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LITHUANIAN ENERGY INSTITUTE

DARIUS KARAŠA

ASSESSMENT OF INVESTMENTS IN
RENEWABLE ENERGY BY APPLYING
FINANCIAL SATURATION THEORY

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Social Sciences, Economics (S 004)

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LIST OF ABBREVIATIONS AND TERMS

The following abbreviations and key terms are used throughout the dissertation. The definitions reflect their interpretation within the framework of Financial Saturation Theory and the developed research model.

Abbreviations:

CELS – NASDAQ Clean Edge Green Energy Index
DH – District Heating
ERIXP – European Renewable Energy Price Index
ETS – Economic Transition Scenario
EU – European Union
GDP – Gross Domestic Product
IEA – International Energy Agency
IRENA – International Renewable Energy Agency
MXACICEI – MSCI ACWI IMI Clean Energy Infrastructure Index
NEO – New Energy Outlook
NZS – Net Zero Scenario
PV – Photovoltaic
RE – Renewable Energy
RES – Renewable Energy Sources
SPGTCED – S&P Global Clean Energy Index

Terms:

Financial saturation – a condition in which accumulated investment (capital) approaches the capacity limit of a system or market. It reflects the extent to which investment inflows fill the available capacity and begin to influence growth dynamics, feedback mechanisms, and system stability.

Financial Saturation Theory – an economic theory explaining capital and market dynamics under limited capacity conditions. The theory is based on logistic growth and interprets economic processes through saturation, feedback, bifurcation, and structural transitions from fundamental to deficit market states.

Saturation level – the degree to which a system or market approaches its capacity limit. In the model, it is expressed as the ratio between the current value of the analysed system variable and its potential capacity.

Saturation interest – a logistic form of compound interest in which capital accumulation follows a growth process constrained by system capacity. It represents the most general form of compound interest under limited growth conditions and forms the basis for modelling financial saturation.

Saturation Paradox – a phenomenon in which increasing saturation level leads to rising profitability, contrary to the classical expectation of diminishing returns. At the same time, higher saturation reduces system stability and increases sensitivity to shocks.

Capacity – the maximum potential level that a system variable (such as capital, price, or installed capacity) can reach under given conditions. In the model, capacity

represents the upper limit that constrains growth and forms the basis for calculating the saturation level.

Logistic growth – a limited growth process in which expansion follows an S-shaped trajectory and approaches a capacity limit asymptotically. In this dissertation, logistic growth is used as the mathematical foundation for financial saturation analysis.

Bifurcation Point – a critical saturation threshold at which the system changes its structural state. In the dissertation, bifurcation marks the transition from a fundamental market state to a deficit market state, where positive feedback and bubble formation may emerge.

Market Duality – a dual market structure in which two regimes are distinguished: a fundamental market before Bifurcation Point and a deficit market after Bifurcation Point. This distinction is based on saturation level, feedback mechanisms, and resulting supply-demand dynamics.

Deficit market – a market state after bifurcation, characterised by high saturation level, where demand exceeds supply. In this regime, increasing investment inflows and positive feedback dominate, returns tend to increase, and self-reinforcing growth dynamics emerge, creating conditions for Saturation Paradox and bubble formation.

Fundamental market – a market state before bifurcation, characterised by relatively low saturation level, where classical supply-demand relations prevail. In this regime, negative feedback dominates, returns tend to diminish, and growth remains stable without self-reinforcing dynamics.

Elasticity – a measure of system sensitivity showing how strongly the growth rate responds to changes in saturation level. In this dissertation, elasticity is used to identify feedback intensity, bifurcation, growth stages, and system stability.

Growth rate – an indicator representing the intensity of logistic system growth. In the developed model, it is expressed as a model-derived coefficient that depends on saturation level and system-specific parameters, does not have a conventional measurement unit, and is interpreted as a relative indicator within the analysed system.

Positive feedback – a self-reinforcing mechanism in which rising prices, returns, or expectations attract additional capital, further increasing saturation and accelerating growth. It is characteristic of deficit market conditions after bifurcation.

Negative feedback – a stabilising mechanism in which deviations from equilibrium are corrected and growth remains moderate. It is characteristic of fundamental market conditions before bifurcation.

Financial bubble – a self-reinforcing process of accelerated price or value growth driven by increasing investment inflows under high saturation conditions. In Financial Saturation Theory, bubbles emerge in deficit markets and are sustained by positive feedback and rising return expectations.

Productive bubble – a post-bifurcation bubble in which investment-driven expansion supports real system development, innovation, or productive capacity. It is associated with Stage II, relative system stability, and positive long-term economic outcomes.

Destructive bubble – a post-bifurcation bubble in which speculative expansion becomes detached from real system development and results in system instability and economic harm. It is associated with Stage III and possible outcomes such as a major correction or collapse.

INTRODUCTION

Relevance of the topic

The successful completion of efforts to mitigate climate change and attain long-term sustainability is contingent upon the global transition to renewable energy. The Paris Agreement and other global frameworks have stimulated significant investments in renewable energy technologies with the goal of significantly reducing greenhouse gas emissions. The economic competitiveness of these products is not solely due to their environmental benefits, but also due to the significant cost reduction that has occurred over the past decade as a result of technological advancements and economies of scale (BloombergNEF, 2024a; IEA, 2024b).

Robust policy support, including subsidies, tax incentives, and renewable portfolio standards, has facilitated the rapid expansion of renewable energy markets. This assistance has facilitated the deployment process and increased capital inflows (European Commission, n.d.; Laan et al., 2024). Technological advancements, supportive policies, and decreasing costs contribute to the increase in investments in the renewable energy sector, which is anticipated to lead to substantial growth. It is anticipated that renewable energy investments will continue to expand at a rapid rate. According to the International Energy Agency (2024a), solar and wind will account for 95% of the nearly 3,700 GW of new renewable capacity that is expected to be operational from 2023 to 2028. Governments and organisations are prioritising decarbonisation, energy efficiency, and the transition to renewable energy sources, which is also leading to a transformative shift in energy policy.

Economic sustainability, one of the pillars of sustainable development, emphasises the importance of economic stability, resilience, and sustainable growth. Sustainable economic development necessitates the management of economic growth. This entails the promotion of growth when it is low and its suppression when it is excessively high. Therefore, the issue is not the reduction of investment itself, but the management of investment intensity in relation to market capacity, saturation level and long-term system stability. This is especially true in light of the significant financial saturation and escalating financial pressures that have been impacting the economies of a multitude of countries and regions. The financial depth statistics of the World Bank (2022) provide evidence of this. As societies became richer, capital accumulation became a continuous process, which led to a gradual increase in the financial depth of economies and, as a result, the saturation of markets. In the post-industrial economy, financial saturation has been further exacerbated, rendering it impossible to ignore. Asset values that are exaggerated beyond their true economic value may result from financial bubbles that occur in conjunction with periods of accelerated market growth, as evidenced by the historical record. The dot-com bubble of the early 2000s and the worldwide financial crisis of 2008 are examples of previous events that illustrate the potential for market instability and abrupt corrections as a result of overvaluation and speculative dynamics (Blanchard & Watson, 1982; Minsky, 1977).

Despite the fact that sustainability is a top priority, the renewable energy sector is not immune to these hazards. High levels of investment, technological confidence,

and government support create conditions for rapid market expansion, but they may also raise concerns about overvaluation and speculative activity. This problem can be interpreted through Shiller's argument that financial markets are shaped not only by rational calculations and fundamental indicators, but also by collective expectations, investor psychology, confidence, social contagion, and economic narratives (Akerlof & Shiller, 2009; Shiller, 2015, 2020). In renewable energy markets, such narratives may be particularly influential because investment expectations are closely linked to climate policy, decarbonisation targets, technological optimism, and the broader social demand for sustainability. Therefore, renewable energy investments may be affected not only by fundamental market conditions, but also by collectively reinforced expectations about future growth and technological transformation.

Recent developments in growth theory further strengthen the relevance of this issue. The 2025 Nobel Prize in Economic Sciences emphasised innovation-driven growth and creative destruction, highlighting that long-term economic growth depends on technological progress, knowledge accumulation, and the replacement of outdated structures by new technologies (Aghion & Howitt, 1992; Mokyr, 2016; Nobel Prize, 2025). In renewable energy markets, this perspective is particularly relevant because innovation, technological substitution, and the replacement of outdated energy structures may create new growth cycles and strengthen expectations regarding future technological transformation. At the same time, this perspective also emphasises the dynamic and cyclical nature of growth, raising the question of how long and how rapidly renewable energy systems can continue to expand under changing technological, institutional, and investment conditions.

Taken together, increasing financial depth, historical examples of financial bubbles, growing expectations regarding technological transformation, and strong policy support for renewable energy indicate that sustainable development may also become vulnerable to unstable investment dynamics. In this context, the relevance of the present dissertation is based on the need to assess not only the growth of renewable energy investments, but also the limits within which renewable energy-related systems can absorb capital, technology, and installed capacity without creating instability. Innovation and creative destruction may shift these limits, but they do not eliminate saturation risks. Rather, they make the relationship between investment intensity, market capacity, system absorption, growth cycles, and possible overheating more dynamic. The Financial Saturation Theory provides a suitable analytical perspective for this purpose, as it allows investment-driven growth to be examined in relation to market capacity, saturation level, growth rate, feedback mechanisms, and bubble formation. Its application to renewable energy investment analysis makes it possible to link contemporary bubble dynamics and cyclicity with the broader challenge of ensuring that sustainable development based on renewable energy remains sustainable.

Level of investigation of the scientific problem

Galileo Galilei (1564–1642), Thomas Robert Malthus (1766–1834) and other scientists of the time were the first in the world to observe and analyse growth trends and predict them. In 1825, Benjamin Gompertz (1779–1865) published a paper on a

new growth model (Stermann, 2000). Limited growth modelling was attributed to Gompertz and Verhulst models in the beginning of the 19th century (Girdzijauskas, 2024). Although the marginalist revolution took place at the end of the 19th century, marginalism and the application of margins based on it remained unpopular for a long time, with statistical and econometric tools being used more frequently. Until the middle of the 20th century, there were a few works based on the ideas of marginalism, e.g. the logistic curve model was widely used in demography (Pearl & Reed, 1920). Since the mid-20th century, logistic growth models have been used as an important instrument for assessing the principle of limited growth. Richards' research (Richards, 1959) enabled the application of the logistic growth model to empirical data modelling in biology, agriculture and botany. The S-curve had been used to predict technological innovation since the early 1960s. Scientific works presented and analysed models developed by Griliches (1957) and Mansfield (1961), which describe indicators for achieving rational development within certain limits.

The concept of innovation spreading according to an S-curve trend was proposed by Rogers (Rogers, 1976). Classic models, such as the innovation diffusion model (Bass, 1969), the technology substitution scheme (Fisher & Pry, 1971), the analysis of energy change waves and technology change (Grübler, 1996; Grübler & Nakićenović, 1991; Marchetti, 1980; Nakićenović, 1986), the diffusion model of new product adoption using Bass and Gompertz logistic growth curves (Mahajan & Muller, 1979), and system dynamics analysis (Stermann, 2000) have shown that rapid growth is always accompanied by a saturation point. Meyer and Ausubel study the effect of this dynamic carrying capacity on the trajectories of simple growth models, and use the new model to re-analyse two cases of the growth of human populations (Meyer et al., 1999). Stermann's contribution is particularly worth mentioning, for in *Business Dynamics: Systems Thinking and Modeling for a Complex World* (Stermann, 2000), he revealed the role played by the development of logistic growth models and highlighted how limited resources, feedback, and growth constraints have determined long-term business and technological developments. This allowed for the integration of quantitative and qualitative data, systematic analysis of growth slowdowns, mechanisms of saturation point formation, and the influence of feedback. Logistic growth in Stermann's model has become a universal structure explaining the dynamics of investment, innovation diffusion, and market development in complex socio-economic environments. In May's (1976) study, the main object of research is the S-shaped model with a saturation parameter. Technological change and fluctuations are linked to Kondratiev's model (Grübler & Nakićenović, 1991; Mialik, 2014). The forecast is based on the assumption that the logistic growth curve corresponds to natural growth, and it has been noted that when the curve is adjusted according to statistical data, there is instability and uncertainty in the growth limits (Kucharavy & de Guio, 2011). Studies of technological changes in the assessment of infrastructure diffusion (channels, railways, roads, etc.) have revealed that their diffusion coincides with logistic growth (Grübler, 1991). Some authors (Mialik, 2014; Tsoularis & Wallace, 2002) generally present 12 or more different growth models, which are essentially obtained by applying different values or expressions of coefficients in the generalised logistic model. Other functions of logistic growth, which are less relevant

to the theory discussed in the dissertation, are also worth mentioning: Linear-limited/Pseudo-logistic function, Von Bertalanffy's growth function, Richard's growth function, Weibull distribution, Heinz von Foerster coalition growth model, and O.C. Ferreira's logistic model (Akaligwo, 2023; Mialik, 2014; Renner-Martin et al., 2018; Teimouri et al., 2013; Tjørve & Tjørve, 2010; Tsoularis & Wallace, 2002).

The application of logistic growth principles and models in economics research is not novel. It has been explored in various works by different authors. Tsoularis and Wallace (Tsoularis & Wallace, 2002) presented a detailed analysis of logistic models, systematically examined logistic models, and demonstrated their wide-ranging application possibilities in biological and social processes. Sornette and his co-authors (Sornette, 2003, 2017; Sornette & Cauwels, 2015) analysed financial crises based on the dynamics similar to those of logistic saturation phenomena and interpreted financial bubbles as a distorted phase of logistic growth. Florio and Colautti (Florio & Colautti, 2005) developed a logistic growth theory of public expenditures and empirically demonstrated that fiscal systems approach saturation in the long run. Smirnov and Wang (2020) formulated a new economic theory in which logistic growth mechanisms are considered to be the fundamental endogenous basis of macroeconomic processes. Koo (2003) links the theory of balance sheet recessions, logistic growth, and financial saturation with limited capacity to absorb credit or capital, S-curve growth trends, and a saturation point beyond which growth slumps into stagnation. Koo developed the balance sheet recession mechanism based on data on the Japanese asset price bubble (Koo, 2003; Koo, 2011a), expanded the model to include the occurrence of balance sheet recessions in the US and Europe after 2008 (Koo, 2011b), and linked post-crisis trends in the US, Europe, and Japan (Koo, 2013a; Koo, 2013b), assessed the limitations of monetary policy and the role of fiscal policy (Lavoie, 2016). Other authors, such as Benšić et al. (2005), Accineli and Brida (2007), Guerrini and Ferrara (2009), Guerrini (2006, 2010), Duscha and Davidavičienė (2016), and Marszk and Lechman (2020), have applied logistic growth mechanisms and models to studies of social, economic, and financial processes. Some authors (excluding the authors and co-authors of the Financial Saturation Theory) applied logistic growth models in investments to predict asset prices (Wang & Hausken, 2023), to analyse the growth of new financial assets (Broadbent et al., 1981), and to estimate international investment position and national income (Gökmen & Mavi, 2021).

The application of logistic growth principles and models in the fields of energy and, later, renewable energy can be found alongside the development of these models. One of the first applied studies was a specific application to forecasting in the US electric utility industry (Bossert, 1977); at approximately the same time, empirical testing and theoretical formulation of logistic learning curve was carried out and applied to the structural evolution of energy systems and systems, related to energy (coal mining) (Marchetti & Nakicenovic, 1979). Clark's second edition book (Clark, 1976, 1990), published at the end of the 20th century, presents a classic formalisation of logistic growth focused on the management of biological resources. This provides a conceptual and mathematical basis for later models of technology diffusion and investment saturation, which are widely used in renewable energy analysis. A research

was conducted on the application of growth curves to energy studies and modelling of the diffusion of energy-consuming durables using several growth-curve models (Ang & Ng, 1992). Simultaneously, analyses and empirical research covering renewable energy are being published: a logistic model developed for integrating wind turbines into diesel-powered grid (Androutson et al., 1993), an empirical study of US installed electric generating capacity with a Bi-logistic growth curve (Meyer, 1994), a logistic and Hubbert theory model applied to the dynamics of resource extraction limitations through the concepts of ‘peak oil’ and ‘Hubbert curve’ (Bardi, 2009; Bardi & Lavacchi, 2009), modelling of RE technology potential and diffusion scenarios utilising S-curves (Sørensen, 2000, 2017), and research using four-parameter multi-cycle logistic growth curve models to forecast US energy production and consumption to 2040 (Harris et al., 2018). Logistic growth models or their principles of limited growth have been applied to energy and renewable energy by various other authors in their publications (Greiner et al., 2014; Hansen et al., 2017; Karasmanaki et al., 2019; Mohamed & Bodger, 2005; Rypdal, 2018; Wei et al., 2016). Currently, international energy agencies and organisations, as well as analytical centres, evaluate, forecast, and model the development of renewable energy and their technologies, and present possible development and growth dynamics. Although the authors do not specify a specific equation as a logistic function, the structure of the models and scenarios is similar to S-shaped growth trajectories on a theoretical and empirical basis (BloombergNEF, 2024a; IEA, 2024a; IRENA, 2024, 2025).

The structure of the discussed models allows for the determination of growth rates and limiting asymptotes, but they are difficult to transform into economic functions such as demand, supply, or total utility. When assessing the level of investigation, there is a lack of assessment of changes in growth rates taking into consideration accumulated capital and potential market capacity in value. The Financial Saturation Theory has proposed a new solution: saturation (general) percentages (in dissertation named ‘interest’), which offer broader analysis possibilities.

The Financial Saturation Theory (referred to as the logistical capital management theory until 2020) was developed from the application of logistical methods to capital management. Stasys Girdzijauskas is considered to be the founder and creator of this theory. In the last decade of the previous century, the author focused mainly on practical issues of financial mathematics (Girdzijauskas, 1997). However, the beginning of the Financial Saturation Theory (at that time called the logistic capital management theory) is considered to be the published work *Draudimas: kiekybinė finansinė analizė* (Girdzijauskas, 2002), in which the new paradigm of economic growth (saturation (logistic) percentages) was formulated for the first time. Saturation percentages reflected limited capital growth. This concept became the cornerstone for the subsequent development of the theory. This was subsequently followed by the works *Finansinė analizė: kiekybiniai metodai* (Girdzijauskas, 2005) and *Logistinė kapitalo valdymo teorija: determinuojieji metodai* (Girdzijauskas, 2006). In these works, saturation percentages are integrated into a broader analysis of capital management.

Published in Lithuanian and English (Girdzijauskas, 2006, 2008), the author argues that capital accumulation and growth are not infinite processes. These processes are subject to logistic growth, and growth trends follow logistic curves, which are associated with the law of diminishing marginal utility (Girdzijauskas & Štreimikienė, 2007). The papers have already defined the achievable growth limits, begun to distinguish market types according to their degree of saturation (Knyvienė et al., 2010), and included Bifurcation Points. Further development of the theory shifted to the application of logistic methods to macroeconomic issues and public finances (Girdzijauskas, 2011). The Financial Saturation Theory was developed in the context of economic bubbles, business cycles, and economic crises by applying logistic growth models (Girdzijauskas, Štreimikienė, et al., 2009; Girdzijauskas & Štreimikienė, 2010; Mackevičius, 2012; Štreimikienė & Girdzijauskas, 2008). The importance of elasticity for the stability of logistic growth has been assessed in publications by Girdzijauskas et al. (2008) and Girdzijauskas and Štreimikienė (2009), and theoretical economic (financial) saturation was modelled in Girdzijauskas et al. (2011). The developing theory was linked to consumer behaviour and expectations: the main factors influencing market saturation were defined, and using a theory-based model, the approaching economic crisis was predicted and the gap between real and nominal GDP was assessed (Koltan et al., 2013).

The principles of logistic growth and the Financial Saturation Theory have been applied to assess the impact of insurance companies' financial results on solvency (Jurkonytė & Girdzijauskas, 2010), and to analyse and compare conventional and logistic annuity insurance rate accounting (Girdzijauskas et al., 2007). The Financial Saturation Theory was developed and applied in the context of sustainable development and sustainable growth. Together with Dalia Štreimikienė, authors applied logistic growth models to analyse the concept of sustainable growth, defining the impact of resources on growth limits (capacity) and showing ways to achieve sustainable growth (Štreimikienė & Girdzijauskas, 2008). The scholars applied an integrated indicator model based on the generalisation of the logistic function, which was used to assess the implementation of the sustainable development strategy in Lithuania (Štreimikienė et al., 2009). Gradually, there has been a shift towards a broader assessment of sustainable development. Authors argue that the most significant obstacle to sustainable economic development is the old paradigm of economic science. They propose changing the paradigm based not on compound interest, but on general, or saturation, interest (Girdzijauskas, 2015; Girdzijauskas & Štreimikienė, 2014).

The evolving theory has acquired clearer terms and areas of application, along with more in-depth research conducted with colleagues. The theory was supplemented by debt and liquidity traps in logistic curves (Girdzijauskas, 2011; Girdzijauskas, Mialik, et al., 2012). The concept of the Saturation Paradox is applied and linked to increasing returns, high market saturation, and resulting economic phenomena, such as overproduction, bubbles, and business cycles (Girdzijauskas, Štreimikienė, et al., 2012; Girdzijauskas, Štreimikienė, et al., 2014). In the monograph (Girdzijauskas, Moskaliova, et al., 2014), the formation of bubbles and financial pyramids were linked to the saturation effect. The study revealed that financial bubbles arose from a sudden

increase in market profitability as it approached the saturation point, linking the dynamics of excess liquidity with bubble growth and credit traps (Dubnikovas, 2013).

At this stage of developing and researching the theory, the theory is already being practically implemented. A model for analysing bank capital was created and adapted using the Loglet Lab software version available at the time, and a diagram-based analysis and forecast of the bank's share capital was obtained (Girdzijauskas, Štreimikienė, et al., 2009). Using the Loglet Lab 2.0 calculation programme, changes in the stock market in the three Baltic countries (Lithuania, Latvia, and Estonia) were analysed, taking into account the formation and bursting of the price bubble (Dubnikovas et al., 2009). Based on the same programme, a bubble formation mechanism was created, aligned with a hypothetical Lithuanian economic growth cycle assessment model (Štreimikienė & Barakauskaitė-Jakubauskienė, 2011). Using a logistic growth model, credit traps and market saturation were analysed for stocks issued by the Bank of Lithuania and which were linked to stock indices (Girdzijauskas, Mialik, et al., 2012). A logistic analysis of the cyclicity of Japan's economic development in the period 1945–2010 was performed based on actual annual real GDP data, calculated logistic saturation values, and regression equations. The stages of development and periods of integration of the analysed system were identified, and the factors that increased the market capacity of the system were assessed (Mackevičius et al., 2013). The logistic model highlighted the specifics of growth dynamics and simultaneously contributed to the disclosure of unknown economic paradoxes. For this purpose, a trustworthy fuzzy model of the US real estate market index was created. This model revealed that it could be used to identify the threat of an impending growth recession if training was carried out during the period of the first bubble formation (Mialik et al., 2015).

Later research and developments in the theory covered inflation, economic paradoxes, bubble logic, and a new market equilibrium model (Girdzijauskas et al., 2022), as well as the theory's links to other economic theories (Čiegis & Girdzijauskas, 2018a; Girdzijauskas et al., 2018; Moskaliova et al., 2018), refinement of the value paradox (Čiegis & Girdzijauskas, 2018b), clearer definition of Market Duality after bifurcation, more precise definition and systematisation of saturation interest rates (Gryshova et al., 2019), and the explanation of the theory's functioning, which was strengthened by the inclusion of feedback processes (Girdzijauskas et al., 2020). In *Ekonominės krizės. Finansinio prisotinimo teorijos įžvalgos* (Girdzijauskas, 2024), the Financial Saturation Theory was presented as a well-developed, systematised theory that encompasses the essential results of the studies conducted to date: a refined market equilibrium model, an adjusted law of value, economic bubbles linked to feedback and physical resonance, a Pareto rule-based concept, an adjusted concept of inflation, the causes of business cycles, etc. The latest articles and studies based on the theory under analysis include the analysis of green bubbles in stock markets (Karaša & Girdzijauskas, 2024) and the re-examination and interpretation of past bubbles in relation to the energy sector and a natural Ponzi scheme (Karaša et al., 2025).

To date, four doctoral dissertations based on the Financial Saturation Theory have been prepared. The practical parts of these dissertations included a logistical

analysis of the nuclear power system to determine the cyclical nature of nuclear power consumption and a logistical analysis of cyclical fluctuations in Japan's GDP (Mackevičius, 2012). A fuzzy model of the Lithuanian real estate market was developed and applied to the analysis of the country's real estate market. The analysis showed that the model can identify the formation of a bubble and the stabilisation of the market after the bubble bursts, but it also revealed the limitations of Loglet modelling approach when analysing the economic market. The model was used to analyse the SEB Bank investment fund, and a fuzzy expert model was developed for the US real estate market (Mialik, 2014). Another dissertation applied economic logistic analysis to conduct an empirical study of the practical applicability of the insurance company solvency management model. Based on the logistic solvency management model for insurance companies, it was found that a company can regulate its solvency margin depending on the level of capital saturation (Jurkonytė, 2011). Another dissertation analysed the Baltic stock market indices, focusing on logistic (limited growth) functions describing the process of capital accumulation. By analysing the adapted software package Loglet Lab 2.0, the study assesses how the logistic growth model corresponds to practical data (Moskaliova, 2009).

The theory has evolved into an interdisciplinary theory combining mathematics, finance, macroeconomics, biology, and physics. Past and current developments indicate that this theory may provide a significant alternative perspective to classical economic paradigms in assessing growth limits, financial stability, and the impact of technological change. Despite the long-standing application of logistic growth models and the theoretical and empirical development of Financial Saturation Theory, previous studies have not sufficiently integrated renewable energy investments, market capacity, saturation dynamics, and bubble formation within this framework. To address this gap, this dissertation contributes by systematising Financial Saturation Theory for the assessment of renewable energy investments and by operationalising saturation through price, accumulated capital, and installed capacity as empirical proxies of investment-driven market saturation.

Scientific problem

How can Financial Saturation Theory be applied to assess the impact of investment dynamics on market saturation and bubble formation in renewable energy markets?

Research object

Investment-driven financial saturation processes and their expression in renewable energy-related systems and markets.

Research aim

To develop and apply a model based on Financial Saturation Theory to assess the impact of renewable energy investments on market saturation dynamics and bubble formation.

Research objectives

1. to establish a conceptual and theoretical framework linking renewable energy development, investment processes, bubble formation, and logistic economic growth, with particular emphasis on the role of policy interventions, externalities, logistic growth, and marginalism as a theoretical framework;
2. to analyse the principles and key mechanisms of Financial Saturation Theory and to examine how saturation, feedback, elasticity, and bifurcation explain bubble formation within its theoretical framework;
3. to develop a model and methodological approach based on Financial Saturation Theory for assessing market saturation dynamics and bubble formation in the context of renewable energy investments;
4. to apply the developed model and its analytical tools to assess the impact of renewable energy investments on market saturation dynamics and bubble formation;
5. to summarise the results of the theoretical analysis and empirical application of the model, and to formulate conclusions and practical recommendations for renewable energy investments in the context of bubble risks based on saturation.

Thesis statements

- Economic growth and investments are limited by capacity, and higher saturation level leads to increasing profitability (Saturation Paradox) but lower stability (high elasticity).
- When a high saturation level is reached, the system passes the Bifurcation Point, the market enters a deficit state, and conditions for positive feedback and bubble formation emerge. Under these conditions, bubbles may become productive or destructive.
- The integration of Financial Saturation Theory with logistic growth, elasticity, and bifurcation principles provides a consistent framework for explaining non-linear investment dynamics and bubble formation.
- The model developed based on Financial Saturation Theory is applicable to renewable energy systems of different scales and types and can identify growth stages, Bifurcation Points, system sensitivity, and bubble risks and types based on saturation level, elasticity, and subsequent system dynamics.

Scientific novelty

— *Theoretical contribution.* The dissertation expands the Financial Saturation Theory by integrating investment dynamics into market saturation and bubble formation analysis. Investment flows are conceptualised as the primary driver of financial saturation, linking capital accumulation with logistic market dynamics. The dissertation develops a theoretical structure that combines saturation level, elasticity, feedback mechanisms, and the Saturation Paradox into a unified analysis.

Its key contribution is the formal integration of bifurcation into the Market Duality framework, where it is used to distinguish transitions between fundamental and deficit market states. Growth stages are more precisely defined and theoretically

grounded by feedback and elasticity. The dissertation also develops a saturation-based classification of financial bubbles, distinguishing productive and destructive bubbles according to their dynamics and economic outcomes. This approach also allows for a deeper interpretation of scarcity and abundance economies, as well as market mechanisms, such as Ponzi schemes and pump-and-dump dynamics.

— *Methodological contribution.* The dissertation develops an original model for the assessment of investment-driven market saturation and bubble formation in renewable energy systems. The model is based on the transformation of logistic growth principles into a functional framework linking accumulated capital, price dynamics, and installed capacity.

A key methodological innovation of this dissertation is the operationalisation of investment-driven saturation through measurable empirical proxies, enabling the assessment of how capital accumulation influences growth stages, Bifurcation Points, and system stability. The model integrates elasticity dynamics, feedback mechanisms, and the Saturation Paradox, allowing for the identification of three growth stages. It also provides a basis for evaluating the non-linear effects of investment intensity on market dynamics and potential bubble formation.

— *Empirical contribution.* Based on the developed theoretical and methodological framework, the dissertation provides empirical evidence on the role of investment-driven saturation in renewable energy markets. The model is applied to three types of systems: (1) biomass-based district heating in the Kaunas region, (2) renewable energy-related financial market indices, and (3) global renewable energy installed capacity projections.

The results demonstrate how investment intensity influences saturation levels, growth stages, and the emergence of bubble dynamics across different market structures. Bifurcation Points are empirically identified, and different bubble types and bubble-related saturation risks are assessed. The findings confirm the applicability of Financial Saturation Theory for the analysis of empirical and scenario-based investment-driven saturation processes and bubble formation in renewable energy markets.

— *Practical contribution.* The dissertation provides recommendations for policymakers and investors on managing investment flows in renewable energy markets by considering system capacity, saturation levels, and bifurcation dynamics. The results offer guidance on how to manage investment and support flows to avoid destructive bubbles while supporting productive growth. The model can be used as a decision-support tool for identifying potentially critical saturation thresholds and managing investment-related bubble risks in the context of energy transition.

Limitations and assumptions

The developed model faces several limitations arising from the assumptions of logistic growth models. These include over-simplification, static market carrying capacity, strict *ceteris paribus* conditions, and a deterministic structure that precludes the explicit incorporation of exogenous shocks. The model also lacks post-saturation dynamics, limiting its ability to describe reversals, crashes, or prolonged negative growth phases. In addition, the assumption of a single-phase equilibrium reduces its

applicability to multi-phase or multi-equilibrium systems. Additional constraints arise from methodological assumptions, including the neglect of time lags between capital flows, price dynamics, and installed capacity growth. The system-specific growth rates hinder cross-market comparability, and the inverse causal sequence of the function does not allow for a direct comparison of prices with the results of classical economic models. The accuracy and reliability of the forecast data used for calculations are not assessed, therefore the results obtained are reliable within the limits of the forecasts. These limitations require cautious interpretation of results and highlight avenues for further model refinement, particularly through the incorporation of dynamic capacity, time lag delays, and reversal dynamics.

Possible practical applications

- The model allows the assessment of system saturation levels and the identification of potentially unsustainable states associated with bubble formation.
- The model enables the assessment of saturation levels and potential bubbles in renewable energy systems and provides recommendations for managing saturation risks. It also offers guidance on how the Saturation Paradox may support system growth in the case of productive bubbles while reducing instability and potential economic damage associated with destructive bubbles.
- The developed framework may also be applied as an analytical tool for monitoring market overheating, identifying early signs of instability, and supporting investment and policy decision-making in renewable energy systems.

Research methods

The research methods employed in this dissertation include logistic analysis, theoretical analysis of scientific sources, synthesis, and generalisation. The analysis of the Financial Saturation Theory and the development of the research model were done using a comparative and logical analyses of scientific publications, research and studies based on comparative, classification and generalisation methods.

In order to test the model, an empirical study was carried out using historical and forecast data from selected economic systems. The Loglet Lab logistic growth software package was used to determine the capacity of the systems. The statistical data used in the model were processed using an MS Excel spreadsheet.

Dissertation structure

The first part of the dissertation analyses the concept and definitions of renewable energy in a broad sense, including energy sustainability, sustainable development, renewable energy sources, technologies facilitating renewable energy use, renewable energy policies, and the internalisation of externalities through renewable energy development. This part also examines financial bubbles in the context of the energy sector and distinguishes between green, productive, and destructive bubbles. Logistic growth and marginalism are analysed as theoretical foundations for understanding growth limits and investment-driven market dynamics.

The second part of the dissertation focuses on the analysis of Financial Saturation Theory and the mechanisms of bubble formation under conditions of

limited growth. The analysis integrates saturation dynamics, the Saturation Paradox, elasticity, feedback mechanisms, bifurcation, and Market Duality into a unified framework explaining investment-driven bubble formation. Based on this theoretical analysis, a methodological model for assessing market saturation dynamics and bubble formation is developed.

The third part of the dissertation presents the empirical application of the developed model. The model is applied across three main analytical levels: a regional biomass-based district heating system in the Kaunas region, renewable and clean energy equity indices based on price and capital flow dynamics, and global renewable energy installed capacity projections for total renewable energy, solar, wind, and battery storage systems. The empirical analysis identifies different saturation dynamics, Bifurcation Points, and productive and destructive bubbles under different market and investment conditions.

The dissertation concludes with general conclusions and practical recommendations based on the theoretical analysis and empirical research results.

Validation of dissertation results

The results of this dissertation have been validated through publications in peer-reviewed international journals and presentations at scientific conferences. The main findings have been published in recognised journals, including *Journal of Risk and Financial Management*, *Energies*, and *Transformations in Business & Economics*, and presented at international conferences, supporting the relevance, applicability, and academic robustness of the proposed approach.

Relationship to prior publications

Parts of this dissertation and the earlier co-authored publications derive from the same doctoral research. Selected theoretical, methodological, and empirical elements were previously published in Karaša and Girdzijauskas (2024), primarily covering subsections 1.2.2–1.2.3, 2.1.1–2.1.2, 2.1.7, 2.2.1, and 3.3.2.1; in Karaša et al. (2025), covering parts of the conceptual discussion presented in Subsection 2.1.9.1; and in Mikalauskas and Karaša (2025), covering the installed capacity-based scenario analysis presented in Subsection 3.4. In the dissertation, this material has been revised, expanded, and integrated into a broader theoretical and empirical framework, including elasticity, bifurcation, bubble classification, additional applications, and a broader interpretation of saturation risks.

1. CONCEPTUAL FRAMEWORK OF RENEWABLE ENERGY INVESTMENT DYNAMICS, BUBBLE FORMATION, AND LIMITED ECONOMIC GROWTH

Renewable energy (RE), investments, bubbles, and economic growth are closely interrelated concepts. If we consider the starting point of RE development more than a decade ago, without massive investments in this sector, the RE would still be extremely small or even insignificant today. Investments, incentives, support, and fiscal and policy measures create the conditions for RE to develop in different directions and at an appropriate pace.

However, excessive support, rapid development, and very large investments go with the risk of bubbles. Bubbles are a side effect of rapid economic development and are not desirable. The principles of economic growth help to understand and assess bubble formation, including in the RE sector. Since growth has limits, the concept of limited growth is important alongside general economic growth, particularly through the paradigm of marginalism. Marginalism and its development help explain the importance of limit consideration in the process of growth.

The initial section focuses on the establishment of a conceptual and theoretical framework linking renewable energy development, investment processes, bubble formation, and logistic economic growth, with particular emphasis on the role of policy interventions, externalities, and marginalism as a theoretical framework. This section explores three main topics: analysis of renewable energy, a review of investments and bubbles, and economic growth models together with the development of marginalism.

The analysis of renewable energy examines the concept and definition of RE, its main types, RE enabling technologies, and the policies and regulations being implemented. The discussion of externalities and their internalisation conclude the RE review. An overview of investments and bubbles in the RE context is then provided, including a distinction between productive and destructive bubbles. The first part of the thesis concludes with a comprehensive examination of growth models, emphasising their importance and the impact of marginalism.

1.1 Renewable Energy: Concepts, Technologies, Policy Instruments, and Internalisation of Externalities

In order to assess investments in renewable energy through the lens of Financial Saturation Theory, it is first necessary to establish a clear understanding and definition of what constitutes RE. To properly delineate the scope and context of the present study, this subsection presents various definitions, conceptualisations, and interpretations of terms associated with RE. In addition, an overview of renewable energy is provided within the framework of sustainable development. Subsequent subsections examine the different types of renewable energy and technologies that enable their utilisation. Finally, the methods of the implementation and promotion of RE are discussed, with particular attention to policy instruments and the consideration of externalities and their internalisation.

