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# Ever More Frequent Negative Electricity Prices: A New Reality and Challenges for Photovoltaics and Wind Power in a Changing Energy Market—Threat or Opportunity, and Where Are the Limits of Sustainability?

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**Abstract:** In recent years, negative electricity prices have ceased to be a rare phenomenon and are becoming a new reality in markets with a high share of renewable energy sources. This introductory article examines the increasing frequency of negative prices—particularly in Germany—as a consequence of the rapid expansion of solar and wind power plants. It highlights the sharp decline in the so-called capture rate for renewable producers and outlines technical, market-based, and regulatory solutions to this challenge. As the energy transition accelerates, key questions emerge concerning grid flexibility, market design, and investment returns. This article also serves as a call to researchers, analysts, and energy professionals to join the ongoing discussion by contributing their insights, case studies, and innovative solutions to this Special Issue of *Energies*. Are negative prices merely a transitional side effect of decarbonization or a warning sign of deeper systemic inefficiencies? Join the debate and help shape the future of sustainable energy.

**Keywords:** negative electricity prices; renewable energy sources; photovoltaics; wind power; capture rate; grid flexibility; electricity market

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## 1. Introduction

According to [1], global energy demand increased by 2.2% in 2024—faster than the average pace over the past decade. Demand for all fuels and technologies grew in 2024. The power sector led this growth, with electricity demand rising by 4.3%, significantly outpacing the 3.2% growth in global GDP. This surge was driven by record-high temperatures, electrification, and digitalization. Renewable energy sources accounted for the largest share of the increase in global energy supply (38%), followed by natural gas (28%), coal (15%), oil (11%), and nuclear energy (8%).

Global electricity consumption increased by nearly 1100 terawatt-hours (TWh) in 2024, more than double the average annual growth over the past decade. This rising global electricity use was driven by factors such as growing demand for cooling due to extreme temperatures, increased industrial consumption, electrification of transport, and the expansion of the data center sector. Electricity consumption in buildings accounted for nearly 60% of the total growth in 2024. The installed capacity of data centers worldwide is estimated to have increased by 20%, or around 15 gigawatts (GW), with most of this growth occurring in the United States and China. At the same time, the continued rise in the number of electric vehicles led to increased electricity consumption in the transport sector. Global sales of electric cars grew by more than 25%, surpassing 17 million units and accounting for one-fifth of all cars sold. In 2024, 80% of the growth in global electricity generation was covered by renewables and nuclear energy. Together, they accounted for 40% of total electricity generation for the first time, with renewables alone providing 32%. New renewable installations reached a record level for the 22nd consecutive year, with around 700 GW of renewable capacity added in 2024—nearly 80% of which came from solar photovoltaics. Electricity generation from solar PV and wind increased by a record 670 TWh, while gas-fired generation rose by 170 TWh and coal-fired generation by 90 TWh [1–3].

The European Union has long supported the development of renewable energy sources as part of its climate policy and energy security strategy. Its goals are to reduce greenhouse gas emissions, decrease dependence on fossil fuels, and ensure a sustainable and stable energy system. A key document framing this policy is the European Green Deal, which sets the objective of achieving climate neutrality by 2050. In response, the EU adopted the "Fit for 55" package of measures, aimed at reducing emissions by 55% by 2030 compared to 1990 levels.

One of the main legislative tools supporting renewable energy is the Renewable Energy Directive (RED III), which sets a binding target for the share of renewables in the EU's energy mix at a minimum of 42.5% by 2030, with a recommended level of up to 45%. To achieve these targets, the EU provides significant financial support through various funds and programs.

In addition to financial support, the EU is also implementing concrete initiatives to accelerate the transition to clean energy. The REPowerEU program is one of the main measures aimed at reducing dependency on Russian fossil fuels and speeding up the development of renewable energy sources. An important part of this strategy is the promotion of wind and solar power, with efforts to simplify and speed up permitting processes so that new projects can be brought online more quickly.

