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The Risk of Financial Bubbles in Renewable Energy Markets

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Abstract: Policy incentives and technological advancements are driving the rapid expansion of renewable energy industries. However, as speculative investment intensifies, concerns about the potential formation of financial bubbles are growing. This paper examines financial saturation in renewable energy markets, emphasizing key bifurcation and overheating thresholds that indicate speculative risks. Using a financial saturation model, the study evaluates market overheating across three major renewable energy sectors—solar PV, wind energy, and battery storage—based on a scenario analysis from Bloomberg's New Energy Outlook (NEO) 2024. The findings reveal that battery storage is the most susceptible to speculative investment, with bifurcation (~70% market saturation) projected by 2031 (medium term) and by 2038 (long term) under the Net-Zero Scenario (NZS), and by 2042 under the Economic Transition Scenario (ETS). In the long term, financial overheating (~90% market saturation) in battery storage is projected by 2048 under the ETS. Solar PV also faces speculative risks, with bifurcation expected by 2030 (ETS, medium term), 2039 (ETS, long term), and 2041 (NZS, long term). Overheating in the solar sector is projected by 2048 (ETS, long term) and 2050 (NZS, long term). Wind energy exhibits a more gradual saturation pattern, with bifurcation expected by 2031 (ETS, medium term), 2038 (ETS, long term), and 2045 (NZS, long term), while overheating is anticipated by 2049 (ETS, long term). These findings highlight the need for regulatory oversight to mitigate speculative investment risks. To enhance financial stability, policy recommendations include gradual subsidy phase-outs, financial stress testing, and diversified investment strategies. Maintaining a stable investment environment is essential for long-term climate goals and energy security.

Keywords: financial bubbles; renewable energy markets; market saturation; sustainability; speculative dynamics; investment risk

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1. Introduction

One of the pillars of sustainable development—economic sustainability—emphasizes the importance of economic stability, resilience, and sustainable growth. Sustainable economic growth requires careful management to ensure long-term viability. Efforts to mitigate climate change and achieve long-term sustainability now critically depend on the global transition to renewable energy. Aiming to greatly reduce greenhouse gas emissions, global frameworks such as the Paris Agreement have prompted large expenditures in renewable energy technologies including solar photovoltaics (PV), wind energy, and battery storage, leading to environmental advantages and economic competitiveness. Due to technological developments and economies of scale, costs have dropped significantly over the past ten years [1,2].

Strong policy support—including subsidies, tax incentives, and renewable portfolio standards—has driven capital inflows and accelerated the expansion of renewable energy markets [3,4]. But as history has shown, times of fast market growth may coincide with financial bubbles, in which case asset values become inflated beyond their inherent economic value. Previous events like the dot-com bubble of the early 2000s and the worldwide financial crisis of 2008 show how overvaluation and speculative dynamics could cause markets to be unstable and result in sudden corrections [5,6]. According to World Bank data [7], economies in many countries and regions have been experiencing increasing financial pressures and significant financial saturation. With economic growth, capital accumulation has become a continuous process, deepening financial markets and increasing market saturation. In the post-industrial economy, this trend has intensified, necessitating greater attention to financial saturation.

Driven by technological advancements, supportive policies, and declining costs, the renewable energy sector is set for significant expansion. According to the International Energy Agency [8], almost 3700 GW of new renewable capacity is projected to come online from 2023 to 2028, with solar PV and wind accounting for 95% of this expansion.

Despite prioritizing sustainability, the renewable energy industry remains vulnerable to financial risks. Although they create conditions for rapid market expansion, high levels of investment, technical confidence, and government assistance also raise questions around overvaluation and speculative activity [9]. The idea of financial bubbles—defined by unsustainable asset-price inflation driven by speculation—offers a helpful perspective for analyzing the possible weaknesses in the markets for renewable energy. Research indicates that financial bubbles form when investor expectations drive market prices beyond their fundamental growth potential [10,11].

Using financial saturation theory and speculative dynamics, this study evaluates the likelihood of financial bubbles in renewable energy markets. It especially looks at how overvaluation results from policy-driven investment behavior, market saturation, and technological optimism. Emphasizing solar, wind, and battery storage, the study finds important thresholds of market heating and overheating using a saturation model and scenario analysis based on Bloomberg's New Energy Outlook (NEO). Through an analysis of these processes, this study offers practical advice for market authorities, investors, and legislators to control speculative risks and therefore promote the worldwide energy transition.

The results highlight the necessity of maintaining a balance between technological innovation and financial stability in renewable energy investments. This finding contributes to the ongoing discussion on how to foster sustainable energy market growth while mitigating the risks of speculative investment cycles. Maintaining investor trust and protecting long-term climate goals depends on financial stability in renewable energy markets being ensured [12,13].

2. Financial Bubbles and Market Saturation

The methodological approach applied to evaluate the danger of financial bubbles in markets for renewable energy is described in this part. Using well-known models and scenario-based techniques, the study combines speculative dynamics with financial saturation theory [1–3].

2.1. Literature Review

The study of financial bubbles has long been a focal point in economic history, emphasizing the rapid rise and collapse of asset prices beyond their intrinsic values [10]. Various theoretical models have been proposed to explain these occurrences, with significant implications for the renewable energy sector, where investor enthusiasm and market optimism raise concerns about overvaluation.

Minsky's [6] Financial Instability Hypothesis outlines the transition from stability to speculative euphoria, ultimately leading to financial collapse. This theory suggests that optimism drives stock prices upward, creating a self-reinforcing cycle until valuations become unsustainable. Similarly, the Rational Bubble Model by Blanchard and Watson (1982) [5] explains how investors knowingly engage in speculative activity, expecting to sell assets at a higher price before the eventual crash. These theories highlight the disconnect between market prices and fundamental economic realities, emphasizing that bubbles are driven by a combination of structural imbalances, investor behavior, and liquidity effects [11].

Financial bubbles form due to a combination of market expectations, investment flows, and psychological trends. Shiller [14] identifies investor optimism as a key driver of self-reinforcing price increases, while Akin and Akin [15] suggest that technological advancements further fuel speculative cycles. Increased investment flows, often spurred by favorable monetary policies and low financing costs, contribute to speculative excesses [16,17]. Additionally, behavioral finance studies highlight how herding behavior, overconfidence, and recency bias lead investors to act irrationally, exacerbating market misalignments [18–21].

The renewable energy sector presents a unique case for analyzing financial bubbles due to the interplay of technological innovation, regulatory frameworks, and market speculation. Investment surges in renewable technologies such as solar photovoltaics, wind turbines, and battery storage have been driven by global climate commitments and favorable policy incentives [1,2]. However, excessive capital inflows can lead to temporary overcapacity and price declines, as seen in the early 2010s solar PV market [22]. Moreover, policy uncertainty, such as abrupt changes in feed-in tariffs, has historically triggered market contractions, as evidenced by Spain's solar market collapse [4,23].

Technological advancements lower costs and enhance efficiency, but they also create speculative bubbles when market expectations outpace actual development. Hype-driven investments in electric vehicles, for instance, have led to inflated stock valuations, with firms like Tesla benefiting from optimistic forecasts [24,25]. Regulatory frameworks, including the European Union's Green Deal and the U.S. Inflation Reduction Act, shape investment strategies, but market reliance on policy support introduces vulnerability to shifts in legislative priorities [3,26].

Historical financial bubbles offer cautionary lessons for the renewable energy sector. The Enron scandal demonstrated how misrepresentation of financial performance can erode investor trust [27,28]. Similarly, the dot-com bubble illustrated the risks of valuing companies based on speculative future earnings rather than actual performance [29,30]. Spain's solar-boom collapse further underscores the impact of policy instability on investor confidence and market sustainability [31].

While extensive literature explores the causes and consequences of financial bubbles, the role of financial saturation in triggering speculative cycles remains underexplored. This analysis aims to investigate the conditions under which capital saturation leads to the saturation paradox, facilitating bubble formation. Understanding these dynamics is crucial for ensuring sustainable investment strategies in emerging markets such as renewable energy.