1.1.1 Definitions and synonyms

Renewable energy is a multi-concept defined with varying emphasis by different authors and institutions related to world energy sector. Its definitions generally converge on energy sources that are naturally replenished, sustainable, and low in carbon intensity. Different authors provide varying definitions and emphasise numerous aspects of renewable energy:

- Boyle (2004) defines renewable energy as energy derived from natural processes that are replenished constantly, including solar, wind, biomass, geothermal, and hydropower.

- Twidell and Weir (2006) emphasise the sustainable aspect by describing renewable energy as energy obtained from flows that are replenished as they are consumed, while distinguishing it from fossil fuels and nuclear energy. The authors also review renewable energy technologies implemented worldwide, highlighting their role in harnessing sustainable resources, mitigating pollution and climate change, and providing cost-effective energy services.

- Ang et al. (2022) claim that renewable energy is the key element of sustainable, environmentally friendly, and cost-effective electricity generation.

- Renewable energy is a type of energy that encompasses specific forms of energy production and is commonly used. The concept of renewable energy became important before climate changes (Raoof & Rahimpour, 2024). This concept has also become a powerful and universal term because of temperature rising and has been applied in climate and energy strategies.

- Panwar et al. (2011) describe renewable energy technologies as technologies that harness energy from continuously available resources, such as solar and wind, and convert it into usable forms with minimal environmental impact. Renewable energy technologies are considered clean energy technologies, and their optimal use can minimise environmental impacts, reduce secondary waste, and contribute to meeting current and future economic and social needs. The authors further emphasise that renewable energy technologies provide significant opportunities to mitigate greenhouse gas emissions and reduce global warming through the substitution of conventional energy sources.

- Renewable energy is an abundant, well-established technology, whose main ingredient is free. An important appeal of renewables is its application of sophisticated technologies with an abundant supply of low or non-polluting sources to address the existing and growing energy needs of modern societies (Kaygusuz, 2001).

- The International Energy Agency defines renewable energy resources as those ‘derived from natural processes’ and ‘replenished at a faster rate than they are consumed’ (Angelou et al., 2013).

- Renewable energy is energy derived from natural sources that are replenished at a higher rate than they are consumed. Sunlight and wind, for example, are such sources that are constantly being replenished. Renewable energy sources are plentiful and all around us (United Nations, n.d.).

— Renewable energies can be defined as energy resources that are not depleted with use. In other words, they can be renewed from their respective sources, e.g. hydroelectric power from water resources (Jaiswal et al., 2022).

Renewable energy refers to sources that are virtually inexhaustible and naturally replenished (Richards & Schaefer, 2010). It is also known as alternative energy due to its potential to replace current energy sources with reduced environmental impact (Baydyk et al., 2019). Solar power utilises photovoltaic cells or thermal collectors, wind power converts wind's kinetic energy into electricity, hydropower harnesses flowing water, and geothermal energy taps into the Earth's heat. The transition to renewable energy is crucial for mitigating climate change, reducing greenhouse gas emissions, and achieving sustainable development (Sharma, 2024). Renewable energy sources are economical, abundant, and clean, thus helping to preserve ecological balance (Baydyk et al., 2019). Some authors define renewable energy as electricity and heat generated from these sustainable sources (Richards & Schaefer, 2010). Renewable energy, also referred to as 'green energy' or 'sustainable energy', is derived from natural processes that are replenished on a human timescale, such as solar radiation, wind, water flow, and biological activity. It contrasts with fossil fuel, which is finite and depletes over time (International Energy Agency, 2018; REN21, n.d.).

The most commonly deployed forms of renewable energy include solar photovoltaic (PV) systems, wind turbines, and hydropower facilities. In addition, bioenergy, derived from organic matter, and geothermal energy, which utilises subsurface heat, are instrumental in specific regional energy portfolios (REN21, n.d.; Twidell & Weir, 2006).

Although some policy frameworks categorise nuclear power as a low-carbon energy source, its classification as a renewable energy is contested. This is largely due to its reliance on uranium, a non-renewable mineral resource, and the environmental and safety concerns surrounding radioactive waste and reactor decommissioning (Sovacool, 2008; World Nuclear Association, 2023). Renewable energy systems are inherently scalable, allowing for deployment in both centralised utility-scale plants and decentralised installations suited for rural electrification or urban integration (International Energy Agency, 2022).

There are various synonyms of RE definitions, which are very similar or identical to the meaning of the main definition. Similar descriptions of RE in the general literature are provided in Table 1.

Table 1. Definitions of renewable energy-related terms in the literature

Term	Definitions in the literature
Clean energy	Clean energy refers to energy systems and technologies intended to meet energy needs while reducing environmental harm, emissions, waste, and resource use, as well as improving overall system efficiency (Dincer & Acar, 2015). Clean energy may include hydro, wind, solar, nuclear, marine, and biomass energy, indicating that the term is not necessarily limited to renewable sources (Liu, 2015). In energy policy, clean energy may encompass renewable energy technologies together with other low-carbon energy sources, including nuclear power (International Energy Agency, 2021).
Green energy	Green energy refers to energy sources with zero or minimal environmental impact that are considered environmentally benign and sustainable. It is commonly associated with solar, hydro, biomass, wind, and geothermal energy and is intended to reduce the environmental effects and emissions associated with fossil-energy use (Midilli et al., 2006).
Sustainable energy	Sustainable energy is derived from sources that are not expected to be depleted within a timeframe relevant to humanity and therefore support the long-term sustainability of human society and natural systems (Lund, 2014). The concept also involves the use of sustainable energy resources and carriers, greater energy-system efficiency, reduced life-cycle environmental impacts, affordability, social acceptability, equity, and consideration of living standards and lifestyles (Rosen & Farsi, 2022).
Alternative energy	Alternative energy can be understood as energy produced from resources that require capital investment and are developed as alternatives to conventional fossil-energy sources (Barreto, 2018). Alternative energy sources may contribute to replacing finite fossil fuels and commonly include solar, tidal, wind, bioenergy, hydroelectric, and geothermal energy (Boyle, 2004). Depending on the classification applied, alternative energy may encompass both renewable sources and non-renewable nuclear power (The Editors of ProCon, 2026). The term commonly includes renewable energy but may be used more broadly for energy sources that replace dominant non-sustainable sources such as coal, oil, and natural gas (Verma & Sharma, 2023).

Green energy is often politically or commercially framed, sometimes excluding large hydro or biomass due to environmental concerns (Kaldellis & Zafirakis, 2011). Sustainable energy is normative, aligning with sustainability principles rather than being technologically prescriptive (United Nations & World Energy Council, 2000). Alternative energy is an older term, now considered ambiguous due to its inclusion of nuclear and synthetic fuels (Sovacool, 2008).

Over the last decade, the terms ‘Renewable Energy’, ‘Clean Energy’ and ‘Green Energy’ have increased in popularity in academic research and amongst the public.

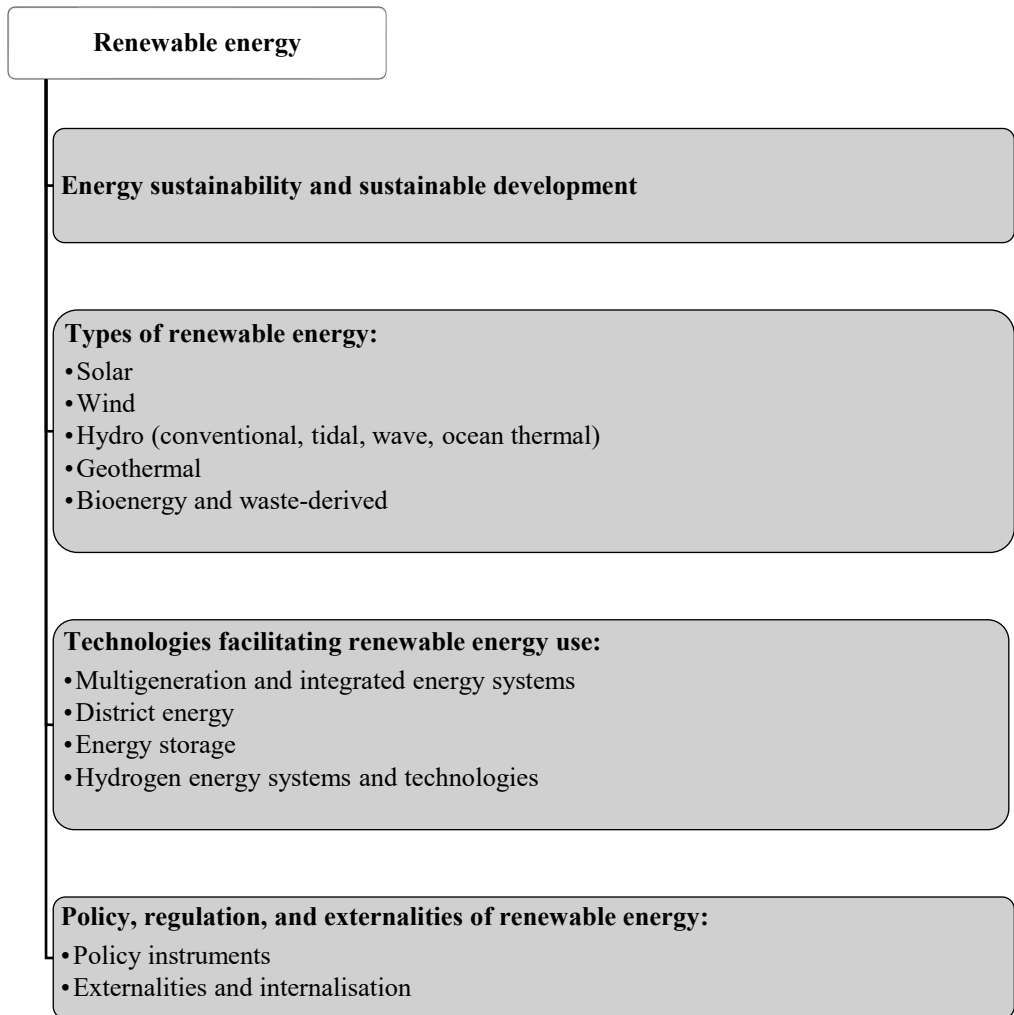
Sometimes, ‘Green Energy’ and ‘Clean Energy’ are used synonymously with renewable energy. The existence of different definitions has led to the confusion about the meaning each term is attributed. Some examples indicate that green energy is regarded as having the same meaning as renewable energy (Mavragani et al., 2016). The summary in comparison of these three definitions is provided in Table 2.

Table 2. Conceptual comparison of renewable, clean and green energy definitions

Green	
Definition	Energy sources that are environmentally friendly and have a minimal impact on the planet
Difference	Green energy focuses on minimal environmental impact, including ecosystem effects, while clean energy focuses primarily on low emissions
Clean	
Definition	Energy sources that produce little to no greenhouse gas emissions or pollutants during its generation
Difference	Clean energy is concerned with low emissions, which includes, but is not limited to, renewable sources. Some non-renewable sources, such as nuclear and natural gas, can be considered clean in terms of emissions
Renewable	
Definition	Renewable energy is derived from sources that are naturally replenished within a human timescale
Difference	Not all renewable energy is considered green, e.g. large-scale hydro projects can have negative ecological impacts

Renewable energy and sources used for energy production are considered in all three definitions (green, clean, renewable), but the present study mainly uses renewable energy, as defined in Table 2. These definitions collectively underscore sustainability, renewability, environmental compatibility, and technological maturity. Further RE review is based on four perspectives as follows (see Fig. 1):

- energy sustainability and sustainable development;
- types of renewable energy;
- technologies facilitating renewable energy use;
- policy, regulation, and externalities of renewable energy.



Source: created by the author based on Koohi-Fayegh and Rosen (2020)

Fig. 1. Renewable energy analysis across four perspectives

Renewable energy is recognised as one of the key elements of sustainable development due to its potential to enhance energy security, reduce environmental externalities, and support long-term economic resilience. The following subsection reviews renewable energy within the context of energy sustainability.

1.1.2 Renewable energy in the context of sustainability

The increasing demand for energy driven by rapid global economic expansion has intensified concerns regarding energy security and environmental sustainability. The realisation that fossil fuel reserves are finite and that carbon emissions contribute significantly to climate change has prompted a global shift toward energy efficiency and environmental preservation (Evans et al., 2009).

A secure and reliable energy supply is recognised as a necessary condition for sustainable development. Sustainability demands that energy resources be available in the long term, at reasonable costs, and without deleterious social or environmental consequences (Garba & Abdulrahman, 2024). Fossil fuels, such as coal, oil, and natural gas, as well as uranium, are inherently finite. In contrast, energy sources such as solar radiation, wind flows, hydropower, and biomass are renewable and thus more aligned with the principles of long-term sustainability.

Renewable energy lies at the heart of sustainable, environmentally sound, and cost-effective electricity generation. Technologies based on solar, wind, hydro, biomass, geothermal, and hydrogen energy are increasingly being adopted to address pressing environmental challenges, particularly climate change and air pollution (Evans et al., 2009; Lund & Mathiesen, 2009). Their ability to generate electricity with minimal to zero air pollutant emissions makes them critical for achieving a clean energy transition.

In addition to environmental benefits, RE contributes to economic sustainability. It can lower electricity generation costs over the long term by harnessing natural, inexhaustible inputs. Moreover, in many grid-connected systems, surplus energy generated by households or businesses can be sold back to the grid, thereby creating secondary income streams and promoting prosumer participation in the energy market (Varun et al., 2009).

Despite these advantages, fossil fuels continue to dominate global power generation due to the intermittency of many RE sources and the relatively high initial capital investments required for deployment (International Energy Agency, 2022). Overcoming these challenges necessitates supportive policy frameworks, innovations in energy storage, and financial mechanisms that mitigate investment risk – elements that are increasingly being incorporated into national and international energy strategies.

A complementary approach involves the deployment of renewable energy sources (RES). These are increasingly being adopted for both centralized power generation and decentralized, stand-alone energy systems (Lund & Mathiesen, 2009). Although RE technologies such as solar photovoltaic, wind, hydro, geothermal, and biomass systems are often characterised by higher capital costs and intermittency, they offer numerous advantages. These include reduced reliance on depleting fossil fuel reserves, lower lifecycle carbon emissions, and the avoidance of risks associated with nuclear power generation (Evans et al., 2009).

From a societal perspective, renewable energy systems are generally perceived as safer and more acceptable, leading to increased public and policy support (Lund & Mathiesen, 2009). Consequently, governments and private entities face the critical decision of selecting the most suitable RE technology (or a combination) for a given location, taking into account resource availability, social acceptance, and environmental constraints (Kunskaja & Pažeraić, 2025).

In an influential comparative analysis, wind, hydro, photovoltaic, and geothermal energy sources were evaluated using a multidimensional framework of sustainability indicators (Evans et al., 2009). These included metrics, such as electricity generation cost, greenhouse gas emissions over the full life cycle, land and

water use, and social impacts. The findings suggested that while wind power ranks highly in terms of emissions and water usage, it requires more land and carries high capital costs. Lund and Mathiesen (2009) further proposed a tripartite strategy for achieving sustainable development through energy systems transformation: energy demand reduction, production-side efficiency enhancements, and complete substitution of fossil energy with renewable sources. Dincer and Acar (2017) and Dincer and Bicer (2020) identify several criteria for sustainable energy systems, which include their being energetically secure, environmentally benign, reliable, energetically sound, integrable, economically feasible, commercially viable, and socially acceptable. Pan et al. (2023), using a bibliometric review, examine the relationship between energy and sustainable development and show that research in this field has expanded considerably in recent years. Low-carbon, efficient, and modern energy systems can contribute to progress across the sustainable development goals, although potential trade-offs may affect a large share of these goals. The authors also note that research has gradually shifted from dual to more plural perspectives, from static to dynamic analysis, and from theoretical discussion to practical application.

Renewable energy systems are central to sustainable development, offering environmentally sound, economically viable, and socially acceptable alternatives to fossil fuels, despite persistent challenges related to intermittency, capital intensity, and system integration. Energy sustainability refers to the ability of energy systems to provide reliable, affordable, and efficient energy services in the long term with minimising environmental impacts, preserving natural resources, and ensuring energy security. Meanwhile, sustainable development is a broader concept that denotes development that meets present needs without compromising the ability of future generations to meet their own needs. It encompasses balanced progress across economic growth, social equity, and environmental protection. Energy is central to economic activity, social well-being, and environmental stewardship.

1.1.3 Classification of renewable energy sources

Another criterion explaining RE is renewable energy sources or their types. Energy renewabilisation refers to the transition from conventional fossil fuel sources to renewable alternatives, including solar, wind, geothermal, hydropower, tidal, and wave energy, and biomass (Dincer & Bicer, 2020). Other authors provide more types in the list, as technologies are constantly developing.

The main forms of solar energy are heat and light, which are absorbed and transformed by the environment in various ways. Some of these processes create renewable energy flows, including biomass and wind energy. Renewable energy resources are expected to be instrumental in the future global energy system. The energy resources have been classified into three categories: fossil fuels, renewable resources, and nuclear resources (Panwar et al., 2011). Renewable energy sources can provide energy continuously and include solar, wind, hydropower, biomass, and geothermal energy; they are also commonly referred to as alternative energy sources (Rathore & Panwar, 2007). The largest components of renewable power capacity are solar, wind, and hydropower. At the end of 2024, global renewable power capacity

amounted to 4,448 GW. Together, solar, wind, and hydropower represented 96% of total global renewable power capacity (IRENA, 2025). Geothermal, bioenergy and waste-derived energy, tidal and wave energy, and ocean thermal energy account for a relatively small share of total renewable power capacity but may play substantial roles in specific regional energy portfolios.

Solar. Solar energy refers to the conversion of the Sun's radiation into electrical and thermal energy. It is among the most abundant renewable energy resources. Solar radiation provides heat and light that can be converted into useful energy through solar thermal systems and photovoltaic cells. Together with wind power, solar energy technologies are regarded as low-carbon technologies. Among renewable and sustainable energy options, it is widely considered abundant, long-lasting, broadly available, scalable, and environmentally favourable. Nevertheless, solar radiation is spatially dispersed and intermittent, making its effective use through advanced and clean technologies a continuing challenge (Jaiswal et al., 2022).

Solar thermal and PV technologies have contributed to the widespread use of solar energy. However, their conversion efficiency and intermittent operation continue to limit their contribution to the global energy supply. Combining these technologies may improve overall efficiency and broaden the utilisation of solar energy. Other solar energy conversion systems are also available. These include alternative PV technologies, thermoelectric systems that convert solar heat directly into electricity, and photosynthetic systems that either produce electricity or store solar energy as molecular hydrogen (Koochi-Fayegh & Rosen, 2020).

Wind. Wind energy is obtained from the kinetic energy of moving air, usually through wind turbines or other conversion systems that transform it into electricity. Wind generation is expanding through technological development and government support. Wind energy can be used directly as mechanical energy or converted into electrical energy (Jaiswal et al., 2022).

Where space for onshore wind turbines is limited, offshore wind energy is gaining importance in many jurisdictions (Østergaard et al., 2020). Other authors (Breton & Moe, 2009) review existing wind energy technologies, the potential of offshore wind resources, and plans for offshore wind parks in North America and Europe.

The use of hybrid wind energy systems, particularly wind/solar systems, is increasing. Current research focuses on system feasibility, optimal sizing through evolutionary optimisation techniques, modelling, control, and cost assessment (Khare et al., 2016).

The intermittent nature of wind energy creates uncertainty when it is integrated into power systems. Its effect on system reliability and stability depends on the penetration rate. Integrating wind and solar energy with energy storage technologies is important for frequency regulation in modern power systems. Such integration supports reliable and cost-effective system operation and the wider adoption of renewable energy sources. Power systems are evolving rapidly as renewable energy integration increases and system architectures change (Ullah et al., 2024). Future developments in wind energy include larger turbines, longer blades, improved

materials and manufacturing techniques, lower costs, and shorter production cycles (Veers et al., 2003).

Hydro. Hydropower is a renewable energy source that converts the kinetic and potential energy of water, replenished through the solar-driven hydrological cycle, into electricity (Twidell & Weir, 2015). Water-based energy includes conventional hydropower and ocean energy. Conventional hydropower uses flowing or falling water and usually requires dams and power plants. Tidal energy uses predictable ocean tides but remains much less widely deployed than conventional hydropower (Jaiswal et al., 2022).

Ocean energy resources can be classified into surface wave, tidal, ocean current, ocean thermal, and salinity gradient energy (Koochi-Fayegh & Rosen, 2020). Among these energy sources, tidal power has the largest installed capacity, followed by ocean current energy, while salinity gradient energy has the smallest contribution (Hussain et al., 2017).

Geothermal. Geothermal energy uses naturally occurring heat stored within the Earth's crust. In geothermal power plants, hot water or steam from underground reservoirs is brought to the surface and used to drive turbines, thus generating electricity for supply to the grid (Jaiswal et al., 2022). However, only a limited share of the available geothermal resources is currently used for electricity generation and heating because conventional technologies depend on accessible natural reservoirs and suitable geological conditions (Clauser & Ewert, 2018).

Bioenergy and waste-derived. Depending on how they are managed, biomass fuels and waste may be considered sustainable energy resources. Biomass consists of material from living or recently living organisms, including energy crops, wood residues, agricultural materials, aquatic plants, and municipal and animal waste. It may be used directly through combustion or converted into biofuels and biogas. Biogas is produced through anaerobic digestion, while waste-to-energy technologies can convert waste into biogas, bioalcohol, or biohydrogen (Koochi-Fayegh & Rosen, 2020).

Liquid biofuels provided approximately 4% of total global transport energy demand in 2022 (International Energy Agency, 2024a). Their contribution may increase because biofuel use can reduce greenhouse gas emissions, provide additional income for farmers, and strengthen energy security.

Biomass feedstocks can be converted into bio-oil, cellulosic ethanol, renewable hydrocarbon fuels, and biodiesel. They include agricultural, food, animal, wood, household, and municipal waste, while biodiesel derived from biomass can be used in transport (Demirbas, 2009). Microalgae have also attracted attention as a feedstock for renewable biofuels. Their use may improve the greenhouse gas balance while providing renewable biomass for biofuel production (Baloyi & Patel, 2025).

The deployment of renewable energy sources alone is insufficient to ensure a stable and sustainable energy transition; it must be complemented by enabling technologies, such as grid modernisation, digitalisation, and storage, which provide the technical and economic conditions for RES to reach their full potential. The next subsection presents technologies facilitating renewable energy use.

1.1.4 Technologies facilitating renewable energy use

Renewable energy sources often require supporting technologies to reduce limitations such as intermittency and facilitate their wider use. These technologies include multigeneration, energy system integration, district energy, energy storage, and hydrogen energy systems (Koochi-Fayegh & Rosen, 2020).

Energy system integration. In this context, integration refers to combining or hybridising energy systems and sources to improve efficiency, cost-effectiveness, resource use, and environmental performance (Dincer & Acar, 2018). The integration of individual subsystems can eliminate the deficiencies of each system. For example, intermittent solar energy may be integrated with geothermal energy, which provides a more continuous energy supply (Dincer & Bicer, 2020).

Multigeneration. A higher share of renewable energy in the primary energy mix can be achieved by integrating resources, such as wind, solar, and biomass, with existing fossil fuel technologies or the electricity grid, and by using multigeneration systems that supply both electrical and thermal energy. Renewable energy availability may vary during the year. Hybrid systems that combine several energy sources can reduce this limitation and improve the use of sustainable and renewable resources (Koochi-Fayegh & Rosen, 2020). Similarly to conventional cogeneration and trigeneration plants, renewable energy systems may provide electricity, heating, and cooling either in combination with fossil fuel plants or as the sole energy source in a multigeneration plant (Petrakopoulou & de la Rocha Camba, 2022).

Multigeneration systems combine different cycles and processes to transform diverse energy sources into several useful outputs (Dincer & Zamfirescu, 2014). The number and type of outputs can be adjusted to the needs of a community. These outputs may be produced from one or several energy sources, while the overall system may consist of several interconnected subsystems (Dincer & Bicer, 2020).

District energy. In district energy systems, thermal energy is produced in a central plant from conventional or renewable sources. It is distributed to users through hot-water or steam networks for space and water heating. Alternatively, it may be supplied to absorption chillers to provide cooling and dehumidification (Koochi-Fayegh & Rosen, 2020). In the EU, fossil fuels account for approximately two-thirds of the district heating energy mix, while biomass is the most common renewable source. District heating networks account for 5% of total EU CO₂ emissions and 19% of emissions from the EU energy sector (Pérez, 2025).

Energy storage. Energy storage helps balance differences between energy supply and demand and supports continuous, efficient, economically viable, and environmentally sustainable system operation. It is important in the transition to sustainable energy systems because it helps meet demand for electricity, heating, cooling, fresh water, drying, and transport. Available storage technologies include pumped storage, electrochemical systems, flywheels, compressed and liquid air, biological, magnetic, chemical, thermal, and thermochemical storage (Dincer & Bicer, 2020; Pamfile, 2023). Energy storage systems are commonly classified as electrochemical, chemical, mechanical, electrical, and thermal technologies (Pamfile, 2023). Other authors distinguish thermal energy storage (Alva et al., 2017; Tian & Zhao, 2013), including sensible, latent, and thermochemical storage, from electrical

energy storage (Carrasco et al., 2006), which includes flywheels, batteries, pumped storage, compressed air, hydrogen, chemical, and magnetic storage (Koochi-Fayegh & Rosen, 2020).

Hydrogen energy. Hydrogen is a versatile energy carrier with high energy density and clean end-use properties, making it suitable for a wide range of applications. It may replace conventional fuels, reduce greenhouse gas emissions, and support the transition towards a more sustainable energy system (Hossain Bhuiyan & Siddique, 2025). Hydrogenisation refers to the wider use of hydrogen as a clean fuel and energy carrier in different systems and applications. For storage purposes, hydrogen may be compressed, liquefied, or converted into other chemical fuels, including ammonia and methanol. Storage options include compressed hydrogen in salt caverns, metal hydrides, and liquefied hydrogen in cryogenic tanks. Ammonia is considered an attractive storage medium because it can be stored at lower pressures than hydrogen (Dincer & Bicer, 2020).

Hydrogen produced from renewable or fossil-based sources can be used in fuel cells to provide stable and continuous energy. Fuel-cell operation generates low or zero greenhouse gas and pollutant emissions at the point of use and may help reduce the effects of intermittency associated with renewable energy technologies. Currently, hydrogen represents one of the few energy carriers that is easily transportable, produces no greenhouse gases or pollutants at the point of consumption, and can be generated from a wide range of renewable and other sustainable energy resources with relatively low emissions (Koochi-Fayegh & Rosen, 2020). Finally, hydrogen enhances energy storage and supports renewable grid integration (Algburi et al., 2025).

Without facilitating technologies, renewable energy would be much more limited in its application. Renewable energy has important limitations, particularly intermittency and temporal supply-demand mismatches. This is especially relevant for variable renewable energy sources, such as solar and wind. As their share in the electricity system increases, their market value may decline because generation often occurs at the same time and does not necessarily coincide with demand. Hirth (2013, 2015) shows that the increasing penetration of wind and solar power can reduce their relative market value, while Hirth et al. (2015) explain that integration costs arise from temporal variability, forecast uncertainty, and location-specific constraints. Therefore, the expansion of renewable energy technologies must be accompanied by energy storage, grid modernisation, balancing capacities, and other flexibility measures. Through facilitating technologies, such as energy system integration, multigeneration, district energy systems, energy storage, and hydrogen energy, RE can be implemented more effectively at a larger scale. Collectively, these technologies enable more flexible, continuous, and low-emission energy supply by integrating multiple energy sources.

Renewable energy sources and renewable energy technologies cannot develop rapidly on their own or operate under market conditions while competing with the traditionally developed energy sector. Renewable energy struggles to function without additional incentives, support schemes, and supportive legal regulation. It is likely that without dedicated RE policies and regulation, renewable energy would remain a very small part of the overall energy sector, and its development rate would be slow.

The following subsection reviews RE policy and regulation and links the traditional energy sector with renewable energy through the concepts of externalities and their internalisation.

1.1.5 Policy and externality internalisation mechanisms shaping renewable energy investment dynamics

Renewable energy development depends not only on resource availability and technological progress, but also on policy support, regulation, and market conditions. Compared with the traditionally developed energy sector, renewable energy technologies face barriers related to cost competitiveness, revenue uncertainty, grid integration, financing, and externalities that are not fully reflected in market prices. Therefore, policy instruments and externality internalisation mechanisms are important for explaining renewable energy investment dynamics. This subsection reviews the main policy instruments and the role of externalities and their internalisation.

1.1.5.1 Policy instruments

Renewable energy development is constrained by a range of barriers that differ across countries and regions. These include economic, technical, financial, regulatory, institutional, administrative, social, environmental, awareness and information, and end-use or demand-side barriers. The integration of variable renewable generation into the grid creates an additional technical challenge, particularly in countries with high shares of renewable power (Painuly & Wohlgemuth, 2022). Policies are the principal catalysts for RE growth, shaping investment flows, deployment rates, and market formation. RE policies can be broadly categorised as regulatory, market-based, financial, and enabling (Aldy & Stavins, 2012; Carley, 2009; del Río & Mir-Artigues, 2014a; IRENA, 2019). These categories are described and structured together with renewable energy policy instruments in Table 3.

Table 3. Classification of renewable energy policy instruments and barriers addressed

Policy category	Instrument	Description	Primary barrier(s) addressed	References
Regulatory policies	Feed-in tariffs (FITs)	Guaranteed fixed or minimum price per kWh for RE electricity over a defined period	Price risk, revenue uncertainty, investment risk	Couture and Gagnon (2010), del Río and Mir-Artigues (2014a); IRENA (2019)
	Renewable portfolio standards (RPS)/Quota obligations	Mandatory minimum share of RE in electricity mix imposed on producers, retailers, or consumers	Market access barriers, demand uncertainty	Carley (2009), del Río and Mir-Artigues (2014a)
	Tradable green certificates (TGCs)	Certificates issued per unit of RE generation, tradable to meet quota obligations	Cost competitiveness, flexibility in compliance	del Río and Mir-Artigues (2014b), Karakosta and Petropoulou (2022)
	Net Metering/Net Billing	Consumers offset electricity consumption with self-generated RE fed into the grid	Demand-side barriers, small-scale investment incentives	Chen et al. (2023), Tanton (2014)
	Grid priority access and Guaranteed purchase	Mandatory grid access and full offtake of RE electricity	Grid access barriers, curtailment risk	Zhang (2019)
Market-based instruments	Certificate trading mechanisms/Renewable energy certificates (RECs)	A mechanism that assigns a distinct and tradable price to the environmental attributes of renewable electricity, independent of the physical electricity commodity	Cost efficiency, competition flexibility, competition	Karakosta and Petropoulou (2022)
	Auctions/Tenders	Competitive bidding for RE support based on price per kWh or capacity	Cost containment, allocative efficiency	del Río and Mir-Artigues (2014b), Toke (2015)
	Grants/Investment subsidies	Direct non-repayable public financial support for RE projects	High upfront capital costs, financing gap, capital access	Abdmouleh et al. (2015)
Financial support instruments	Low-interest loans	Public or publicly supported loans with reduced interest rates and longer maturities	Financing costs, capital access	Abdmouleh et al. (2015), Liptow and Remler (2012)
	Loan guarantees	Government-backed guarantees reducing lender risk and borrowing costs	Credit risk, cost of capital, capital access	Liptow and Remler (2012)

	Structural funds (in EU)	Cohesion policy instruments supporting RE in disadvantaged regions	Regional disparities, investment capacity	Štreimikienė et al. (2007)
Fiscal incentives/tax-based investment incentives	Favourable/Preferential loans	Loans with preferential conditions provided by private or mixed institutions	Financing barriers, commercialisation gaps	Abdmouleh et al. (2015)
	Investment tax credits/exemptions	Reduction of tax burden based on installed RE capacity	High capital costs, investment risk	del Río and Mir-Artigues (2014b), Walsh (2014)
	Energy or excise tax, VAT reduction	Reduced consumption taxes on RE-related equipment or energy	Cost competitiveness, political feasibility, payback period	Abdmouleh et al. (2015), Cui et al. (2023)
	Accelerated/Flexible depreciation	Faster write-off of capital expenditures increasing project net present value	Capital recovery, financial attractiveness	Koowattananianchat et al. (2019)
	Production-based tax credits/payments	Tax relief or premiums linked to electricity output	Operational efficiency, revenue stability	Eksioglu and Karimi (2014)
Carbon pricing instruments	Carbon taxes	Direct taxation of greenhouse gas emissions	Fossil fuel externalities, price distortion	Kirkpatrick (2022)
	Emissions trading systems (ETS)	Cap-and-trade system with tradable emission allowances	Emissions reduction, market efficiency	Narassimhan et al. (2018)
Enabling policies	Research and development (R&D) support programmes	Grants or loans for technology development and innovation	Technological maturity, learning effects	Abdmouleh et al. (2015), Hogg and O'Regan (2010)
	Capacity building, grid modernisation	Institutional strengthening and infrastructure upgrades	Integration of variable RE, system flexibility	IRENA (2019)
	Emerging technology frameworks	Support for hydrogen, storage, and next-generation renewable energy technologies	Long-term decarbonisation, technological maturity, system flexibility	IRENA (2019), Onabowale (2025)
	Primary Instruments (FiTs, Quotas, TGCs, Auctions/Tenders)	Main revenue-determining mechanisms for RE investments	Core investment incentives	Abdmouleh et al. (2015), del Río and Mir-Artigues (2014b)
Analytical classification of support instruments	Secondary Instruments (Fiscal, Financial, Enabling)	Complementary measures supporting primary instruments	Risk reduction, cost efficiency	Abdmouleh et al. (2015), del Río and Mir-Artigues (2014b)

Table 3 systematises the diversity of instruments and their barrier-specific roles. It should be noted that, although the categories are analytically distinct, some instruments have hybrid characteristics. Tradable green certificates may function as part of a regulatory quota system, while also operating as a market-based certificate trading mechanism. Auctions may also combine regulatory design with competitive price discovery. Therefore, the classification presented in the table should be interpreted as analytical rather than strictly exclusive.

Renewable energy deployment has traditionally been supported through three principal mechanisms, with their costs generally passed on to consumers: feed-in laws, quota systems combined with tradable green certificates (TGCs), and competitive tenders or auctions. The RE support literature commonly distinguishes between primary and secondary policy instruments, although the terminology varies and includes expressions such as dominant instruments, main support schemes, and primary or secondary measures. This classification separates the instruments that provide the core framework for RE support from those that perform a complementary role. Most RE investments in EU countries have been triggered by feed-in laws or quotas with TGCs, whereas financial, fiscal, and enabling instruments usually perform a supporting role by reducing investment costs, lowering risks, improving access to finance, supporting innovation, or strengthening grid and institutional capacity (del Río & Mir-Artigues, 2014b).

Overall, renewable energy policy instruments differ in their design and in the specific barriers they address, including revenue uncertainty, high upfront investment costs, financing constraints, and grid integration challenges. Primary support mechanisms mainly aim to secure stable revenues and enable market entry for renewable energy projects, while secondary instruments support investment by reducing costs, lowering risks, and strengthening the institutional and technological framework. Fundamentally, the justification for these policy interventions lies in the existence of environmental and system-related externalities that are not reflected in market prices. As a result, investment decisions are distorted in favour of conventional energy sources, creating the need for the internalisation of externalities, which is discussed in the following subsection.

1.1.5.2 Externalities and their internalisation mechanisms

Sustainable energy development necessitates the rectification of various energy market failures, most notably externalities, information asymmetry, and income inequality. These failures inhibit progress toward environmental and social objectives by distorting the true cost-benefit calculus of energy technologies. As a result, conventional energy technologies are systematically favoured over cleaner alternatives, despite their significantly higher environmental and social impacts. To achieve sustainability, policies must internalise the external costs and benefits associated with energy production and consumption. Renewable energy technologies, characterised by significantly lower life-cycle externalities compared to fossil fuels, are central to this transformation (Bento et al., 2020; Lu et al., 2020; Savitz & Gavrilletea, 2019).

Energy market failures and internalisation mechanisms. The absence of defined property rights over environmental goods such as clean air contributes to these market failures. In such cases, Pigouvian taxation (levying a tax equivalent to the marginal social damage) offers a corrective approach to internalise these costs. If revenues are used to compensate those harmed, the externality is effectively addressed (Bilan et al., 2020; Klaassen & Riahi, 2007; Mishchuk et al., 2018).