Despite strong support, the development of renewable energy in the EU faces several challenges. These include bureaucracy, slow permitting procedures, and the need to modernize electricity grids to handle the growing share of renewables. Nevertheless, the EU continues to expand its renewable energy policy and investments in sustainable energy to meet its climate goals and ensure long-term energy independence.

In recent years, negative electricity prices have increasingly appeared on the European power market. This means that electricity producers must pay consumers to take electricity off the grid. This phenomenon is a result of the rising share of renewable energy sources (RESs), which generate electricity based on weather conditions, combined with the limited flexibility of the energy system. The main cause of negative prices is overproduction of electricity from wind and solar plants at times when demand is not high enough. When there is strong wind or intense sunlight, these power plants generate large amounts of energy that cannot always be consumed immediately. The situation is further complicated by limited storage capacity—battery storage and other energy storage technologies are expensive and currently cannot absorb all the excess energy.

Another contributing factor is conventional power plants, such as nuclear, coal, or gas plants, which cannot be switched off and on quickly. Operators of these plants sometimes prefer to pay for electricity to be taken from the grid rather than bear the costs of temporarily shutting down production.

Although negative electricity prices may appear beneficial for consumers, they also present serious challenges. On the one hand, they can encourage businesses and households to consume electricity during periods of surplus, improving system efficiency. On the other hand, they put pressure on electricity producers, who may suffer financial losses, especially if such price events occur frequently. Moreover, they can lead to market instability, discouraging investment in new energy projects.

Table 1 shows the increase in the number of hours with negative electricity prices in Germany. A rising trend in negative electricity pricing is evident, with the exception of 2021 and 2022, which were marked by unique geopolitical circumstances. However, in the past year, Germany recorded 459 h of negative electricity prices—an all-time high. A similar situation is occurring in other countries, not only in Germany [3–9].

**Table 1.** Number of negative electricity price for 2015 to 2025 in Germany.

| | Number of Negative Electricity Price | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Month** | **2015** | **2016** | **2017** | **2018** | **2019** | **2020** | **2021** | **2022** | **2023** | **2024** | **2025** |
| January | 12 | 5 | 3 | 44 | 34 | 3 | 0 | 4 | 14 | 16 | 14 |
| February | 8 | 14 | 5 | 5 | 9 | 84 | 9 | 4 | 0 | 4 | 0 |
| March | 14 | 6 | 0 | 21 | 46 | 41 | 27 | 6 | 9 | 12 | 20 |
| April | 14 | 0 | 16 | 3 | 18 | 40 | 22 | 5 | 11 | 50 | 0 |
| May | 17 | 21 | 17 | 31 | 9 | 36 | 38 | 16 | 33 | 78 | 0 |
| June | 0 | 0 | 0 | 0 | 26 | 8 | 9 | 3 | 20 | 66 | 0 |
| July | 3 | 2 | 7 | 0 | 0 | 24 | 11 | 2 | 56 | 81 | 0 |
| August | 0 | 0 | 8 | 0 | 11 | 4 | 11 | 0 | 23 | 68 | 0 |
| September | 13 | 0 | 8 | 3 | 15 | 6 | 0 | 0 | 22 | 40 | 0 |
| October | 0 | 0 | 39 | 6 | 5 | 18 | 7 | 0 | 38 | 25 | 0 |
| November | 18 | 14 | 1 | 0 | 0 | 9 | 0 | 0 | 3 | 11 | 0 |
| December | 11 | 35 | 42 | 21 | 38 | 25 | 5 | 29 | 72 | 8 | 0 |
| Sum | 110 | 97 | 146 | 134 | 211 | 298 | 139 | 69 | 301 | 459 | 34 |

Figure 1 shows a graph of the cumulative negative electricity price, where an increase over the past few years can also be observed. While the number of negative prices is an important piece of information, their actual value is equally significant.

