence of the merit-order effect is referred to as the cannibalization effect. Numerous mitigation strategies have been proposed in the literature, such as energy storage, carbon taxes, and sector coupling, each with its own advantages and limitations. In this paper, we review the literature on the cannibalization effect and explore how proposed countermeasures interact in both theoretical and practical contexts. Finally, we highlight the lack of literature assessing the economic feasibility of certain interventions and emphasize the need for a modeling framework that identifies the most cost-effective policy mix to address these challenges.

Key words: merit-order, cannibalization effect, energy storage, sector coupling

JEL Code: Q41, Q42, Q48

Introduction

The global shift towards renewable energy has played a crucial role in addressing the challenges of climate change. Variable Renewable Energy (VRE) sources, such as wind and solar, have gained prominence thanks to their low operating costs and minimal carbon emissions. According to the Statistical Review of World Energy (Energy Institute, 2024), wind and solar contributed more new energy, about 460 GW and 67% more than the previous year, to the global mix in 2023 than any other source. The total share of renewable energy in the global mix rose to a record of 14.6%, underscoring the accelerating pace of the clean energy transition.

However, integrating these sources into electricity markets presents significant challenges, most notably, the merit-order effect. This occurs when low-cost renewable energy sources, since their generation peaks at the same time, temporarily displace more expensive conventional sources, pushing down electricity prices. While this temporarily benefits consumers, it reduces the revenue streams for VRE producers, threatening the financial viability of new projects and discouraging further investment. This effect is compounded by the high upfront costs of renewable infrastructure. Although VRE technologies are environmentally sustainable, their market performance often suffers in systems not designed to accommodate high levels of renewable penetration. The decline in profitability with the increase of the VREs market share, commonly referred to as the cannibalization effect (Hirth, 2013), represents a major hurdle to continued investment in renewables precisely when their expansion is critical to achieving global sustainability targets.

Both the merit-order and cannibalization effects are well documented in global electricity markets for example by (Halttunen et al., 2020), (Pena et al., 2022) or (López et al., 2019), and numerous policy measures have been proposed to mitigate it (Mills & Wiser, 2014), (Brown & Reichenberg, 2021). These have been well studied individually and each has its drawbacks. For example, with higher penetration of VREs, the need for energy storage and thus their costs increase faster than linearly (the more variable energy sources I have, the more I need storage to balance variability), for example (Zerrahn & Schill, 2018) modeled storage needs of Germany and to go from 80% to 100% renewables, the necessary storage tripled; carbon pricing loses effectiveness at higher levels of renewable penetration as market sensitivity to carbon taxation decreases with increasing penetration, because there is less generation affected by the tax, (Brown & Reichenberg, 2021). Real-time pricing has limited feasibility like cost of infrastructure (Sioshansi & Short, 2009), limited elasticity of consumers (Roscoe & Ault, 2010). The full-scale sector coupling requires more mature P2X technologies (Ramsebner et al., 2021). The way these measures interact, however, and the question of what constitutes the optimal mix remains insufficiently explored.

1 Merit-order and cannibalization

At any given time, the spot market electricity price is determined by the marginal cost of the cheapest available electricity generation technology that meets the demand. Ranking the electricity sources by their marginal costs is called the merit-order. When adding variable renewable energy sources such as wind and solar that are known to have the marginal cost of generation basically zero into the generation mix, according to the merit order they are the first in line to sell their electricity. As their penetration grows, the chance of them (or a different technology having slightly higher cost) meeting the demand is higher, resulting in lowering the average electricity price. This phenomenon is known as the merit-order effect and has been measured to some extent in most of the electricity markets. For example, (Gelabert et al., 2011) estimated roughly €1.86 /MWh, around 4%, price decrease for every additional GWh of renewable electricity production in Spain. Similar study has been done on Italian power market by (Clò et al., 2015) reporting declines of €2.3/MW (3.3%) for solar and €4.2/MWh (6%) for every GWh added. While the merit-order effect is measurable in almost any market, its magnitude can vary heavily. (Tselika, 2022) used quantile regression to compare the merit-order effect of wind in Germany and Denmark, which turned out to differ by order of magnitude (around €0.193/MW and €5.515€/MW on average), contributing it to market structure differences, generation mixes and installed capacities. A thorough review of the results of the merit-order effect and its estimation on most of the global markets has been done by (Halttunen et al., 2020). They report a global average merit-order to be €0.68±€0.54/MWh for every additional percentage point of VRE penetration.