In practice, the internalisation of externalities is pursued through a combination of policy instruments. The main mechanisms for internalising externalities include fiscal instruments (e.g. carbon pricing, fossil fuel taxation), regulatory measures, subsidies for clean energy technologies, and public information campaigns (García Redondo & Román-Collado, 2014; Liao et al., 2019). Among negative externalities, atmospheric pollution is a key negative externality of fossil fuel combustion, which results in profound environmental and health consequences not reflected in electricity prices (Ortega-Izquierdo & del Rio, 2016).

Quantification of external costs and life-cycle impacts. The external costs of electricity production, often expressed in EUR cents per kWh, require life-cycle assessment methods for comprehensive evaluation (Karkour et al., 2020). Fossil fuel-based power generation causes most environmental and health damage during the combustion phase, whereas for renewables, emissions are primarily associated with equipment manufacturing. Nonetheless, fossil fuels dominate in negative impacts due to their significant health-related costs, particularly in urban and densely populated areas.

According to the ExternE project, the external costs associated with the coal fuel chain range from 0.2 to 4 EUR/kWh, with costs being particularly high in densely populated areas (Bickel et al., 2005; European Commission, Directorate-General for Energy et al., 2020). Under average European conditions, external costs are estimated at approx. 5 EUR/kWh for coal-fired power generation and approx. 1 EUR/kWh for combined cycle gas turbine technologies (Rabl & Spadaro, 2016). These findings underscore the necessity of internalising health-related externalities into electricity pricing frameworks to reflect the true societal costs of power generation.

Competitiveness effects and investment implications. Empirical research suggests that internalising these externalities would rapidly enhance the market competitiveness of renewable technologies (Kilinc-Ata, 2016; Sansyzbayeva et al., 2020). Although combined cycle natural gas plants currently hold a financial advantage under prevailing market conditions, renewable technologies are becoming increasingly competitive due to R&D advancements and economies of scale. Full internalisation of external costs would confer a clear social cost advantage to renewables, incentivising cleaner technologies and promoting energy efficiency (Bento et al., 2020; Štreimikienė, 2021).

Key policy instruments facilitating this transition include carbon taxes, removal of fossil fuel subsidies, and targeted support for renewables (Bento et al., 2020; Neverauskienė & Rakauskienė, 2018). Integrating external costs into electricity tariffs not only facilitates low-carbon transitions but also justifies subsidies for renewables to address market entry barriers and investment risks (Štreimikienė & Ališauskaitė, 2016).

Positive externalities of renewable energy. Renewable energy technologies generate significant positive externalities that are insufficiently captured by market mechanisms. These include reductions in air pollution and greenhouse gas emissions, improvements in public health outcomes, enhanced energy security, stimulation of local economic development, and job creation. Such benefits justify public support for renewable energy and its prioritisation within energy policy frameworks (Batra, 2023).

Comparative assessments reveal that while conventional energy sources, such as coal, oil, and gas, generate significant negative global externalities, particularly through their contribution to climate change, renewables offer an increasingly viable and less harmful alternative. However, empirical studies examining the economic and social co-benefits of renewables vary widely in methodological approach, geographical scope, and valuation techniques, resulting in substantial variation in the reported evidence. Only a limited number of studies evaluate the local acceptance of renewable technologies by comparing their positive and negative externalities (Hoffmann et al., 2022).

Health, economic growth, and long-term sustainability. A comprehensive scenario-based analysis examining the substitution of fossil fuels with low-carbon energy sources demonstrate substantial public health benefits. Evidence from China, the European Union, India, and the United States indicates that low-carbon energy deployment has prevented tens of millions of premature deaths over recent decades, with further significant health gains projected under continued energy transitions (Sovacool & Monyei, 2021). These results highlight the critical role of renewable and low-carbon energy in reducing mortality while simultaneously mitigating climate change.

Beyond health impacts, empirical evidence indicates that renewable energy development can stimulate economic growth by fostering technological innovation, generating employment, and attracting investment. A nuanced analysis of EU economies reveals that the relationship between renewable energy adoption and economic growth is shaped by the initial economic conditions and investment dynamics of each country (Dirma et al., 2024). Although the transition to renewable energy systems may initially appear economically unfeasible, long-term macroeconomic analyses suggest that the increased integration of renewable energy sources yields significant economic dividends. These include enhanced energy security, reduced import dependency, and the creation of green jobs. Over time, the consistent deployment of renewable energy contributes positively to sustainable economic development by stabilising energy prices and fostering a resilient low-carbon economy (Jaiswal et al., 2022).

Policy synthesis and justification. Renewable energy requires targeted promotion and policy support due to the internalisation of positive externalities and the correction of traditional energy market failures. Fossil fuel-based energy systems generate substantial unpriced external costs, particularly related to climate change, air pollution, and public health. Clean air and climate stability constitute public goods, and their protection necessitates collective intervention. Renewable energy technologies, offer clear societal advantages when these costs are internalised.

Market mechanisms alone are insufficient to capture the full societal value of renewable energy. Consequently, comprehensive policy frameworks are essential, including carbon pricing, greenhouse gas emission charges, public subsidies and fiscal incentives for renewables, and regulatory support for grid integration and innovation. Without such interventions, renewable energy would be unlikely to develop and expand at the scale required within a free-market environment. Therefore, policies function as principal catalysts for renewable energy growth by correcting market failures, shaping investment flows, and enabling the transition toward sustainable energy systems.

The technological and regulatory conditions discussed above directly shape the structure of investments in the renewable energy sector, influencing both the concentration of capital and price fluctuations in the market. In this study, the concept of RE is employed in a broad sense, emphasising its importance and the necessity of promoting its development. Given the critical role of promotion and support policies, there is an inherent risk of excessive or speculative investment stimulation. Large-scale incentives and financial support, while intended to foster growth, can potentially generate risks in the form of bubbles. Therefore, the following subsection focuses on the analysis of investments in the context of RE and the emergence of market bubbles.

1.2 Investment Dynamics and Bubble Formation in Renewable Energy Markets

Policies are the primary drivers of renewable energy growth, directly shaping investment flows, deployment rates, and market incentives. Such policy-driven expansion, combined with technological uncertainties and substantial capital inflows, creates conditions conducive to the formation of financial bubbles. The interplay between regulatory support, investor behaviour, and market expectations renders the RE sector particularly sensitive to speculative dynamics. In this context, the following subsection explores a range of academic studies that analyse the causes of bubbles and investigate how investments and investor behaviour influence their development and potential consequences, especially in RE sector.

1.2.1 Structural and behavioural mechanisms of bubble formation in renewable energy markets

Bubbles remain subject to debate and are not yet fully understood. They are also rarely identified with precision before bursting. Sornette and Cauwels (2015) describe a financial bubble as an unsustainable phase in which the price of an asset rises at an accelerating rate. During this phase, prices may follow an accelerating, non-linear trajectory. Since bubbles generate identifiable patterns, these signals may allow them to be detected before collapse. A power law describes a functional relationship in which one variable changes as a constant power of another. In economic systems, power-law behaviour is often associated with scale effects, extreme events, and non-linear growth patterns. Bubbles (Ghosh et al., 2022) often develop through repeated phases and may change after reaching a critical point, such as a crash. During this process, asset valuations can rise substantially. However, extreme events such as COVID-19 may accelerate bubble development and make its dynamics more difficult to analyse fully.

The occurrence of financial bubbles in economic history has been established as periods where prices rise swiftly from far below their intrinsic value to inflated levels. Later they are followed by abrupt declines (Afilipoaei & Carrero, 2023). Over the years, theoretical models have been proposed to describe the formation and behaviour of these bubbles. Bubbles are strongly related to energy sector (including renewable), as heightened investor optimism and market exuberance have prompted concerns. This is related to the potential overvaluation of green technologies in this sector. To understand these bubble dynamics in RE markets, several theoretical frameworks have been developed.

The classical economic approach explains market saturation primarily through diminishing marginal returns and corrective market mechanisms. As capital inflows increase and more participants enter a market, additional investments may generate progressively lower expected returns. Market saturation is therefore associated with stronger competition, reduced opportunities for further expansion, and declining investment attractiveness. Under the market efficiency perspective, asset prices and returns remain linked to underlying economic fundamentals (Dalby et al., 2009; Vassalou, 2012).

The Financial Instability Hypothesis (Minsky, 1977) explains how financial markets move from stability to euphoria and eventually towards a crash. This is another important theoretical approach. Minsky (1977) suggests that stability arises when markets initially allow investment based on sound fundamentals. Optimism subsequently propels stock prices upward, establishing a self-perpetuating cycle. This phase, called euphoria, witnesses excessive speculation, as investors anticipate a continual increase in prices. As capital asset prices escalate, valuations become progressively untenable, resulting in fragility and establishing a conducive atmosphere for a crisis as confidence eventually diminishes.

The Rational Bubble Model proposed by Blanchard and Watson (1982) presents an alternative perspective in which bubbles can arise under rational expectations. Under the model, investors recognise that prices exceed fundamental values, but they continue to purchase assets because they expect to resell them at a higher price before the collapse of the market confidence in those fundamentals. This situation creates a cycle where investors invest more, further inflating the bubble as prices increase and attracting additional capital. Rational Bubble Models do not deny that investors are aware of the possibility of a market correction. Instead, they posit that participants think there is ample warning before such an event and continue to trade until just before the collapse.

Although these models evidently address distinct aspects of bubble dynamics, they ultimately concentrate on a critical characteristic. Bubbles are indicative of a gap between market prices and the fundamental state of the economy. According to Lim (2018), this gap indicates that bubbles are not exclusively the result of irrational behaviour. Bubbles may also stem from structural imbalances, investor conduct, and market liquidity effects.

The emergence of financial bubbles is a complex phenomenon influenced by stochastic factors, including market expectations, investment flows, and psychological trends (Afilipoaei & Carrero, 2023). In real world conditions, these

factors interact in ways that can cause asset prices to deviate significantly from their fundamental value.

Market expectations are instrumental in the formation of financial bubbles. Shiller's works show that asset prices may deviate from fundamental values not only because of rational speculative behaviour, but also because of investor psychology, confidence, manipulation, social contagion, and economic narratives. In this view, bubbles develop when collectively shared expectations about future growth become self-reinforcing and begin to influence investment decisions, demand for assets, and market prices. Such dynamics may turn price growth into a self-fulfilling process, where investors continue to buy assets not only because of current fundamentals, but because they expect other market participants to maintain the same optimistic belief (Akerlof & Shiller, 2009, 2016; Shiller, 1989, 2000, 2015, 2020).

This mechanism is particularly relevant for renewable energy markets. Narratives about climate transition, decarbonisation, technological breakthroughs, energy independence, and future green growth may strengthen investor confidence and attract additional capital. Positive news, policy support, or technological progress can increase expectations of future returns, raise demand for renewable energy-related assets, and support a self-reinforcing rise in prices (Akin & Akin, 2026). In this sense, narrative-driven expectations may become one of the channels through which investment waves and potential bubbles are formed in renewable energy markets.

Investment flows are another important trigger for bubble formation. Capital flow into emerging markets may be increased during periods of excessive liquidity, which are defined by reduced financing costs or expansionary monetary policies (Allen & Gale, 2000). Investors are attracted to sectors with this possibility because of the potential for future growth and substantially higher returns, which leads to an increase in prices. This phenomenon was observed in historical episodes such as the global financial crisis in 2008 and the real estate bubble. In such situations, markets become more vulnerable to sharp corrections when liquidity conditions shift or investor expectations change, especially as continued capital inflows drive prices beyond sustainable levels (Calvo, 2012).

In the context of this dissertation, investment flows are interpreted not only as short-term market drivers but also as a cumulative process that may drive financial saturation. As capital accumulates within a given market or sector, the system tends to approach its capacity limits, leading to increasing levels of saturation. This process creates potential structural conditions for feedback mechanisms to intensify and contribute to bubble formation.

Beyond narrative-driven expectations, broader behavioural finance factors also play an important role in bubble formation. The role of psychology in the making of bubbles is analysed by many behavioural finance studies. Human behaviour often contributes to bubble formation (herding behaviour, overconfidence, and recency bias), which leads investors to decisions that diverge from true assessments of value. Herding occurs when investors follow the actions of other market players, but do not conduct their own analysis; in this way, they amplify market trends. Overconfidence leads investors to downplay risks, thinking they are better at timing markets than

others. As suggested by Sathya and Gayathiri (2024) and Jlassi and Bensaïda (2014), recency bias can result in the belief that a rising trend will continue indefinitely.

These psychological dynamics create the conditions for bubble formation, as investors start behaving more like herds and stop valuing assets according to their fundamentals. As an increasing number of buyers enter the market, motivated by speculation regarding escalating prices, markets deviate further from their intrinsic value. This misalignment ultimately becomes unsustainable and leads to a situation where negative information or a shift in sentiment triggers a rapid market correction (Andraszewicz, 2020).

These dynamics are particularly evident in renewable energy investments, where high expectations and strong policy support can amplify speculative behaviour. The global push to combat climate change, enhance energy security, and promote long-term sustainable economic growth is creating significant opportunities in the renewable energy sector. Three main factors (technological innovation, supportive policies, and strong investor interest) have driven rapid changes in market dynamics, including the fast expansion of electric vehicle (EV) and solar panel markets. However, this rapid growth also carries risks, including market bubbles and overvaluation, which may arise when speculative expectations and investor behaviour amplify capital inflows beyond fundamental market conditions (Ghosh et al., 2022; Lehnert, 2023; Padmavathy, 2024).

The worldwide move to renewable energy has seen a wave of investments in diverse technologies, such as solar photovoltaics, wind turbines, battery storage, and electric vehicles. This push has aimed at reducing greenhouse gas emissions to meet global climate agreements, e.g. the Paris Agreement. Related reports (International Energy Agency, 2023) highlight the magnitude of investment required to achieve net-zero carbon emissions by 2050, which is anticipated to amount to trillions of dollars, thereby facilitating new markets and innovation (BloombergNEF, 2024a; IEA, 2024a).

The increase in investment has expedited the deployment of renewable technologies. From a financial saturation perspective, this rapid accumulation of investment capital can be interpreted as a process of increasing market saturation, where capital inflows progressively reduce the system's capacity to absorb additional investment efficiently. As saturation rises, the likelihood of non-linear dynamics, including accelerated growth and potential bubble formation, may also increase. Yet, it has also exposed challenges that may result in market distortions. As reported by Bloomberg (2024a), excessive investor enthusiasm can result in capital inflows exceeding immediate market demand or technological capability. Periods of substantial investment may lead to system saturation, resulting in price fluctuations. The increase in solar PV manufacturing capacity in 2010s resulted in a dramatic decline in panel prices, causing financial challenges for manufacturers despite rising demand (Jones-Albertus et al., 2018).

Moreover, an obsession with accelerating renewable energy could conceal the imperative for market-validated investment approaches. The risk of overvaluation increases when investors speculate on prospective technological or policy changes rather than responding to current market conditions. This exposes the system to

sudden shifts in market expectations and investment flows, potentially resulting from delays in technological progress or policy changes, thus causing price volatility (Cheng et al., 2023; Selivanova, 2018).

Technological innovation has been essential, enabling the creation of advanced technologies that lower costs and enhance efficiencies, thus driving growth in renewable energy. In the last ten years, considerable progress has been achieved in solar photovoltaic efficiency, wind turbine design, and battery storage technology. Research conducted by Goodrich et al. (2012) reveals that improvements in the manufacturing processes of solar panels significantly reduced costs. The adoption of solar energy on a large scale has increased in competitiveness with fossil fuels. Advances in lithium-ion battery technology have also reduced energy storage costs. This made it easier for renewable energy sources to be further integrated into the electrical grid (Hamdan et al., 2024).

Technological advancements often pose the risk of speculative bubbles. When investors aim to capitalise on anticipated future profits, enthusiasm increases. The fervour for emerging technology can create cycles where initial successes lead to inflated expectations about its long-term sustainability. This trend is evident in the electric vehicle sector, where companies such as Tesla have attained high stock valuations driven by optimistic forecasts of future market dominance. Although these investments have stimulated growth, they also present the risk of overvaluation if the market does not fulfil these heightened expectations (Vaiman, 2023; Ward, 2021).

Regulatory modifications profoundly affect renewable energy markets, markedly influencing the demand for renewable technologies. Historically, mechanisms such as feed-in tariffs, renewable energy certificates, tax incentives, and carbon pricing have been pivotal in promoting renewable energy. Throughout the 2000s, feed-in tariffs in Germany and Spain stimulated substantial growth in solar and wind capacity (Gipe, 2013; World Future Council, n.d.). However, abrupt changes, such as subsidy reductions or alterations in grid access, have sometimes triggered market downturns. The decline of the Spanish solar market in the early 2010s, attributed to reductions in feed-in tariff support and subsequent regulatory changes, illustrates how regulatory modifications can convert market optimism into uncertainty (del Río & Mir-Artigues, 2014a; Milder, 2022).

Long-term national decarbonisation commitments stimulate markets and encourage further innovation. Policy frameworks, such as the European Union Green Deal (European Commission, n.d.) and the United States Inflation Reduction Act (US Environmental Protection Agency, 2022), promote the expansion of renewable energy. The market's reliance on policy signals creates a situation where modifications or postponements in policy implementation can lead to sudden shifts in investment strategies and asset valuations. The intrinsic benefits of policies are generally incorporated into share prices by investors, making the markets susceptible if those expected policy actions are not realised.

Historical financial bubbles offer insights into the effects of speculative dynamics on emerging industries and act as cautionary lessons for the renewable energy sector. The Enron collapse of the early 2000s serves as a relevant example, despite its lack of significance for renewable energy, but is related to energy sector. It

indicates that investors may lose confidence in the market if individuals attempt to influence it or make excessively optimistic forecasts (Brunet & Shafe, 2007). Enron was a significant player in the energy markets. It falsified its profitability and manipulated electricity pricing to appease investors and maintain elevated stock prices. The belief in continuous growth drove stock prices to unsustainable levels. The revelation of Enron's true financial status precipitated its downfall, resulting in substantial losses and diminishing confidence in energy markets (Karaša et al., 2025; Nix et al., 2021). Significant insights can be derived from Enron, particularly regarding inflated projections and market transparency (Salter, 2008). Innovation and technology drive investment in renewable energy; however, there is a risk that companies may exaggerate future performance to obtain funding. For example, exaggerating the performance of a new battery technology or the expected profits of a solar project can create unrealistic expectations. This can attract investors looking for high returns, pushing valuations above levels supported by actual technological progress or market demand.

The dot-com bubble of the late 1990s illustrates a parallel, characterised by the attractiveness of internet company models, that resulted in swift capital influxes and escalating stock prices. Likewise, the renewable energy market, the technology sector during the dot-com era was perceived as a transformative force with boundless promise. Many companies were evaluated primarily on anticipated future growth instead of current earnings, resulting in exaggerated values. As market optimism diminished, the bubble collapsed, resulting in substantial losses for investors and a reassessment of internet business strategies (Fan, 2022; Potrykus, 2024). This example underscores the dangers of evaluating assets based on projected potential value rather than existing fundamental value. This situation might potentially arise in the renewable energy sector if investors' expectations exceed actual advancements.

The historical decline of the solar boom in Spain offers a more distinct lesson in the renewable energy sector. Spain enacted substantial subsidies for solar energy via feed-in tariffs. It resulted in an accelerated expansion of solar systems. Investors invested in the market, as they relied on stable policy support and substantial returns. However, when the government significantly reduced subsidies due to fiscal constraints, the market experienced a sharp contraction. This led to bankruptcies and financial losses (Shirazi & Shirazi, 2012). The example emphasises the significance of policy stability for renewable energy markets, illustrating how abrupt policy changes can transform investor optimism into market failure. Even in sectors with considerable long-term potential.

These examples underscore the essential importance of transparency, rational market expectations, and stable policies to protect emerging markets from speculative bubbles. The renewable energy sector, despite prioritising sustainable development and clean environment, remains sensitive to various risks and changes in the markets. The industry is especially susceptible to factors that have previously caused bubbles in other sectors. The inclination of investors to emphasise future potential rather than current market conditions, coupled with their dependence on governmental support, elucidates these tendencies. These historical lessons highlight the necessity of

prudence and a measured investment strategy that accounts for both technological potential and the risks of market exuberance.

Based on the presented review, different aspects of bubbles identified by various authors are summarised in Table 4, which synthesises the key dimensions of bubble formation discussed above, including definitions and recognition patterns, theoretical frameworks, structural and behavioural drivers, and renewable energy-specific factors.

Table 4. Key aspects and drivers of financial bubbles

Aspect of bubbles	Reason/Trigger	Authors
Definition and recognition	Periods of unsustainable growth, faster than exponential power law growth, recognisable by specific patterns	Sornette and Cauwels (2015)
Phase transitions and external shocks	Repetitive nature, critical point crash, accelerated by events such as COVID-19	Ghosh et al. (2022)
Historical perspective	Rapid price rises above intrinsic value, followed by abrupt declines	Afilipoaei and Carrero (2023)
Classical market saturation approach	Oversupply of investments, declining returns, saturation point leading to corrections	Dalby et al. (2009), Vassalou (2012)
Financial Instability Hypothesis	Transition from stability to euphoria, ending in crisis due to unsustainable optimism	Minsky (1977)
Rational Bubble Model	Buying assets under rational expectations for resale at higher prices, being aware of the possibility of an eventual collapse	Blanchard and Watson (1982)
Structural and behavioural drivers	Structural imbalances, market liquidity effects, psychological factors such as herding, overconfidence, and recency bias	Jlassi and Bensaïda (2014), Lim (2018), Sathya and Gayathiri (2024)
Investment flow	Expansionary monetary policies, over-liquidity, capital inflow into speculative markets	Allen and Gale (2000), Calvo (2012)
Psychological dynamics	Herding, overconfidence, recency bias leading to speculative behaviour and misalignment with fundamentals	Andrzejewicz (2020), Shiller (2015)
Narrative and behavioural dynamics	Collective expectations, confidence, investor psychology, social contagion, manipulation, and economic narratives	Akerlof and Shiller (2009, 2016), Shiller (1989, 2015, 2020)
Renewable energy sector	Excessive investment inflows, policy dependency, technological hype, and overvaluation risks	Ghosh et al. (2022), Lehnert (2023), Padmavathy (2024)
Technological innovation	Hype around new breakthroughs inflating expectations and valuations (e.g. EVs, solar PV, batteries)	Goodrich et al. (2012), Hamdan et al. (2024)

Policy and regulatory influence	Sudden changes in subsidies or tax incentives leading to market distortions and volatility	Cheng et al. (2023), Selivanova (2018)
Historical financial bubbles and lessons	Overvaluation due to manipulation (Enron), reliance on future potential (dot-com bubble), policy-driven crashes (Spain)	Fan (2022), Potrykus (2024), Shirazi and Shirazi (2012)

Although different authors identify various, and partly overlapping, drivers of financial bubbles, Shiller's contribution deserves particular attention in the context of behavioural and narrative explanations of market instability (Akerlof & Shiller, 2009, 2016; Shiller, 1989, 2015, 2020). His works may be interpreted as an important paradigmatic shift in bubble analysis, moving the explanation of financial instability beyond purely rational and fundamental approaches towards behavioural and narrative-based dynamics. Shiller explains how collective expectations, investor psychology, confidence, social contagion and economic narratives may generate speculative market movements and contribute to deviations of asset prices from fundamental values. However, this perspective mainly explains why collective investment waves emerge, while it does not fully explain when such dynamics become structurally unstable. This creates a theoretical link with the further analysis of Financial Saturation Theory, where the structural role of saturation, elasticity, feedback and growth limits is examined in greater detail. In the present dissertation, Shiller's behavioural and narrative interpretation is therefore treated as a theoretical background for the later explanation of a possible behaviour of expectation-driven investment waves in systems approaching saturation.

In this context, investment-driven saturation can be considered a key mechanism linking capital inflows with the formation and dynamics of bubbles in renewable energy markets. While renewable energy investments are essential for achieving global climate and energy goals, the combination of financial saturation, speculative expectations, narrative-driven optimism, and reliance on policy support makes the sector particularly susceptible to bubble formation. In renewable energy markets, these bubbles often take on specific characteristics, reflecting the interaction of technological innovation, long-term policy incentives, investor optimism, and limited market capacity. Building on this foundation, the following subsections examine green bubbles in greater detail and demonstrate how they can be either productive by driving innovation and sector growth, or destructive by leading to overvaluation and market instability.

1.2.2 Green bubbles in renewable energy markets

Parts of the literature review and synthesis presented in this subsection were first published in Karaša and Girdzijauskas (2024). In the present dissertation, this material has been revised, expanded, and integrated into a broader analysis of renewable energy investment bubbles.

Green bubbles are a sector-specific manifestation of general bubble dynamics in the renewable energy sector. Considering that, together with renewable energy, this is a relatively new term in scientific literature and is closely related to the topic of the

dissertation, green bubbles deserve separate treatment compared to generic bubbles, discussed in the previous section. Green bubbles are ambiguous phenomena, not inherently negative.

Green bubble refers to the potential overvaluation and speculative investment in the renewable energy sector and other green technologies. This phenomenon can occur when investor enthusiasm and capital flow into green projects and companies at a rate that exceeds the actual development and profitability of these technologies. The key characteristics of a green bubble include excessive asset valuations, heightened speculative investment activity, and an elevated risk of abrupt market corrections. The contributing factors to green bubbles are as follows (Lehnert, 2023; W.-F. Pan, 2020; Shao & Chen, 2022):

- government policies and subsidies;
- public and investor sentiment;
- technological hype.

Some researchers have identified bubble-like dynamics in the green stock market. Lehnert (2023) argues that the expected large-scale adoption of green technologies may contribute not only to overvaluation in green energy stocks but also to broader stock market growth. Using a recursive testing procedure and dating algorithm applied to S&P 500 data, the study identifies an explosive market movement beginning in June 2021. Similar dynamics appeared in green stocks approximately one year earlier, suggesting that the later market-wide movement may have originated in the green technology segment.

Drawing an analogy to the dot-com bubble, Bell (2008) argues that rapid growth in renewable energy investment may create a large market bubble and lead to substantial losses for investors who remain exposed when it bursts. Conversely, others (Chan et al., 2024) suggest that firms engaged in clean energy and environmentally friendly production may not generate sufficient future revenues to justify their current market valuations. Their share prices may instead be supported mainly by perceived environmental credentials. If these expectations are revised, the prices of such companies may decline, revealing an overvaluation of green firms. An asset bubble occurs when the market price of an asset persistently and substantially exceeds its intrinsic value (Brunnermeier et al., 2020). Green and carbon bubbles describe such dynamics in the green and brown sectors, respectively.

Methodologically, green bubbles have been analysed using the log-periodic power law (LPPL) model (Ghosh et al., 2022). Over the past decade, this approach has been widely applied in order to identify bubbles and crashes in different markets. The analysis identified bubble dynamics in green energy companies during the COVID-19 period. Under these stressed conditions, the average drawdown was approximately four times greater than that of the conventional S&P 500 index. Such bubbles do not necessarily destroy public wealth in the long term; instead, they may temporarily stimulate economic activity and accelerate the growth of green energy companies.

The significance of green bubbles within the renewable energy sector is growing as investments continue to accumulate. An increasing number of studies are identifying and analysing the early signs of green bubbles. However, it is important to

emphasise that at this stage of sector development, a green bubble cannot be considered unequivocally negative, as different types of bubbles can emerge. Therefore, it is essential to assess bubble types more broadly, based on their potential impact on markets. To enhance the understanding of green bubbles, the following subsection examines productive and destructive bubbles in greater detail.

1.2.3 Typology of bubbles: Productive and destructive dynamics

Related to the description of green bubbles in previous subsection, bubbles evaluation should be based on economic function, not moral judgment. Bubbles, based on their outcomes, can be categorised into two distinct types: productive (sometimes called ‘good’ or ‘growth-enhancing’, ‘constructive’) and destructive bubbles (‘bad’ or ‘destabilising’). Productive bubbles play a pivotal role in financing technological advancements, although at the expense of investors who incur losses. In contrast, destructive bubbles have the potential to destabilise financial systems, often precipitating severe economic crises. According to Janeway (2018), bubbles are not inherently wasteful, as they facilitate the process of inefficient trial-and-error experimentation, which is integral to scientific and technological progress. Success in such endeavours, however, often depends on a degree of fortune.

Perez (2002) identified five major technological revolutions throughout human history (from British railway mania to the dot-com bubble), where financial capital fostered productive bubbles. These bubbles provided the necessary funding for large-scale technological projects, which delivered long-term societal benefits that far exceeded their costs. Moreover, the high prices observed during bubbles serve as powerful market signals, attracting skilled talent to these emerging fields. This influx of expertise helps to solidify the foundational assets within the sector, ultimately transforming speculative bubbles into enduring technological gold. Consequently, productive bubbles have been instrumental in driving many of the technological breakthroughs in history.

In contrast, destructive bubbles are characterised by excessive speculation, significant financial leverage, and credit booms. Such bubbles pose substantial systemic risks, as they can lead to the collapse of financial and banking systems, thereby dismantling the fundamental infrastructures that underpin economic and business activities. This often results in profound financial depressions and extensive economic losses (Sornette, 2003; Sornette & Woodard, 2009). Destructive bubbles are typically zero-sum games, wherein speculators trade assets, such as financial derivatives, real estate, or equities using borrowed capital. These speculative activities contribute nothing to productivity and amount to financial gambling aimed at redistributing wealth.

Productive bubbles are positive-sum games that enhance overall productivity. A productive bubble has the potential to encourage and nurture innovation, leading to many more people becoming entrepreneurs. This may result in a virtuous growth cycle. This bubble for companies may even bring in innovations and technological breakthroughs, which may be beneficial to many other industries as well. Bubbles by nature seem to create an environment that attracts capital for technologically intensive projects, which can have a tremendous positive economic impact (Quinn & Turner,

2020). On the other hand, structured financial products epitomise destructive bubbles. These instruments were designed to manage financial risk, but they became mechanisms for speculation and systemic instability, illustrating the detrimental impact of destructive bubbles on both the financial system and broader economic output.

Raurich and Seegmuller (2019) show that under certain conditions, speculative bubbles (often regarded as destructive bubbles) can become productive bubbles, as they provide liquidity that supports long-term capital investment and output. The model of their overlapping generations demonstrates that young agents can short-sell bubbles to finance productive investments, while middle-aged agents purchase them to transfer wealth, thereby linking speculation and growth. However, the benefits are fragile, since technological biases, fiscal policy, or bubble crashes can quickly reverse this effect and generate instability and inequality.

The main criterion distinguishing productive and destructive bubbles is their outcomes. Productive bubbles are beneficial to the economy and have the following characteristics (Clain-Chamosset-Yvrard et al., 2024; Farmer & Schelnast, 2013; Pástor & Veronesi, 2009; Raurich & Seegmuller, 2019, 2022):

- facilitation of technological progress by funding large-scale innovation, even ignoring investors losses;
- positive-sum dynamics: long-term societal gains outweigh short-term financial losses;
- historical association with major technological revolutions (e.g. railways, the dot-com boom);
- help building foundational infrastructure for future industries and productivity growth;
- encouragement of innovation and entrepreneurship, potentially catalysing cross-sectoral development;
- representation of speculative surges that transform into enduring assets with wide economic benefits.

Destructive bubbles are harmful for economy and have the following characteristics (Afilipoaei & Carrero, 2023; Cahuc & Challe, 2012; Corsi & Sornette, 2014; Girdzijauskas, 2024; Otaki, 2016):

- driven by excessive speculation, financial leverage, and credit expansion, market saturation;
- systemic risks, potentially triggering banking collapses and crises;
- involve zero-sum games, assets/property is merely redistributed through speculative instruments;
- centred around assets that do not contribute to productivity (e.g. real estate speculation);
- resulting in financial instability and erosion;
- leading to long-term economic harm, with little or no societal benefit;
- unsustainable growth.

Productive bubbles are financial phenomena that can enhance economic growth by providing liquidity and enabling investment under specific conditions. Meanwhile destructive financial bubbles are characterised by unsustainable asset price growth driven by complex psychological and economic feedback mechanisms. If destructive bubbles are better understood and more thoroughly researched, then the evidence of productive bubbles is primarily theoretical, with multiple economic models supporting the concept but limited empirical validation. More research is needed to definitively establish the broader economic implications of productive bubbles.

Renewable energy investments share several characteristics with historically productive bubbles, as they may accelerate technological development, infrastructure expansion and market formation. However, the same investment dynamics may also become destructive when capital inflows exceed the system's ability to absorb them. The analysis of renewable energy investments and green bubbles therefore shows that their effects cannot be fully understood solely through price dynamics, expectations, or investor behaviour. It is also necessary to consider the systemic limits within which investment-driven growth takes place. This requires a theoretical perspective that explains how additional investment contributes to growth as a system approaches its capacity and why its marginal effects may change over time. For this reason, the following section turns to economic growth theories and marginalism, which provide the theoretical basis for explaining growth limits, market capacity, and the need to assess renewable energy investments from the perspective of Financial Saturation Theory.

1.3 Economic Growth Theories, Marginalism and Growth Limits

To connect investment dynamics, bubble formation, and financial saturation, a broader theoretical perspective on economic growth is needed. Economic growth models and the concept of marginalism provide such a framework by highlighting the role of growth limits, diminishing marginal effects and system capacity. This discussion establishes the conceptual basis for the further analysis of Financial Saturation Theory, which is addressed in the following section.

1.3.1 Evolution of economic growth models and theoretical approaches to economic growth

Modern economics is based on mathematical models that analyse macroeconomic principles dating back to the early 19th century. The definition of a model varies, but in general terms, a model is an artificial construct that represents an object or phenomenon that actually exists (Girdzijauskas, 2006). An economic model, on the other hand, is defined and understood differently, depending on the time period and the author. Varian (2010) emphasises an economic model as a theoretical construct that represents economic processes by a set of variables and a set of logical and/or quantitative relationships between them. Samuelson (1947) emphasises analytical simplicity and the role of models in drawing general conclusions about economic behaviour. According to him, an economic model is a set of equations or logical constructs that simplifies the complex processes of the real economy for the purpose of analysis. Economic models are artificial constructs that are not meant to mirror

reality directly, but to enable the deduction of empirical implications (Lucas, 1980). Lucas (1980) underlines the predictive utility of models rather than their descriptive realism, a view central to modern macroeconomics and dynamic stochastic general equilibrium modelling. Rodrik (2015) supports a pluralist and pragmatic use of models in development and policy analysis, arguing that economic models are stylized representations of economic mechanisms that abstract from many features of the real world in order to focus on causal relationships. Cartwright (2007) similarly views models as constructive tools that generate regularities under specific conditions rather than as direct representations of reality. Accordingly, the meaning and function of an economic model vary across philosophical traditions and schools of thought, ranging from predictive tools to explanatory mechanisms (Cartwright, 2007; Lucas, 1980; Rodrik, 2015).

The Keynesian growth model builds upon the ideas introduced by Keynes (1936) in *The General Theory of Employment, Interest and Money*. While Keynes himself did not construct a formal growth model, later economists, e.g. Harrod (1939) and Domar (1946), extended Keynesian principles to model long-run economic growth. These authors formed the basis of what is now referred to as the Harrod-Domar growth model. This model shows how investment, savings, and the capital-output ratio determine economic growth. The neoclassical Solow-Swan growth model is one of the foundational frameworks in modern economic growth theory, emphasising long-term equilibrium, factor accumulation, and technological progress. The Solow-Swan growth model, developed independently by Solow (1956) and Swan (1956), was built on the basis of classical economics but introduced important refinements, including diminishing returns to capital and exogenous technological progress. This model demonstrates how capital accumulation, labour growth, and exogenous technological progress drive economic growth. Post-neoclassical endogenous growth explains how economic decisions and policies (e.g. investment in human capital, R&D) can drive sustained growth without diminishing returns.

Romer's (1990) model of endogenous growth includes technology as a function of R&D investment and knowledge spillovers. Lucas' (1988) model focuses on human capital as the driver of productivity and growth. Based on the neoclassical growth model, the endogenous growth theory incorporates an innovation process. The unified growth theory represents a paradigm shift in economic thought by integrating demographic, technological, and institutional factors to explain the full sweep of human development. It transcends earlier models by focusing not only on how growth happens, but why it began and why it occurred at different times across regions. It synthesises elements from classical, neoclassical, and endogenous growth theories to explain how economies transition from low-income, agrarian societies into industrialised, high-income ones. The theory was pioneered and extensively developed by Galor (2011; Galor & Weil, 2000). The innovation-based evolutionary Schumpeterian growth model explains growth as a process driven by entrepreneurial innovation, technological discontinuities and creative destruction, where new technologies and business models replace outdated structures (Aghion & Howitt, 1992; Schumpeter, 1983). The contemporary relevance of this perspective is further reflected in the 2025 Nobel Prize in Economic Sciences, which emphasised

innovation-driven growth and sustained growth through creative destruction (Nobel Prize, 2025).