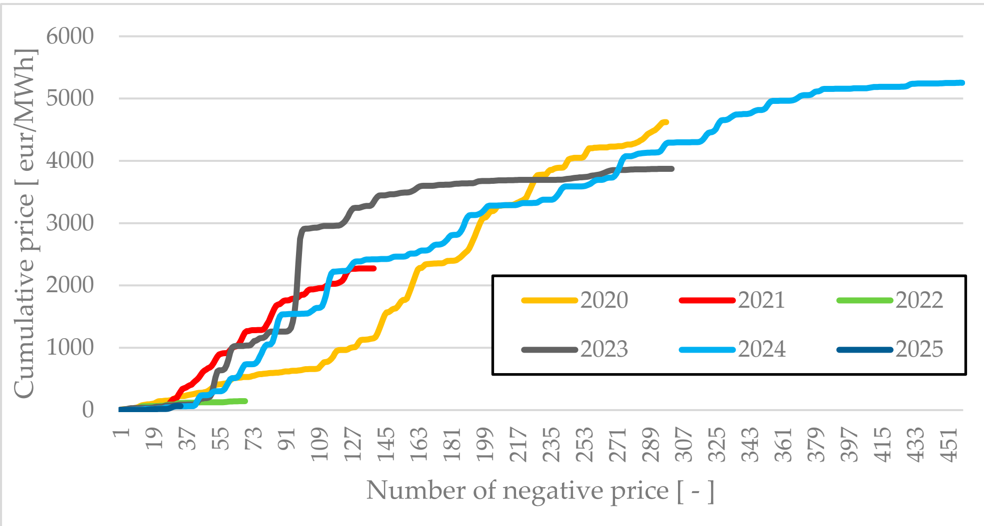


**Figure 1.** Cumulative negative price for Germany—2015–2025.

Negative electricity prices are a consequence of the ongoing transformation of the energy sector and are expected to occur more frequently as the share of renewable energy sources continues to grow. On particularly windy or sunny days, renewables can generate more electricity than the average demand. If there is not enough storage capacity available, the excess energy must be fed into the grid, which can cause prices to drop below zero.

One of the indicators of the current situation in the electricity market is the capture rate, which represents the actual average electricity price achieved by renewable energy producers compared to the average market price over a given period. It is calculated as follows [7]:

$$Capture\ Rate\ Solar = \frac{Capture\ Price\ for\ Solar\ (CPS)}{Average\ Market\ Price\ of\ Electricity} \cdot 100\%$$

If:

- Capture rate < 100%—The producer sells electricity at a price lower than the market average (typical for solar and wind sources, as they generate power during times of surplus, causing prices to fall).
- Capture rate = 100%—The producer receives exactly the market average price.
- Capture rate > 100%—The producer sells electricity at a price higher than the market average (less common, may occur with flexible sources such as hydropower).

In Figures 2–4, capture rate values are shown for solar (Figures 2 and 4) and wind (Figures 3 and 4). The wind data include both onshore and offshore wind farms.

Based on the analysis of the capture rate for solar and wind power plants in Germany, significant differences can be observed in their trends and impacts on the electricity market. In the past, solar energy often achieved a capture rate above 100%, meaning producers could sell electricity at prices higher than the market average. However, since 2022, there has been a sharp decline, especially during the spring and summer months. In April, May, and June 2024 and 2025, the capture rate even fell below 50%, indicating a high surplus of solar production during daytime hours when consumption is relatively low and the market becomes saturated. On the other hand, winter months (November–February) show more stable values closer to 100%, due to lower solar production and higher electricity demand.

| Capture Rate (%) | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 114% | 110% | 109% | 117% | 119% | 109% | 104% | 106% | 104% | 98% | 101% |
| February | 100% | 108% | 104% | 99% | 98% | 104% | 91% | 91% | 95% | 95% | 86% |
| March | 97% | 94% | 96% | 98% | 100% | 71% | 86% | 81% | 86% | 76% | 52% |
| April | 88% | 96% | 86% | 91% | 85% | 51% | 84% | 87% | 79% | 61% | |
| May | 99% | 83% | 98% | 94% | 93% | 80% | 78% | 85% | 66% | 49% | |
| June | 101% | 102% | 98% | 100% | 90% | 94% | 93% | 87% | 75% | 54% | |
| July | 101% | 98% | 98% | 99% | 99% | 87% | 91% | 83% | 67% | 53% | |
| August | 97% | 96% | 98% | 100% | 92% | 95% | 92% | 86% | 80% | 53% | |
| September | 98% | 97% | 103% | 95% | 93% | 91% | 91% | 91% | 74% | 57% | |
| October | 95% | 101% | 102% | 100% | 102% | 95% | 91% | 84% | 77% | 78% | |
| November | 107% | 106% | 106% | 105% | 107% | 103% | 104% | 88% | 93% | 88% | |
| December | 104% | 116% | 106% | 116% | 116% | 110% | 122% | 99% | 96% | 103% | |