The cannibalization effect of variable renewable energy sources is a direct consequence of the merit order effect. Even though more renewables penetration drives down electricity prices during sunny and windy periods, which is beneficial for consumers, it also shrinks the revenues of producers making it less appealing for potential new investors to come in. The concept of renewables lowering revenues, be it their own or those of conventional generators, has been known before in the literature. A popular metric to measure this is the value factor, calculated as the ratio between the average renewable's revenue, wind for example, to the average electricity price overall. Values less than one indicate that renewables earn less than the average producer on the market.

One of the main approaches in cannibalization modeling is using the historical price and generation data to calculate the value factors and then applying regression or other econometric techniques to find their trends and significant variables affecting them (such as

VRE penetration). In California according to (Mills and Wiser, 2014), initially when the penetration is low, the value factor is around one for wind and even greater than one for solar. On penetration levels of 40% and 30% respectively, it falls to 0.6 and 0.28. Other studies such as (Nicolosi, 2012) report similar trends. (Hirth, 2013) came with novel econometric approach to model how the variable renewables market values change with their penetration, and this has been one of the standards of cannibalization estimation ever since, replicated (with some improvements) in (López et al., 2019) or (Pena et al., 2022).

Another stream of literature is theoretical, trying to find the expressions describing the value factors analytically. Most recently (Reichenberg et al., 2023) employed a stochastic analytical model deriving closed form expressions for the expected revenues and their variance under cannibalization. According to their model, cannibalization lowers profit relative to the investment cost from 33% to between 13% all the way to -40% depending on the assumed future VRE capacity expansion. These models, however, are usually quite complicated, even before considering some of the cannibalization mitigating strategies that we are going to mention in the second chapter.

A different way of modelling cannibalization, if we do not want to rely on historic conditions, are bottom-up energy dispatch models, usually using linear optimization. These models represent the energy system in detailed technological terms and optimize system operation or investment to minimize costs or emissions. Besides cannibalization estimation, they are also useful for capturing the impact of variable renewable energy on system dynamics and technology competition. (Hirth, 2013) created European Electricity Market Model (EMMA) that specifically calculated the market value of renewables for different levels of penetration. (Zerrahn & Schill, 2017) introduced a more general Dispatch and Investment Evaluation Tool with Endogenous Renewables (DIETER) model which was meant to find the optimal combination of generation, demand side management and storage that minimizes cost. (Zerrahn & Schill, 2018) then used it to analyze the role of storage under high renewables penetration.

2 Mitigation measures

The cannibalization effect obviously goes against the global efforts to transform the energy sector into (close to) zero net emissions state. (Mills & Wiser, 2014) suggested multiple mitigation measures such as building new energy storage, real-time pricing, geographic diversity of generation and sector coupling. (Brown & Reichenberg, 2021) theorize that a carbon tax is an effective policy to avoid cannibalization.

There are many options of energy storage, however two of the most promising, with respect to efficiency and speed of dispatch, are hydrogen electrolyzation (Ruhnau, 2021) and batteries (Mallapragada et al., 2020). This solves the poor time-transferability problem of electricity. The energy storage provides demand in periods of high VRE generation and makes it possible to sell the electricity later in time of scarcity for better price, reducing price swings and raising the average marginal value of VRE. It can be shown by a simple argument that if we had zero cost, sufficiently large energy storage, the value factor of renewables would be 1. In practice things are not so simple however. (Mallapragada et al., 2020) report that often the storage value is not enough to compensate its costs and (Cloete et al., 2020) conclude that using only hydrogen electrolysis leads to low capacity utilization and includes heavy infrastructure costs.

Under real-time pricing, consumers shift flexible loads into periods of high renewable output (when prices drop), increasing demand precisely when VRE is available. This elevates low-price hours and improves the capacity value of renewables. (Sioshansi, 2009) showed in his dispatch model that real-time pricing increases market value (revenue per MWh) of wind energy by cutting its integration (“redispatch”) costs and eliminating lost-load events, which has a similar effect to the energy storage, at least at zero costs.

By diversifying the locations of variable energy sources, the probability of meeting generation peaks at individual power plants is reduced, which "flattens" the supply curve and thus reduces the cannibalization effect. (Eising et al., 2020) did a study on wind energy in Germany and concluded that while diversifying geographicaly certainly makes sense, it is not enough just to spread the generation uniformly, in which case the market value actually declined faster. One has to diversify between areas with high but little correlated outputs.

Allowing other sectors such as heating or transportation causes greater flexibility in the market and the possibility of absorbing cheap energy at times of high generation by variable sources. (Bernath et al., 2020) conducted a scenario analysis which showed multivalent district heating grids increased VRE market value significantly. On the other hand, the effect of electric vehicles charging turned out to be small.