Economic growth models can be classified through various lenses, one of which involves identifying shared structural assumptions. One of them is a constant savings rate. Another commonly used categorisation distinguishes between exogenous and endogenous growth frameworks. Exogenous models, typically grounded in the neoclassical production function, assume diminishing marginal productivity of production factors. Exogenous models posit that long-run growth is determined by external technological progress. These models often predict income convergence across nations, where lower-income economies are expected to grow faster than their higher-income counterparts (Chirwa & Odhiambo, 2018).

Conversely, endogenous growth models endogenise a technological progress. These models posit that the productivity of inputs (especially human capital and knowledge) is at least constant or even increasing. As a result, these models do not necessarily predict convergence. These models imply that countries with a greater stock of intangible assets may experience sustained and divergent growth paths compared to less endowed economies (Piętak, 2014). Yet, renewable energy development aligns more closely with endogenous growth logic due to innovation and learning effects.

The analysed theories of economic growth also reflect two contrasting perspectives on the balance of the growth process. In the case of Schumpeterian theory, economic development is characterised as an inherently unbalanced process, driven primarily by the stochastic emergence of innovations and entrepreneurial activities. In contrast, structural models such as those proposed by Lewis and Rostow (Piętak, 2014) suggest that while economic growth may initially exhibit disequilibrium, it tends to converge toward a balanced trajectory over the long term. This distinction is crucial for understanding how different growth dynamics shape the outcomes of investment booms, determining whether they contribute to sustainable development or evolve into productive or destructive bubbles.

It is important to acknowledge that certain theoretical predictions derived from these models are not always confirmed by empirical evidence. For instance, the so-called ‘scale effect’ predicted by Romer’s (1990) endogenous growth model has not been consistently supported by cross-country data. This underscores the need for continued refinement of growth models and a nuanced understanding of their empirical applicability. This further illustrates that growth models offer incomplete guidance for real-world investment dynamics.

There are numerous models developed to explain economic growth, most of which implicitly assume that expansion can continue indefinitely. As noted by Girdzijauskas (2006), each model extends previous approaches by emphasising different growth factors, their influence on growth rates, and underlying dynamics. Growth models constitute a fundamental subset of economic models aimed at explaining long-term expansion in productive capacity, income, and capital accumulation. However, despite their diversity, these models remain largely fragmented and lack a unified framework capable of explaining growth under conditions of limited resources or market saturation. This gap highlights the need for

alternative approaches that explicitly incorporate capacity constraints and saturation dynamics. Consequently, the following subsection examines marginalism as a theoretical framework for analysing growth limits.

1.3.2 Marginalism as a framework for analysing growth limits

The limitations of traditional growth models identified in the previous subsection require a theoretical approach that explicitly considers marginal effects, capacity constraints, and saturation. Marginalism provides such a perspective by explaining how the value or productivity of additional units changes as a system approaches its limits.

Historically, social sciences, particularly economic theory, have expressed scepticism regarding mathematical analysis. Conversely, mathematics has occasionally misused the complexity of its tools, resulting in qualitatively and quantitatively insufficient generalisations (Derakhshan, 2014; McCloskey, 2005; Mirowski, 2012; Palaşcă, 2013; Socaciu, 2010). In recent decades, an increasing number of economists have contended that the prevalent mathematised approach in scientific articles is frequently excessively specialised and artificially inflated, thereby obstructing the clear communication of the core ideas presented. According to critics, the growing importance of mathematics and econometrics as analytical tools in academic discourse has been achieved at the expense of a deep understanding of economic processes (Sapir, 2003).

The dominance of mathematical analysis has been interpreted by some economists as a dangerous deviation; economic theory has allegedly become a ‘third-rate branch of mathematics’, difficult to understand for a broad audience and practically inaccessible to non-professionals (Rothbard, 2009). In this context, statistical, so-called ‘black box’ models (Kalmykov & Kalmykov, 2024) began to spread, whose internal mechanisms are poorly interpreted and whose analytical focus is on the accuracy of forecasting rather than on understanding economic phenomena themselves. In contrast, ‘white box’ models, which allow for a more detailed disclosure of the interrelationships between variables and the principles of the model’s operation, have so far been inferior in terms of their predictive accuracy.

The intersection of the quantitative and social sciences, especially in the field of economics, has led to theoretical stagnation over time (Carter, 2009; Cochrane, 2011). This is based on the inertia of the old economic growth paradigm. However, the increasing dominance of correlation-based methods shifted attention away from the causal and marginal relationships emphasised by marginalist analysis. Although the latter allowed for the modelling of relationships between variables, it was not a suitable tool for solving the problems posed by marginal analysis, which should have initiated a paradigm shift. These limitations hinder the analysis of saturation phenomena.

The old paradigm limited fundamental research: financial saturation, economic overheating, financial bubbles, debt traps, demand inflation, business cycles, etc. Its inadequacy prompted renewed interest in the assumptions of marginalism. These circumstances also led to intensified research into limited growth and financial saturation (Girdzijauskas, 2024).

After Thomas Malthus (1766–1834) suggested the idea of infinite economic growth, the problem of saturation became universal, as researchers in various fields began to look for alternatives to exponential growth. The principle of diminishing utility was established in this context, serving as the foundation for the marginalism school; the principle of diminishing utility underpins the modern Financial Saturation Theory.

Marginalism is an economic approach that explains decision-making and value formation based on marginal changes in utility, cost, and productivity. Practically, this represents an economic perspective grounded in the principle of diminishing marginal utility, whereby each additional unit of a consumed good subjectively loses value until the saturation point is attained, which is a crucial element of the value theory.

The primary thesis of marginalism involves employing functional relationships and differential calculus techniques to address rational choice issues. This methodology enables the examination of value production processes at both microeconomic and macroeconomic levels. The principal characteristics of marginalism (Čiburienė, n.d.) include the following:

- subjectivism: examining phenomena from the viewpoint of the individual subject;
- dismissal of production as the primary source of value – emphasis on static analysis in the short-term;
- utilisation of marginal analysis techniques to investigate functional dependencies;
- conceptualisation of the market economy as an equilibrium system;
- employment of mathematical analytical methods;
- assessment of product value based on the extent of need satisfaction.

In this dissertation, marginalism is used not as an independent theory of value, but as a theoretical basis for interpreting economic limits, saturation processes, and growth dynamics. The theoretical advancements of marginalism are diverged into two trajectories:

1. the political economy perspective of Menger, Wieser, and Böhm-Bawerk, which was founded on a linguistic analysis and the concept of marginal utility;
2. the neoclassical approach, exemplified by Jevons, Walras, and Pareto, which utilised marginal values to examine the interplay between supply and demand.

The marginalism revolution, as one of the most important transformations in economic theory, is often associated with the works of Walras, Jevons, and Menger, which were published independently but at almost the same time. However, the fundamental principles can also be found in the works of earlier authors, such as Cournot, Dupuit, von Thünen, and Gossen (Čiegis, 2006). Around 1870, marginalism became the dominant research principle, known as the ‘marginal revolution’.

Despite a significant theoretical progress, marginalism was largely neglected in economic theory for an extended period. Its mathematical basis seemed too complex for contemporary economists. Gossen, one of the first theorists of marginal utility, emphasised the inevitability of mathematics in creating a coherent economic system.

However, his article ‘Die Entwicklung der Gesetze des menschlichen Verkehrs’ (Gossen, 1854) remained largely unrecognised by contemporaries, despite its methodological importance, and was only later acknowledged as a foundational contribution to marginalism theory.

Some economists, especially the Austrian school (Menger, Böhm-Bawerk, Wieser), chose verbal, causal analysis, forming ‘marginalism without mathematics’. Although this approach facilitated the understanding of the theory, it limited the depth of economic theory; some topics such as compound interest are compact from a mathematical point of view, but become cumbersome and difficult to apply in practice when expressed verbally.

At the beginning of the 20th century, marginalist analysis began to be replaced by correlation analysis. After 1930, econometrics established itself as an independent discipline when the Econometric society was founded and the journal *Econometrics* began publication. One of the influential black box models was Leontief’s input-output analysis, which transformed the analysis of economic sectors (Leontief, 1986).

Despite the progress of econometrics, it failed to explain the causes of the Great Depression due to the complex, multifaceted nature of financial crises that cannot be captured by simple correlation models (Betz, 2013). Peetz and Genreith (2011) similarly critique classical economic models for inadequately accounting for financial sector developments, and Castañeda (2010) supports the need for alternative analytical frameworks. According to the view presented in the monography (Girdzijauskas, 2024), the main cause of the crisis was financial saturation, a phenomenon that cannot be properly analysed with correlation models. It can be explained in detail using marginalist tools, after changing the growth paradigm.

This marginalism logic is particularly relevant in the contemporary renewable energy sector. Hirth’s (2013) analysis provides an energy-sector example of how the marginal economic value of additional generation or installed capacity may decline as the penetration of variable renewable energy increases. Additional solar or wind capacity does not automatically generate proportional additional economic value, because its market value depends on the timing of generation, electricity market prices, system flexibility, grid constraints, and the overall penetration level of these technologies (Hirth et al., 2015). Therefore, the development of renewable energy also requires a limited-growth perspective, where additional investment and capacity expansion are assessed not only according to their absolute increase, but also according to their marginal contribution to the stability and value of the system.

This marginalism interpretation can also be linked with innovation-driven growth and creative destruction. Recent developments in growth theory emphasise that technological progress and knowledge accumulation may replace outdated structures and create new growth cycles (Aghion & Howitt, 1992; Mokyr, 2016). In renewable energy systems, such innovation may shift effective market capacity and delay or transform saturation processes. However, it does not remove saturation risks. Therefore, the Financial Saturation Theory remains relevant because it allows the analysis of investment dynamics when capital inflows approach the capacity limits of a specific system.

The review of renewable energy, investments, and bubble dynamics conducted in the first part of this dissertation demonstrates that renewable energy is a broadly defined and policy-driven sector. The sector is strongly shaped by regulatory intervention aimed at internalising externalities and correcting market failures associated with traditional energy systems. In recent years, various renewable energy promotion policies have accelerated sectoral development and attracted significant investment flows. As shown in the preceding analysis, bubbles tend to emerge in environments characterised by high expectations, technological novelty, and strong financial incentives, and these conditions are also present in the renewable energy sector.

Some authors interpret the emerging dynamics as early signs of a green bubble, whereas others emphasise the potentially productive nature of such dynamics by highlighting their role in financing innovation and infrastructure. The distinction between productive and destructive bubbles therefore becomes crucial in assessing the appropriate degree of support and investment. The literature reveals a notable lack of unified indicators for bubble identification and no consensus regarding their underlying causes. Although authors commonly agree on the consequences of destructive bubbles, existing research rarely incorporates the role of market capacity or growth limits in the explanation of bubble formation.

The analysis conducted in this section reveals a significant research gap: the absence of unified and unambiguous indicators for bubble identification, as well as a lack of a unified explanation of its causes. Current studies on bubble dynamics do not explicitly account for market saturation or growth constraints as potential risk factors. However, in the context of rapid sectoral growth and intensive policy support, limit assessment becomes essential for understanding long-term market stability. A review of economic growth models and marginalism suggests that renewable energy development should be examined through the lens of limited or logistic growth rather than assumptions of endless expansion. This perspective makes it possible to interpret bubble formation not only as a result of speculative behaviour, but also as a consequence of investment-driven growth approaching the capacity limits of a system.

Consequently, the second part of this dissertation applies the Financial Saturation Theory to analyse the influence of growth constraints on investment dynamics and bubble formation. Renewable energy requires a saturation perspective to adequately capture its unique structural and possible financial vulnerabilities. The following section therefore analyses and integrates the Financial Saturation Theory as a framework for assessing possible bubble dynamics in RE investments.

2. ANALYSIS OF FINANCIAL SATURATION THEORY AND BUBBLE FORMATION: DEVELOPMENT OF A METHODOLOGICAL MODEL FOR ASSESSMENT

The second section of the present dissertation is dedicated to the second and third research objectives and is structured around two main subsections: the analysis of the principles of the Financial Saturation Theory and the mechanisms of financial bubble formation within its framework, and the development of a research model and methodological approach based on this analysis. The analysis of the Financial Saturation Theory is aimed at explaining bubble formation through the perspective of limited growth, saturation, bifurcation, elasticity, and feedback mechanisms under the assumption that markets and economic systems follow logistic rather than unlimited growth patterns. The second subsection focuses on the development and refinement of a model for identifying and assessing market saturation dynamics and financial bubble formation in the renewable energy sector based on the principles of Financial Saturation Theory.

2.1 Theoretical Foundations of Financial Saturation, Growth Limitations, and Bubble Dynamics

The analysis begins with the broader context of limited growth in economic systems. In the long-term, economic growth is constrained by structural, technological, resource, and market-related factors. Therefore, sustained infinite growth is unlikely. Growth processes in economic systems tend to slow down as they approach capacity limits, resulting in structural changes, adjustments, or transitions to new stages of development. This perspective provides the theoretical basis for analysing logistic growth, financial saturation, and bubble dynamics within the framework of Financial Saturation Theory.

Parts of subsections 2.1.1, 2.1.2, and 2.1.7 are adapted from the theoretical discussion previously published in Karaša and Girdzijauskas (2024). In the present dissertation, these elements are revised, systematised, and integrated with elasticity, bifurcation, Market Duality, and the developed bubble classification framework.

2.1.1 Logistic growth models and saturation interests

Logistic growth is a mathematical model that describes how a quantity grows rapidly at first, then slows, and eventually stabilises as it approaches a carrying capacity: the maximum value sustainable under given conditions. Early limited-growth models were developed by Gompertz and Verhulst in the 19th century (Girdzijauskas, Moskaliova, et al., 2014). Their applications differ across fields: the Verhulst model is common in biology, while Bass and Gompertz functions are often used in social sciences. However, classical logistic models were not developed for interest calculations because their variables are not expressed in interest-rate terms.

Some authors (Mialik, 2014; Tsoularis & Wallace, 2002) generally present 12 or more different growth models, which are essentially obtained by applying different values or expressions of coefficients α , β and γ in the generalised logistic model.

Table 5. Differential and functional forms of growth models

Model	Differential form of growth models	Growth model	Coefficient values
Generalised logistic model	$\frac{dK}{dt} = m \cdot K^\alpha \cdot \left[1 - \left(\frac{K}{K_p} \right)^\beta \right]$	K – the size of population at the time moment t ; K_p – the size of potential population; m – growth coefficient; α , β , γ – growth parameters.	Initial conditions: $t = 0, K = K_0$
Malthus's (simple interest)	$\frac{dK}{dt} = m$	$K(t) = K_0 + m \cdot t$	$\alpha = 0; \beta \neq 0; \gamma = 0$
Malthus's (compound interest). Exponential growth	$\frac{dK}{dt} = m \cdot K$	$K(t) = K_0 \cdot e^{m \cdot t}$	$\alpha = 1; \beta \neq 0; \gamma = 0$
Verhulst equation – logistic growth model	$\frac{dK}{dt} = m \cdot K \cdot \left[1 - \left(\frac{K}{K_p} \right) \right]$	$K(t) = \frac{K_p}{1 + (K_p/K_0 - 1) \cdot e^{-m \cdot t}}$	$\alpha = \beta = \gamma = 1$
General growth function	$\frac{dK}{dt} = m \cdot K^{1+\beta \cdot (1-\gamma)} \cdot \left[1 - \left(\frac{K}{K_p} \right)^\beta \right]^\gamma$	$K(t) = \frac{K}{\left[1 + \left[(\gamma - 1) \cdot \beta \cdot m \cdot K^{\beta \cdot (1-\gamma)} t + \left[\left(\frac{K}{K_0} \right)^\beta - 1 \right]^{1-\gamma} \right]^{\frac{1}{\beta}} \right]}$	$\alpha = 1 + \beta \cdot (1 - \gamma)$
Gompertz's growth function	$\frac{dK}{dt} = m \cdot K \cdot \left[\ln \left(\frac{K_p}{K} \right) \right]$	$K(t) = K_0 \cdot e^{-\beta \cdot (e^{\alpha t} - 1)}$	$\gamma = 1, \beta \rightarrow 0$

Source: adapted by the author from Mialik (2014)

Table 5 highlights the most important growth models related to logistic growth and the subsequent conversions to interest rates described later. Compared with broader reviews of growth models, the table does not include functions that are less relevant to financial saturation, such as the linear-limited/pseudo-logistic function, the von Bertalanffy growth function, the Richards growth function, Weibull distribution, Heinz von Foerster coalition growth model, and the Ferreira logistic model (Akaliwo, 2023; Mialik, 2014; Renner-Martin et al., 2018; Teimouri et al., 2013; Tjerve & Tjerve, 2010; Tsoularis & Wallace, 2002).

The summarised growth models and their formulations are inapplicable to the examination of economic events. Nonetheless, these models are standardised and articulated through general variables and coefficients, facilitating their seamless adaptation to the necessary aspect in instances of conversion. In this instance, a significant variable m is identified, facilitating the move to a logistic growth model. Interest rate models that are already appropriate for financial and economic computations are obtained by evaluating market saturation, applying discounting, and expressing this parameter as $m = \ln(1 + i)$ (Girdzijauskas, 2024; Mialik, 2014). The compilation of the list of the most prevalent interest rates and their corresponding models is conducted in this manner. Table 6 presents simple, compound, nominal, and continuous interest rates, together with the Gompertz logistic growth function. The saturation coefficient K/K_p ($K_0 < K < K_p$), which ranges from 0 to 1, is considered an independent variable.

Table 6. Structure of the interest system under saturated and unsaturated growth conditions

Name of interest	Partial growth (Malthus or unsaturated growth)	General growth (saturated)	Interest rate
Simple	$K = K_0 \cdot (1 + t \cdot i)$	$K = \frac{K_p \cdot K_0 \cdot (1 + t \cdot i)}{K_p - K_0 + K_0 \cdot (1 + t \cdot i)}$	$i = \frac{K - K_0}{t \cdot K_0 \cdot (1 - K/K_p)}$
Compound	$K = K_0 \cdot (1 + i)^t$	$K = \frac{K_p \cdot K_0 \cdot (1 + i)^t}{K_p - K_0 + K_0 \cdot (1 + i)^t}$	$i = \sqrt[t]{\frac{K}{K_0} \cdot \frac{1 - K_0/K_p}{1 - K/K_p}} - 1$
Nominal	$K = K_0 \cdot \left(1 + \frac{j}{k}\right)^{k \cdot t}$	$K = \frac{K_p \cdot K_0 \cdot \left(1 + \frac{j}{k}\right)^{k \cdot t}}{K_p - K_0 + K_0 \cdot \left(1 + \frac{j}{k}\right)^{k \cdot t}}$	$j = k \cdot \left(\sqrt[t \cdot k]{\frac{K}{K_0} \cdot \frac{1 - K_0/K_p}{1 - K/K_p}} - 1\right)$
Continuous	$K = K_0 \cdot e^{j \cdot t}$	$K = \frac{K_p \cdot K_0 \cdot e^{j \cdot t}}{K_p - K_0 + K_0 \cdot e^{j \cdot t}}$	$j = \ln \left(\sqrt[t]{\frac{K}{K_0} \cdot \frac{1 - K_0/K_p}{1 - K/K_p}} \right)$
Gompertz's (logistic growth function)	—	$K = K_p \cdot \left(\frac{K_0}{K_p}\right)^{(1+i)^{-t}}$	$i = \sqrt[t]{\frac{\ln(K_0/K_p)}{\ln(K/K_p)}} - 1$

Source: adapted by the author from Girdzijauskas (2024)

It is worth noting that such a division logically reflects the interest structure. Partial growth (as separate cases of unsaturated or infinite growth) compound interest can be easily derived from the general growth (saturated) compound interest. Based on the already proven derivation (Gryshova et al., 2019), the general growth compound interest formula is used:

$$K = \frac{K_p \cdot K_0 \cdot (1+i)^t}{K_p - K_0 + K_0 \cdot (1+i)^t}, \quad (1)$$

where K is the accumulated value of product (capital) over period t , K_0 is the initial value of a product (capital), K_p is the potential (maximum) value of product (capital capacity), t is duration (number of periods), and i is the growth (interest rate) parameter expressed per unit of time t .

In the context of this dissertation, these variables are further interpreted in relation to investment processes, where K represents accumulated capital or investment, and K_p reflects market capacity (carrying capacity), i.e. the ability of the system to absorb investment. Accordingly, the parameter i is interpreted as reflecting the return dynamics of investment under conditions of limited market capacity.

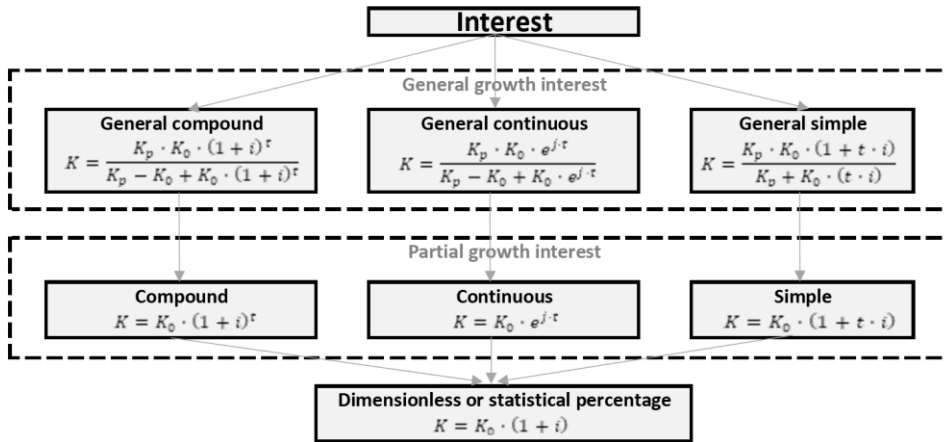
In subsequent sections, the growth parameter is also expressed using the notation r , which is conceptually related to the interest rate parameter (i). At this stage, i is retained as the primary representation of growth, while the formal transformation to r is introduced later in the context of function transformation and model development.

When the growth limit is indefinitely increasing ($K_p \rightarrow \infty$), formula (1) reduces to compound interest expression (2):

$$\lim_{K_p \rightarrow \infty} K(t) = \lim_{K_p \rightarrow \infty} \frac{K_p \cdot K_0 \cdot (1+i)^t}{K_p - K_0 + K_0 \cdot (1+i)^t} = K_0 \cdot (1+i)^t \quad (2)$$

This transformation enables the integration of all interest models into a general structure, as all simple interests are converted to compound interest, and compound interest is readily converted to dimensionless percentages. In an effort to streamline the scope of the models and their transformations, the following figure (see Fig. 2) organises the most critical interests for future research on the subject. The interest rate models' structure, as previously indicated, is illustrated in Fig. 2. It illustrates how parameters are consistently altered to transform one type of interest into another. It should be noted that 'general compound interest' appeared at the beginning of the development of the model (or the theory itself). However, due to verbally similar usage and confusion with the widespread partial growth interest, 'saturation interest' was adopted instead.

Saturation interest is defined as a logistic form of compound interest in which capital accumulation follows a growth process constrained by system capacity. It represents the most general form of compound interest under limited growth conditions and forms the basis for modelling financial saturation.



Source: adapted and extended by the author from Gryshova et al. (2019)

Fig. 2. Conceptual structure of the interest system under saturated and unsaturated growth conditions

The figure above properly structures and depicts the growth models analysed so far, revealing the specifics of bubbles and the influence of limits (according to marginalism) through the prism of interest rates. Economic processes have so far been explained mainly through partial growth interest, i.e. assuming that growth is infinite or applying the assumption that the growth limit is indefinitely increasing ($K_p \rightarrow \infty$). Logistic growth models explain growth through limits. Therefore, combining limited growth and interest in this transformation results in general growth interest, which allows economic growth with limits to be mathematised. This can be considered a continuation of the economic thought of marginalism.

A limited growth model, prior to the development of the Financial Saturation Theory, sometimes was called saturation or logistic growth. This model based on theory can estimate the financial saturation of a market. For this reason, the formula modelling saturation has an additional parameter: potential capacity. As mentioned in the subsection discussing growth models, the prototype was published by the Belgian mathematician and demographer Verhulst (Bacaër, 2011) in the first half of the 19th century. This model was used to estimate population growth and had no direct link to the function of compound interests. The financial saturation model applied is slightly modified, with coefficients specifically adapted to economic problems and calculated in (general) compound interest (Girdzijauskas, 2002).

Based on the marginalism political economy approach and applying the verbal analysis method characteristic of this approach, the author of this dissertation provides a descriptive interpretation of general growth interest based on the author of the Financial Saturation Theory (Girdzijauskas, 2024). An interpretation of general growth interest is presented and linked to accumulated capital, saturation level, and market capacity. In the context of a financial saturation analysis, accumulated capital, market capacity, and hence the saturation level of that market, are among the most important characteristics and therefore provide important information on the state of

the economic system. Proper interpretation is important for further analysis of the Financial Saturation Theory and adaptation of the model.

This key element of the model is the capital (K_p) or potential (market) capacity. Based on general growth compound interest formula (1), the accumulated capital after the exact number of periods (accumulated product value or capital after n periods) is given by the saturation model. This model could be expressed in a simplified verbal formula (Girdzijauskas, 2024):

$$\text{Accumulated capital} = \frac{\text{Potential value (capacity)} \times n \text{ period compound interests}}{\text{Initial value (niche)} + n \text{ period compound interests}} \quad (3)$$

Here the potential value (market capacity, K_p) is the total amount of financial resources that can be productively absorbed in the market or system. The value of market capacity used in saturation models is usually measured in monetary (value) terms and is referred to as potential capital (K_p). In further analysis, the market capacity will also be the investment capacity. The initial value or niche ($K_p - K_0$) is an initial market niche in the beginning of the period, i.e. the unused part of the initial market capacity by a value equal to the difference between the market capacity (K_p) and the initial capital (K_0) (Girdzijauskas et al., 2014). The initial capital is value amount, invested or accumulated in the system (market) in the beginning of the period. The accumulated capital (K) is referred to as real capital or simply as an investment volume at a given period.

The model development relies on the concept of saturation level, which is defined as the ratio of accumulated capital to market capacity K/K_p :

$$\text{Saturation level} = \frac{\text{Accumulated capital}}{\text{System (market) capacity}} \quad (4)$$

Saturation level together with accumulated capital and market capacity later are transformed to economic variables such as price, quantity in value terms. The application of growth models with limits to the economic system has important assumptions and limitations.

At this stage of the transformation of logistic growth models into interest rates, it is important to consider the limitations of the transformed models. These limitations will later need to be taken into account when developing the research model and interpreting the results. In the opinion of the author of the dissertation, authors associated with the Financial Saturation Theory and their works focus insufficiently on and poorly examine the limitations and restrictions of the application of logistic growth models. The limitations and criticisms of logistic growth models must be considered before delving more into the notion of financial saturation and creating a research model based on it. Certain authors emphasise the subsequent deficiencies and constraints of logistic growth models:

- Over-simplification. Assumption of static carrying capacity (K_p), which is often dynamic in real-world systems. The logistic model assumes a fixed carrying capacity (K_p), which represents the system's potential capacity to absorb the analysed variable under given conditions. In real-world economic or financial

systems, K_p is dynamic, influenced by policy changes, technological advances, and global markets (Grubb et al., 2015).

- Ignorance of exogenous shocks such as externalities (e.g. geopolitical events, tech breakthroughs). Logistic models are deterministic and fail to account for external shocks, such as geopolitical crises, pandemics, or breakthrough innovations. They can abruptly alter growth trajectories (Grübler, 1990).

- Homogeneity assumption may not reflect diverse investor behaviours or institutional asymmetries. Logistic models generally assume homogeneous agents (e.g. investors, consumers), which overlooks the heterogeneity in preferences, access to information, and risk tolerance. These are key drivers of real investment behaviour (Shiller, 2015).

- Inability to model reversals or crashes. Logistic growth models describe saturation but not necessarily reversal. Additional mechanisms (e.g. log-periodic power law models) are needed to capture post-saturation dynamics (Sornette, 2003).

- Absence of feedback mechanisms. Logistic growth models do not inherently capture systemic feedback (positive or negative) that can amplify or dampen growth. They are essential features in economic and ecological systems (Sterman, 2000).

- Poor fit for multi-phase or multi-equilibrium systems. Logistic growth assumes a single-phase transition to equilibrium, whereas real-world systems may exhibit multiple growth phases, tipping points, or equilibria due to policy interventions, network effects, or innovation spillovers (Wilson & Grübler, 2011).

All these disadvantages and limitations are very important and need to be included in the model to be developed when analysing the assumptions, limitations, and evaluation of the results obtained. The general compound interests (saturation interests) will be used to measure the growth of capital in the systems. The general or saturation interests modelling saturation are fundamentally different from all previous models of simple or compound interests. Based on saturation interest, one of the most striking and important discoveries of the author of the theory is increasing productivity when approaching the system limit (market capacity maximum value). Increasing productivity growth allows for further analysis of economic phenomena and can be compared with demand, supply, and marginal utility. Therefore, the following subsection reveals the essence of this phenomenon and paradox in the context of model formation.

2.1.2 Saturation Paradox as non-linear productivity dynamics in limited growth systems

The study of saturation interests has revealed an unusual feature – the phenomenon of increasing productivity (profitability), called the Saturation Paradox. This paradox can be described as follows: 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) (Gryshova et al., 2019; Girdzijauskas, Malik, et al., 2012;

Girdzijauskas, Štreimikienė, et al., 2012). When the system's saturation increases, the system's productivity increases. When the saturation level approaches to 1, the productivity of the system starts to increase hyperbolically. 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 unrestricted (Girdzijauskas, 2024).

For the analytical purposes of this dissertation, capital K is assumed to be transformable into output quantity (Q) in value terms. Importantly, quantity (Q), similar to capital, is expressed in value terms rather than physical units. This allows capital accumulation, production volume, and market value to be analysed within a unified financial framework. Under the assumption of infinite market capacity, such a saturation limit would not exist. In reality, however, all markets face structural constraints that impose limits on sustainable expansion.

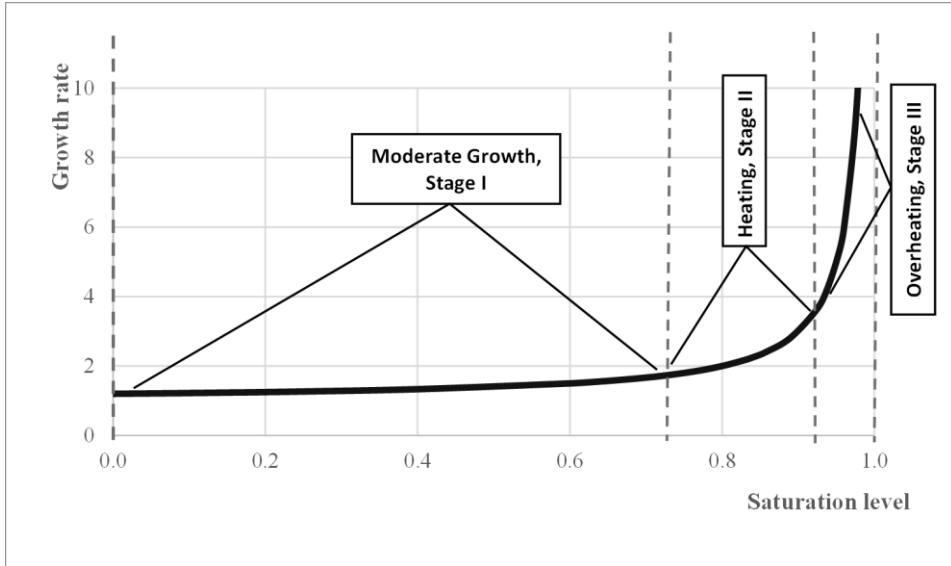
The existence of a potential quantity threshold (Q_p) fundamentally alters the behaviour of the supply function. As this threshold is approached, the supply curve exhibits increasingly steep growth. This dynamic transforms the traditional upward-sloping supply curve into a saturation-driven function. This phenomenon captures the essence of saturating growth and challenges the assumption of unlimited productivity expansion. A formal transformation between capital, price and quantity together with their functional relationships, is developed in detail in Subsection 2.2.1, where the mathematical framework of financial saturation is developed.

Modelling growth (Girdzijauskas, Štreimikienė, et al., 2012) using saturation interest reveals that the internal rate of return increases as saturation increases. This is particularly relevant for consumer expectations, and the ability of markets to adapt to a changing environment (changes in supply and demand). The internal rate of return is easily transformed into price, which is a fundamental economic category and plays a decisive role in many market positions.

Analysis of the Saturation paradox (increasing productivity paradox) (Gryshova et al., 2019) is based on the functional dependence of the interest rate on saturation. One of the most characteristic figures of this dependence is given in Fig. 3. The figure illustrates the dependence of the rate of return on the level of market saturation K/K_p . The saturation varies over the interval from 0 to 1. The saturation is increased by changing the market capacity from infinite to close to the initial investment. Increasing saturation leads to a steadily rising curve, similar to supply curve.

Although the authors of the discovery and development of this paradox (Gryshova et al., 2019; Girdzijauskas, Mialik, et al., 2012; Girdzijauskas, Štreimikienė, et al., 2012; Girdzijauskas, 2011; Girdzijauskas, 2015) evaluate the theoretical example of the Saturation Paradox several times, distinguish growth stages, and compare it with the supply curve, there is a lack of more accurate assessments and calculations, as well as justification of what growth rate or saturation level define the growth stages. Only one author's work provides more theoretical description of growth stages. Gryshova and other scholars (Girdzijauskas, 2011; Gryshova et al., 2019) suggest, that the growth could be divided into three stages. The Stage I (moderate growth stage) represents 75% of the growth range and is characterised by a relatively slow increase. As saturation increases from 0% to 75%,

profitability increases from 10% to 40%. The Stage II (heating stage) covers the next 20% of saturation (from 75% to 95% saturation). It is characterised by a rapid, accelerating increase in profitability from 40% to 200% (of the initial profitability). The Stage III (overheating stage) is the final saturation level, which increases above 95%. It is characterised by an extremely rapid and unrestricted growth, with a characteristic of explosive growth rate (see Fig. 3).



Source: extended by the author from Karaša et al. (2025) and Mikalauskas and Karaša (2025)

Fig. 3. Saturation Paradox: Growth rate dynamics with respect to saturation level

It is observed that the figure above clearly shows that the phenomenon of increasing profitability (the Saturation Paradox) is consistent with the well-known Pareto or the 80/20 rule. However, the 80/20 rule is considered a mnemonic and does not necessarily represent precise proportions. It can be argued that the theoretical basis of the Pareto rule is related to saturation interest.

It should be noted that a clear definition of the limits of the growth stages is important for the formation of the model. However, as mentioned earlier, the limits have not been properly analysed in previous works, and the current work provides a more expert assessment of the limits. Therefore, in this dissertation it is proposed to review, refine, and more clearly justify the growth boundaries. The respective studies by the author of the dissertation Karaša et al. (2025) and Mikalauskas and Karaša (2025) represent saturation level values of 0–70% (Stage I), 70–90% (Stage II), and exceeding 90% (Stage III). The following subsection examines the three stages, which include the Bifurcation Point, elasticity, and feedback. This enables the clarification of the relationships and distinctions between stages, as well as the enhancement of their precision and occurrence.

2.1.3 Feedback, elasticity and bifurcation in limited growth systems

In order to define and refine the boundaries of growth stages more precisely, a broader approach linked to market mechanisms is needed. Since the Saturation Paradox and the logistic growth curve are linked to the supply curve, the refinement of boundaries is linked to and explained by the principles of market functioning. Therefore, feedback and elasticity are analysed in more detail in the following discussion and explain and substantiate the important points of the analysis of the Financial Saturation Theory related to the Saturation Paradox, growth limits, and bifurcation. It is beneficial to elucidate the reason why bifurcation occurs and speculative investment behaviour takes over when market saturation reaches approximately 70%. The risk of overheating increases significantly and the system becomes unstable when saturation exceeds 90%.

2.1.3.1 Feedback mechanisms under saturation

Feedback in the market is one of the key elements, explaining Saturation Paradox and hyperbolic growth or collapse in the market at some stages. Feedback is the mechanism by which the results of a system's operation influence its subsequent activity. If feedback stimulates (strengthens) the system's processes, it is considered positive. If feedback inhibits system's processes, it is considered negative. Feedback helps to correct the effect of direct communication, while also helping to achieve the system's goals and obtain the desired results.