The marginalism applied in this study is closely linked to research on market saturation and the paradigm shift in economic growth. Traditional simple or composite percentages are being replaced by saturation percentages at a higher hierarchical level (logistic), reflecting more complex economic processes. Saturation percentages open up the possibility of uncovering new patterns of economic dependence that cannot be detected using composite percentages or traditional statistical methods. The application of these percentages makes it possible to explain the phenomenon of increasing returns, to refine the market equilibrium model, to gain a deeper understanding of the origins of economic bubbles, to assess the mechanisms of inflation more accurately, to uncover the causes of business cycles, and to fill other gaps in economic science. The importance of mathematics in economic research is stressed, with particular emphasis on the superiority of marginal methods compared to traditional econometric methods. The use of marginal methods provides a clearer understanding of economic phenomena and allows the formulation of more accurate models. Financial saturation theory and marginalist methods of analysis provide effective tools for modeling and managing economic processes, leading to more effective economic policy and market regulation decisions.

2.2. Theoretical Framework

This section outlines the methodology used to assess the risk of financial bubbles in the renewable energy market. A limited growth model, often called saturation or logistic growth, can estimate the financial saturation of a market. For this reason, the formula modeling saturation has an additional parameter—potential capacity.

The prototype of this model, published by the Belgian mathematician and demographer P. Ferhulst [32] in the first half of the 19th century, was used to estimate population growth and had no direct link to the compound interest function. The saturation (general–logistic) model used is slightly modified, with coefficients specifically adapted to economic problems and calculated in compound percentages [12]. This model's key element is the capital Kp or potential (market) capacity. The amount of capital after the exact number of periods (n) (accumulated product value or capital after n periods) is given by the saturation model:

$$\text{Accumulated capital} = \frac{\text{Potential value (capacity)} + \text{n period compound interests}}{\text{Initial value(niche)} + \text{n period compound interests}}, \quad (1)$$

where potential value (capacity) is the total amount of financial resources that can be productively absorbed in an investment environment. The value of market capacity used in saturation models is usually measured in monetary (value) terms and is referred to as potential capital.

The theory of financial saturation introduces a market equilibrium model with a specialized supply function, enabling the estimation of market capacity and equilibrium in saturated or closed markets [13]. The identification of saturation percentages has shown that the composite or simple percentages used so far are only approximations of saturation percentages. What is important is not the measures used to model saturation (saturation percentages) themselves, but the new phenomena discovered on the basis of them—the derivatives of percentages. One of the most important such phenomena is the saturation paradox, which is revealed by discounting cash flows using saturation percentages. This phenomenon describes the ability of a bounded system (a single market or the economy as a whole) to increase its growth intensity (growth rate) as the degree of filling of the system increases, i.e., saturation. The essence of the paradox is that, in the normal case of non-saturation, the constraint on growth is regarded as a disturbance that weakens the intensity of growth, whereas in the case of saturation, growth intensifies [33].

The saturation percentages have revealed an unusual feature—the phenomenon of increasing productivity (profitability), called the saturation paradox. This paradox can be described as follows [34]: if a population (capital) grows in a determinate environment and saturates that environment when it grows, the growth rate of the population also increases as saturation increases, and this growth is hyperbolic (explosive). When the system's saturation increases, the system's productivity increases. When the saturation approaches 100 percent, the productivity of the system starts to increase in a hyperbolic manner. The economic meaning of the saturation paradox can be defined as follows: if capital is invested in a closed (deficit) market and the financial saturation of that market increases, the profitability of the investment rises unrestrictedly.

The study is based on financial saturation theory and saturation paradox, which posits that profitability in the markets grows rapidly as it reaches the saturation point. These phenomena evolve through distinct phases—moderate growth, heating, and overheating—as they approach saturation [4,5]. Saturation occurs after market bifurcation, when investment flows exceed the absorptive capacity of the market, creating speculative dynamics that inflate prices beyond their intrinsic value. Such a market is characterized by a rapid rise in the equilibrium price, reinforced by positive feedback, and by the emergence of linkages (speculative dynamics) that do not apply in classical economic theory. For example, in a closed, saturated market (where demand exceeds supply), the rise in prices stimulates speculative activity, which pushes prices even higher. In this environment, the principles of classical theory no longer apply, because the market does not rebalance itself—on the contrary, positive feedback loops lead to further price increases.

This framework has been applied to study financial bubbles in various markets, including real estate, technology, and stock prices [6,9]. The model identifies critical thresholds of market saturation, particularly at 70% (bifurcation) and 90% (overheating), where speculative dynamics dominate [5].

Figure 1 illustrates the saturation paradox—growing productivity (profitability) as the saturation level increases. The theoretical unsaturated growth rate is visualized as a stable line. When the difference in the saturated and unsaturated growth rate becomes significant, a shift from a fundamentally driven investment to expectation-driven speculation occur (bifurcation). Figure 1 visualizes the three stages of market saturation when the growth rate is significant (bifurcation point) and the growth rate starts to increase exponentially (overheating).

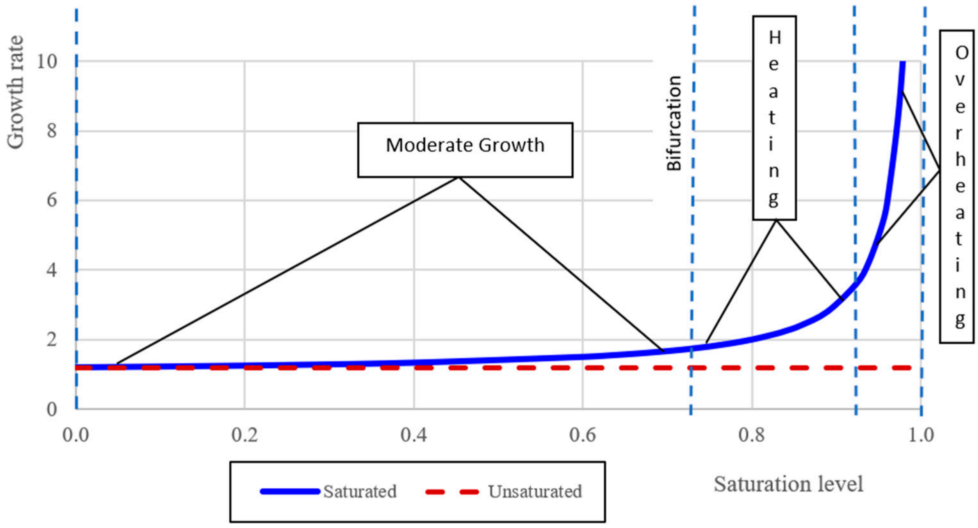

Figure 1. Three stages of market saturation level and growth rate. Source: created by authors.

The results indicate that when market saturation reaches approximately 70%, bifurcation occurs, and speculative investment behavior begins to dominate. Beyond 90% saturation, the risk of financial overheating increases significantly and the system is unstable.

2.3. Bubble Mechanism

In the context of financial saturation, both theoretical and empirical explanations of the bubble's formation mechanisms are possible. The theoretical explanation of the bubbles is based on the mechanism of saturated market equilibrium, in which a deficit situation develops in the market, with high demand being followed by supply [35].

At a theoretical level, positive feedback loops arise when economic (or other) growth becomes restricted, i.e., when there is a disproportionate investment in resource-constrained markets of limited size. Positive feedback at a sufficient frequency intensifies and resonates with the cyclical investment process, with the saturation phenomenon affecting positive expectations, and the market heating up. In other words, intensively rising prices increase demand and hence profitability expectations, which are shaped by the phenomenon of rising profitability (saturation). The feedback loop further stimulates price increases, thereby accelerating investment. This is called speculative dynamics.