**Figure 2.** Capture rate for solar in Germany—2015–2025.

| Capture Rate (%) | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| January | 75% | 85% | 80% | 77% | 81% | 90% | 89% | 81% | 78% | 88% | 79% |
| February | 87% | 85% | 85% | 90% | 91% | 82% | 92% | 87% | 85% | 89% | 91% |
| March | 82% | 88% | 92% | 82% | 82% | 83% | 76% | 83% | 86% | 88% | 90% |
| April | 88% | 96% | 84% | 93% | 93% | 68% | 85% | 80% | 91% | 83% | |
| May | 91% | 84% | 88% | 86% | 95% | 76% | 81% | 80% | 101% | 91% | |
| June | 93% | 96% | 86% | 89% | 77% | 85% | 88% | 91% | 99% | 83% | |
| July | 85% | 88% | 89% | 95% | 92% | 74% | 87% | 91% | 82% | 82% | |
| August | 94% | 94% | 88% | 93% | 84% | 88% | 90% | 100% | 76% | 84% | |
| September | 89% | 91% | 82% | 89% | 88% | 87% | 94% | 85% | 90% | 85% | |
| October | 94% | 93% | 74% | 84% | 88% | 89% | 83% | 86% | 83% | 83% | |
| November | 84% | 87% | 78% | 93% | 91% | 85% | 83% | 82% | 86% | 81% | |
| December | 86% | 68% | 74% | 84% | 85% | 81% | 77% | 67% | 71% | 70% | |

**Figure 3.** Capture rate for wind in Germany—2015–2025.

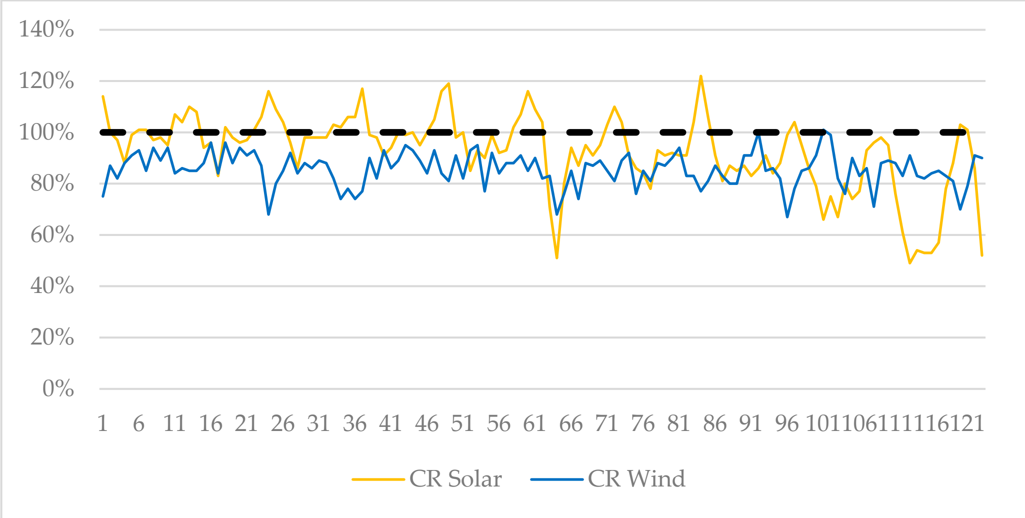


**Figure 4.** Capture rate trends: solar vs. wind (2015–2025).

In contrast to solar energy, wind power plants have shown a more stable capture rate, generally ranging between 80 and 100%. The highest values are reached during winter months (January, February, November, December), when electricity demand is higher. In some cases, such as July 2023, the capture rate even reached 100%. While summer months did see slight decreases, they were not as significant as in the case of solar energy, suggesting that wind is a more diversified source with a smaller impact on price volatility.