The final results of negative feedback (output signal) inhibit (suppress) the initial effect (input signal). Negative feedback makes the system self-regulating. This increases its stability and reduces fluctuations (Girdzijauskas et al., 2020). The best-known example of negative feedback in economics is the invisible hand. This is a metaphor used by Adam Smith (1723–1790) in his famous 1776 work *The Wealth of Nations* (Smith, 2004) to describe the mechanism of market prices. Essentially, it refers to negative feedback. It is well known that this type of feedback stabilises the functioning of the system. Over time, the invisible hand concept has developed based on this negative feedback: when prices go up, production increases, which in turn increases supply and then lowers prices. The decline in prices slows down production (has a negative effect) and thus the process stabilises – production and prices settle at a certain level. Contrary, nowadays the invisible hand is understood as a nuanced phenomenon. Economists recognise that market coordination is not guaranteed, and the metaphor can mask underlying systemic tensions (Evensky, 1993). The positive feedback loops can ultimately undermine, rather than enhance, societal coordination.

Positive feedback is a process in which changes in the results of the system's operation (output signal) reinforce the initial effect (initial signal – input impulse). Positive feedback is ensured when the sign of the feedback signal change coincides with the sign of the input signal change. This amplifies the initial action and can lead to instability of the entire system. When the amplification coefficient is positive and greater than 1, rapid (exponential) growth usually begins, and various deviations from equilibrium occur (Girdzijauskas et al., 2020).

Feedback is quite common in economics because, as noted by Arthur (1990), traditional economic theory is based largely on diminishing marginal returns (local

negative feedback). Feedback in economics manifests itself in a wide variety of forms: through supply or demand, economic growth, consumer behaviour, free competition or state regulation, political developments, climate change, and similar factors.

The majority of authors restrict themselves to an abstract evaluation of feedback. Some of them (Agliardi, 1998; Arthur, 1990) attempt to explain financial bubbles by the influence of positive feedback, but are unable to reveal its nature. Meanwhile, the aforementioned authors associate positive feedback with behavioural economics and thus attempt to explain why negative feedback turns into positive feedback. It has been observed that feedback ensures business stability under certain conditions. In order to ensure business continuity, it is required that negative feedback always outweighs positive feedback.

The herding behaviour is a psychological phenomenon that is worth discussing in the context of feedback. It is often used to explain the nature of financial bubbles. In management psychology, the herding behaviour is called autosynchronisation (Manstead & Hewstone, 1995). Its essence is that if 5% of individuals (initiators, pioneers) in a group begin to behave in a certain way, the remaining 95% automatically begin to imitate them. This effect is also known as the five percent rule. This is only a relative value that can vary in different situations. Mass collapse or growth can occur even with much lower values.

The herding behaviour, or the five percent rule, can also be explained by the formation of positive feedback. It is precisely positive (not negative) feedback that is formed due to the saturation effect (paradox) (Čiegis & Girdzijauskas, 2018a). A crowd is a limited (closed) system, which is why the saturation (filling) effect can occur in it. The five percent rule reveals that there is an empirically observable whole that exhibits an externally tangible effect. On the other hand, if the same individuals are scattered and do not form a crowd (have no connection with each other), synchronisation will not occur, the initiators' efforts will be futile, and therefore the five percent rule will not work for them.

This interpretation is close to Shiller's behavioural and narrative explanation of market instability, where collective expectations, social contagion, and shared economic narratives may synchronise investor behaviour and reinforce speculative movements. In the context of Financial Saturation Theory, such synchronisation can be interpreted structurally as the emergence of positive feedback in a limited system.

The condition for positive feedback is that the totality of individuals must become a crowd (a collective, a group, a mass, etc.), i.e. individuals must share certain common characteristics, the scattered totality must acquire the structure of a closed system, and certain virtual connections must arise between individuals. According to the Saturation Paradox, as the saturation (filling) of such a whole increases, the feeling of the crowd (autosynchronisation) intensifies. The herding behaviour in financial markets manifests itself through intensive (relatively collective) market monitoring. The concentration of investors in active markets, which has emerged as a result of this monitoring, increases demand and drives price growth in those markets. A few proactive individuals, once positive feedback has been established, trigger a self-reinforcing effect among market participants, in this case, an increase in capital flows (Girdzijauskas et al., 2020).

However, the Saturation Paradox and the herding behaviour create conditions for various forms of fraud (a classic Ponzi or dump and pump scheme) or a natural phenomenon in the market (naturally occurring Ponzi scheme), which are analysed in next subsections. If positive feedback helps explain the causes of rapid growth and the Saturation Paradox, elasticity allows the sensitivity of the system to changes in saturation level to be assessed. In other words, elasticity indirectly shows the extent to which feedback (in the context of analysis, positive feedback) has occurred and the sensitivity it has created in the system (market). Elasticity, analysed in the next subsection, also shows the (in)stability of the system.

2.1.3.2 Elasticity as an indicator of system sensitivity

One of the fundamental indicators used to quantify the responsiveness of economic indices to changes in underlying variables is elasticity. In the context of capital dynamics, elasticity with respect to time can be conceptualised as the ratio of time to capital, multiplied by the rate of change of the capital function. More formally, elasticity is defined as the derivative of the function with respect to its independent variable, normalised by the function itself.

Mathematically, the elasticity of a function with respect to its argument reflects the average percentage change (either increase or decrease) in the dependent variable in response to a one percent change in the independent variable. Let $y = f(x)$ represent a differentiable economic function, where x (e.g. capital stock, investment level) is the independent variable and y the dependent outcome (e.g. growth rate, price). If the change in x is denoted by Δx , and the corresponding change in y is Δy , then the relative change in x is $\Delta x/x$, and the relative change in y is $\Delta y/y$. The elasticity $E_x(y)$ is approximated by the ratio of these two relative changes (Girdzijauskas, Moskaliova, et al., 2014):

$$E_x(y) \approx \frac{\Delta y}{y} : \frac{\Delta x}{x} \approx \frac{\Delta y}{\Delta x} \times \frac{x}{y} \quad (5)$$

In the limit, as $\Delta x \rightarrow 0$, the exact elasticity is given by the following differential expression:

$$E_x(y) = \frac{dy}{dx} \times \frac{x}{y} \quad (6)$$

This formulation is widely employed in economic modelling to assess the sensitivity of outputs to changes in inputs, particularly in dynamic systems, such as investment flows and capital accumulation over time. This expression captures the instantaneous rate of percentage change in the dependent variable y resulting from a one percent change in the independent variable x . In economic analysis, this measure is critically important, as it quantifies the relative responsiveness of economic quantities to marginal changes in influencing variables. By convention, when elasticity is calculated, it is essential to specify the variable with respect to which it is measured.

In the context of this subsection, elasticity is introduced in its general mathematical form. The specific definition of dependent and independent variables is

further specified in the subsequent sections, where elasticity is applied within the framework of Financial Saturation Theory and the developed model.

The calculated meaning of elasticity may be both positive and negative. The negative meaning expresses an inverse dependence of the variables' interrelation. Therefore, when comparing the elasticities and seeking to avoid confusion, only the absolute quantity of elasticity is indicated. In general terms (Varian, 2010):

1. A function is considered elastic if the absolute value of its elasticity exceeds 1 ($|E_x(y)| > 1$), indicating a more than proportional response to changes in the independent variable.

2. If the absolute value is less than 1 ($|E_x(y)| < 1$), the function is inelastic, denoting a less than proportional response.

3. When $E_x(y) = 1$, the function exhibits unitary elasticity, meaning the percentage change in the dependent variable exactly equals the percentage change in the independent variable.

In economics, two prominent forms of elasticity include price elasticity of demand and price elasticity of supply. Demand elasticity quantifies the sensitivity of consumer demand quantity to price changes. Supply elasticity, conversely, measures the responsiveness of producers' or sellers' supply quantity to changes in market prices (Snieska, 2006).

The application of elasticity in the development and refinement of the concept of financial saturation is not a new phenomenon. Girdzijauskas and his co-authors (Girdzijauskas et al., 2008; Girdzijauskas & Štreimikienė, 2009) assessed elasticity by explaining the hyperbolic growth and stability of the system, saturation, and project feedback through the desired elasticity. However, the values of elasticity were not specifically linked to the level of saturation, and the elasticity characteristic of specific growth stages was not assessed. The results of the elasticity studies were general in nature and concluded that further research on elasticity was needed. In Financial Saturation Theory analysis, elasticity can be considered an indicator of feedback strength; therefore, feedback, elasticity, and the stages of the analysed growth model are integrated into a single conceptual framework.

2.1.3.3 Integration of elasticity and feedback: Bifurcation dynamics

In this subsection, feedback and elasticity are combined by integrating them into the Financial Saturation Theory. In this way, the theory is supplemented, the stages of growth are more clearly defined, and are substantiated with the phenomena under consideration.

According to the definition of positive feedback, when the amplification factor is positive and greater than 1, an exponential increase usually starts and various deviations from equilibrium occur. In relation to elasticity, positive feedback starts to occur when the coefficient of elasticity exceeds 1 ($|E_x(y)| > 1$), i.e. the function is considered elastic. Correspondingly, negative feedback occurs when the elasticity coefficient is below 1 ($|E_x(y)| < 1$), i.e. the function is considered inelastic.

The relationship between elasticity and positive feedback in the economy can be analysed from both microeconomic and system dynamics perspectives, especially in the context of financial saturation and investment cycles. Elasticity, particularly

price elasticity of demand or investment, determines the responsiveness of agents (consumers, investors, and producers) to changes in economic variables. In systems exhibiting positive feedback, high elasticity can accelerate amplification mechanisms. For instance, in renewable energy investment, if returns are perceived as rapidly improving, and investors exhibit elastic behaviour, capital inflows may overshoot the sector's absorptive capacity, intensifying saturation and growth rate (the Saturation Paradox). In this sense, the expectation-driven and narrative-based dynamics described by Shiller (2020) can be structurally interpreted through elasticity: when saturation increases, the same collective expectations may generate stronger responses in growth rates, prices, and capital inflows.

Elasticity can function as an indicator of the transition between negative and positive feedback regimes (Girdzijauskas, 2024; Girdzijauskas et al., 2011):

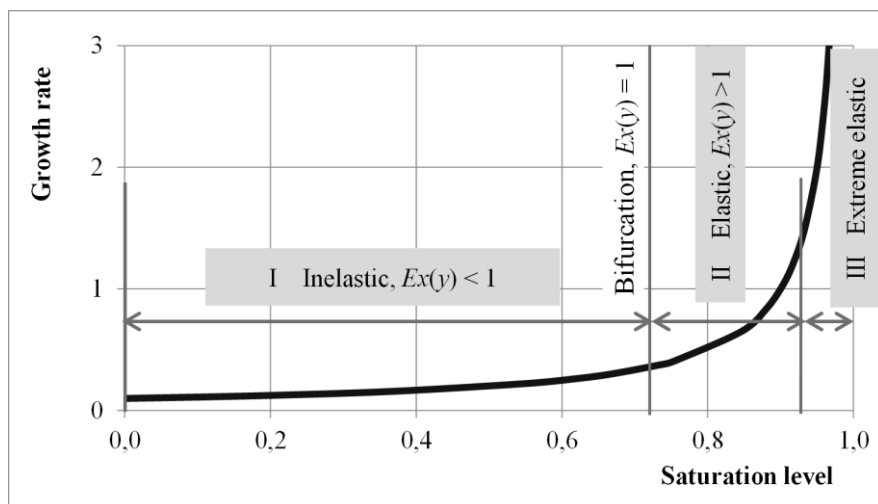
- During the initial growth stage, negative feedback dominates and elasticity remains relatively low. As saturation increases, rising elasticity indicates growing system sensitivity and the strengthening of positive feedback, and may contribute to self-reinforcing investment behaviour.

- Elasticity evolves throughout the investment cycle and can act as an early-warning indicator of increasing saturation and instability.

- The Bifurcation Point marks the transition from negative to positive feedback. At this point $E_x(y) \sim 1$, indicating unit elasticity.

As explored by Girdzijauskas (2024), when the market situation changes and an unsaturated market becomes saturated, market bifurcation occurs. Therefore, market types are classified according to their duality after bifurcation, i.e. after a change in the relationship between supply and demand in the previous market. Thus, market saturation or its transition from an active supply market to an active demand market turns the market into a deficit market. For this to happen, the D/S ratio must change. When $D/S > 1$, a saturated market with positive feedback is formed, and when $D/S \leq 1$, an unsaturated market is formed, in which balancing negative feedback operates.

Analysis of saturation is based on the functional dependence of the growth rate on the saturation level. As the authors (Gryshova et al., 2019) analyse this relationship (see Fig. 3), the change in the growth rate based on the saturation level is assessed. In other words, the elasticity of the growth rate with respect to the saturation level is assessed and based on this, three conditional stages of growth are distinguished within the Saturation Paradox. Based on the assessed elasticity, the Saturation Paradox graph can be refined by including a distribution based on elasticity (see Fig. 4).



Source: extended by the author from Girdzijauskas (2024) and Mikalauskas and Karaša (2025)

Fig. 4. Elasticity dynamics and bifurcation across saturation levels

As shown in Fig. 4, until market bifurcation (Stage I), inelastic supply (growth rate) dominates, depending on changes in the saturation level. The growth rate of such a market is moderate, with negative feedback acting as a balancing force. When the saturation level reaches the Bifurcation Point, elasticity becomes equal to 1. This point marks a market transition, when relative elasticity prevails in the market and, as the saturation level continues to grow, increasingly strong positive feedback begins to function (Stage II). Stage III marks a significant increase in positive feedback and a significant increase in elasticity, which is approaching to absolute elasticity.

Some scholars (Girdzijauskas, 2024; Gryshova et al., 2019; Karaša & Girdzijauskas, 2024; Mikalauskas & Karaša, 2025) precisely define the boundaries of growth stages in their works and publications. However, when analysing and determining the boundaries based on elasticity, each case in the system may have different situations depending on the function and variable values. Therefore, the growth stages presented should be treated as approximate, and in order to determine the exact boundaries of the stages, it is necessary to calculate each case separately, assessing elasticity. On the other hand, once the stage boundaries have been defined, it remains important to determine and define the boundary at which elasticity and positive feedback become significant, and the boundary at which the system becomes particularly elastic (the beginning of Stage III). It is likely that, assuming bifurcation occurs when relative elasticity ($Ex(y) > 1$) is present, the positive feedback in the market will be insignificant at first and may not have a significant impact. Therefore, the limits presented should be considered relative and, in each case, individual, with the limits to be determined after conducting broader research and assessments covering a wide range of different systems.

After evaluating the elasticity of the growth rate in the presented example (see Fig. 4 and Appendix 1) with respect to the saturation level (see Fig. 5), it was determined that Stage I, characterised by relatively inelastic growth and dominant negative feedback, occurs within the saturation interval of approximately 0–0.633.

The Bifurcation Point is reached when the saturation level approaches 0.633, where elasticity becomes equal to 1 and the market begins to transition from a stable market state towards a deficit market dynamic.

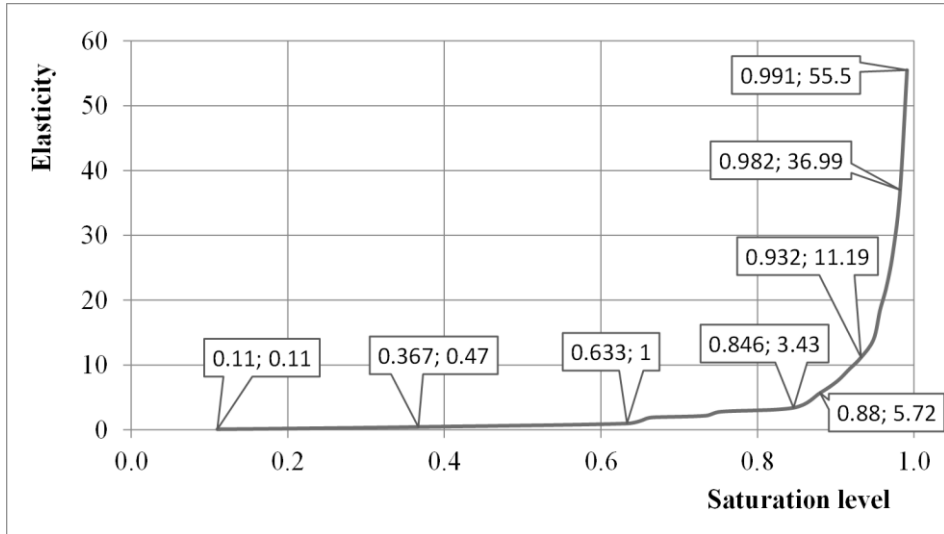


Fig. 5. Growth rate elasticity across saturation levels

As the saturation level increases further, elasticity rises rapidly and increasingly strong positive feedback emerges. A particularly significant increase in elasticity is observed within the saturation interval of approximately 0.846–0.932, indicating the transition towards Stage III. This stage is characterised by highly elastic growth dynamics, accelerating positive feedback, and growing systemic instability. In the presented example, the maximum relative elasticity ($E = 55.5$) is reached when the saturation level approaches 0.991, reflecting near-absolute sensitivity of the growth rate to marginal changes in saturation level.

Based on the theoretical review and the elasticity analysis presented above, this dissertation summarises the growth process into three indicative stages according to the saturation level, profitability or growth rate dynamics, elasticity, and feedback type. These stages provide a simplified analytical framework for identifying the transition from a relatively stable growth to heating and, eventually, to overheating. The detailed characteristics of the stages are presented in Table 7.

Table 7. Growth stages based on saturation level, elasticity, and feedback type

Stage	Saturation level	Profitability/ growth rate dynamics	Elasticity	Feedback type
Stage I: moderate (stagnant) growth	From 0 to 0.70–0.75	Slow and steady increase	Relatively inelastic	Negative feedback
Stage II: heating/ accelerating growth	From 0.70– 0.75 to 0.90– 0.95	Rapidly increasing	Increasing; transitional to relatively elastic	Transitional to positive feedback
Stage III: overheating/ hyperbolic growth	Above 0.90– 0.95	Hyperbolic and rapidly increasing	Relatively elastic, approaching absolute elasticity	Strong positive feedback

The summarised stages indicate that feedback intensity and elasticity increase non-linearly as the system approaches its capacity limit. In later analysis, these stages are used to explain the transition from a relatively stable market state to heating and, eventually, to overheating and bubble formation. However, the boundaries between the stages should be interpreted as relative rather than universal. Their location may vary depending on the selected function, system structure, parameter values, and empirical characteristics of the analysed market. Therefore, the proposed stage limits should be treated as indicative thresholds that require separate elasticity assessment for each specific system under investigation.

By connecting elasticity, feedback, and the Saturation Paradox, it becomes possible to further explain the market processes described by Financial Saturation Theory. This connection leads to the identification of the Bifurcation Point, which marks the transition from a classical market equilibrium model to a deficit market equilibrium model. In this dissertation, the Bifurcation Point is treated as the boundary of Market Duality, separating the relatively stable pre-bifurcation market from the post-bifurcation deficit market characterised by increasing elasticity and positive feedback. This transition is examined in greater detail in the following subsections.

The next subsection explains how the Saturation Paradox, expressed through the growth rate and its elasticity with respect to the saturation level, is related to market demand, supply, quantity demanded, and price. A clearer link between the logistic growth function and its transformation into supply and demand functions allows for a more accurate assessment of assumptions and limitations that have not yet been emphasised or systematised. After this transformation, the defined growth stage limits based on saturation level and elasticity can be applied in the subsequent model development.

2.1.4 Transformation of the logistic growth function into demand and supply functions: Assumptions and limitations

Based on the transformation presented by the author of Financial Saturation Theory, the dissertation consistently explains the conversion of the logistic growth function into demand and supply functions. Alongside this transformation, the subsection distinguishes the main assumptions and limitations, which are discussed in

more detail at the end and evaluated in terms of their possible impact on further model development.

Supply and demand functions can be based on compound or saturation interest models. The interest rate, or the profitability parameter associated with it, is directly linked to price, which is a key variable in determining the quantities of supply and demand. By transforming compound and saturation interest models in this way, supply and demand functions can be obtained. For this purpose, the transformation of interest rate is carried out in several stages and under certain assumptions. It should be noted that the transformation presented below is based on the works of the author of Financial Saturation Theory and his co-authors (Girdzijauskas, 2006, 2024; Girdzijauskas et al., 2022; Mialik et al., 2015). The transformations presented below are not treated as an original theoretical contribution of the dissertation author, as they are based on the works cited above. The author's contribution lies in the systematisation of these transformations, the clearer definition of their procedural stages, and the explicit identification of the assumptions, limitations, and restrictions relevant for further model development.

Transformation of the supply function

— The transformation of the supply function is based on the general growth expression given in formula (1), which serves as the starting point for all subsequent transformations.

— *Basic interest equation.* For analytical convenience, the growth expression is reparametrized by defining $r = 1 + i$, allowing the transformation to be expressed in terms of a generalised growth coefficient. At this stage, capital (K) is expressed in terms of product value (Q), assuming that accumulated capital is reflected in the value of goods or services supplied in the market ($K \approx Q$). Then, based on formula (1), a basic interest equation is formed, where r is the independent variable and Q is the dependent variable:

$$Q = \frac{Q_p \cdot Q_0 \cdot r^t}{Q_p - Q_0 + Q_0 \cdot r^t}, \quad (7)$$

where r is the transformed growth coefficient or profitability-efficiency parameter, Q is the product quantity expressed in value terms, Q_0 is the initial product quantity expressed in value terms, Q_p is the market capacity expressed in value terms, or the potential product value. In this context, r is a transformed growth parameter derived from the interest rate ($1+i$). It does not have a direct measurement unit and is interpreted as a relative indicator.

— *The core of the supply equation (function).* Basic interest equation (see formula 7) is solved for r . This transformation expresses the growth coefficient (r) as a function of quantity (Q), forming the analytical core of the supply relationship.

$$r = \sqrt[t]{\frac{Q_p - Q_0}{Q_0} \cdot \frac{Q}{Q_p - Q}} \quad (8)$$

— *Supply equation (function).* Under the assumption that the growth (profitability) parameter reflects the cost of capital, r is interpreted as a proxy for price (P) at the core of the supply equation (see formula 8). Price is expressed based on the profitability parameter:

$$P = \alpha \cdot P_0 \cdot r, \quad (9)$$

where P is the current price of the product (price at time t), P_0 is the base or initial price, α is the price balance coefficient. If the supply price balance coefficient and the base price are normalised, so that $\alpha = 1$ and $P_0 = 1$, the following basic normalised supply equation is obtained:

$$P = \sqrt[t]{\frac{Q_p - Q_0}{Q_0} \cdot \frac{Q}{Q_p - Q}} \quad (10)$$

Transformation of the demand function

— *The core of the total utility equation (function).* To derive the demand function, the same logistic saturation structure used in formula (7) is applied by treating quantity (Q) as the independent variable and the transformed growth or utility-related parameter (r) as the dependent variable. This results in the core of the total utility equation, where the independent variable is now Q , and the dependent variable is r :

$$r = \frac{Q_p \cdot Q_0 \cdot Q^t}{Q_p - Q_0 + Q_0 \cdot Q^t} \quad (11)$$

— *The basis of the demand function regression equation (function).* The derivative of the core of the total utility equation (see formula 11) is calculated with respect to quantity (Q), i.e. the marginal utility is obtained:

$$r'(Q) = \frac{t \cdot Q_0 \cdot Q_p \cdot Q^{t-1} \cdot (Q_p - Q_0)}{(Q_p - Q_0 + Q_0 \cdot Q^t)^2} \quad (12)$$

— *Demand equation (function).* Assuming that marginal utility corresponds to market price, the derivative of the total utility function with respect to quantity is interpreted as price, i.e. $r'(Q) = P$. If the demand price balance coefficient β and the base price P_0 are normalised in the same way as in the supply function, so that $\beta = 1$ and $P_0 = 1$, the following normalised demand equation is obtained:

$$P = \frac{t \cdot Q_0 \cdot Q_p \cdot Q^{t-1} \cdot (Q_p - Q_0)}{(Q_p - Q_0 + Q_0 \cdot Q^t)^2} \quad (13)$$

The results of the transformation, including generalised forms with balance coefficients, are summarised in Table 8.

Table 8. Transformation of logistic growth into demand, supply, and total utility functions

Supply function	$P_S = \alpha \cdot \sqrt[t]{\frac{Q_p - Q_0}{Q_0} \cdot \frac{Q}{Q_p - Q}}$
Total utility function	$r_{bn} = \beta \cdot \frac{Q_p \cdot Q_0 \cdot Q^t}{Q_p - Q_0 + Q_0 \cdot Q^t}$
Demand function	$P_D = \beta \cdot \frac{t \cdot Q_0 \cdot Q_p \cdot Q^{t-1} \cdot (Q_p - Q_0)}{(Q_p - Q_0 + Q_0 \cdot Q^t)^2}$

Source: Girdzijauskas (2024)

In order to interpret the supply function more clearly in relation to logistic growth and the financial saturation level, several assumptions and transformations are introduced specifically for this P_S function (see Table 8). These assumptions are introduced to simplify the model structure and to enable direct interpretation of the saturation level as the ratio Q/Q_p :

- The price balance coefficients are normalised to 1 ($\alpha = 1$ and $\beta = 1$).
- The entire period of formation of the supply function is treated as one period, therefore $t = 1$.
- Mathematical transformations are made in order to express the financial saturation level as Q/Q_p .

The final simplified supply function is derived:

$$P = \frac{Q_p - Q_0}{Q_0} \cdot \frac{Q/Q_p}{1 - Q/Q_p} \quad (14)$$

Generalised assumptions for the transformation of demand and supply functions are as follows:

- $1+i = r$, and under the assumptions of the model, the growth parameter r is interpreted as a proxy for price (P). In the transformation of the supply function, this parameter is operationalised as price, assuming $\alpha = 1$ and $P_0 = 1$.
- Since the price balance coefficient is omitted and the base price is normalised to 1, the obtained supply function should be interpreted as a normalised form. Therefore, the calculated r values, or the transformed price values derived from them, reflect the internal dynamics of a specific system and should not be directly compared across different systems without additional balancing coefficients.
- The growth parameter r does not have a direct measurement unit and is interpreted as a relative coefficient within the model.
- In the transformation of the functions, the roles of the variables are re-specified: r is treated as the independent variable and Q as the dependent variable, whereas in the transformed function Q becomes the independent variable and P , derived from r , becomes the dependent variable. This is a modelling transformation rather than a strict algebraic inversion.

- The amount of capital is treated as corresponding to the value of the product or service, $K \approx Q$.
- The demand price is interpreted as the derivative of total utility, $r_{bn}'(Q) = P$.

After completing the transformation, it is worth returning to the broader context and discussing some of the assumptions in more detail. In the transformation of the supply function, price is interpreted from a market perspective as the monetary expression of the value and usefulness of a good or service. It reflects the amount of money for which a seller is willing to supply a unit of output and is determined by the interaction of supply and demand under competitive market conditions. Within the model framework, this allows price to be linked with the transformed growth or profitability parameter r , which is used as a proxy for price under the accepted normalisation assumptions.

When assessing supply, the supply curve shows how much producers want to sell their products at different prices at a given time. The quantity of goods supplied varies in line with price changes. Empirically, it has been established that the graphical representation of the supply curve is an upward-sloping (positive slope) curve and illustrates the relationship between market prices and the quantity of output sold. When comparing the supply graph with the visualisation of the Saturation Paradox (see Fig. 3), no significant differences can be found. The obtained Saturation Paradox curve can be linked to the supply curve. Under the accepted assumptions, the transformed supply function can therefore be interpreted as conceptually consistent with the upward-sloping supply logic associated with Cournot's supply function.

The remaining differences, such as differences in the names of variable and related representation axes, have already been discussed in the transformation. The variable price of the typical supply function, represented on the vertical axis, match the same variable of the increasing profitability function on the same axis. As previously noted, price and growth parameter is interpreted as a proxy for price under the normalisation assumptions of the model. Similarly, the supply quantity (Q_s), expressed in value terms, is linked to the saturation level through the ratio Q/Q_p , because capital (K) is converted into quantity (Q) in terms of value. Then, either the value of capital or the value of supply quantity (Q) is directly dependent on the market saturation rate or saturation level (see formula 4).

In contrast to the classical interpretation of Cournot's model (Amir & Evstigneev, 2017), the Financial Saturation Theory model re-specifies the analytical relationship between variables: the independent variable is defined as the quantity Q in value terms, while the dependent variable is price. This is the reverse of the traditional supply and demand model. To rephrase Cournot's supply function, in logistic growth, the supply function is $S = f(Q)$, where S is the supply price; Q is the quantity of supply in value terms; and f is a mathematical function based on logistic growth.

The process of demand transformation is analogous to the transformation of supply, but it is based on the relationship between demand and marginal utility. According to the law of demand, there is an inverse relationship between the quantity of goods or services demanded and the price that buyers are willing and able to pay

(Snieška, 2006). In the transformation applied here, the demand function is derived from the total utility function, and the derivative of total utility with respect to quantity is interpreted as demand price. Therefore, diminishing demand and diminishing marginal utility are treated as functionally related within the assumptions of the model. As in the case of supply, the Financial Saturation Theory model re-specifies the analytical relationship between variables: the quantity of demand (Q), expressed in value terms, is treated as the independent variable, while price (P) is treated as the dependent variable. As a result, the demand function in logistic growth is denoted as $D = f(Q)$, where D represents the price of demand, Q represents the quantity of demand in value terms, and f is a mathematical function that is based on logistic growth and marginal utility.

The price is not the sole determinant of demand and supply; other factors that are specific to each demand or supply also play a role. Income levels, social structure, population size, seasonality, fashion, natural conditions, advertising and consumer expectations, changes in market capacity, and other factors can all contribute to changes in demand (shifts to the left or right). The number of producers and sellers, technology, production resource costs, price expectations, taxes, subsidies, and market capacity can all influence supply shifts. The significance of the factor in the function and the magnitude of the change in the factor itself determine the magnitude of the change in both demand and supply. Nevertheless, the *ceteris paribus* condition is assumed to be the case when examining functions and their transformation, as all of the factors that determine demand and supply remain unchanged.

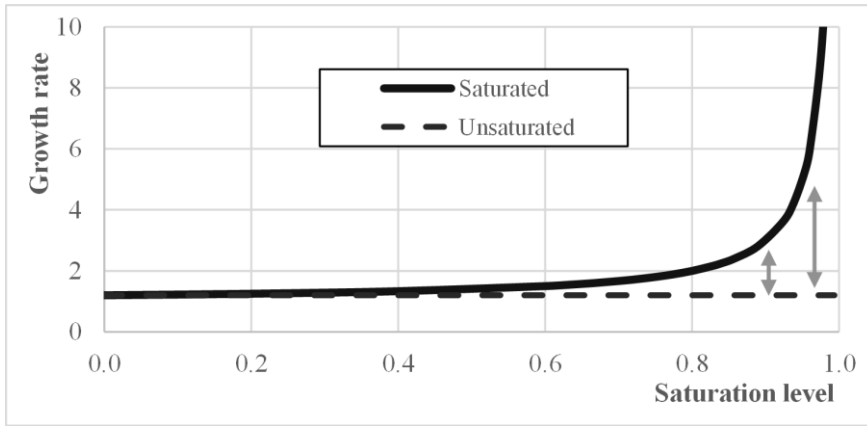
After converting the logistic growth function into demand and supply functions, the transformation enables a consistent interpretation of economic processes under conditions of limited growth and market saturation. In the following subsections, the author of the dissertation further extends the application of the Financial Saturation Theory by distinguishing and comparing classical and deficit market equilibrium models, defines bubble mechanisms and bubble types in relation to productive and destructive, and interprets Ponzi and pump and dump schemes based on financial saturation.

2.1.5 Classical market equilibrium model and deficit market equilibrium model under financial saturation

Based on the discussed Saturation Paradox, elasticity and feedback mechanisms, as well as the supply and demand transformations performed above, this subsection compares logistic growth with unsaturated growth commonly assumed in economics. The comparison presented in this subsection is interpreted within the framework of Financial Saturation Theory and under the assumptions of the transformed demand and supply functions discussed above. Therefore, the concepts of bifurcation, deficit market equilibrium, positive feedback and the Saturation Paradox are treated as model-based mechanisms explaining market behaviour under increasing saturation.

As shown in Fig. 6, the rate of infinite growth does not depend on the level of saturation and remains stable throughout the entire interval. This stable growth rate is based on the current economic paradigm, in which the saturation level and the

Saturation Paradox are not taken into account in the formation of bubbles or economic cycles.



Source: adapted and extended by the author from Girdzijauskas (2024)

Fig. 6. Comparison of classical (unsaturated) and saturation-based growth dynamics

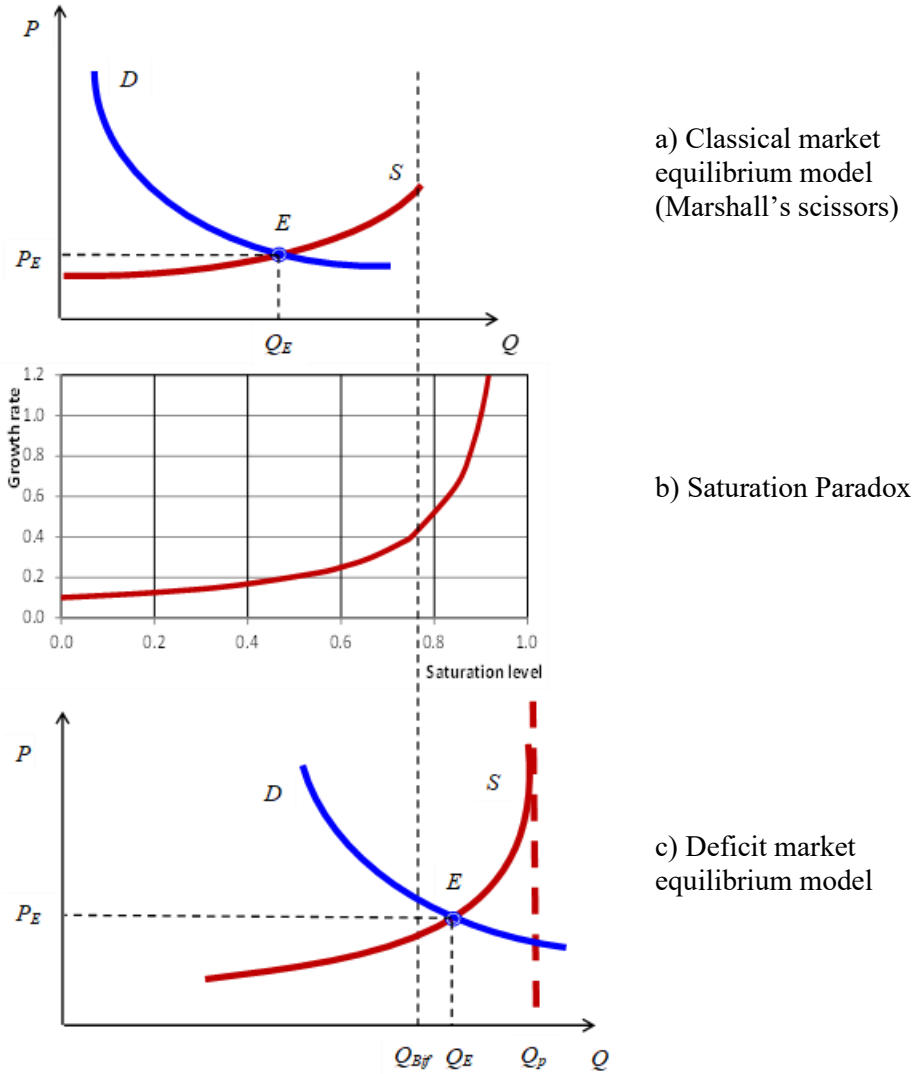
Logistic (saturated) growth diverges significantly from unsaturated growth as the growth rate accelerates due to the Saturation Paradox as the saturation level increases. Both growth rates initially coincide or differ only slightly when the saturation level is low. Nevertheless, the distinction becomes apparent as the saturation level rises and approaches full saturation. The authors who investigate this issue (Girdzijauskas, 2024; Gryshova et al., 2019; Mikalauskas & Karaša, 2025) and the analysed Bifurcation Point and growth stages (see Subsection 2.1.3.3) have observed a significant difference in growth rates when the saturation level reaches 0.7–0.75 or 70–75%. Growth rates begin to diverge significantly, and the model indicates a transition to a different market regime. Thus, market bifurcation occurs. The classical market equilibrium model can be considered sufficient under these conditions, as growth rates coincide or differ insignificantly prior to bifurcation. Consequently, there is no significant difference between the application of unsaturated or saturated growth estimates to the economy.