If the market has unlimited productive resources (unlimited capacity), then there is no saturation—the phenomenon of increasing profitability does not work. The supply curve is at its lowest point and moderately increasing. This leads to a lack of optimistic expectations, the feedback becomes negative, the price increase is minimal, and the whole system is stable. It is common to consider such a market stagnant [34,36]. Overcoming stagnation requires the mobilization of a sufficient number of investors who have optimistic (enthusiastic) expectations.

At the empirical level, positive feedback occurs when intensive investment leads to a saturation of the market externally—demand exceeds supply, and a deficit market is created. In a deficit market, a rising price increases demand further, investors become optimistic, positive feedback is generated, and the bubble is deflated. A slowdown in investment leads to lower yields and lower demand, the deficit disappears, the feedback loop turns negative, growth becomes rational, and prices converge to fundamental levels. To stimulate the market (to accelerate growth of profitability), financial saturation must be increased, and demand must be activated.

3. Materials and Methods

3.1. Data Sources

The primary data source for this study is Bloomberg's New Energy Outlook (NEO) 2024, which provides comprehensive forecasts for renewable energy capacity, investment flows, and market dynamics. Two key scenarios are utilized:

- Net-Zero Scenario (NZS): reflects an accelerated transition to renewable energy with challenging deployment targets.
- Economic Transition Scenario (ETS): represents a more conservative trajectory, with gradual market expansion.

Energy economics research makes extensive use of these scenarios to replicate policy effects and growth paths [10,11]. The International Energy Agency (World Energy Outlook) and peer-reviewed publications [1,3] provide further statistics, including historical patterns in renewable energy investments and technology developments.

3.2. Modeling Approach

The calculation of growth rate r ($r = 1 + i$) and the ratio of installed capacity to maximum capacity K_a/K_p, is based on saturation (general) percentages (interest). The model is based on Formula (1) [13]:

$$K_a = \frac{K_p \cdot K_0 (1+i)^t}{K_p - K_0 + K_0 (1+i)^t}, \tag{2}$$

where

K_p is the market capacity or potential (maximum) value of the invested capital in the market;
K_0 is the initial value of the investment;
K_a is the accumulated investment (the amount of the capital in terms of its value) over periods;

i is the interest or growth rate;
t is the duration of the investment or the number of periods of the investment.

To quantitatively assess the risk of a financial bubble, this study uses a saturation model based on installed renewable energy (RE) capacity. The model tracks the growth of installed capacity over time and evaluates how close the market is to saturation. The saturation level of the market is calculated by equating K_a/K_p with the predicted installed capacity K_a over time. The converted formula below (2) is used for calculating the growth rate r from K_a is as follows:

$$r = \sqrt[t]{\frac{K_p - K_0}{K_0} \cdot \frac{K_a}{K_p - \mathrm{K_a}}} \tag{3}$$

where

t is the duration of the investment or the number of periods of the investment;
K_p is the market capacity or maximum absorptive capacity of the market, representing the theoretical upper limit of installed capacity given current technology and market conditions over the entire period, in GW;
K_a is the predicted total installed renewable energy capacity at a given each year, in GW;
K_0 is the initial installed renewable energy capacity in the beginning of the period, in GW;
r is the logistic growth rate.

3.3. Scenario Analysis

To assess speculative risks, the study considers two timeframes according to business cycles types and length:

1. Medium-Term Scenario (10–12 Years). The Juglar cycle refers to an economic cycle characterized by fluctuations in investment and business activities; it is rooted in the interplay between investment, credit, and economic productivity. It typically spans a period of 7 to 11 years and is considered a medium-term business cycle. This period captures late signs of market saturation and speculative growth between investment, credit, and economic productivity in the sector [37,38].
2. Long-Term Scenario (25 Years). The Kuznets cycle (long swing or infrastructure investment cycle) refers to economic fluctuations with an estimated duration of 15 to 25 years. This type of cycle is driven by structural transformations such as urbanization, demographic shifts, and infrastructure investment. This timeframe, according to the Kuznets cycle, examines the link to infrastructure development: the cycle is particularly evident in patterns of investment in transportation, housing, utilities, and public works, which have long gestation periods and require significant capital. [37,39,40].

Each scenario provides insights into the timing of bifurcation and overheating, based on projections from Bloomberg's NEO [10].

3.4. Assumptions and Limitations

Key assumptions include:

- The model relies on functional relationships, with installed capacity as the independent variable and growth rate as the dependent variable. Other variables are treated as constant, unique to each scenario, period length, and sector.
- Market capacity (K_p), the duration of the investment (t), and the initial value of the investment (K_0) remain constant over time, a simplification consistent with prior saturation models [4,6]. Market capacity (K_p) and the initial value of the investment (K_0) are unique for each period, scenario, and sector analysis. Reliability and the accuracy of fixed variables are not assessed.

- The reliability and accuracy of the forecast for the key variable (installed capacity) (K_a) are not assessed, and the market is assumed to develop according to the calculated scenarios.
- Investment costs per unit of installed capacity are assumed to be stable to isolate saturation effects [5].
- External shocks (e.g., geopolitical events, technological disruptions) are not explicitly modeled, aligning with prior studies [41].
- Investment time lag. Infrastructure or renewable energy investments have long gestation periods, where capital is allocated, and returns (saturation in installed capacity) are not immediately realized. Saturation and possible bubbles in related financial markets appear before saturation in installed capacity [42].

4. Results

Emphasizing the risk of probable bubbles in installed capacity in the renewable energy market, this part offers the results of the research. Using forecast data from Bloomberg's New Energy Outlook (2024), financial saturation theory and market saturation models underlie the results. Important revelations include the identification of bifurcation points depending on installed capacity (GW), overheating hazards, and sectoral differences among the solar, wind, and battery-storage sectors.

It is necessary to describe the current state of the relevant markets. As illustrated in Figures 2 and 3, there are clear tendencies towards markets' (sectors') saturations. Significant growth regarding RE in solar, wind and related battery-storage installed capacity began around 2020–2021. The beginning of the analysis period, precisely at the start of the 2020–2021 energy-source price shock, has driven the development and installation of RES technologies. The research period is defined as 2020–2031 for the medium term and 2020–2050 for the long term. These periods are the most characteristic for logistic growth analysis.

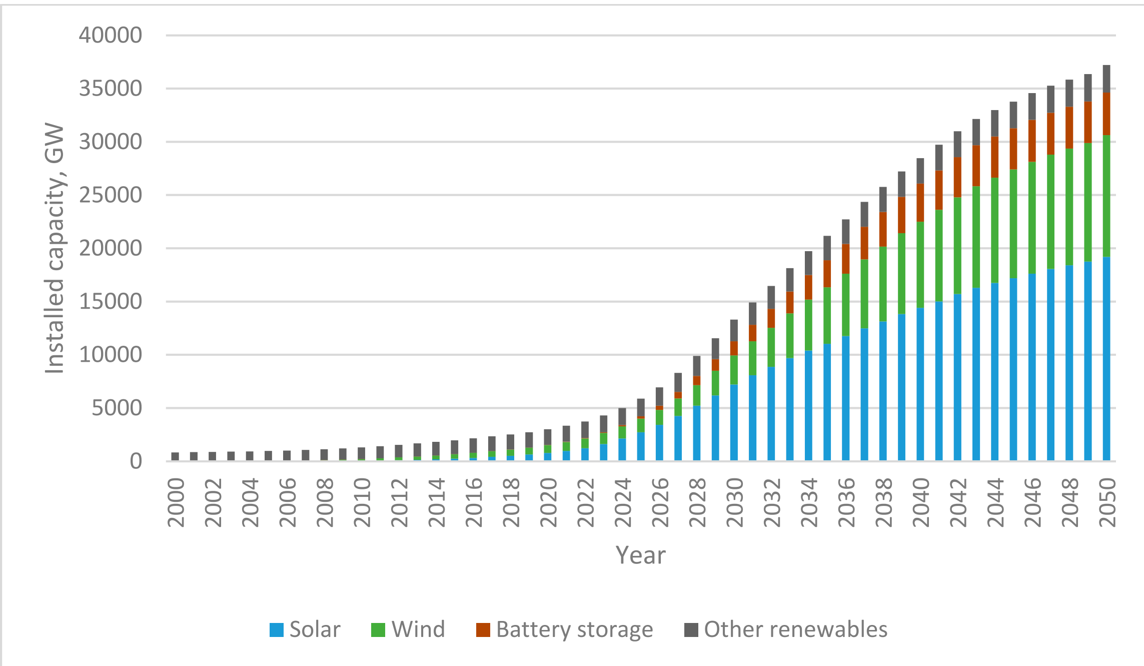

Figure 2. Renewable energy market saturation under the Net-Zero Scenario (NZS). Source: created by authors.