A comparison between solar and wind energy reveals that solar producers face greater challenges. Their capture rate is declining more rapidly, especially during peak production periods, which means that the profitability of solar projects is increasingly dependent on mechanisms such as long-term Power Purchase Agreements (PPAs) or battery storage systems. In contrast, wind power plants offer more balanced returns on investment and lower price volatility, making them a more stable option for long-term contracts.

Research in this area can yield significant results. The decline in the capture rate, especially for solar energy, represents a major challenge, as it reduces producers' revenues and increases uncertainty for long-term investments. The solution lies in a combination of measures that can mitigate negative impacts and stabilize the electricity market.

One of the most effective strategies is better integration of battery storage systems, which allow surplus electricity to be stored during hours of low or negative prices and sold later when demand is higher. Hybrid solar–battery systems can delay immediate market sales and help prevent price crashes. At the same time, more flexible Power Purchase Agreements (PPAs)—with dynamic pricing models that better reflect changing capture rates, such as contract-for-difference mechanisms—can also help stabilize revenues.

Another essential part of the solution is the expansion of interconnection capacity and cross-border electricity trading, enabling the export of excess electricity to regions with higher demand. Stronger transmission networks within Europe would support better electricity distribution and reduce pressure on local markets.

According to [10], investment plans by 2035 include the following:

1. Vietnam: USD 15 trillion;
2. China: USD 205 trillion;
3. India: USD 110 trillion;
4. Spain: USD 8 trillion;
5. France: USD 104 trillion;
6. United Kingdom: USD 49 trillion.

Additionally, the development of hybrid projects combining solar and wind energy with battery storage can make a substantial contribution. Since wind and sun often complement each other—wind tends to be weaker on sunny days and vice versa—the combination helps balance production and stabilize the capture rate [11].

Another key measure is demand-side flexibility, where dynamic tariffs would encourage consumers to align their usage with the availability of cheap electricity. Industrial facilities could shift production to low-price periods, while electric vehicle charging and operation of large cooling systems could be optimized based on real-time market conditions.

In the longer term, the development of hydrogen technologies can play a crucial role. Excess solar and wind energy can be used to produce green hydrogen. Electrolyzers with flexible operation can run only when electricity is cheap or free, thus stabilizing the market and creating new demand for surplus electricity [12,13].

In summary, the decline in the capture rate is caused by an oversupply of solar energy during specific hours and the market's limited ability to efficiently utilize it. The solution lies in a combination of improved storage, flexible PPAs, cross-border trade, hybrid projects, and support for hydrogen technologies. If implemented correctly, these measures can help maintain the economic viability of solar and wind projects well into the future [10,13,14].

## 2. Conclusions

This article highlighted an increasingly important phenomenon in the modern energy landscape—the rising occurrence of negative electricity prices linked to the growing share of renewables in the energy mix. A detailed analysis of the situation in Germany revealed a record number of negative-price hours. Using the capture rate indicator, we showed that solar energy in particular is facing significant challenges in terms of profitability and market stability.

The findings suggest that the sustainable development of renewables requires the implementation of multiple measures: battery storage, flexible contracts (e.g., dynamic-price PPAs), expanded cross-border transmission, hybrid energy projects, and hydrogen technologies. Demand-side flexibility will also play a crucial role.

However, several open questions remain that future research could address:

- How can market design be optimized to better reflect renewable variability?
- Which technologies (e.g., AI, predictive control, adaptive pricing) can mitigate the impact of energy surpluses?
- What are the social and economic implications of prolonged negative prices for small- and medium-sized producers?

We believe that further research and open dialog on these topics will contribute to building a more efficient, resilient, and equitable energy system for the future.

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