The general equilibrium theory primarily analyses feedback in terms of negative feedback (Girdzijauskas et al., 2020). The classical market equilibrium model is limited to conditions prior to market bifurcation (Q_{Bif}). To this point, the market is either unsaturated or balanced, with a moderate rate of return (growth) that is similar to the rate of constant and infinite growth. In this instance, Smith’s (2004) ‘Invisible Hand’ functions as a self-regulating market mechanism. In the terminology used in this dissertation, this corresponds to a negative feedback mechanism. Before the Bifurcation Point is reached, the supply curve remains relatively smooth and follows the assumptions of the classical equilibrium model. The market equilibrium, which is often illustrated by Marshall’s scissors or a Marshallian Cross, explains the mechanism of market operation (Humphrey, 1992).

As the author of the theory notes in his latest monograph (Girdzijauskas, 2024), the equilibrium point (E) indicates that supply and demand, which are opposing

market forces, are in equilibrium. This equilibrium is a representation of the efficient market outcome, as the market is entirely balanced in a state of equilibrium. There is no intrinsic motivation for either the seller or the buyer to disturb the equilibrium. Therefore, the equilibrium price is the price that supports efficient market operation of the market by balancing supply and demand as a result of the forces of competition. This relationship is often illustrated by the metaphor of Marshall's 'scissors', which emphasises that both supply and demand jointly determine equilibrium. Specifically, supply does not exist independently of demand, and demand cannot operate without supply. As already mentioned, this balance is ensured by the negative feedback. However, negative feedback remains effective only up to the Bifurcation Point.

The situation is different in a saturated market. Under certain conditions, the demand curve may shift to the right, or the supply curve may shift to the left due to non-price factors. The Bifurcation Point (Q_{Bif}) is reached when the equilibrium quantity (Q_E) exceeds the bifurcation threshold, and the market enters a saturated state. The demand curve begins to shift to the right, resulting in a further increase in prices once the market becomes saturated. This shift is influenced by positive feedback. A deficit market emerges accompanied by increased demand and expectations. The deficit market and its increasing profitability attract new investors, causing higher prices. Investors may be misled by the booming market and the emergence of a bubble, creating the deceptive impression of perpetual growth and the perception of self-sustaining growth. This mechanism is consistent with Shiller's interpretation of speculative dynamics, where collective optimism and narratives about future growth may reinforce the belief that price increases will continue (Shiller, 2015, 2020). However, in the deficit market equilibrium model, such expectations are not treated only as behavioural factors. They become structurally amplified by saturation, positive feedback, and increasing elasticity. Positive feedback reinforces the rapid equilibrium price growth that characterises such a market, and factors that are not pertinent in the classical equilibrium model begin to operate. The principles of classical theory become less applicable in this context, as the market fails to maintain equilibrium; rather, positive feedback induces additional price increases, as illustrated by the comparison of classical and deficit market equilibrium models in Fig. 7



Source: adapted and extended by the author from Blanchard et al. (2010) and Girdzijauskas (2024)

Fig. 7. Comparison of classical and deficit market equilibrium models

The nature of development is a significant distinction between these models. In unsaturated markets, the classical model is effective when the saturation point (Q_P) is extremely distant or where infinite growth is achievable. Negative feedback executes an optimal regulatory function in this scenario. In saturated markets, the Saturation Paradox is at play: the intensity of price growth does not diminish when market saturation increases, as classical theory would predict, but rather increases, indicating that positive feedback is in effect. In markets with restricted capacity, the profitability of investments increases as capital saturation increases, which is in direct opposition to classical theory, which posits that an increase in supply should diminish

profitability. This discrepancy implies that the Financial Saturation Theory provides novel perspectives on inflation, financial bubbles, and economic crises. It reveals the Bifurcation Point and the subsequent processes, which are becoming more prevalent as a result of the accelerating pace of technological advancement, the increasing opportunities for financial saturation, and the growth of investment volumes. The next section examines the differences between these models in more detail through Market Duality.

2.1.6 Market Duality and structural transformation of scarcity and abundance economies

The classical market equilibrium model and the deficit market equilibrium model can be assessed through duality. There is no strict definition of economic dualism in economic science. Economic dualism refers to the coexistence of two distinct and often disconnected economic systems within a single country or region. These dual sectors differ structurally in terms of productivity, technology, income levels, institutional arrangements, and access to capital. Typically, the dichotomy is represented as a modern (formal, capitalist) sector, characterised by higher productivity, capital intensity, integration into global markets, and formal labour arrangements, and a traditional (informal, subsistence) sector, characterised by low productivity, labour intensity, limited access to finance and markets, and informal employment. Boeke (1954) proposed that the transplantation of Western capitalist institutions into Eastern societies led to a dual economy. There, traditional social structures remained dominant in rural areas while urban centres adopted modern capitalism. One of the influential formalisation of economic dualism, Lewis' (1954) dual sector model explains development as a process of labour transfer from a low-productivity traditional agricultural sector to a high-productivity industrial sector. Meanwhile, critics of the dualism concept such as Todaro and Smith (2020) argue that it may oversimplify dynamic processes and overlook hybrid forms and linkages between sectors. Modern development economics increasingly emphasises structural transformation and institutional integration over dualistic dichotomies. In this dissertation, the concept of duality is applied more narrowly to distinguish between two market equilibrium regimes rather than between structurally different sectors of an economy.

The difference in market equilibrium models is determined by the type of market, which is defined by the relationship between supply and demand. This relationship is directly related to market saturation. Taking a dualistic approach, markets can be classified according to the relationship between supply (S) and demand (D) into fundamental and deficit markets.

In this dissertation, the term fundamental market is used within the economic dualism approach to the Financial Saturation Theory. It serves as a general concept that integrates traditional terms, such as free, open, self-regulated, surplus, and unsaturated markets. These terms are treated as the same and are referred to as the fundamental market when analysing Market Duality. In contrast, the term deficit market describes the opposite market state after bifurcation. It integrates concepts, such as closed, speculative, restricted, saturated, unregulated, and limited markets.

These terms are collectively referred to as the deficit market in the analysis of financial saturation and Market Duality.

In a fundamental market, supply is always slightly higher than, or at least approximately equal to, demand. Meanwhile, deficit markets, where supply is lower than demand, are restricted and behave completely differently from fundamental markets. In typical deficit markets, demand must exceed supply for a relatively long period of time. A stable deficit causes prices to rise and, at the same time, market fluctuations. Such markets experience an excess of invested capital, which ultimately leads to overproduction (Girdzijauskas, 2024). The Market Duality diagram (see Fig. 8) demonstrates that a fundamental market can, under certain conditions, transform into a deficit market. The financial saturation level of the market determines the severity of the deficit: a highly saturated market has a pronounced deficit and a strong positive feedback loop. The opposite transformation is also possible: a deficit market can become a fundamental market when the supply-demand ratio changes. Market saturation, or its transition from an active supply market to an active demand market, turns the market into a deficit market. For this to happen, the D/S ratio must change. When $D/S > 1$, a deficit market is formed as a saturated system, while when $D/S \leq 1$, a fundamental market is formed as an unsaturated system. The turning point is the Bifurcation Point described and mentioned in the previous subsection.

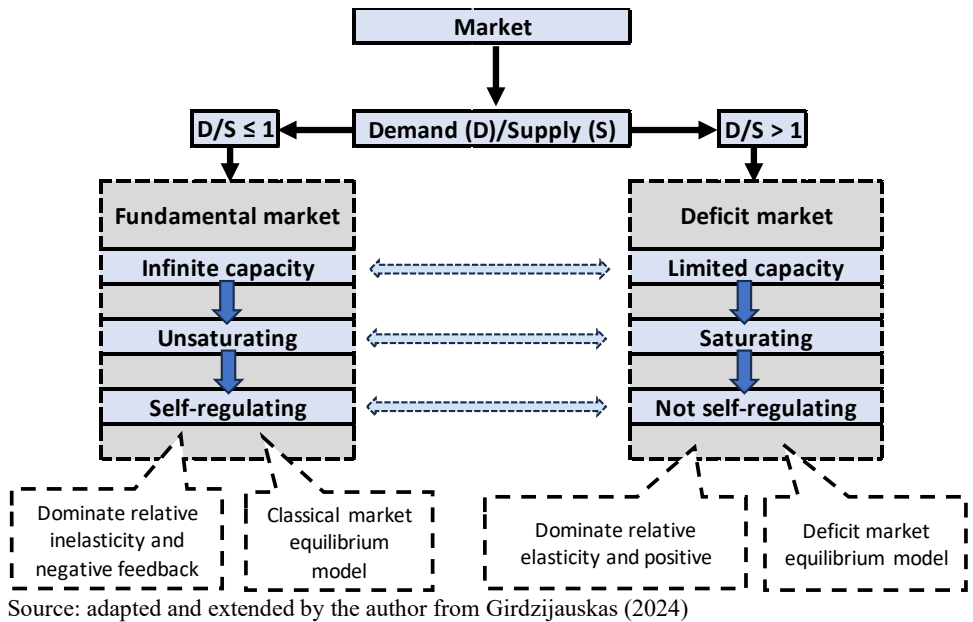


Fig. 8. Market Duality and transition between fundamental and deficit markets

If the market is fundamental, the rise in prices ends with a decrease in demand. The principles of classical theory are suitable for such a market. In a deficit market, rising prices increase speculative activity, leading to further price increases, and here the principles of classical theory no longer apply. In closed systems, as saturation increases, the model shows an increase in productivity (profitability). The scenario for increased profitability could be as follows: for one reason or another, investments are

made in the financial sector, triggering an initial increase in demand. If demand outstrips supply, the cycle begins. Small-scale and temporary market participants (speculators) who do not intend to consume these goods but only intend to buy cheaply and sell at a high price enter the market. As the cycle continues, price growth accelerates. The market heats up and hidden overproduction emerges. These dynamics are examined in more detail in Subsection 2.1.7

Classical economic theory focuses primarily on fundamental market conditions where Smith's Invisible Hand operates, negative feedback dominates, and relative inelasticity prevails. In contrast, the Financial Saturation Theory extends the analysis to saturated market conditions. This enables a comparative interpretation of scarcity and abundance economies within the framework of Market Duality.

The scarcity-abundance continuum is a foundational economic concept describing resource availability relative to human needs. Classical economics, as developed by Adam Smith (2004) and David Ricardo (2004), assumes perpetual scarcity, where resources are limited and must be efficiently allocated. In contrast, modern technological and post-industrial paradigms, particularly in digital and renewable sectors, introduce the possibility of abundance economies, where marginal costs approach zero and production is decoupled from material constraints (Rifkin, 2014).

Within this dichotomy, economic dualism manifests as the coexistence of:

- scarcity economies in underdeveloped, resource-constrained sectors (traditional);
- abundance economies in advanced, digitally-integrated, or innovation-driven sectors (modern).

This dual structure complicates macroeconomic planning and investment strategies, particularly in transitional economies where both systems co-exist and interact. Chase's (1934) key contribution is to frame dualism not just as a developmental disparity but as a functional failure of economic imagination. Here institutions enforce scarcity in a world that could support abundance. The author's vision of an 'economy of abundance' aligns with ideas of moving from a scarcity-focused economy to one that prioritises access and resource sufficiency, a notion that resonates with the current push for sustainable development and a post-scarcity economic model.

Fundamental market is similar to a scarcity economy in terms of its characteristics and operating principles. Like the scarcity economy, the classical market has existed for many years, with negative feedback loops, relying on scarcity of resources to meet consumer desires, and a persistent lack of investment and progress. The distinguishing features of both the scarcity economy and fundamental markets overlap:

- limited access to capital, technology, and infrastructure;
- dependence on exhaustible resources (e.g. fossil fuels, agricultural land);
- inelastic supply due to rigid production structures.

Meanwhile, the deficit market and abundance economy corresponds to the modern/formal sector and is enabled by:

- technological innovation (e.g. AI, solar photovoltaics, blockchain);
- network effects and zero marginal cost production (especially in digital sectors);
- scale economies and decoupling of input-output relations;
- access to capital, technology, and infrastructure leading to saturation.

An abundance economy alters the logic of value creation. Information, knowledge, and renewable energy become the primary inputs rather than finite physical resources.

Integrating scarcity and abundance into the analysis of economic dualism helps to explain contemporary inequalities not only in terms of income or geography, but also in terms of uneven access to technological regimes, infrastructure, and the benefits of abundance-oriented development (Daoud, 2018; Kop, 2022). It reflects a multi-speed economy in which some sectors move rapidly toward efficiency, technological upgrading and sustainability, while others remain constrained by resource scarcity, institutional limitations and restricted access to infrastructure.

This theoretical perspective aligns with the framework of Financial Saturation Theory, where fundamental markets can be interpreted as scarcity-based markets, while deficit markets can be interpreted as abundance-based markets. In the fundamental market, scarcity, limited access to capital, technology and infrastructure, and negative feedback support the logic of classical equilibrium. In contrast, the deficit market reflects an abundance-driven regime, where access to capital, technological expansion and increasing investment flows may lead to saturation, positive feedback, overvaluation, and bubble formation. Therefore, the market duality discussed above can be interpreted as a distinction between scarcity and abundance economic regimes. Within the framework of Market Duality, bubbles are understood as phenomena characteristic of deficit markets. Based on the analysis of Financial Saturation Theory, this provides a foundation for examining the mechanisms of bubble formation, their causes and their economic implications.

2.1.7 Mechanism of bubble formation in Financial Saturation Theory

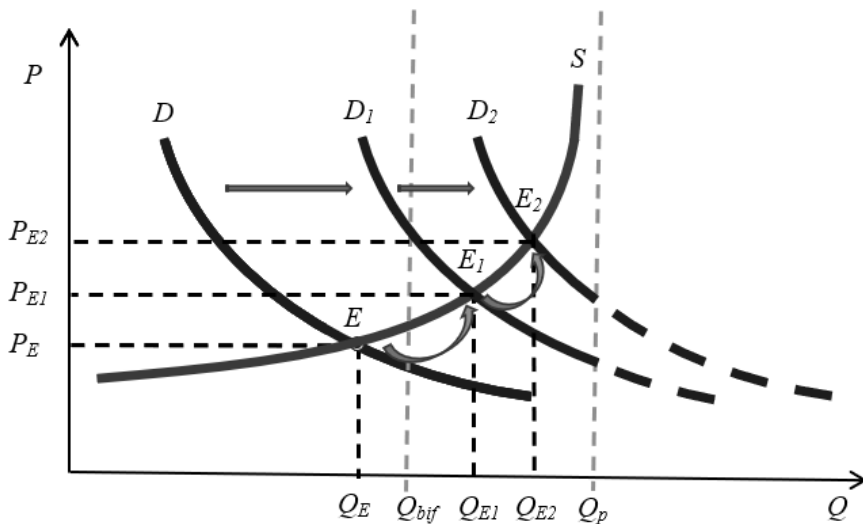
The bubble formation mechanism integrates and visualises the main components of Financial Saturation Theory discussed and analysed in this dissertation: logistic growth, feedback and elasticity, the Saturation Paradox, bifurcation and Market Duality, demand and supply transformation, and classical and deficit market equilibrium models. This subsection presents the bubble analysis developed by the author of Financial Saturation Theory and provides a systematised interpretation of the bubble formation mechanism for the purposes of this dissertation. Combining the analysed components of the theory into a single mechanism provides a clearer theoretical basis for the further development of the research model based on Financial Saturation Theory. In the context of financial saturation, both theoretical and empirical explanations of bubble formation mechanisms become possible.

The theoretical explanation of the bubbles is based on the mechanism of deficit market equilibrium. Bubbles are a phenomenon of deficit markets. In this type of market (in Stages II and III), positive feedback at a sufficient frequency intensifies

and the saturation phenomenon affecting positive expectations. Market is in the heating stage. In other words, intensively rising prices increase demand and hence profitability expectations, which are shaped by the phenomenon of rising profitability (the Saturation Paradox). The positive feedback of rising prices further stimulates price increases, thereby attracting and accelerating investment.

On the contrary, if the market has unlimited productive resources (unlimited capacity or market is fundamental), saturation is not possible – the Saturation Paradox does not work. The supply curve is at its lowest point and moderately increasing. The market is in moderate growth stage (Stage I). This leads to a lack of optimistic expectations, and feedback transforms to a negative one, price increase is minimal and the whole system is stable. It is common to consider such a market as stagnant (Girdzijauskas, Štreimikienė, et al., 2012; Gryshova et al., 2019). Overcoming stagnation requires the mobilisation of a sufficient number of investors who have optimistic (enthusiastic) expectations.

At the empirical level, the dissertation author's interpretation of bubble formation is presented in Fig. 9. It combines and visualises the Financial Saturation Theory and its components discussed and analysed so far: logistic growth, feedback and elasticity, the Saturation Paradox, bifurcation and Market Duality, demand and supply transformation, and classical and deficit market equilibrium models. The formation of the bubble mechanism reflects the partially dynamic model of this theory. Under *ceteris paribus* conditions, there are several variables in the model that influence the shift in demand and the dynamics of price and quantity.



Source: adapted and extended by the author from Girdzijauskas (2024)

Fig. 9. Conceptual model of bubble formation under financial saturation

First of all, it is summarised that both demand and supply are derived from a logistic growth model, where each growth has its own limit. In this case, this limit is reflected by Q_P and the supply (S) approaching this limit. In the model, the supply

price (P) corresponds to the growth rate, and the quantity corresponds to the quantity of goods or services (Q) in terms of accumulated capital or the value of the supply quantity. The form of supply reflects the Saturation Paradox – increasing profitability as the market saturation level increases, i.e. rising prices as the quantity approaches its potential limit ($Q \rightarrow Q_p$). It should be reminded that the independent variable is quantity, while the dependent variable is price.

The Bifurcation Point (Q_{Bif}) marks the relative unit elasticity that distinguishes the relatively inelastic and relatively elastic supply price with respect to quantity. Elasticity and bifurcation define the operation of negative and positive feedback in the market, as well as the duality of the market and the dividing line between the market types discussed above. Up to the Bifurcation Point (left side), negative feedback is at effect, allowing the market to regulate itself and moderate growth to prevail. This market type is best described by the classical market equilibrium model. Beyond the Bifurcation Point (to the right of the point), positive feedback begins to operate due to relative elasticity, and a significant Saturation Paradox emerges in supply. In the analysis, the Bifurcation Point also marks a market transition when the market is considered dual. Then, the left side of the market is considered fundamental, where supply prevails ($Q_S > Q_D$). Meanwhile, from the turning point, the right side of the market is considered to be deficit, where the influence of demand prevails ($Q_D > Q_S$).

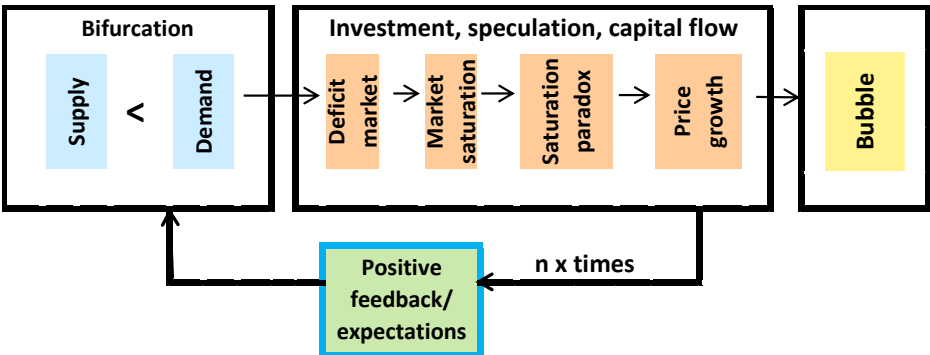
In the presented model, apart from price and quantity, the *ceteris paribus* condition applies to other variables. As already described and indicated in the following analysis, this condition does not apply to the expectation criteria. The static situation of the mechanism under consideration is characterised by the fundamental market before bifurcation (the left side of the Bifurcation Point). Negative feedback is present, the market regulates itself, and moderate growth prevails. This is reflected in points P_E , Q_E , and E .

After describing the static situation, the analysis shifts to certain changes in the market, i.e. a shift in demand to the right (increasing demand). The transition of demand from D to D_1 is not clearly defined or mentioned in the Financial Saturation Theory. Shiller's behavioural and narrative approach helps to interpret this initial demand shift. Narratives about future growth, technological transformation or exceptional investment opportunities may strengthen collective expectations and stimulate additional demand (Shiller, 2020). In the framework of Financial Saturation Theory, such narrative-driven demand shifts become structurally important when they move the market beyond the Bifurcation Point and activate positive feedback.

In this context, investment flows can be interpreted as one of the primary drivers of demand shifts and increasing market saturation. As capital accumulates within the system, rising saturation levels may activate feedback mechanisms and push the market beyond the Bifurcation Point, creating conditions for bubble formation. External factors could be described as the factors, which shift demand curve to right (Girdzijauskas, 2024; Snieska, 2006): income level, social structure, population, seasonality, fashion, natural conditions, advertising and buyer expectations, changes in market capacity, etc. It is assumed that a change in one or more factors shifts demand to such an extent that the new equilibrium quantity exceeds the Bifurcation

Point. A larger quantity (Q_{E1}) with a higher price (P_{E1}) is formed at the new equilibrium point E_1 . Then, regardless of other factors, feedback (expectations) is triggered by the fact that prices will continue to rise. The market becomes deficit and demand dominates. Therefore, a disproportionate investment in market of limited size further increases demand. Demand shifts further to the right to point E_2 , where a new higher price (P_{E2}) and quantity (Q_{E2}) are established. This result attains investors and capital even more, i.e. positive feedback is further strengthened by expectations. It causes demand to move further to the right, and such cycles can occur many times. The author of the Financial Saturation Theory described this process as resonance or quasi-resonance. According to Girdzijauskas (2024), feedback and the described cyclical demand create a quasi-resonant price rise mechanism that inflates the price bubble. The bubble is shaped by the resonating demand created by the investment and comes out in conditions of intense saturation. A market without investment could be considered a decaying market. The intensity of the decline in market activity in the absence of investment could be considered as an individual characteristic of the market, analogous to the swing's own frequency of oscillation. Negative feedback provides stability to the market, whereas positive feedback may amplify price fluctuations. Some investment impulses are likely consistent with the market's individual characteristics (the market's own frequency). Investment impulses that coincide with the phase of market price volatility amplify the amplitude of price fluctuations. This leads to an increase in prices or a market change. Due to the chaotic nature of the investment process, the resonance process is often not fully realised.

Based on theory and resonance, the cyclical bubble scheme (financial resonance) works as follows: when demand exceeds supply (usually in the case of well-publicised long-term technological projects), a deficit market is created (Girdzijauskas, n.d.). Such a market becomes saturated. By investing in this market, the short-run market equilibrium mechanism is triggered: the Marshall's scissors are twisted, and the point of convergence is shifted upwards (the price goes up). Continuous investment in a deficit market further increases the saturation level of that market. The process is even accelerated when speculators step in and sharply increase demand, saturation, profitability, etc. (see Fig. 10).



Source: adapted and extended by the author from Girdzijauskas (2024)

Fig. 10. Positive feedback cycle in deficit markets

The phenomenological approach shows that a bubble can only form through a cyclical process and additional stimulation. That additional stimulus is investment under saturation, i.e. the increasing returns resulting from saturation. The Financial Saturation Theory allows a bubble to be defined as a resonant phenomenon. A simplified definition of a financial bubble could be formulated (Girdzijauskas, 2024): a financial-resonance bubble is an intense increase in asset class prices resulting from repeated and resonant investment cycles with positive feedback shaped by optimistic expectations, resulting from the increase in returns in a deficit market, which is the consequence of financial saturation.

The Financial Saturation Theory is based on the fact that infinite growth does not exist. The bubble formation diagram is no exception, where the number of cycles is also finite. There are several reasons for this. First of all, the more the demand curve shifts to the right, the closer the equilibrium point approaches the market potential (Q approaches Q_P). This implies an increasing Saturation Paradox, i.e. increasing profitability. However, at the level of high saturation, there is a very high relative price elasticity of quantity. This level of elasticity means that a small change in quantity leads to a great change in price. Under these conditions, the system becomes unstable. A slight change in circumstances due to external factors can trigger feedback effects on both growth and decline. The more saturated the system is, the stronger the feedback will be, with different polarities. In the case of negative polarity feedback, there appears a bubble burst. Other circumstances that can lead to the end of a positive feedback cycle include a change (increase) in the capacity of the market, a decrease in capital flows due to external causes.

When discussing the concept of resonance used in theory to explain the bubble mechanism, a fundamental methodological question arises: is it possible to describe the dynamics of economic systems, especially financial bubbles, using deterministic models? At the micro level, the formation of bubbles is inevitably influenced by stochastic noise: random fluctuations, external shocks, information surprises, and other factors that are difficult to predict. In modern statistical physics and econophysics, the prevailing view is that the dynamics of financial markets are most often modelled using stochastic time series, random processes, or stochastic differential equations, which allow for an adequate description of fluctuations, noise, and the impact of external triggers (Girdzijauskas et al., 2026).

However, the Financial Saturation Theory does not seek to replace stochastic methods or deny their importance. On the contrary, it is based on the assumption that economic systems are stochastic at the micro level, while at the macro level it is possible to identify recurring structural cycle stages: growth, saturation, overheating, and collapse. This theory focuses not on predicting random fluctuations, but on revealing the logic of changes in the internal states of the system.

Therefore, the concepts of saturation and resonance used in the theory are not a direct transfer of statistical physics or signal theory to financial markets. They are understood as phenomenological concepts used to describe system state transitions and cyclical dynamics. Stochastic and deterministic approaches are not opposed here, for they are applied at different levels of analysis. Stochastic methods allow for the assessment of external factors, noise, and short-term fluctuations, while the Financial

Saturation Theory seeks to identify internal structural mechanisms of bubble formation.

In the author's opinion, a direct application of the concepts of resonance or quasi-resonance in the model under development would be premature. Although resonance is often mentioned in the development of the theory and is given an important explanatory meaning, the direct transfer of the physical phenomenon to economic analysis would require broader empirical research, which would go beyond the scope of the objectives and tasks of this dissertation. Therefore, in this work, the resonance bubble is treated more broadly. A financial bubble and its formation principle is based on the deficit market equilibrium mechanism. Bubbles are considered a phenomenon that occurs in deficit markets, where positive feedback, the Saturation Paradox, expectations, and other mechanisms discussed earlier are at work. In line with the deterministic approach, external factors and random noise are not directly modelled in the explanation of the bubble mechanism and the model developed below. It is assumed that certain external shocks or structural changes could have initiated market bifurcation and a transition to a deficit state, which is already dominated by internal self-reinforcing processes.

Thus, the theory and the model based on it focus on identifying internal structural bubble mechanisms and analyse cycle stages at the macro level: growth, saturation, overheating, and collapse. Based on this approach and including the saturation factor, the theory distinguishes three types of bubbles: price, financial, and inflationary bubbles. The interaction between these types and their classification as productive or destructive bubbles is discussed in the next subsection.

2.1.8 Bubble classification based on financial saturation: Productive and destructive bubbles

Within the framework of Financial Saturation Theory, bubbles are interpreted not merely as speculative anomalies, but as structural phenomena emerging in market saturation conditions. Considering the mechanism of the analysed bubbles in the preceding subsection, classical understanding of economic bubbles has some similarities regarding expectations and speculations. As described by Kindleberger (1996), a bubble is a sustained and significant rise in the price of an asset, driven by expectations of further price increases. These expectations attract new market participants. Speculators' motivation shifts from the asset's income-generating capacity toward anticipated capital gains.

Based on saturation and bubbles mechanism, the theory distinguishes three main types of bubbles (Girdzijauskas, n.d., 2024; Girdzijauskas et al., 2022; Girdzijauskas & Dubnikovas, 2026):

— **Price bubbles** arise in markets for scarce, highly demanded goods. These typically involve unique or limited-supply assets, such as rare artworks, collectibles, archaeological units, or exceptional natural resources. In such markets, supply is inherently constrained. The supply curve becomes quasi-vertical near the equilibrium point. Thus, the bubble emerges from a structurally limited supply combined with unusually intense demand.

— **Financial bubbles** develop in broader asset markets, such as real estate, commodities, or financial instruments. Their formation is linked to the inflow of financial resources' approach to the market's capacity. The market is in a deficit (Demand > Supply). Positive feedback between rising prices and investor expectations reinforces demand, thereby producing self-sustaining price acceleration.

— **Inflationary bubbles** represent the macroeconomic aggregation of multiple financial bubbles. This is a macroeconomic phenomenon where aggregate demand reaches the market (economy) capacity frontier, i.e. immediately approaching potential GDP and saturating the economy. As sectoral bubbles proliferate, their cumulative effect pushes the aggregate demand and aggregate supply interaction into the upper price level, generating systemic overheating and demand-driven inflation. Inflationary bubbles emerge when numerous sectoral bubbles coincide and interact at the macro level.

Among the three bubble types identified within the Financial Saturation Theory, financial bubbles are the most relevant for the empirical framework developed in this dissertation, particularly in the context of renewable energy investment dynamics:

— Financial bubbles emerge primarily in asset and investment-driven markets, including equities, infrastructure, commodities, and technology-intensive sectors. In this study, the empirical analysis encompasses the broader RE sector, including capital flows into technologies, financial instruments, and large-scale projects. These investment-based dynamics directly correspond to the structural environment in which financial bubbles arise.

— The empirical model aims to evaluate how investment inflows influence sectoral development, growth stability, and long-term sustainability in relation to market or sectoral capacity. The mechanism of financial bubbles explicitly links capital inflows with market limits (capacity), making it conceptually consistent with a framework that interprets growth as a process constrained by saturation.

— The model seeks to assess capital saturation, system stability, and the emergence of speculative dynamics. The financial bubble mechanism incorporates these elements.

— Deficit market equilibrium model is particularly suitable for modelling sectors such as renewable energy, where physical, technological, regulatory, and infrastructural constraints can gradually increase elasticity and intensify price and investment volatility.

— Financial bubbles incorporate behavioural and expectation drivers. These mechanisms are especially relevant in emerging sectors, e.g. renewable energy, where policy support, technological optimism, and long-term transition strongly influence investor expectations.

For these reasons, financial bubbles represent not only a theoretical category but also the most appropriate analytical mechanism for developing an empirical model that links investment flows, market capacity, saturation dynamics, and structural instability in the renewable energy sector.

While the Financial Saturation Theory classifies bubbles according to their structural origin, it does not explicitly distinguish them by their economic

consequences. From a broader developmental perspective, bubbles may be conditionally differentiated into productive and destructive forms. These types of bubbles were theoretically analysed in the first part of the dissertation (see Subsection 1.2.3).

Three stages of growth (see Subsection 2.1.2), which provide a basis for linking, justifying, and more clearly defining the distinction between productive and destructive bubbles, are identified in the analysis of Financial Saturation Theory. Therefore, in the following discussion, the author connects the previously analysed productive and destructive bubbles with the Stage II (heating) and Stage III (overheating) phases of growth.

Financial productive bubbles and heating growth stage (Stage II) have the following similarities:

- Productive bubbles can generate long-term economic benefits despite short-term financial misallocations, contributing to the creation of durable productive assets. Similarly, the heating stage (Stage II), despite increasing productivity, remains stable. Although elasticity (or sensitivity to fluctuations) increases and may lead to minor financial misallocations, the system as a whole remains stable and the risk of collapse is minimal. Due to the Saturation Paradox operating under stable conditions, the system exhibits positive-sum dynamics, where societal gains exceed private losses. This is a defining feature of productive bubbles.

- Productive bubbles accelerate technological progress by channelling capital into innovation and infrastructure. The heating stage corresponds to a deficit market, where positive feedback and increasing productivity/profitability (the Saturation Paradox) become visible and attract investors.

- Because the system in Stage II remains stable while experiencing positive feedback and rising profitability, it naturally attracts investor capital. The inflow of capital and expectations of returns help build foundational infrastructure for future industries, encourage innovation, and foster entrepreneurship. These features directly correspond to the characteristics of productive bubbles.

- Other mechanisms based on financial saturation and the Saturation Paradox may also represent speculative surges that ultimately transform into enduring assets with broad economic benefits. For example, Natural Ponzi dynamics (see Subsection 2.1.9.1) and the operation of Ponzi-type mechanisms in Stage II can represent speculative expansion that still contributes to real capacity building. This behaviour is characteristic of productive bubbles.

Based on this phenomenological comparison and the identified similarities, it can be argued that a financial productive bubble may be interpreted as a Stage II growth bubble. The distinguishing features of this stage and bubble type include a deficit market, positive feedback, the Saturation Paradox, overall system stability, and a saturation level ranging approximately from 0.7 (70%) to 0.9 (90%).

Such bubbles may play a constructive role in sectors such as renewable energy, where large upfront investments and high uncertainty are inherent to technological transitions. In early and intermediate stages of market development, speculative

expansion may help push the sector beyond structural bottlenecks and adoption thresholds.

At higher levels of saturation, the system becomes unstable, growth becomes uncontrollable, and the bubble transforms into a financially destructive one, while system growth shifts into Stage III (overheating). Destructive bubbles are harmful to the economy. The essential similarities between the overheating stage and destructive financial bubbles include the following:

- Destructive bubbles are associated with heightened systemic risk and an increased likelihood of financial crises. The overheating stage is characterised by a steep, approaching hyperbolic growth phase, where sensitivity to internal and external factors becomes highly pronounced. The system at this stage becomes unstable.

- Destructive bubbles are characterised by excessive financial leverage, rapid capital expansion, and purely speculative trading. The overheating stage features strong positive feedback and an intensified Saturation Paradox, where profitability grows hyperbolically. This attracts speculative capital and creates conditions for profit-seeking detached from fundamental value, as asset price growth becomes disconnected from real productive capacity.

- As the system becomes unstable in Stage III, the risk of collapse rises sharply. Given the advanced stage of development and the large volume of invested capital already embedded in the system, destructive bubble characteristics emerge, such as zero-sum or negative-sum redistribution effects and long-term damage to sectoral or macroeconomic stability. System instability further increases systemic risk and the likelihood of financial crises. Together these are key outcomes of destructive bubbles.

Based on this phenomenological comparison and the identified similarities, a destructive financial bubble may be interpreted as a Stage III growth bubble. The distinguishing features of this stage and bubble type include a deficit market, extremely strong positive feedback, an intensified Saturation Paradox, system instability (with hyperbolically increasing elasticity and profitability), and a saturation level above 0.9 (90%).

However, it cannot be claimed that all systems entering Stage III automatically represent destructive financial bubbles. Although this stage shares many characteristics with destructive bubbles, one additional condition is required for confirmation. This is the manifestation of negative and harmful effects on the system (market, sector, or economy). The type of bubble can be assessed by its consequences, which is not captured by logistic growth models, but can be an additional criterion to define the type of bubble formed. Therefore, linking growth stages with destructive bubbles requires two conditions:

- a saturation level corresponding to Stage III (above ~90%);
- observable harmful consequences, such as system collapse or bubble bursting.

From the perspective of Financial Saturation Theory, both productive and destructive bubbles may emerge from similar structural conditions. The distinction

depends on the stage of saturation, elasticity of supply, and the real economic outcomes of the investment surge. As long as the bubble supports capacity expansion, innovation, and productivity growth within the elastic range of market development, it may remain productive. Once the saturation level increases further, elasticity increases sharply, and price growth becomes detached from real expansion, the bubble tends to transform into a destructive phase.

Thus, the objective for both market participants and policymakers is not necessarily to eliminate bubble dynamics altogether, but to prevent the transition from productive expansion to destructive overheating. In line with Shiller's perspective, the same collective optimism and growth narratives may support productive investment waves in earlier growth stages, but under high saturation they may also contribute to destructive overheating when expectations become detached from real capacity expansion (Shiller, 2015, 2020). As saturation levels increase and positive feedback mechanisms strengthen, these self-reinforcing dynamics may also manifest themselves in specific market schemes and strategic actions aimed at accelerating capital inflows and price increases. Such mechanisms may emerge organically from market conditions, but they can also be deliberately exploited by market participants. Therefore, the following subsection examines additional mechanisms related to financial saturation and bubble growth, including Ponzi dynamics and pump and dump schemes.

2.1.9 Market schemes and mechanisms under financial saturation

Based on the previously discussed bubble mechanisms (Saturation Paradox, positive feedback, and changing elasticity, bifurcation, expectations, etc.), it is possible to re-examine other market mechanisms from the same structural perspective. Some of these mechanisms operate in ways similar to productive or destructive financial bubbles. They may emerge consciously or unconsciously as participants seek to increase asset values and attract capital. Importantly, these mechanisms often aim to raise the level of market saturation and benefit from the increasing profitability created by the Saturation Paradox. Analysis examples include naturally occurring Ponzi dynamics and pump and dump schemes. A classical Ponzi scheme, however, does not belong to this category, as it is a direct fraud in which collected funds are not invested in the real economy but merely redistributed among participants.