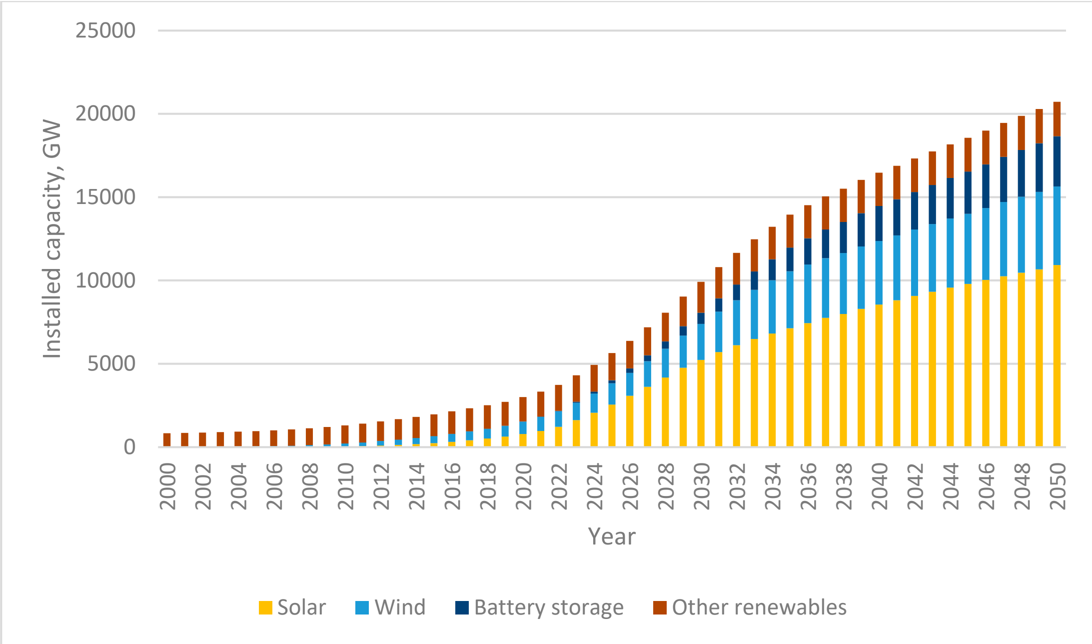

Figure 3. Renewable energy market saturation under the Economic Transition Scenario (ETS). Source: created by authors.

4.1. Renewable Energy Growth Trends Under NZS and ETS

Figures 2 and 3 illustrate the projected market saturation trajectories under the Net Zero Scenario (NZS) and the Economic Transition Scenario (ETS).

Because of aggressive deployment plans under the NZS, possible higher saturation levels occur, which raises the risk of market overheating. By comparison, the ETS produces a more measured expansion, therefore lowering speculative risks but maybe postponing the meeting of climate targets.

4.2. Renewable Energy Growth: Solar, Wind and Battery Storage

The sector of renewable energy shows varied dynamics of saturation between several technologies. While battery storage is essential in integrating variable renewable energy sources into the grid, solar PV and wind power account for the most proportion of newly installed technologies. Still, these industries have quite different financial saturation concerns and growth paths.

4.2.1. Solar and Wind Energy Trends

Solar PV and wind energy continue to expand under both the Net-Zero Scenario (NZS) and the Economic Transition Scenario (ETS). However, their market saturation trends show key differences.

Figures 4–7 illustrate the projected saturation levels of solar and wind energy under both scenarios.

Figure 4 represents the NZS medium-term installed RE saturation and growth rate. In this case, the maximums of solar saturation reached 0.63 and the growth rate 26.29, wind 0.63 and 9.86, and total RE 0.6 and 10.92. The bifurcation point was not reached.

Figure 5 represents the ETS medium term installed RE saturation and growth rate. In this case, the maximums of solar saturation reached 0.82 and the growth rate 36.06, wind 0.77 and 10.97, and total RE 0.82 and 15.5. The bifurcation point for solar and total RE was reached in 2030; wind bifurcation was calculated to be 2031. The overheating point was not reached.

Figure 6 represents NZS long-term installed RE saturation and growth rate. In this case, the maximums of solar saturation reached 0.91 and the growth rate 256.81, wind

0.8 and 72.16, and total RE 0.87 and 88.22. The bifurcation point for solar was reached in 2041, wind bifurcation was calculated to be 2045, and total RE was 2042. The overheating point was reached for solar in 2050.

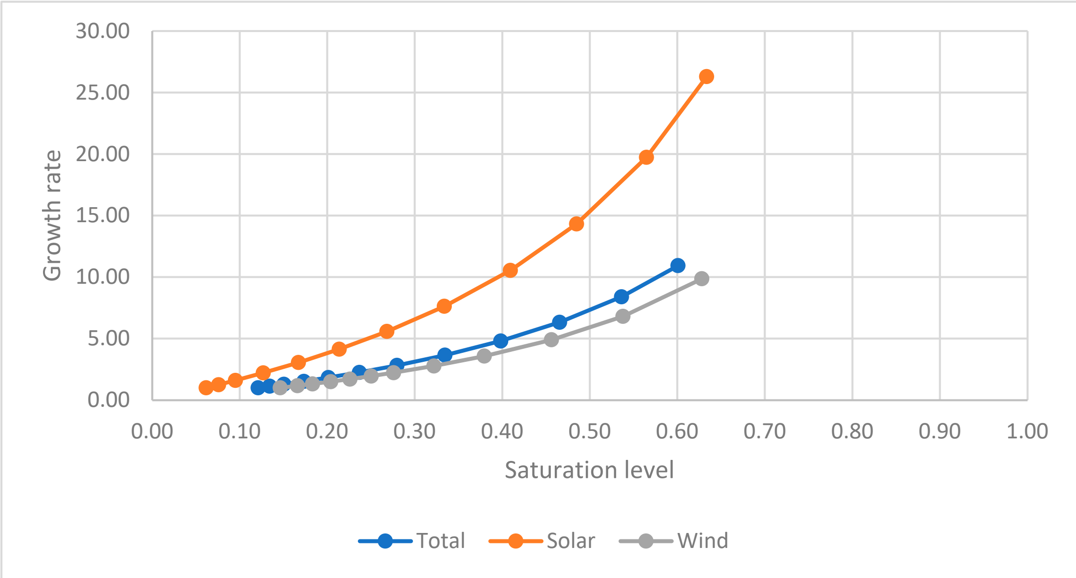

Figure 4. NZS medium-term installed RE saturation and growth rate, globally. Source: created by authors.