The last measure we researched is the carbon tax, which has been a feature of many electricity markets for years. Rather than directly subsidizing renewables, it increases the marginal cost of fossil-fired generation by internalizing CO_2 emissions. Whenever a conventional power plant sets the clearing price, that price now reflects both its fuel cost and the CO_2 levy, lifting wholesale rates precisely at times when wind and solar injections would otherwise depress them. Empirical work for Germany shows that each additional €1 / t CO_2 raises wind's average market value by about €0.91 /MWh and solar's by about €0.87 /MWh, meaning a carbon price near €40 / t CO_2 is sufficient to neutralize the self-cannibalization effect at current penetration levels (Liebensteiner & Naumann, 2022). In contrast with technology-specific support schemes which depress effective bids and thus suppress spot prices whenever renewables run, a rising CO_2 price uniformly shifts up the supply curve of all polluting generators. In long-term, cost-minimizing power-system models, this means renewables' market values remain anchored at their levelized costs regardless of their share, avoiding the decline in average revenues that characterizes subsidy-driven expansion (Brown & Reichenberg, 2021). In other words, carbon taxation not only addresses the externality of greenhouse-gas emissions but also counteracts the merit-order effect that would otherwise erode renewable revenues.

From an economic perspective, all the policies above are simply ways to better allign supply with demand to reduce extreme price movements in systems with high VRE penetration. The effect of the measure on cannibalization has been well studied in the literature, however some important adjacent questions have not yet been answered in the literature.

First it is not clear whether all of them are economically viable, meaning if the investment costs, for example building a sufficiently large energy storage, are justifiable against the revenue recovered by the VRE producers and if they are not, how big of a cost reduction is needed. Second, the possible synergies between the measures have not been modeled. Even if a policy turned out not viable on its own, it can still potentially be beneficial with others. For example according to (Liebensteiner & Naumann, 2022) carbon pricing loses its effectivness in systems with high VRE penetration, the demand of storage grows exponentially with penetraton (Zerrahn & Schill, 2018), real-time pricing and sector coupling have limited feasibility or high costs. This naturaly leads to a question of how to combine the measures for them to have maximal effect.

It is not yet clear what exactly is the best metric for "maximal effect", a simple proposition could be the difference between the recovered VRE revenue and the costs of implementing the measures. This however does not take into account the social welfare, a standard economic criterion for comparing various policy measures, so we should also look at the sum of consumer and producer surplus, which is economists' main interest. Out of the approaches discussed in the previous section, the bottom-up dispatch models seem by far the most suitable to answer these questions. All the measures can be added into the model with their respective costs and their viability calculated from the model outputs. To the best of our knowledge, no model with such scope and mainly purpose has yet been proposed and we find this gap a good direction of future research.

Conclusion

In this review, we have synthesized a modestly extensive body of literature on the merit-order and cannibalization effects arising from high penetrations of variable renewable energy (VRE), as well as the principal mitigation measures proposed to address the resulting economic challenges. Our analysis confirms that while energy storage, real-time pricing, geographic diversification, sector coupling, and carbon taxation each have been shown to help against revenue cannibalization, their individual cost-effectiveness and practical feasibility vary substantially across market contexts. Notably, energy storage offers temporal arbitrage benefits but may entail prohibitive capital costs that are not always offset by price premiums; real-time pricing can enhance demand flexibility but faces barriers in consumer adoption and regulatory implementation; geographic diversification must be strategically targeted to achieve de-correlation benefits; sector coupling yields varying impacts depending on technology specificity; and carbon taxation loses marginal efficacy at extreme renewable shares.

Importantly, our survey highlights two critical gaps. First, the existing literature lacks comprehensive economic-feasibility assessments that rigorously compare implementation costs against incremental revenue gains for each mitigation strategy. Second, the synergistic interactions among measures, especially within integrated, techno-economic dispatch frameworks, remain underexplored. We therefore advocate the development of a unified bottom-up dispatch and investment model that can endogenously represent multiple interventions, capture their combinatorial effects, and optimize policy mixes based on clearly defined welfare metrics (e.g., net producer surplus, sum of consumer and producer surplus, or simply revenue-cost difference).

Such a modeling framework would enable policymakers and system operators to identify Pareto-efficient portfolios of mitigation measures tailored to specific market designs and VRE penetration levels. By quantifying both the individual and collective impacts of storage deployment, demand-side flexibility, spatial resource diversity, sectoral integration, and carbon pricing, future research can furnish actionable guidance for aligning renewable expansion with economic viability. Addressing these gaps is imperative to ensure that the rapid growth of wind and solar capacity continues unabated, thereby advancing global decarbonization objectives without sacrificing market stability or investor confidence.

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