Parts of the conceptual discussion of Natural Ponzi dynamics presented in the next subsection were previously published in Karaša et al. (2025), building on the financial saturation and positive feedback framework developed in Karaša and Girdzijauskas (2024). In the present dissertation, this material is integrated into the broader framework of bubble classification and market mechanisms.

2.1.9.1 Ponzi schemes and natural Ponzi

The fundamental differences between a bubble, a classical Ponzi scheme, and natural Ponzi dynamics are reflected in the presence or absence of direct or indirect intent (Boyle & Peng, 2025). In the case of a bubble, there is neither direct nor indirect intent. Price increases are driven by prevailing market conditions. In the case of a natural Ponzi dynamic, a bubble forms in the presence of indirect intent, and the funds

raised are invested in real businesses or markets. In contrast, in a classical Ponzi scheme, no genuine bubble is formed: funds collected through deliberate fraudulent activity are not invested in the real economy (businesses or markets) but are merely redistributed among existing investors and the scheme organisers (see Table 9).

Table 9. Comparison of natural and classical Ponzi schemes

Naturally occurring Ponzi (Natural Ponzi)	Classical Ponzi
A naturally occurring Ponzi scheme is an economic phenomenon that arises in environments characterised by systemic instability, where self-reinforcing market dynamics lead to speculative asset bubbles. Unlike traditional Ponzi schemes, which involve intentional fraudulent based on fake investments, a naturally occurring Ponzi structure emerges organically due to the interaction of investor psychology, market expectations, and economic imbalances. Natural Ponzi could transform to real business or financial bubble and its collapse.	A classical Ponzi scheme is a fraudulent financial structure that operates within an environment of economic instability, where systemic weaknesses allow its perpetrators to manipulate market expectations for personal gain. Unlike a naturally occurring Ponzi scheme, which emerges due to speculative market dynamics, the classical Ponzi scheme is intentionally designed, relying on deception, misrepresentation, and the continuous inflow of new investors to sustain itself. The capital raised is not invested in a real business or market, but is redistributed as profit to previous investors and the authors of the scheme.

Source: adapted and extended by the author from Karaša et al. (2025), based on Boyle and Peng (2025), Minsky (1986), and Shiller (2015)

Building on Basu (2014) and Minsky (1986), the definition of a Natural Ponzi scheme previously formulated in Karaša et al. (2025) is applied in this dissertation. A Natural Ponzi is a market mechanism where financial saturation and strong positive feedback loops lead to an increase in market profitability, and the excess capital of investors creates a bubble, based on expectations and the involvement of new entrants, rather than on fundamental economic rationale. As the bubble expands, its contraction or bursting may be temporarily masked by financial interventions, but after the Bifurcation Point has been reached, a subsequent reduction in the flow of new investors may trigger the collapse of the system. It is important to note that a financial bubble forms without the intervention of a deliberate manipulator and arises from natural market forces, but that deliberate manipulation can occur later to prevent or postpone a market crash. In the case of a natural Ponzi, manipulation is also possible in the earlier stages, but its manifestation and effect require the appropriate market conditions: bifurcation and financial saturation, the Saturation Paradox, and a strong positive feedback loop.

It is important to stress that the goal of business activity is not the Natural Ponzi itself, but the higher returns (profitability or growth rate) it promotes. The problem is that better business performance relies on the formation of a bubble, which can lead to a complete Natural Ponzi and bubble burst. Often this transformation goes unnoticed by entrepreneurs/managers or is noticed too late when the bubble has become unmanageable. In some cases, the process is successful in returning to business as usual, but if it is not possible to turn the nascent bubble into a real business,

the bubble overheats and bursts. It is also possible that the process is visible to the entrepreneurs themselves, but not yet visible (betrayed) to outside observers (market participants). In this case, the natural Ponzi turns into a deliberate fraud with classic Ponzi characteristics (Boyle & Peng, 2025). An increasing proportion of the funds raised (capital) is then used not to rescue or develop the real business, but to maintain the bubble by redistributing the funds as a sop to the previous investors.

The most important element of a Natural Ponzi scheme is the expectation that the future price will increase, i.e. a positive feedback loop (Shiller, 2015). In this dissertation, this expectation is interpreted not only as a behavioural factor, but also as a structural element that becomes stronger when market saturation increases and positive feedback is activated after bifurcation. Only in the presence of significant positive feedback can the scheme manifest itself and produce tangible results. The occurrence of a Ponzi scheme is based on positive feedback, the strength of which depends on the level of financial saturation. The level of financial saturation (bifurcation, stages) is determined on the basis of the Financial Saturation Theory based on logistic growth.

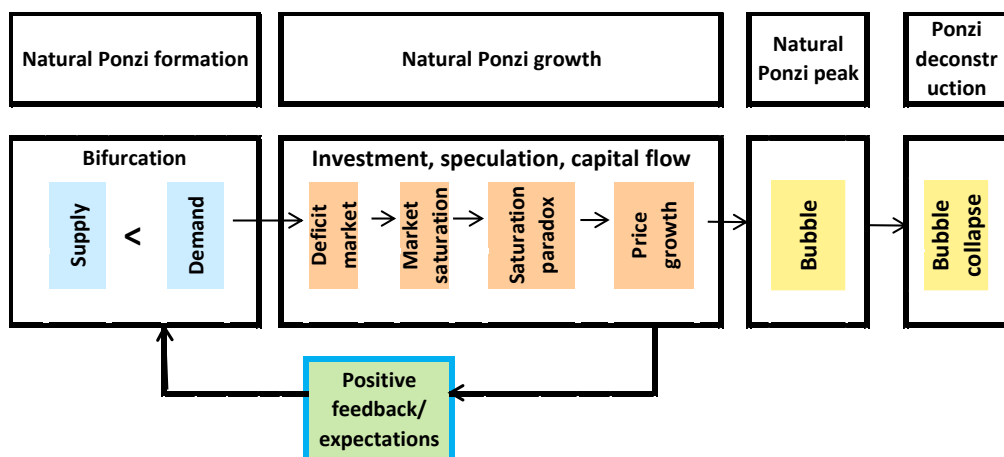
Table 10 summarises the types of schemes and its fundamental reasons, connecting Classical and Natural Ponzi and providing a scheme in the context of saturation and positive feedback as a result.

Table 10. Types of Ponzi schemes and their mechanisms under financial saturation

Type of scheme	Fundamental reasons
Classic Ponzi scheme	Investors' expectations, fake investments, money redistribution, financial pyramid, fraud, deception, lack of ethical behaviour, direct intent, collapse
Naturally occurring Ponzi (Natural Ponzi)	Investors' expectations, large-scale investment, strong positive feedback, implicit intent, transformation to real business or collapse
Ponzi scheme in the context of financial saturation	Demand > Supply, bifurcation, strong positive feedback, market saturation, Saturation Paradox, hyperbolic growth, financial bubble, bubble transformation to real business or collapse

Source: adapted and extended by the author from Karaša et al. (2025)

The relationship between the Ponzi scheme and financial saturation in the context of positive feedback is illustrated in Fig. 11.

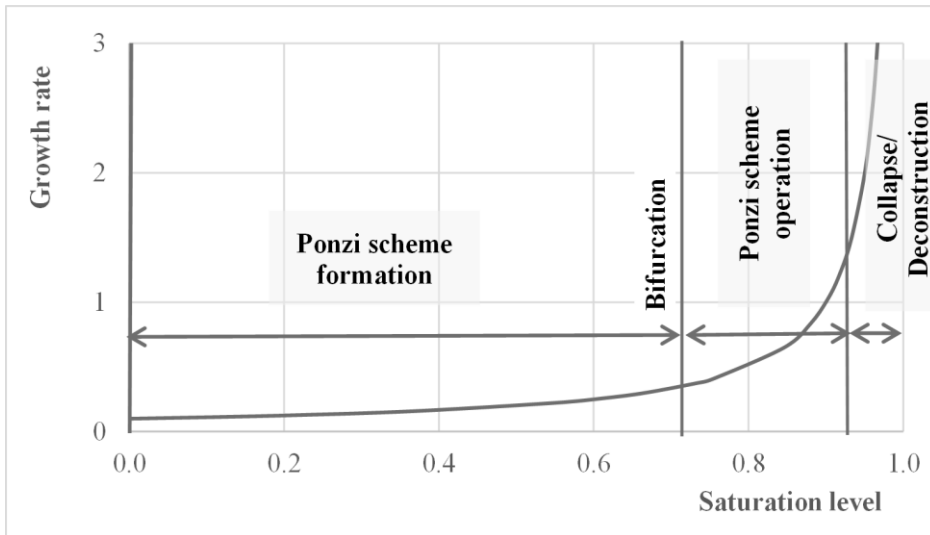


Source: adapted and extended by the author from Karaša et al. (2025), based on Girdzijauskas (2024)

Fig. 11. Dynamic process of natural Ponzi formation and bubble evolution under financial saturation

The diagram above combines the Natural Ponzi scheme with the financial saturation process. This diagram is the expanded model of principles of positive feedback cycle (see Fig. 10) with added Natural Ponzi stages and bubble collapse.

Bubble analysis based on Financial Saturation Theory and Natural Ponzi dynamics is conducted by evaluating the market saturation level in terms of capital. It is assumed that once a certain level of saturation is reached, the likelihood of market overheating increases and the growth rate becomes extremely high, which affects market prices and output. Saturation level and growth rate are related to natural occurring Ponzi scheme. As analysed before, the saturation model identifies critical thresholds of market saturation, particularly moderate growth, Bifurcation Point, heating and overheating stages. In Stage III, speculative dynamics dominate (Mikalauskas & Karaša, 2025). Based on these thresholds, Fig. 12 illustrates the three stages of market saturation and Ponzi schemes stages.



Source: adapted and extended by the author from Karaša et al. (2025), based on Girdzijauskas (2024)

Fig. 12. Mapping of market saturation stages to natural Ponzi dynamics

In the formative phase of a natural Ponzi scheme, the conditions are created or are being created for a positive feedback loop through the Saturation Paradox once the deficit market is reached. In Stage II, following bifurcation, there is market saturation and strong growth due to feedback from the Saturation Paradox, which is reinforced by the scheme formed in Stage I. It should be noted that this pattern can also develop in Stage II. If Stage III is reached and a bubble is formed, this is the stage where the Natural Ponzi is fully operational. The bubble and the scheme as a whole become unstable due to its rapid growth and high sensitivity to change (elasticity). If, as mentioned above, this process is not translated into real business and the flow of capital is maintained, the bubble bursts, a collapse occurs which exposes the Ponzi (deconstruction, Stage III) and causes damage to investors and business owners. Unlike Stages I and II, Stage III has a high probability of shifting to deliberate deception and fraud in order to maintain existing growth and value creation. In other words, the higher the saturation (or the stronger the feedback loop) in the business/market, the more likely it is that a Natural Ponzi will have the characteristics of a classic Ponzi.

In cases where the scheme does not reach its peak (bubble), a correction occurs or growth is supported by real business activity, investors do not suffer significant losses, and the business does not face bankruptcy or substantial depreciation. In such cases, Natural Ponzi dynamics may go unnoticed and be considered insignificant or only partially manifested. For this reason, it can be argued, that Ponzi dynamics may be more widespread in the economy than is typically recognised. In this context, Natural Ponzi dynamics can be compared to the tip of an iceberg, where only a visible portion is observed, while the underlying processes remain largely hidden (Basu, 2014).

2.1.9.2 Pump and dump schemes

Another mechanism, based on Saturation Paradox leading to increasing profitability, is a pump and dump scheme. A pump and dump scheme is a form of securities fraud in which false or misleading positive information and coordinated buying are used to artificially increase the price of an asset (pump). After purchasing the asset at a lower price, the scheme's organisers sell their overvalued holdings at the higher price (dump). When these sales begin and the artificially created demand weakens, the price declines, causing losses for misinformed investors and those who entered the market at a late stage. Xu and Livshits (2019) observed that such schemes are particularly prevalent among small-cap cryptocurrencies and microcap stocks, which are securities issued by companies with low market capitalisation and limited public information (U.S. Securities and Exchange Commission, 2013). A pump and dump scheme is a type of market manipulation in which the price of a financial asset, typically a low-liquidity, small-cap stock or cryptocurrency, is artificially inflated ('pumped') through exaggerated, misleading, or false statements. The coordinators of the scheme sell ('dump') their overvalued holdings at a profit once the price is driven up by heightened demand, which is frequently generated by coordinated buying and social hype. Consequently, the price declines, resulting in substantial losses for investors who are either misinformed or in the late stages of the investment process.

Much of the literature on pump and dump schemes focuses on their use in traditional stock markets. Allen and Gale (2000) distinguish three main forms of market manipulation: information-based, action-based, and trade-based schemes. Pump and dump schemes typically involve a combination of trade-based and information-based manipulation. Mei et al. (2004) demonstrate that it is feasible to implement pump and dump schemes solely by exploiting investors' behavioural biases. The form of this fraud is contingent upon the capabilities of the technologies of the era. In the early 18th century, the South Sea Bubble (Temin & Voth, 2004) was promoted through the application of night wind hawkers to distribute shares. However, as technology advanced and spread, the potential for the scheme to be implemented through media channels, such as a fake press release or telemarketing from 'boiler room' brokerage houses, emerged. As reported by Frieder and Zittrain (2008), the internet boom in the early years of 2000 led to the birth of a new e-mail-based pump and dump scheme, which is also active nowadays. It has gained new vitality in the loosely regulated cryptocurrency market. This scam is typically orchestrated by groups of individuals who are highly coordinated, typically on Telegram and Discord (La Morgia et al., 2023). Alongside evolution, the pump and dump scheme evolved, adopting new names and variations in form, including 'scalping', 'hack', 'short and distort', and 'crowd pump'.

From the perspective of Akerlof and Shiller's (2016) analysis of manipulation and deception, pump and dump schemes can be interpreted as an intentional use of narratives, distorted information, and asymmetric incentives to stimulate demand and attract uninformed investors. The Financial Saturation Theory adds that such manipulation becomes especially effective when the targeted market is small, illiquid or close to market limit, because price elasticity and feedback effects are stronger.

Despite the changes and improvements and adaptations of the scheme, the essence remains the same: to take advantage of the benefits of the Saturation Paradox. Summarising key characteristics of pump and dump model, it could be easily explained using the analysed Financial Saturation Theory and Saturation Paradox:

- *Artificial price inflation*: it occurred as a result of coordinated misinformation campaigns utilising social media, newsletters, forums, or insider groups. In order to increase demand, measures are implemented to relocate it to the right of the Bifurcation Point. The objective is to capitalise on the Saturation Paradox, which entails an increase in profitability as the saturation level increases.

- *Low market capitalisation assets*: due to their price susceptibility, this strategy frequently targets penny stocks, illiquid securities, or low-volume cryptocurrencies. The desired level of saturation (Bifurcation Point) and the benefits of the Saturation Paradox for increasing profitability are more easily achieved when the market potential (maximum) capacity is lower.

- *Asymmetric information*: outsiders act on manipulated information, while orchestrators have prior knowledge of the dump phase. This is similar to the Natural Ponzi dynamics that were previously discussed, in which managed demand growth is achieved through information management and manipulation.

- *Short-term price volatility*: a rapid price increase that is followed by a sharp decline after the manipulators exit the market. The sudden price fluctuations of equities or other manipulated assets are explained by the Saturation Paradox, which is a result of the increasing relative elasticity of supply. Volatility increases as saturation levels increase. In this instance, feedback is generated through artificial means at the pump stage.

- *Retail investor losses*: capital destruction and distrust in financial markets are the norm when non-insiders are left with depreciated assets. This mechanism is facilitated by a negative feedback loop, which is induced by the return of the demand curve to the left following the completion of coordinated misinformation campaigns that halt artificial price inflation. When the saturation level is high, even minor fluctuations in demand result in significant price fluctuations, this time as a negative ‘correction’ (dump).

From the viewpoint of Financial Saturation Theory, these mechanisms imitate bubble dynamics in a distorted way. They strengthen feedback loops, increase saturation, and raise system elasticity without expanding the real economic base. Because of this, they usually lead to short-lived and destructive bubble phases. In empirical modelling, this can be treated as warning signs of unsustainable market dynamics and speculative behaviour, which could lead to fraud.

2.1.10 Synthesis of Financial Saturation Theory and implications for bubble analysis

A consistent analysis of Financial Saturation Theory and its phenomenological application to the deconstruction and evaluation of bubble-based mechanisms and schemes has been conducted. This demonstrates that the results of the theoretical

analysis are suitable for assessing and explaining economic phenomena and mechanisms through the concept of saturation within this framework.

The preceding subsection, which discusses market schemes and mechanisms under financial saturation, completes the implementation of the second research objective. The analysis starts from a broader context (limited growth models) and gradually moves toward saturation interest. This enables the identification and analysis of the Saturation Paradox and the definition of growth stages based on the saturation level.

In order to clarify causal relationships, to analyse the Saturation Paradox in more detail, and to define more precisely the identified growth stages, feedback, elasticity, and bifurcation are introduced into the analysis. This makes it possible to explain the transition to the deficit market equilibrium model and compare it with the classical market equilibrium model. This comparison helps to define Market Duality and to present the bubble formation mechanism through saturation and the increasing productivity associated with the Saturation Paradox.

The developed analysis is applied phenomenologically to explain mechanisms and schemes based on bubble principles. This analytical framework, together with the author's contributions, provides the basis for the further development of the dissertation through model construction and its application in the empirical part.

The analysis also shows how behavioural and narrative explanations of bubbles can be integrated with the structural logic of Financial Saturation Theory. Shiller's works explain why collective expectations, narratives, confidence and investor psychology may generate speculative investment waves (Akerlof & Shiller, 2009, 2016; Shiller, 1989, 2015, 2020). The Financial Saturation Theory complements this interpretation by explaining when such waves become structurally unstable: when capital accumulation increases saturation level, elasticity rises, positive feedback strengthens, and the system approaches its capacity limit (Girdzijauskas, 2024). Therefore, in this dissertation, bubble formation is interpreted as a combined behavioural-structural process, where narratives and expectations may initiate or amplify investment flows, while financial saturation determines the conditions under which these flows become unstable. This interpretation also highlights the endogenous nature of the model's core mechanisms, as capital accumulation, rising saturation, increasing elasticity, and strengthening positive feedback develop within the system itself.

The results of the analysis of financial bubble formation based on Financial Saturation Theory are presented in Fig. 13. The analytical path is visualised through the relevant parts of the theory, while non-essential components are de-emphasised. These parts are not used in the present analysis but remain important for the broader theoretical context. Saturation interest, derived from the logistic growth model, reveals the Saturation Paradox. Together, these elements enable the transformation of demand, supply, and total utility functions within the logistic growth framework.

The transformed supply and demand curves form a deficit market equilibrium model, in which the Saturation Paradox contributes to market bifurcation. After bifurcation, positive feedback emerges in the market, which leads to bubble formation. The most relevant bubbles in market contexts, especially in the energy sector, are

financial bubbles that form in specific markets and sectors. The analysis therefore explains the formation of financial bubbles in markets and sectors based on financial saturation and potential (maximum) growth limits.

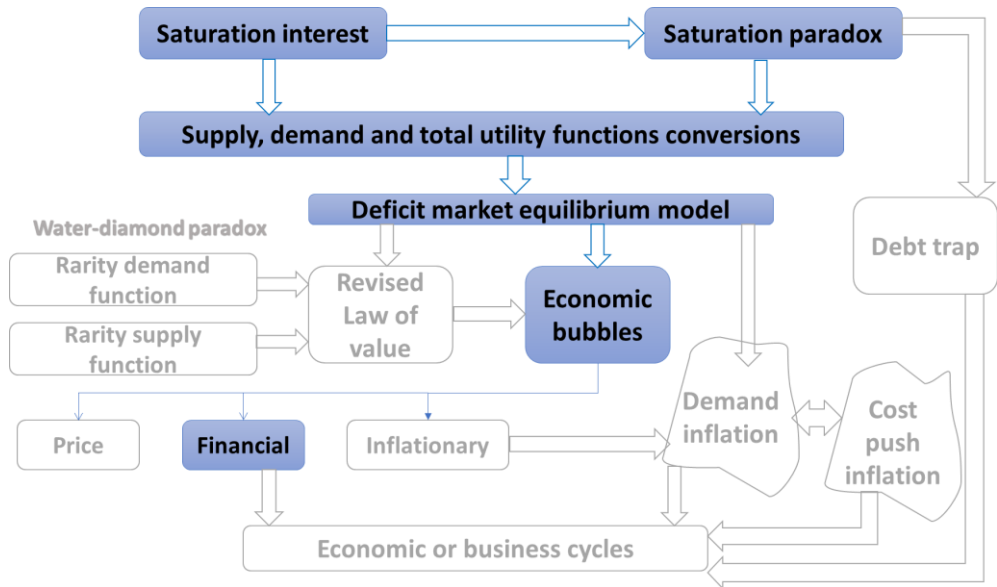


Fig. 13. Analytical framework of Financial Saturation Theory in bubble formation

The analysis of financial bubble formation based on Financial Saturation Theory has led to the identification of several principles and the refinement of elements important for the development of both the theory and the saturation-based bubble analysis model. The analysis builds on the works of Girdzijauskas and his co-authors; a significant part of the analysis is based on existing research in this field. In order to distinguish the author's contribution to the development of the theory more clearly, the extended analysis with additional findings is presented in Fig. 14. Blue boxes indicate the main analytical path, while green boxes show the author's additions and refinements to the theory

The Saturation Paradox is extended by including the positive feedback loop and elasticity. Bifurcation is then explained through the interaction of positive feedback and elasticity. The growth stages based on the saturation level are revised according to the elasticity of the function, which is treated as one of the main measure for defining stages and identifying bubbles.

During the transformation of functions into demand and supply curves, limitations were systematically identified. These, together with the limitations of logistic growth models, are used to define the developed model. The deficit market equilibrium model is compared with the classical market equilibrium model, and the differences are explained through Market Duality, type of feedback, and elasticity.

A deficit market can generate bubbles, which are further classified as productive or destructive depending on the saturation level and post-bubble outcomes. The main type of bubble (financial bubbles) is analysed in the context of Ponzi and pump and

dump schemes. Additional comparisons are also made, including Market Duality as a scarcity versus abundance economy framework and growth stages in relation to the Pareto (80/20) rule.

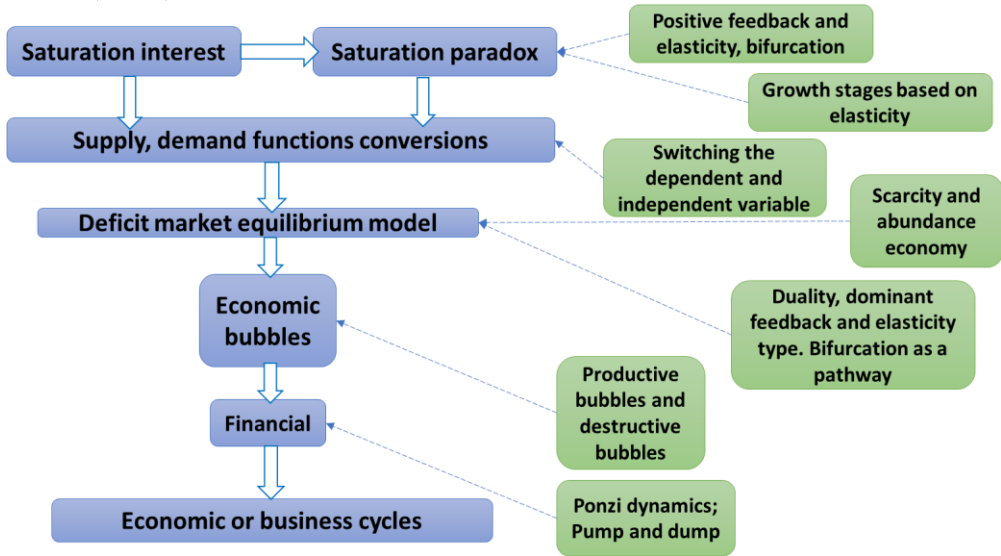


Fig. 14. Extended analytical framework of Financial Saturation Theory with author's contributions

The analysis of Financial Saturation Theory and bubble mechanisms, together with the extended evaluation and systematisation of the theory, provides the theoretical basis for developing a methodological model for the assessment of market saturation dynamics and bubble formation in the context of renewable energy investments. Based on the results of this analysis, the present dissertation proceeds from the theoretical examination of financial saturation and bubble mechanisms to the development of a model and methodological approach grounded in Financial Saturation Theory. The comprehensive theoretical analysis and the author's extensions ensure a consistent transition from the second research objective (the analysis of Financial Saturation Theory and bubble formation mechanisms) to the third research objective: the development of a methodological framework for assessing saturation dynamics and bubble formation in renewable energy markets.

2.2 Development of a Methodological Model for Bubble Analysis Based on Financial Saturation Theory

Following the analysis and extension of Financial Saturation Theory, this subsection is devoted to the implementation of the third research objective: the development of a methodological model and research approach for assessing market saturation dynamics and bubble formation in the context of renewable energy investments. The model is developed to operationalise Financial Saturation Theory for the analysis of financial bubbles in markets and economic systems. Within the Market Duality framework, the empirically identified Bifurcation Point is interpreted as the transition from a fundamental to a deficit market state.

Bubble analysis is conducted through the assessment of investment-driven saturation based on capital, price, and installed capacity. The model assumes that once a certain saturation level is reached, the likelihood of market overheating increases and the growth rate may accelerate sharply, affecting prices, output, and system stability. The model seeks to identify the saturation level reached during periods of significant growth and to evaluate its relationship with the elasticity of the growth rate with respect to the saturation level. Although narratives, investor psychology and collective expectations are not directly modelled, they are treated as possible external or interpretative factors that may initiate investment flows and demand shifts, while the model focuses on the structural response of the system under saturation.

The fundamental features of the model are as follows:

- The model evaluates whether the development of the analysed system (market or sector) follows a logistic pattern. The limits of economic system growth are defined according to the principles of logistic growth and Financial Saturation Theory.

- The model analyses a system with a constant capacity throughout the analysis period, as the processes occurring within the system depend on the size of its potential capacity. The Loglet Lab software is employed to ascertain the system's potential capacity based on historical or forecast data.

- The model evaluates the formation of a bubble in accordance with the criteria established in Financial Saturation Theory, determining the Bifurcation Point and refining the growth-stage boundaries based on elasticity and saturation level. It calculates the saturation level and growth rate.

- Capital and its empirical proxies are aggregate values in the calculations. Other factors are subject to *ceteris paribus* conditions in the model. In contrast to classical demand and supply functions, the independent and dependent variables are switched. Saturation level, represented by quantity, is treated as the independent variable, while the growth rate, interpreted as price in the transformed function, is the dependent variable.

The model for bubble analysis based on Financial Saturation Theory includes four research stages, in which statistical, mathematical, and comparative methods are applied. Each stage and the relationships between them are discussed in more detail below:

1. **Definition of the system and its parameters.** The system under investigation is defined during the initial phase. For the proper selection of the system, the conditions that the system under research must meet are formulated. Since the fundamental processes of the model (such as the Saturation Paradox, Bifurcation Point, etc.) can only occur in systems with limited capacity, the suitability of the system for saturation analysis is evaluated. At this point, the system's research period is established by considering the logistic nature and the dynamics of development. The data utilised in the study, including the selected empirical variable (price, accumulated capital, or installed capacity) are further described.

2. **Determination of the system's potential capacity, calculation of saturation level, and elasticity.** Historical or forecast statistical data under analysis

for the specified period are used to determine the system's potential capacity. The calculation is performed using the Loglet Lab software. Several possible capacity estimates are generated, and the most suitable potential capacity is selected based on the model fit to empirical data. Given all the necessary variables, the system's saturation level and growth rate are subsequently calculated using the logistic growth rate formula (8) and supply function (see formula 14). The formulas are adapted by applying capital, price, or installed capacity as the analysed variable, depending on the selected system data type. Based on the data and the growth rate (supply) function, the elasticity of the growth rate with respect to the saturation level is calculated (see formula 5).

3. **Bubble identification and its effect on the system.** The third stage involves the evaluation of bubble formation using calculated data and the stages described in the analysis of Financial Saturation Theory. Several steps are involved in this assessment stage:

a. The Bifurcation Point is determined by saturation level and the elasticity of the growth rate with respect to the saturation level. If the calculated data does not indicate a Bifurcation Point, the conditions for potential bubble formation are not identified, and conclusions and generalisations regarding the system under research are provided.

b. The elasticity and saturation level are further evaluated after a bifurcation is identified in the system. Where data allow, the identified growth stage, further development prospects, and outcomes (further development, system correction, or collapse) are evaluated, as well as the dynamics of change, the duration of growth, capital flows entering the system, and speculative activity.

c. System growth after bifurcation is classified as either a productive or a destructive bubble based on the analysis of system's saturation level, elasticity, and feedback dynamics within the Financial Saturation Theory framework. The classification also considers the observed impact of the bubble at the end of the study period, including outcomes such as further system development, correction, or collapse.

4. **Conclusion and summary.** The final part of the research model is designed to provide an extensive overview of the previous sections and to draw conclusions, summarising the identified saturation dynamics, Bifurcation Point, growth stage, and bubble assessment.

The research model discussed above is presented in Fig. 15, which illustrates the analysis of system saturation based on the selected empirical variable. The data are further analysed to determine whether a bubble has formed and, if so, to identify its type. A detected bifurcation indicates the emergence of conditions for potential bubble formation.

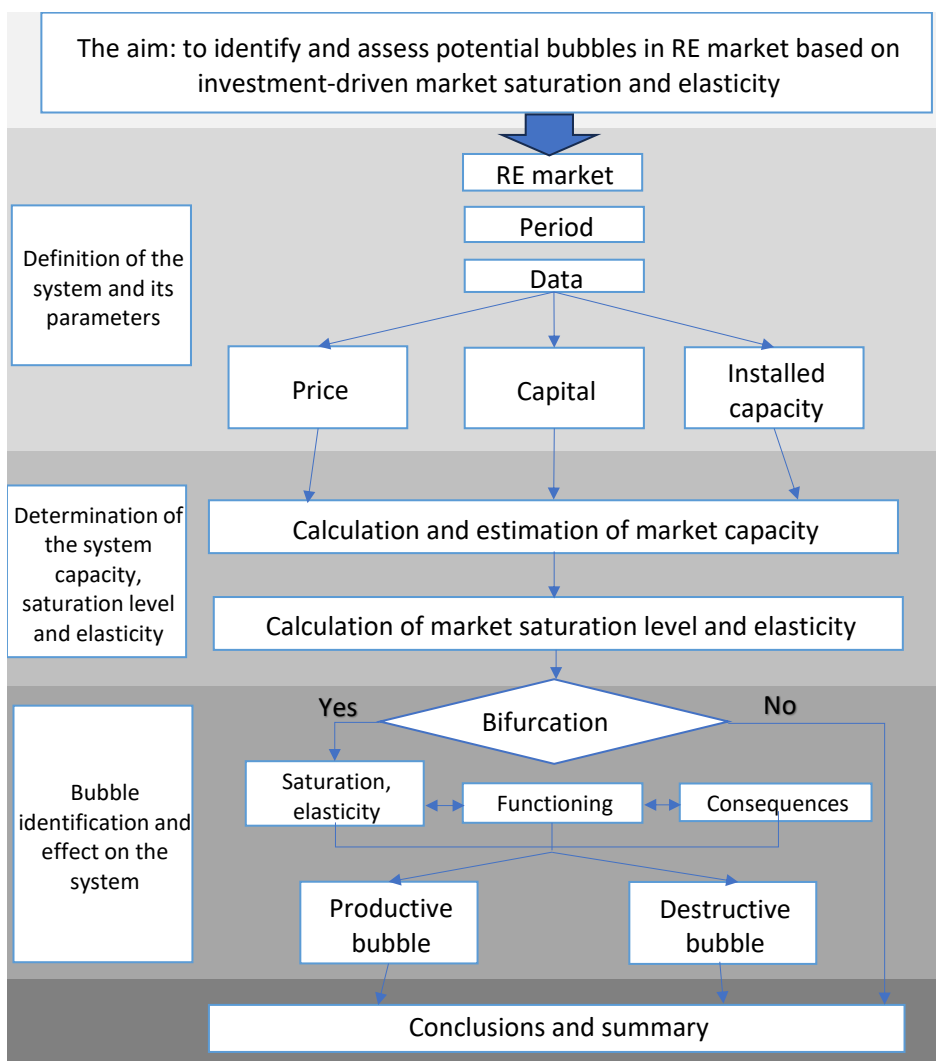


Fig. 15. Methodological model for bubble analysis based on financial saturation

The transformation of the logistic growth function when the capital is replaced with price or installed capacity is further discussed in order to clarify the research model. In addition, a more comprehensive explanation of the Loglet Lab software and its role in determining the system's potential capacity is provided. The assumptions and limitations of the model, which apply to the research as a whole or to its specific sections, are addressed in the final subsection.

The capital-based formulation of the model presented in the next subsection builds on the methodological approach first published in Karaša and Girdzijauskas (2024). In this dissertation, the model is generalised to price and installed capacity variables and extended through the integration of elasticity, bifurcation, and bubble classification.

2.2.1 Transformation of model variables: Capital, price, and installed capacity under the logistic growth framework

The transformation presented in Subsection 2.1.4 was primarily developed to link the logistic growth framework with demand and supply functions and to provide a theoretical interpretation of price formation under financial saturation. However, for the purposes of empirical application and model construction, the transformation must be adapted to operationalise the logistic growth framework in terms of measurable system variables. In this study, the logistic growth framework is applied to quantify growth dynamics in terms of accumulated capital, price, and installed capacity. Therefore, the transformation is adapted to derive the growth rate parameter (r) as a function of system saturation and system-specific variables.

All model calculations are based on formula (1), which is converted to logistic growth rate, when taking $1+i = r$. By solving the logistic growth expression with respect to the growth parameter, the following functional form is obtained:

$$r = t \sqrt{\frac{K_p - K_0}{K_0} \cdot \frac{K_a/K_p}{1 - K_a/K_p}}, \quad (15)$$

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 or capital; K_a is the accumulated investment (the amount of the capital in terms of its value) over periods; t is the duration of the investment or the number of periods of the investment (measured in the same units of time as time in the interest rate).

At this stage, r is formally interpreted as the logistic growth rate of the system. In this formulation, the growth rate (r) is expressed as a model-derived coefficient without a conventional measurement unit. It reflects the intensity of growth dynamics as a function of market saturation rather than a directly observable economic quantity. Given the assumptions applied in the model, the resulting values of r are specific to the analysed system and depend on its structural parameters.

In the general formulation of logistic growth, the independent variable is typically time (t), and the dependent variable is accumulated capital (K_a). In this model, the functions are solved concerning the dependent variable (the variable on the left-hand side of the equation (r)). In the context of the model, the independent variable is defined as market saturation, expressed as the ratio K_a/K_p , while K_a represents the dynamic component of saturation and K_p is treated as constant. Other parameters, such as K_0 and t , are treated as constants under the model assumptions.

Under these simplifying assumptions, the growth rate expression is reduced to a simplified functional form suitable for model implementation:

- K_0 takes the first value of the system under analysis for the period.
- K_p is calculated using the Loglet model for a given period of significant growth periods.
- time (t) is taken to be of long-term duration, i.e. $t = 1$ and all period of logistic growth considered to be 1.

According to these assumptions, the root formula of logistic growth for model calculations is derived:

$$r = \frac{K_p - K_0}{K_0} \cdot \frac{K_a / K_p}{1 - K_a / K_p}, \quad (16)$$

where all variables are the same as in the preceding formula (see formula 15). If the assumptions applied in the supply function transformation (see Subsection 2.1.4) are imposed, the expression becomes analytically equivalent to the supply function derived under financial saturation.

According to the research model, the saturation of the system is calculated in terms of accumulated capital, cost, and installed capacity. These variables are considered as independent variables in the model for the calculation of the growth rate and the saturation level. The following is a modification or addition to the basic growth rate function (see formula 16) based on these variables.

K_a as accumulated capital or based on capital flow. Here is an assumption that the independent variable K_a is the accumulated amount of investment (capital) during all periods. K_a is calculated according to formula:

$$(K_a)_n = K_0 + \sum_{j=1}^n F_j, \quad (17)$$

where F is the aggregate net fund flows during the analysis period. Other variables are the same as in the root formula (15). Aggregate net fund flows (F) for the period are added to the previous period's K_a to obtain the accumulated capital (investments) at the end of the period. The specific assumptions of this derivation are the neglect of time lag, i.e. it is assumed that the aggregate net fund flows and the index price dynamics have no time difference. However, the eliminated time lag is later evaluated separately by comparing the results of the research.