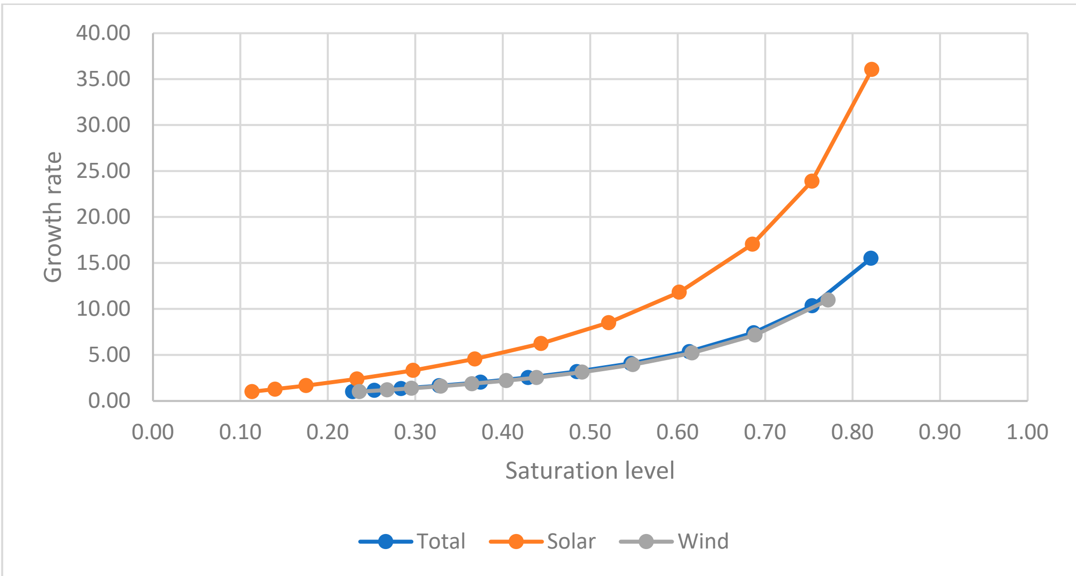

Figure 5. ETS medium-term installed RE saturation and growth rate, globally. Source: created by authors.

Figure 7 represents ETS long-term installed RE saturation and growth rate. In this case, the maximums of solar saturation reached 0.95 and the growth rate 274.28, wind 0.92 and 69.16, and total RE 0.96 and 133.18. The bifurcation point for solar was reached on 2039; the wind and total RE bifurcation point was calculated to be 2038. Overheating points were reached for solar and total RE in 2048, and for wind in 2049.

The projected saturation points and speculative risks for solar and wind energy are outlined below, indicating the timeframes for potential financial instability in each sector:

- Solar Energy. The results show the bifurcation point (~70% saturation) arriving at different times according to the scenario and period: for the long period, in 2041 (NZS) and in 2039 (ETS); for the medium period, only in 2030 (ETS). Overheating (~90% saturation) is expected in long periods by 2048 (ETS) and 2050 (NZS). Solar energy follows a faster saturation trajectory. Policy support, reducing costs, and growing efficiency all help to foster this explosive development. The great investment flows into solar, however, render it more susceptible to financial bubbles and speculative expansion.

- Wind Energy. Reaching the bifurcation point (~70%) around 2031 (ETS, medium term), and for the long term by 2045 (NZS) and by 2038 (ETS). Overheating (~90% saturation) is expected in the long period by 2049 (ETS). Wind power has a slower saturation curve. Longer project schedules, more expensive infrastructure, and grid integration restrictions all affect the slower expansion of the sector. Wind energy seems less prone to overheating than solar; hence, it is a rather low-risk investment in terms of financial saturation.

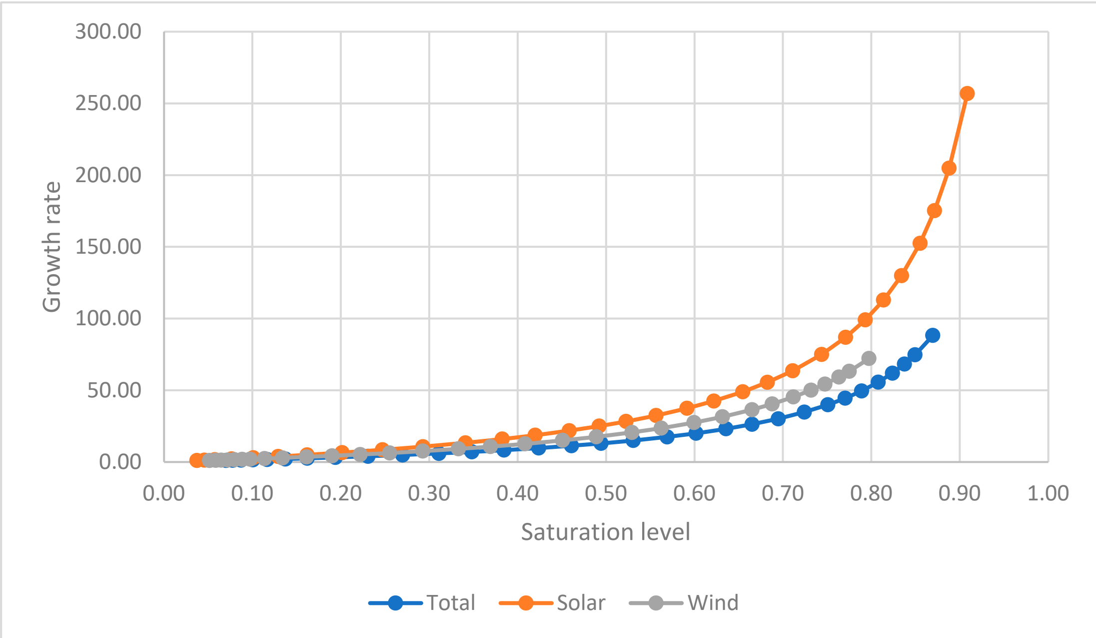

Figure 6. NZS long-term installed RE saturation and growth rate, globally. Source: created by authors.

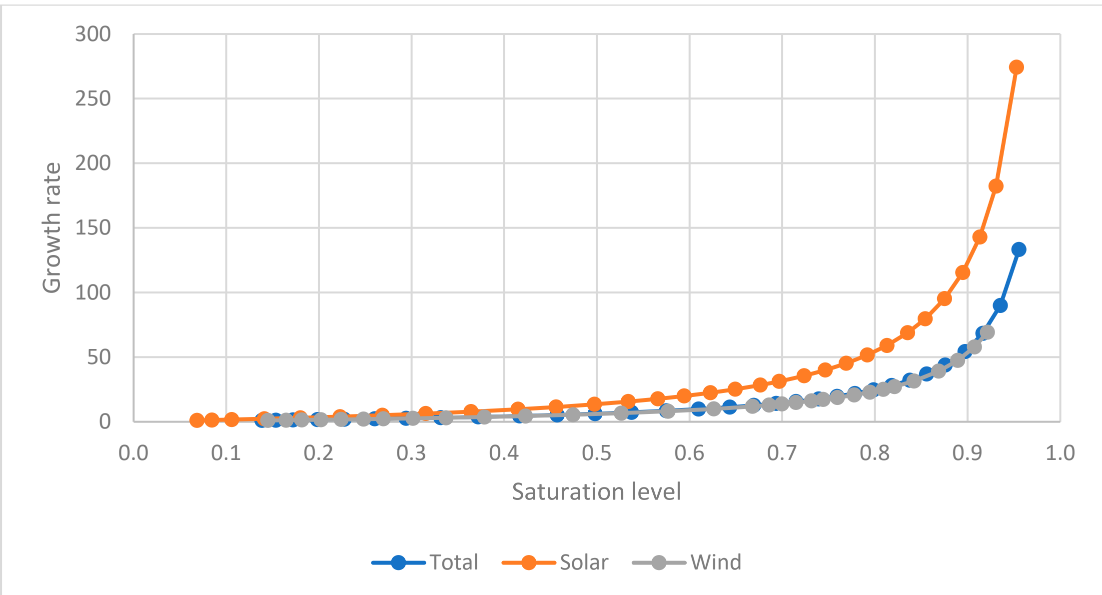

Figure 7. ETS long-term installed RE saturation and growth rate, globally. Source: created by authors.

4.2.2. Battery-Storage Market Trends

Although stabilizing renewable energy grids depends mostly on battery storage, its dynamics differ greatly from those of solar and wind. Starting with low initial capacity in 2020, the industry experienced a steeper increase rate than other technologies.

Figures 8–11 illustrate the projected battery-storage installation trends under the NZS and ETS.

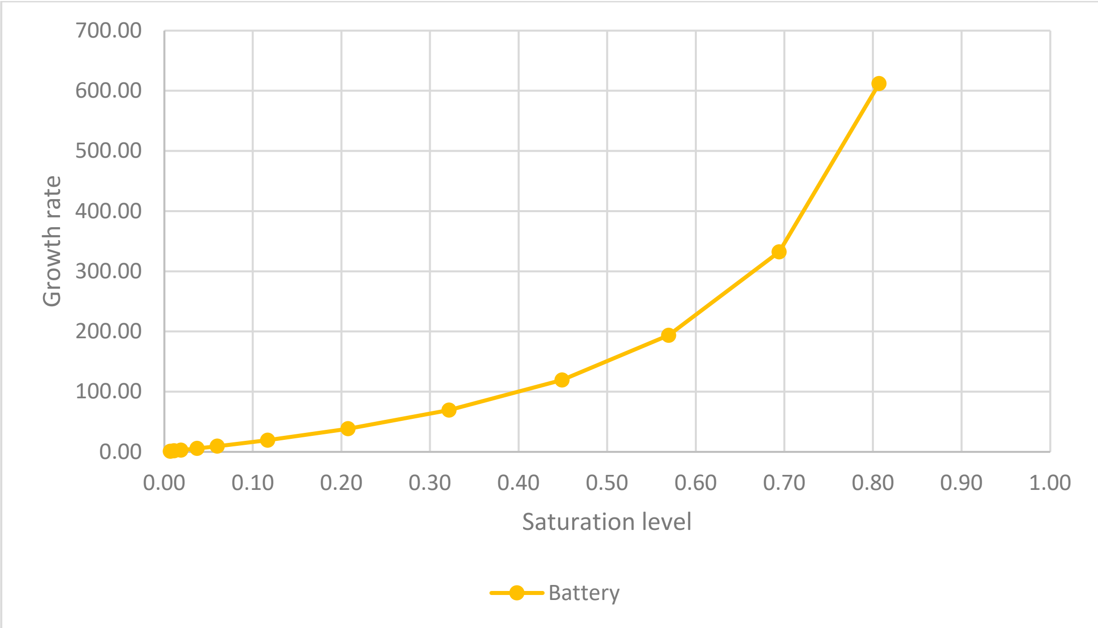

Figure 8. NZS medium-term battery-installed saturation, globally. Source: created by authors.

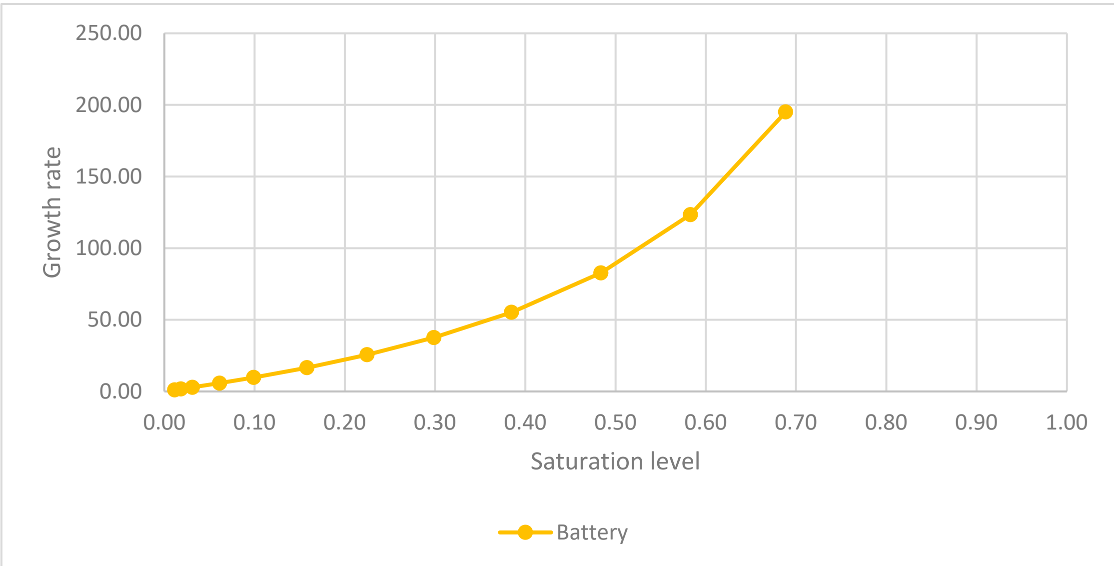

Figure 9. ETS medium-term battery-installed saturation, globally. Source: created by authors.

Figure 8 represents the NZS medium-term battery-installed saturation level and growth rate. In this case, the maximum of battery saturation reached 0.81 and the growth rate 611.92. The bifurcation point was reached by 2031.

Figure 9 represents the ETS medium-term battery-installed saturation level and growth rate. In this case, the maximum of battery saturation reached 0.69 and the growth rate 195.1. Bifurcation was not reached.

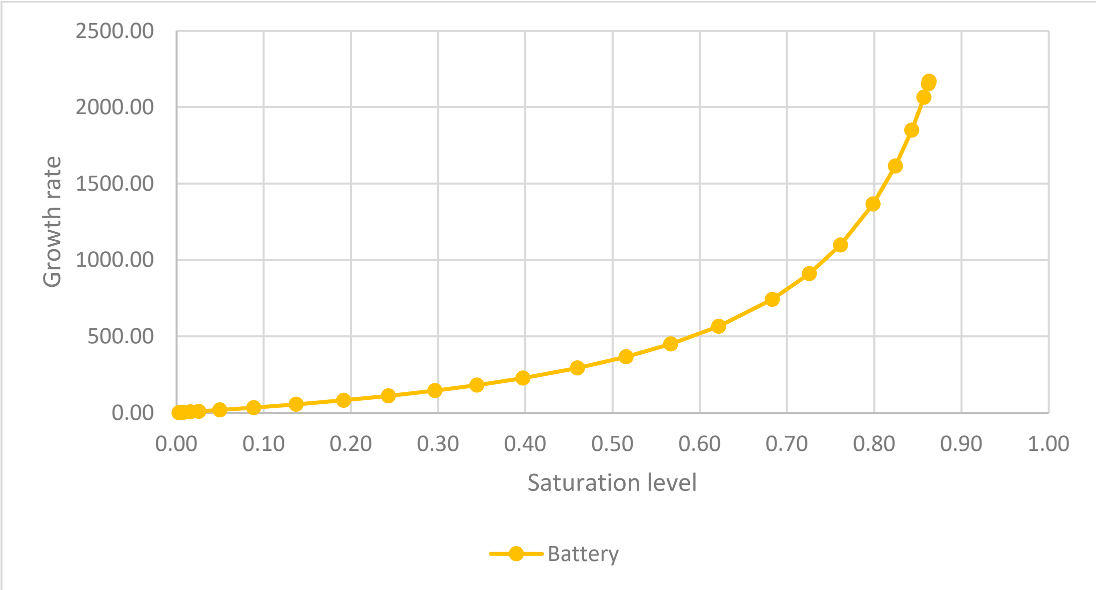

Figure 10. NZS long-term battery-installed saturation, globally. Source: created by authors.

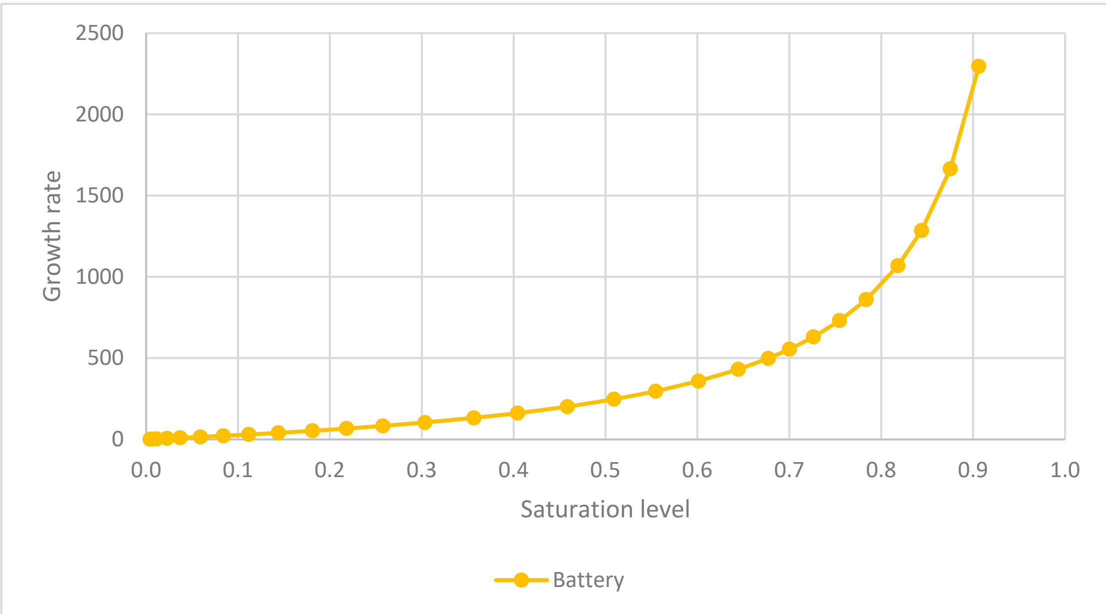

Figure 11. ETS long-term battery-installed saturation, globally. Source: created by authors.

Figure 10 represents the NZS long-term battery-installed saturation level and growth rate. In this case, the maximum of battery saturation reached 0.89 and the growth rate 2715.14. The bifurcation point was reached by 2038.

Figure 11 represents the ETS long-term battery-installed saturation level and growth rate. In this case, the maximum of battery saturation reached 0.97 and the growth rate 8779.9. The bifurcation point was reached by 2042 and the overheating point by 2048.

The following timeline summarizes the key saturation thresholds for the battery-storage market, illustrating its heightened risk of speculative overheating compared to solar and wind:

- Unlike solar and wind, battery storage is expected to reach its bifurcation point (~70% saturation) as early as 2031 (NZS, medium term) and by 2038 (NZS) and 2042 (ETS) for long periods. This therefore initiates a highly speculative period. Battery markets

may reach overheating (~90% saturation) by 2048 (ETS, long term), hence raising the probability of a financial bubble.
- The sector's accelerated growth is driven by technological advancements and declining battery costs, making it a focal point for investors. However, the rapid capital influx increases the risk of overvaluation, making battery storage the most vulnerable sector to speculative investment cycles.

These results highlight how largest financial saturation risks are in the battery-storage industry, followed by solar energy; wind power is still the most reliable. Table 1 summarizes the projected onset of these phases across different renewable energy sectors under two future scenarios: the Net-Zero Scenario (NZS) and the Economic Transition Scenario (ETS).

Table 1. Estimated timing of heating (bifurcation) and overheating phases in renewable energy markets under NZS and ETS.

	ETS							
	Long-Term				Mid-Term			
Stage	**Total**	**Solar**	**Wind**	**Battery**	**Total**	**Solar**	**Wind**	**Battery**
Heating (2nd period) start or bifurcation, year	2038	2039	2038	2042	2030	2030	2031	-
Boiling (3rd period) start, year	2048	2048	2049	2048	-	-	-	-
	NZS							
	Long-Term				**Mid-Term**			
	Total	**Solar**	**Wind**	**Battery**	**Total**	**Solar**	**Wind**	**Battery**
Heating (2nd period) start or bifurcation, year	2042	2041	2045	2038	-	-	-	2031
Boiling (3rd period) start, year	-	2050	-	-	-	-	-	-

4.3. Financial Saturation and Risk of Speculative Bubbles

The findings indicate that the renewable energy market undergoes distinct phases of financial saturation, affecting the probability of speculative bubbles. As markets near full saturation, growth accelerates, shifting from fundamentals-based investment to speculation-driven valuation.

4.3.1. Identifying Speculative Phases

As mentioned in earlier sections, three main phases of saturation characterize renewable energy markets:

1. Moderate Growth Phase (below 70% saturation):
   - Investment is primarily fundamental and based on market needs.
   - Growth remains stable, with limited speculative behavior.
2. Heating Phase (~70% saturation, bifurcation point):
   - Speculative behavior starts amplifying investment cycles, leading to price overvaluation.
   - Investment inflows exceed fundamental demand, creating conditions for a financial bubble.
3. Overheating Phase (~90% saturation, risk of bubble burst):
   - Market reaches saturation, and new investment no longer yields proportional returns.
   - High risk of speculative corrections, driven by shifting investor sentiment.

4.3.2. Sectoral Risk Comparison

While all renewable energy sectors are subject to financial saturation dynamics, the risk intensity varies:

- Battery storage is the most vulnerable sector, with bifurcation (70%) expected by 2031 (NZS, medium term) and by 2038 (NZS) and 2042 (ETS) for the long term and overheating (~90%) by 2048 (ETS, long term). Rapid technological advances and aggressive investor speculation increase the risk of overvaluation.
- Solar energy follows, with its bifurcation expected around 2041 (NZS) and 2039 (ETS) for the long term and 2030 (ETS) for the medium term, and overheating (~90% saturation) expected in the long term by 2048 (ETS) and 2050 (NZS). High policy-driven incentives contribute to speculative surges.
- Wind energy is the least vulnerable, with a longer development cycle and more stable investment trends, delaying speculative saturation.

4.3.3. Regulating Speculation in Renewable Energy Markets

The presence of speculative phases in the renewable energy market underscores the need for strategic policy interventions and investment regulations. Unregulated speculative growth could lead to price collapses, similar to historical financial bubbles in other sectors. Key risk-mitigation strategies include:

Regulatory frameworks to prevent excessive speculative capital inflows.

- Gradual subsidy reductions instead of abrupt policy shifts to maintain market stability.
- Encouraging long-term investment models over short-term speculative strategies.

To prevent excessive speculative capital inflows, regulatory mechanisms such as investment caps, stricter financial oversight, and gradual subsidy reductions should be implemented. Policies such as the European Union's Renewable Energy Directive and national-level financial stress-testing frameworks can help mitigate the risk of financial bubbles in renewable energy markets.

5. Discussion

Particularly in high-growth industries such as solar photovoltaics (PV) and battery storage, the results of this study show that markets for renewable energy are prone to financial saturation and speculative bubbles. The results underline the need for spotting bifurcation points (~70% saturation) and overheating phases (~90% saturation) to reduce investment risk. This part compares results with previous studies, places them in the larger framework of financial and energy policies and presents policy and investment ideas meant to stop financial instability.

5.1. Comparison with Existing Literature

Bubbles in RE have not been deconstructed to identify their embedded pattern and have not been evaluated through a new perspective of capital flows, investments, and possible financial saturation in the market. So far, there has been no assessment of the impact on the invested capital and how it could affect the markets. Although the authors analyze the bubble (e.g., Green Bubbles), the analyses do not include financial saturation and the impact of capital/investment on bubble formation. The existing body of research in this field, especially from a theoretical standpoint, is insufficiently developed and applied [35].

The following timeline summarizes the key saturation thresholds for the battery-storage market, illustrating its heightened risk of speculative overheating compared to solar and wind:

Particularly in technologically advanced sectors, the results coincide with earlier research on financial market saturation and bubble dynamics. Previous studies on financial bubbles imply that when market expectations differ from basic values, speculative behavior gets more intense, which causes asset overvaluation and consequent corrections [1,2]. Driven by governmental and environmental aims, the renewable energy sector follows similar investment trends, whereby fast development can cause possible overheating [3].

- Battery storage is the most speculative sector. The findings reflect earlier studies showing that newer technologies with fast growth rates—such as battery storage—are more prone to financial speculation [4,5]. Early bifurcation of battery storage (2031 in the medium term, 2042 in the long term) and expected overheating (~2048) point to this industry being most vulnerable financially.
- High investment volatility of solar energy. Policy-driven incentives, including feed-in tariffs (FiTs), have helped overcome price rises and crashes (e.g., Spain's solar market collapse) according to historical studies of solar-energy investment cycles [6,9]. This work supports these results by determining 2030 (medium term) and 2039 (long term) as the crucial solar PV bifurcation point.
- Unlike solar and battery storage, wind energy shows reduced saturation risks, which corresponds with past research stressing longer investment cycles and infrastructural restrictions as natural stabilizing forces [10].

These comparisons show that distinct investment and policy measures are needed for renewable energy financial risks since they are technologically specific.

5.2. *Policy and Investment Implications*

5.2.1. Managing Speculative Risks in Renewable Energy Markets

The existence of speculative investment cycles implies the necessity of government actions to stop market overheating. Renewable energy markets may suffer asset price collapses without appropriate protections, much like prior financial bubbles in other sectors [11].

Key policy recommendations include:

1. Gradual Phase-Out of Incentives:
    - Governments should avoid abrupt subsidy removals, as seen in past crises (e.g., Spain's FiT reduction in 2013) [6].
    - Instead, gradual reductions in incentives can help maintain investment stability while preventing speculative surges.
2. Stronger Financial Oversight:
    - Regulatory bodies should monitor financial saturation levels (~70% and ~90% thresholds) to intervene if speculative risks increase.
    - Financial stress tests for high-growth renewable energy sectors could prevent overleveraging and mitigate market crashes.
3. Diversification of Investment Models:
    - Encouraging long-term infrastructure investments (e.g., Power Purchase Agreements) over short-term speculative capital flows would reduce financial instability.
    - Governments could support public–private partnerships that focus on sustainable financing.

5.2.2. Implications for Investors

The findings underline for investors the importance of risk-adjusted portfolio management in the markets for renewable energy:

- Battery-Storage Investment Risks: Investors should carefully evaluate market values and refrain from too strong short-term speculation given the great chance of overheating in the battery sector by 2031 and 2038 in different periods.

- The volatility of the solar business calls for hedging techniques like diversified portfolios balancing solar investments with more reliable energy sources.
- Wind energy as a reduced-risk option: Because of its slower saturation trajectory and reduced speculative risks, investors looking for consistent, long-term returns might give wind energy top priority.

5.3. Long-Term Sustainability of Renewable Energy Markets

Beyond only financial concerns, the possibility of speculative bubbles in markets for renewable energy has wider consequences for energy security and climate targets. A financial crisis in renewable energy could cause:

- Slowness in investments, postponing the energy changeover.
- Loss of public trust, so lowering political and financial backing for next initiatives.
- Market corrections, therefore raising the capital cost for sustainable energy.
- Energy markets should concentrate on sustainable, policy-driven investment strategies instead of speculative development patterns if we are to guarantee long-term stability.

5.4. Limitations of the Research

While this study provides valuable insights into the dynamics of financial saturation and speculative bubbles in the renewable energy market, several limitations should be acknowledged:

- Forecast Dependency: The analysis relies heavily on forecast data from Bloomberg's New Energy Outlook (NEO). While these projections are based on robust methodologies, they remain subject to uncertainties related to future market conditions, technological advancements, and policy changes. The accuracy of the study's conclusions is inherently tied to the reliability of these forecasts.
- Simplified Model Assumptions: The financial saturation model employed in this study simplifies several variables, such as treating market capacity (Kp) as constant over time. In reality, market capacity is likely to evolve due to technological progress, policy shifts, and infrastructure investments. Future research could refine the model by incorporating dynamic changes in market capacity.
- Time-Lag Complexity: The time lag between financial saturation and market saturation is a critical factor in bubble formation, but its precise dynamics were not fully captured. Quantifying this lag more accurately and understanding its implications across different sectors would enhance the predictive capability of the model.
- Sectoral Generalizations: While the study identifies distinct growth trajectories and saturation dynamics across sectors, it does not delve deeply into sub-sectoral variations or regional differences. For example, market dynamics in developed regions may differ significantly from those in emerging economies.
- Exclusion of External Shocks: The study does not explicitly account for external shocks, such as geopolitical events, macroeconomic instability, or sudden technological disruptions, which could significantly alter market behavior and saturation dynamics.
- Behavioral Factors: Although speculative behavior and investor psychology are discussed conceptually, their quantitative impact on bubble formation was not analyzed. Integrating behavioral finance frameworks could offer deeper insights into how market sentiment influences speculative growth.

6. Conclusions

1. Financial bubbles in renewable energy markets emerge as markets approach saturation. The study confirms that bifurcation (~70% saturation) marks the onset of

speculative investment, while overheating (~90% saturation) signals a heightened risk of market corrections.

2. The model is based on functional relationships, with installed capacity as the independent variable and growth rate as the dependent variable, while other variables remain constant for each scenario and sector. Their accuracy is not assessed. The forecast reliability for the installed capacity is not evaluated, assuming market development follows predefined scenarios. Additionally, the model accounts for investment time lags, recognizing that financial market saturation and potential bubbles may occur before physical capacity saturation.
3. The conclusions and recommendations should be seen as theoretical and direction-setting rather than directive. Market capacity and the fulfillment of forecast scenarios are key variables that will determine the accuracy of the study results. Therefore, in order to be able to rely on the results of the studies, it is necessary to assess whether there is no significant change in the capacity of the market and whether the market is evolving according to the scenarios identified. Further studies are recommended to assess the impact of these variables on the accuracy of the estimates.
4. Battery storage is the most vulnerable sector to speculative investment. With bifurcation expected by 2031 (NZS, medium term), and by 2038 (NZS) and 2042 (ETS) for the long term, as well as overheating by 2048 (ETS, long term), rapid growth and investor enthusiasm increase the likelihood of market overvaluation.
5. Solar PV shows high volatility due to policy-driven investment cycles. The sector is projected to reach bifurcation by 2041 (NZS) and 2039 (ETS) for the long term, and 2030 (ETS) for the medium term, with overheating expected in the long term by 2048 (ETS) and 2050 (NZS), with past market fluctuations indicating sensitivity to policy shifts and financial speculation.
6. Wind energy follows a more stable growth trajectory. With a bifurcation point about 2031 (ETS, medium term), by 2045 (NZS) and by 2038 (ETS) for the long term, with overheating at the long term by 2049 (ETS), wind energy benefits from longer investment cycles and infrastructure constraints, making it less prone to financial overheating.
7. Strategic regulatory oversight is needed to prevent speculative risks. Gradual subsidy reductions, financial monitoring of market saturation, and diversified investment models can reduce the impact of speculative booms and crashes.
8. Ensuring financial stability in renewable energy markets is essential for the energy transition. If speculative bubbles burst, the consequences could delay renewable deployment, increase financing costs, and undermine investor confidence, ultimately affecting climate targets and energy security.
9. Future research should refine financial saturation models and assess regional differences. Expanding models to include geopolitical risks and economic factors can improve accuracy, while comparative studies across global markets will provide further insights into policy effectiveness.

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Abbreviations

The following abbreviations are used in this manuscript:

ETS	Economic Transition Scenario
FiT	Feed-in Tariff
IEA	International Energy Agency
MDPI	Multidisciplinary Digital Publishing Institute
NEO	New Energy Outlook
NZS	Net-Zero Scenario
PPA	Power Purchase Agreement
PV	Photovoltaic
PPPs	Public–Private Partnerships
RE	Renewable Energy

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