K based on system price (value). In this case, the capital variable (K) is reinterpreted as price (P), assuming that price dynamics reflect the underlying accumulation of capital in the system. Growth rate calculation formula transforms to the following expression:

$$r = \frac{P_p - P_0}{P_0} \cdot \frac{P_a / P_p}{1 - P_a / P_p}, \quad (18)$$

where P_p is the potential (maximum) price level in the system over the analysed period; P_0 is the initial value of the price in the beginning of the period; and P_a is the different historic prices over the analysis period.

The main assumption of this transformation ($K \rightarrow P$) consists of two parts:

- Prices have a maximum level (maximum price) in the system at an exact period. The prices may not increase indefinitely and have limits.
- Prices reflect capital flows in the system. There is a correlation between accumulated capital in the system and price. Therefore, the relationship may be analysed within the framework of Financial Saturation Theory, including the Saturation Paradox and bifurcation.

The assumption in this subsection implies a plausible limitation of the model – the time lag.

K based on installed capacity. Here is an assumption that the variable K and its derivatives are the installed capacity (C) in power units and its derivatives in the system (market). In this interpretation, installed capacity serves as a physical proxy

for accumulated capital, reflecting the materialisation of investment in the system. In this case ($K \rightarrow C$), the growth rate calculation formula transforms to the following expression:

$$r = \frac{C_p - C_0}{C_0} \cdot \frac{C_a / C_p}{1 - C_a / C_p}, \quad (19)$$

where C_p is a maximum absorptive installed capacity of the system, representing the theoretical upper limit of installed capacity given current technology and system conditions over all periods, in power units; C_a is a total installed capacity at a given each step in the period, in power units; C_0 is the initial installed capacity in the beginning of the period, in power units.

There are assumptions of this transformation:

- Installed capacity has a maximum level within a given system and a defined period. Therefore, the installed capacity system is treated as limited by a potential capacity threshold.
- Installed capacity reflects invested (accumulated) capital in the system. There is a correlation between accumulated capital and installed capacity. Therefore, installed capacity can be used as a proxy for capital, allowing the application of financial saturation principles (Saturation Paradox, bifurcation, etc.).
- Time lag between capital flow (investment) and installed capacity. The system must be filled with capital, which is then converted into installed capacity. The level of saturation and the rate of growth of installed capacity is therefore a lagging indicator of previous saturation in capital-related systems.
- The saturation level and growth rate of installed capacity, as well as the subsequent emergence of heating or bubble dynamics, may indirectly affect related capital, resource, and production systems.

To calculate the saturation level and growth rate for the selected system variable, the system's potential capacity must first be determined.

2.2.2 Determination of system potential capacity using Loglet Lab software

Loglet Lab is a software tool developed at Rockefeller University in the United States in 1994. The developers, Perrin S. Meyer, Jason W. Yung, and Jesse H. Ausubel, focused on the analysis of growth and diffusion processes. Building on established exponential and logistic growth models, they developed Loglet analysis for decomposing complex growth into logistic components (*Loglet Lab 5*, n.d.; Mialik, 2014). Physicists were the first to use differential equations to model motion.

Logistic growth models and related analytical tools are applied across a broad range of scientific disciplines, including the social sciences and economics (Foucher, 2006; Girdzijauskas, Štreimikienė, et al., 2009). The Loglet Lab software was developed to facilitate the fitting and evaluation of component logistic curves in empirical datasets. One form of logistic behaviour described by the authors of Loglet Lab (Yung et al., 1999) is the process of interaction between competitors in a market. A competitor's market share may initially expand, but it eventually approaches a limit and begins to decline as a competing substitute gains a larger share of the market.

Loglet analysis is based on a three-parameter S-shaped logistic growth model. Its main advantage is its parsimonious structure, in which each of the three parameters has a clear physical interpretation. The Loglet Lab software can be applied to suitable time-series datasets. Its interface supports straightforward analysis of a single logistic curve, while its fitting engine also enables the examination of complex datasets and compound processes (Meyer et al., 1999).

The structure of the tool itself is quite simple. The tool has a wide range of functionality to allow results to be displayed in different sections. Data can be analysed in a single $K(t)$ equation, or in the derivatives of several equations. The growth test, which produces a logistic growth curve based on historical or forecast data, can be repeated several times in the software. In this way, the most accurate fit to the data can be obtained. Some of the predicted values of the study can be adjusted to adapt the study to the available data and model dynamics. Loglet calculates and forecasts four indicators (*Loglet Lab* 5, n.d.):

- k is system saturation (K_p equivalence in the research model);
- d is initial system size (K_0 equivalence in the research model);
- t_m is midpoint (inflection time);
- a is amplitude (scaling coefficient).

In Loglet Lab research, these values are applied by the software itself based on the data provided. By manually adjusting these parameters and repeating the test, the most accurate logistic growth function can be obtained. As illustrated in the theoretical example of a logistic test (see Fig. 16), for a given growth of the system, a logistic growth curve is calculated by days. The data provided by the system are represented by the points on the graph, while the curve is plotted based on the Loglet Lab calculation. The dashed line represents the predicted fit of the logistic curve.

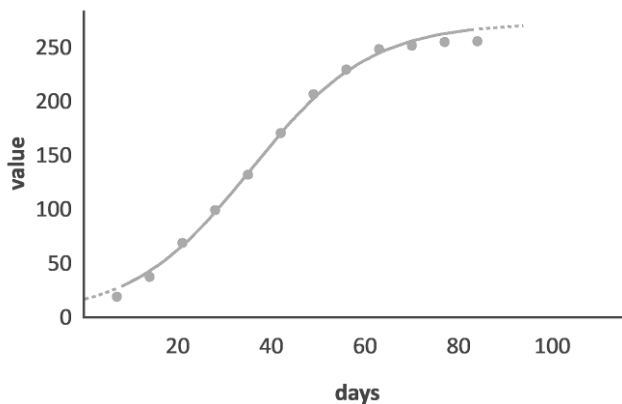


Fig. 16. Logistic growth curve fitting and system capacity estimation using Loglet Lab

The calculated indices (see Appendix 2) for the graph shown are $k = 271.53$; $d = 0$; $a = 55.63$; $t_m = 35.61$. Since the plotted curve is consistent with the system data, no corrections are required and the results can be used in the study model, particularly the indicator k , which represents the capacity of the system under research K_p . This

value is calculated using the Loglet model for a given period of significant growth in the system. The Loglet model, which is a variation of the logistic growth function, allows for precise estimation of growth trajectories and market saturation points. K_p is calculated for different analysis systems, and these values are fixed for all periods in analysis.

2.2.3 Assumptions and limitations of the bubble analysis model based on financial saturation

In addition to the specific assumptions and limitations associated with capital, price, and installed capacity-based formula transformations, the general limitations of the model are summarised. Some of the limitations flow directly from the assumptions made in the model. These limitations are based on criticisms of logistic growth models and their limitations in general:

- Over-simplification. Assumes static carrying capacity (K_p), which is often dynamic in real-world systems. The model is built on five key variables, with three held constants to simplify calculations. Strict *ceteris paribus* is implemented. In real-world economic or financial systems, K_p is dynamic, influenced by policy changes, technological advances, and global markets (Grubb et al., 2015).

- Logistic models are deterministic and fail to account for external shocks, such as geopolitical crises, pandemics, or breakthrough innovations, which can abruptly alter growth trajectories (Grübler, 1990). The model does not explicitly incorporate external triggers as endogenous variables but treats them as possible initiating or interpretative factors, while focusing on the endogenous mechanisms of financial saturation, including the Saturation Paradox, bifurcation, changes in the growth rate, and elasticity.

- Logistic models generally assume homogeneous agents (e.g. investors, consumers), which overlooks the heterogeneity in preferences, access to information, and risk tolerance – key drivers of real investment behaviour (Shiller, 2015). Model agents are assumed as homogeneous investors with homogeneity in preferences, access to information, and risk tolerance. Investor psychology, herding, and speculative sentiment are acknowledged but not quantitatively integrated into the model.

- Inability to model reversals or crashes. The model describes saturation but not reversal mechanisms, and it does not capture post-saturation dynamics (Sornette, 2017). Corrections or negative dynamics may distort the model and the results of the research, challenging their analysis or comparison.

- Logistic growth assumes a single-phase transition, whereas real-world systems may exhibit multiple growth phases, tipping points, or equilibria due to policy interventions, network effects, or innovation spill-overs (Wilson & Grübler, 2011). Market corrections are treated as predictable outcomes of saturation rather than results of complex external shocks.

- The specific assumption of derivation for the model is the neglect of time lag, i.e. it is assumed that the aggregate net fund flows and the index price

dynamics have no time difference. However, the eliminated time lag should be evaluated separately by comparing the results of the research.

— As the logistic growth rate (r) is a model-derived absolute indicator without a conventional measurement unit (the balancing coefficients are fixed ($\alpha = \beta = 1$)), its values are not directly comparable across systems. It should therefore be interpreted in a relative and structural context, while high numerical values reflect the mathematical properties of the model rather than directly interpretable economic magnitudes.

— Reversed functional relationship in the model. The analysed system variable (capital, price, or installed capacity) is used to determine the saturation level, which is treated as the independent variable, while the logistic growth rate is the dependent variable. Unlike variables in classical demand, supply, and equilibrium models, the model-derived logistic growth rate cannot be directly compared with observed prices or across the analysed systems.

The second section addressed the second and third research objectives. It analysed Financial Saturation Theory as a framework for explaining bubble formation through logistic growth and developed a methodological model for assessing saturation dynamics and bubble formation. The resulting model integrates system capacity, saturation level, growth rate, elasticity, bifurcation, and bubble classification into a structured analytical framework. This framework provides the basis for the empirical assessment of renewable energy systems presented in the following section.

3. EMPIRICAL ASSESSMENT OF FINANCIAL SATURATION AND BUBBLE FORMATION IN RENEWABLE ENERGY SYSTEMS

The third section addresses the fourth research objective by applying the developed model and its analytical tools to assess investment-driven saturation dynamics and bubble formation in renewable energy systems. The empirical analysis examines the relationships between saturation level, growth rate, elasticity, bifurcation, and bubble formation across economic systems of different sizes, types, and time horizons. This application is used to evaluate the functionality, generality, and applicability of the methodological model.

3.1 Research Design and Description

Several research investigations have been performed on economic systems of varying sizes, types, and mutual independence in order to apply the developed model and its analytical tools to detect and assess bubble formation:

- regional biomass-based district heating market;
- renewable energy-related stock indices covering different regions and index types;
- global installed capacity scenarios for total renewable energy, solar, wind, and battery storage systems.

Based on the nature and type of the system data, the analysis determines the appropriate transformation, which evaluates growth in terms of installed capacity, price, and capital. In an effort to optimise the empirical research and the implemented model, numerous scenarios are estimated in accordance with possibilities for data variation.

The research model was developed in the second part of the work (see Fig. 15). Based on this model, a research instruments grid was developed (see Table 11). This grid is designed to facilitate the model's seamless, understandable application and the conduct of empirical research in accordance with a logical framework.

Table 11. Framework for the application of the bubble analysis model

No.	Stage name	Objective	Description
1	Definition of the system and its parameters	Evaluate the system and its main characteristics	The selected system is analysed, the period is studied, data is selected, and the period of potential bubble formation is determined
2	Determination of the system capacity, saturation and elasticity	Calculate the system's capacity, saturation level, growth rate, and elasticity for a defined bubble formation period	a) Calculation of the potential capacity for the defined period using Loglet Lab b) Calculation of the logistic growth rate, saturation level, and elasticity of the system based on the data and the calculated capacity c) Drawing graphs
3	Bubble identification and effect on the system	Determine the growth stage and assess the bubble type	Based on the calculated data, it is identified whether the system has reached the Bifurcation Point. If the Bifurcation Point has been reached, the growth stage and bubble type are assessed. Where data allow, additional analytical methods are used to refine the interpretation of the bubble type

Based on this instrument grid, the following sections present the results of empirical research in different systems.

3.2 Biomass-Based District Heating System in Kaunas Region: Installed Capacity Analysis

The first part of the research examines the regional biomass-based district heating system. The variable used to assess the saturation of this system is the installed capacity and its derivatives. Logistic growth is analysed according to the installed capacity. In this part of the research, the installed capacity is used as a proxy for physical and technological saturation caused by investment-driven expansion. Therefore, the analysis does not treat the installed capacity as a direct financial bubble indicator, but as a system-level variable that reflects the accumulation of investment in heat production capacity and the possible emergence of overcapacity.

The development of the Kaunas district heating system was shaped by a distinctive market structure before 2012 and by the subsequent liberalisation of heat production. To provide a clearer basis for the analysis, the broader market context is outlined.

The Kaunas district heating (DH) network is operated by AB Kauno Energija (KE), which is also one of the main heat producers and suppliers in the Kaunas heat market. It is distinguished by its modernised infrastructure, which includes a cogeneration power plant, biomass-fired boilers, and heat storage capacities, as well as its extensive coverage (more than 90% of the city's buildings are connected to the network). The DH system in Kaunas uses a heat supply mix primarily based on waste

heat and biomass. KE supplies heat energy to consumers in Kaunas and holds the largest share of the heat market. The company is engaged in the production and distribution of electricity and heat, as well as the provision of hot water.

To explain the subsequent expansion of biomass-based heat production, it is necessary to consider the market structure that existed before 2012. A contract was signed in 2003 for the Kaunas Combined Heat and Power Plant (KTE). The new owners agreed to provide heat to the Kaunas market until 2018. Under the agreement, KE was required to procure at least 80% of the heat consumed in the integrated network from KTE, thereby effectively formalising a monopoly in heat production. As a result, the local district heating system could not respond flexibly to changes in the fuel market, plan the development of generating capacities, increase competition among heat producers, implement new technologies or optimise excess reserve generating capacities. Despite the agreement's provision for KTE to invest LTL 400 million in the renovation of the power plant in stages, the obligations were not fulfilled as a result of legal disputes with the municipality. At the same time, the heat pricing methodology used in Lithuania at that time did not provide AB Kauno Energija with the opportunity to invest in the necessary modernisation of the city's central heating supply system. Due to the failure to fulfil the investment and modernisation obligations, the existing monopolistic supplier exploited its position in the market, and the situation restricted the entry of new heat producers. There were minimal opportunities to lower heat prices for end users, the heat produced was costly, and the reliability of the heat supply was compromised by these circumstances (Augutis et al., 2012). Consequently, the cost of heat in Kaunas was one of the highest in Lithuania, on average 1.5 times higher than in small towns that had adopted biomass-based heating systems. The privatisation contract included only limited safeguards, mainly the right to impose fines on KTE. However, their magnitude was negligible in comparison to the profit (Eigirdas, 2012).

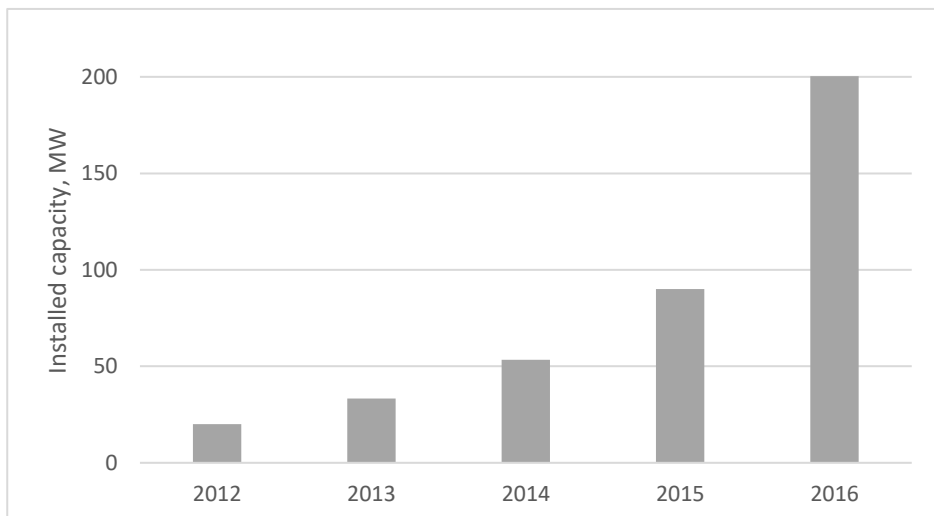
The termination of these contractual restrictions marked a structural change in the Kaunas heat production market. This agreement with KTE and other adverse circumstances prevented the development of biomass-based heat production in the Kaunas heat market. Although the agreement originally created long-term obligations in the Kaunas heat market, its termination in September 2012 changed the market conditions and enabled the development of biomass-based heat production and the entry of independent heat producers (Bakas, 2014). Additionally, in response to the National Commission for Prices and Energy Control's approval of the new heat base price period (2013–2016) and the changing regulatory environment, both KE and independent heat producers (IHP) developed ambitious development plans. Under these plans, the majority of investments in 2013–2015 were allocated to the modernisation of heat sources and the development of heat production from renewable energy sources. The primary objective of the transformation was to install biomass boilers in existing boiler houses and construct new ones. Furthermore, amendments to the Law on Heat Economy of the Republic of Lithuania and other legal acts that regulate heat supply and purchase activities created favourable conditions for investing in the construction and modernisation of heat production sources. This

contributed to increased competition in the heat production sector and a reduction in heat prices for consumers (Miškinis et al., 2016).

In 2012, the Kaunas DH market experienced the introduction of the first independent heat producer which utilised biomass. This is regarded as the start of the data period for the system under research, which continues until the end of the development process in 2020. In the market, IHPs and KE-owned heat producers are permitted to operate, and these producers may be regulated or unregulated. This leads to the selection of the following two scenarios for the system's analysis:

— Scenario I includes only the biomass-based heat production capacities of independent heat producers in Kaunas. The period begins in 2012 with market liberalisation and ends in 2016, when the expansion of IHP biomass heat production plants was completed. The system is evaluated in terms of the installed capacity (MW) of biomass-based heat production connected to the Kaunas DH system. Fig. 17 illustrates the installed capacity dynamics of this scenario.

— Scenario II includes the biomass-based heat production capacities of IHPs and KE, together with additional competing heat production capacities connected to the Kaunas DH system. Therefore, this scenario represents a broader heat production capacity system rather than a biomass-only system. The period begins in 2012 with market liberalisation and ends in 2020, when the last major expansion of installed capacity was integrated into the system. The Kaunas cogeneration plant, connected to the DH system in 2020, is included in this scenario not as a biomass producer, but as a competing heat generation source that affects the market position of biomass-based heat producers. Fig. 18 illustrates the installed capacity dynamics of this scenario.

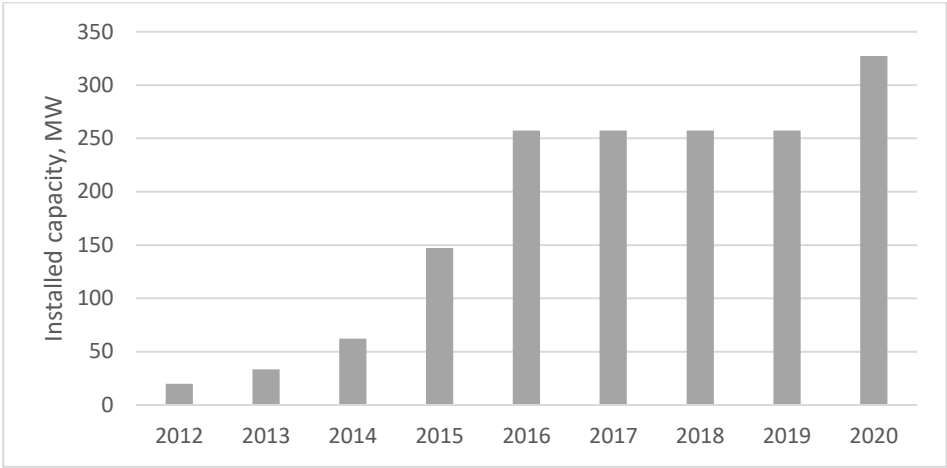


Source: created by the author based on Bakas (2018) and Valstybinė energetikos reguliavimo taryba

Fig. 17. Scenario I: Dynamics of installed capacity in biomass-based DH system

Fig. 17 illustrates the total installed capacity of biomass-based heat production plants operated by IHPs in Kaunas, excluding KE capacities and the Kaunas

cogeneration power plant that was connected in 2020. These installed capacity data are used to assess the saturation level and bubble formation over the research period (2012–2016).



Source: created by the author based on Bakas (2018) and Valstybinė energetikos reguliavimo taryba

Fig. 18. Scenario II: Dynamics of installed capacity in biomass-based and competing heat production DH system

Fig. 18 illustrates the total installed heat production capacity included in Scenario II, covering biomass-based capacities of IHP and KE as well as the Kaunas cogeneration plant connected in 2020. These installed capacity data are used to assess the saturation level and potential bubble formation over the research period (2012–2020).

The analysis tools are employed to calculate the saturation level, bifurcation, growth rate, and elasticity of the system after defining the system under research, data, and period. The first step is to determine the potential installed capacity of the analysed system for the specified period. According to the research model, potential system capacity may be estimated using Loglet Lab software. In this case, however, expert estimates from relevant reports are used. Compared to the theoretical estimates generated by Loglet Lab, these capacity data are more precise. The maximum heat power demand for the periods under research is estimated annually by KE. These estimates (see Table 12) are used to perform additional calculations.

Table 12. Maximum heat demand in biomass-based DH system

Year	2020	2021	2022
Demand, MW	290	440	307

Source: Kauno energija, AB (2023)

This maximum power demand is used as the potential system capacity (C_p) in the research. In Scenario I, the value of 2020 (290 MW) is used for C_p , while in Scenario II, the value of 2021 (440 MW) is used. Eventually, the logistic growth rate, system saturation level, and elasticity are measured. The constant variables of the

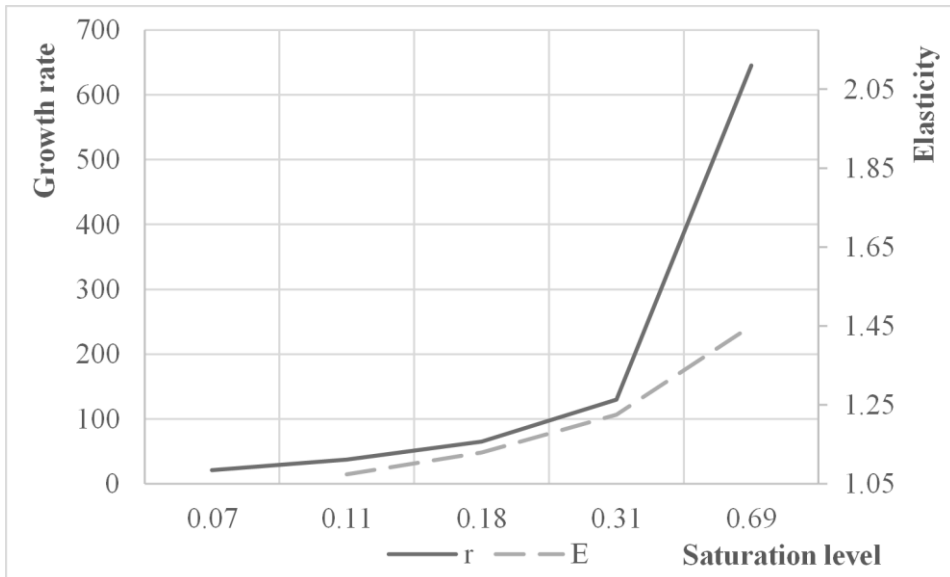
logistic growth rate formula (19) presented in Table 13 have been used for the calculations.

Table 13. Input parameters for installed capacity-based calculations in the biomass-based DH system

I C_p	II C_p	I and II C_0	Formula
290	440	1	$r = \frac{C_p - C_0}{C_0} \cdot \frac{C_a / C_p}{1 - C_a / C_p}$

In the table of input parameters, the parameters of Scenario I and Scenario II are combined. In order to simplify the calculation, it is assumed that $C_0 = 1$, as this was probable in 2011. The first power plant was under construction at the time, and the analysed systems had no installed capacity.

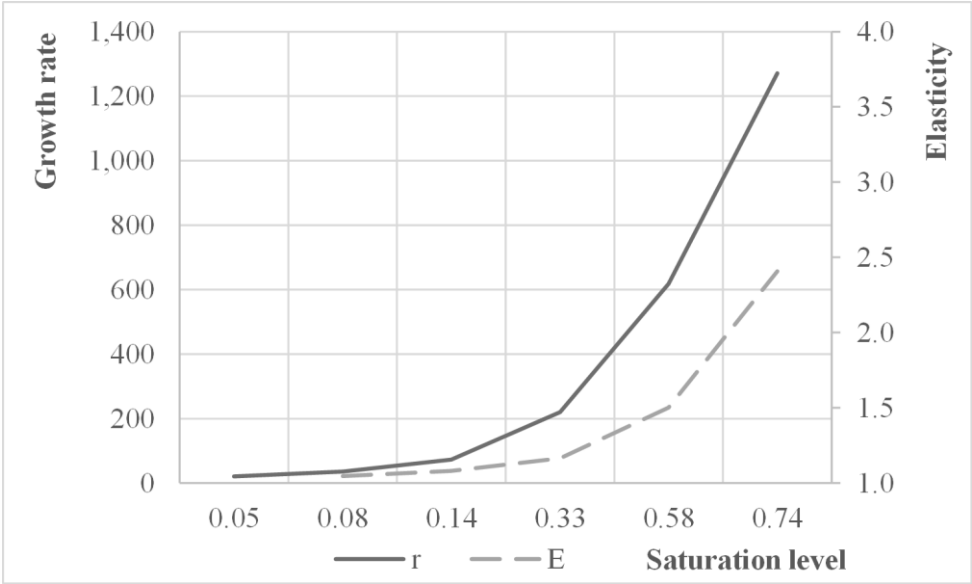
Fig. 19 (Scenario I) and Fig. 20 (Scenario II) illustrate the calculation results (see Appendix 3) for the dynamics of installed capacity (C_a), the corresponding saturation level, growth rate, and elasticity. The growth rate (r) is expressed as a model-derived indicator without a conventional measurement unit. This interpretation applies to all subsequent figures and is not discussed further. The graphical representation illustrates the possible emergence of the Saturation Paradox as the saturation level increases, provided that the Bifurcation Point is reached. Simultaneously, it shows the elasticity of the logistic growth rate with respect to the saturation level.



Source: author's calculations based on Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.), and Kauno energija, AB (2023)

Fig. 19. Scenario I: Growth rate, saturation level, and elasticity of biomass-based DH system

In Scenario I, the Bifurcation Point is not reached in the analysed system, as demonstrated by the graph. The saturation level does not exceed 0.7, while elasticity increases only slightly to 1.45, indicating that feedback remains relatively weak. The highest saturation level is 0.69. According to the research model, these results do not indicate the heating stage or bubble formation, and the system therefore remains in growth stage (I).



Source: author’s calculations based on Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.), and Kauno energija, AB (2023)

Fig. 20. Scenario II: Growth rate, saturation level, and elasticity of biomass-based DH system

In Scenario II, the analysed system reaches and passes the Bifurcation Point, as illustrated in Fig. 20. Once the saturation level exceeds 0.7, the elasticity of the growth rate with respect to the saturation level increases, indicating a strengthening of feedback. The elasticity, which previously fluctuated between 1.04 and 1.51, rises to 2.4 during the rapid growth period, while the highest saturation level reaches 0.74. Although these values do not indicate particularly intense heating, the research model identifies that Scenario II entered the heating stage (II). Since the analysis is based on installed capacity, this result should be interpreted as productive bubble dynamics associated with physical and technological saturation and the risk of overcapacity, rather than as direct evidence of a financial bubble. Secondary data and subsequent market developments support this interpretation.

Table 14 provides an overview of research, which evaluates system saturation by analysing the accumulated installed capacity in different scenarios.

Table 14. Summary of biomass-based DH system scenario analysis results

Scenario	C_p	C_{max}	r_{max}	Max saturation	Max elasticity	Bifurcation/ bubble	Heating, years	Overheating, years	Bubble type
I	290	200	645	0.69	1.45	No	-	-	-
II	440	327	1,270	0.74	2.41	Yes	1	-	Productive

Source: author's calculations based on Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.), and Kauno energija, AB (2023)

Both scenarios have extremely high growth rates, reaching 645 and 1,270, respectively. The extremely low initial installed capacity (C_0) at the beginning of the research period is the factor of the growth rate, as there was no initial 'capital' in the system. Consequently, the growth rate is simply a supporting indicator and is not a critical factor for determining limits when addressing the formation of bubbles. The saturation level and the feedback loop, which is reflected by elasticity, are the most critical indicators for determining the growth stages and the formation of a bubble. The results of Scenarios I and II were determined based on these criteria: in the first scenario, a bubble was not detected, while in the second scenario, a productive bubble was detected. Nevertheless, the review evaluates the financial saturation of this scenario as a productive bubble, as indicated by secondary data and the research model, with a possible degree of uncertainty arising from model assumptions, which is not evaluated separately.

The analysis of the system (market) enables a more comprehensive evaluation and discussion of the results. Upon the liberalisation of the DH market in Kaunas at the beginning of the analysed period (2012), market participants maintained high expectations. This was the result of a variety of factors:

- The price regulation and pricing of the time, in conjunction with the transition from a monopoly to a semi-free (partially regulated) market, resulted in high expectations for low heat production costs and high heat purchase prices. The primary factor in determining or regulating the heat purchase price in 2012 was the cost of heat production from gas. From 2010 to 2016, the average heat price in the country varied by 2.5 to 3 times when comparing production from gas and biomass. For instance, in mid-2012, the heat price reached 4.7 ct/kWh (gas) and 1.7 ct/kWh (biomass), and at the end of 2016, it was 3.5 ct/kWh and 1.2 ct/kWh, respectively (Jasas, 2017). The development of biomass power plants in Kaunas DH and the entry of new market participants were made possible by the favourable conditions that were established. It should be noted that the fuel component accounts for the largest share of the heat sales price.

- The favourable legal regulation and promotion of biomass deployment, which were previously mentioned in the study, further boosted the high expectations of market participants.

Large capital flows were attracted to the Kaunas DH market as a result of the high market expectations. High profit expectations, as previously mentioned in the research model and in the theoretical section, contributed to substantial capital inflows into the system as it approached the Bifurcation Point, further growth, heating, or even overheating stages. Scenario I partially confirms this trend, as the saturation level based on installed capacity approaches 0.69. Nevertheless, further capacity expansion subsequently stopped. This can be explained by several kinds of factors:

- The installed capacity in the markets associated with the system does not provide direct feedback. The growth of installed capacity, which was expected at the beginning of the period, has stopped as competition increased. Profit expectations have not been boosted, and the number of new participants has decreased. Speculative investment (in stock, resource markets) is limited by the underdeveloped regional financial market, thereby limiting the potential for a positive feedback mechanism.

- Raw materials market. In the biomass fuel market, there are no price growth trends. This is due to the fact that biomass is purchased through the biomass exchange, where market-based pricing mechanisms operate. Additionally, the Energy Regulatory Commission's (VERT) supervision and the insufficient financial development of the market discourage speculative price increases.

- Technology market. During the period under review, an increase in the cost of biomass-based heat production equipment and boiler infrastructure could have been expected. However, the absence of sufficient data and the small market share render it impossible to identify market trends.

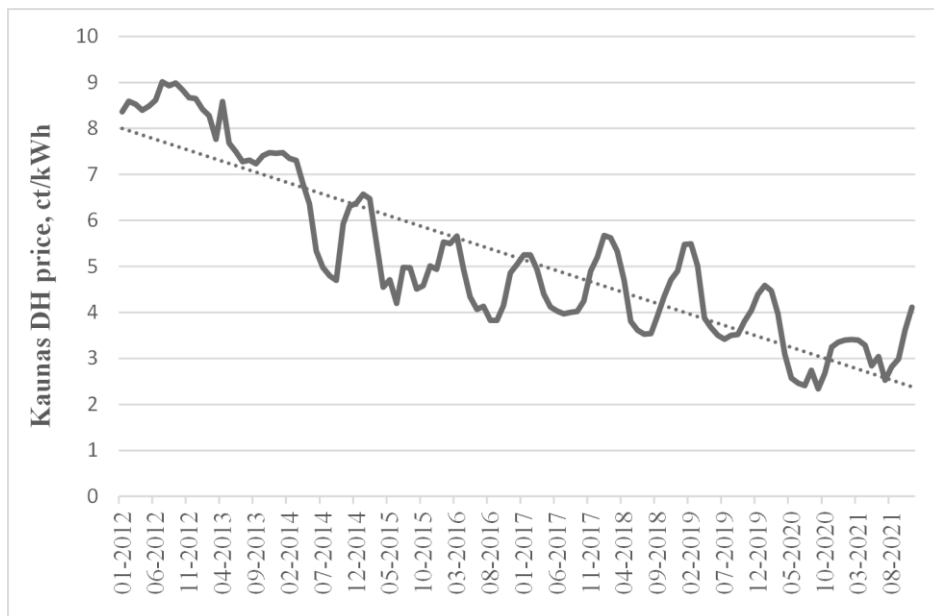
- Legal market regulation. VERT regulates the centralised DH of Kaunas city. Regulated suppliers are compensated for both fixed and variable costs, and prices are determined by the justification and methodology approved by the VERT. IHPs operate under a competitive pricing mechanism. The competitive mechanism includes the Baltpool biomass fuel exchange, heat balancing auctions, and purchase procedures.

Despite the reduced expectations for market entry due to regulation and insufficient feedback, a cogeneration power plant entered the Kaunas DH market in 2020 as a result of external factors (pollution obligations, waste surplus, and EU financial support). In Scenario II, the system reaches the Bifurcation Point as the saturation level increases to 0.74 following installed capacity growth that was largely driven by external factors. This indicates the formation of a productive bubble and the system's transition to growth stage (II).

Nevertheless, legal regulation constrains further growth, as in Scenario I. No strong self-reinforcing positive feedback develops. Moreover, the structure and level of development of the system do not create conditions for speculative behaviour to emerge.

In general, the saturation that was achieved prior to the bifurcation resulted in a positive outcome (Scenario I). Together with external factors such as the introduction of third-party access to the supply side and a one-sided auction (Pažėraitė et al., 2022), the heat price in Kaunas is consistently decreasing (see Fig. 21), despite the fact that the price of raw materials (biomass) remains stable and the heat purchase price is

determined through auctions. The implementation of biomass technologies in the Kaunas DH system was accelerated by the high expectations that were present at the beginning of the period. This initiative enabled the reduction of pollution and the promotion of sustainable development.



Source: created by the author based on Valstybinė energetikos reguliavimo taryba

Fig. 21. Dynamics of DH prices for residential consumers in Kaunas

The following indicators, reflecting secondary effects in the economic system, can be used to determine a specific degree of financial saturation (Scenario II):

- After the launch of the Kaunas cogeneration power plant, the economic and financial outcomes of the IHP biomass power plants have declined. In 2017, there was a concern regarding the potential impact of installed capacity saturation. DH experts issued a cautionary note regarding the potential decline in capacity utilisation, increase in heat prices, extension of the payback period for investments in biomass power plants, and intensification of competition. However, until 2020, the heat production price was considered optimal, investment payback periods remained satisfactory, and the level of competition was considered appropriate (Bakas, 2017).

- A Bifurcation Point was reached in 2020, and the system entered a faster growth stage following the entry of a new market participant, the cogeneration power plant. The analysed biomass-based heat production market was significantly affected by this new participant, which benefited from favourable regulation, financial support, and an operating model under which the fuel used, namely waste, was compensated. Government support was also provided to IHPs through compensation for reserve capacity, as existing biomass-based heat producers faced increasing difficulties in competing in the market (Jasas, 2017).

— Low utilisation rates of IHP power plants, particularly during the winter months. Kaunas was among the cities with the lowest heating prices in 2021 and 2022. In the same years, Kaunas purchased the most heat (70% and 72%) from IHP among the country's major cities (LSTA, 2022). In 2022, VERT amended the legislation regulating heat auctions several times and created exceptional conditions for systems with a high concentration of IHP in Kaunas (LSTA, 2023). These could be indirect signs of overproduction (structural imbalance) arising from capital-driven financial saturation and from other external factors affecting the market during the period under investigation.

In conclusion, the expansion of installed capacity in the Kaunas DH market benefited consumers through lower heat prices but had adverse effects on producers, reflecting the system's proximity to the Bifurcation Point in Scenario I and the higher financial saturation level identified in Scenario II. The government provides subsidies to businesses that can guarantee heat production and reserve capacities, as this is a regulated and specific sector. The high expectations for the price of heat in Kaunas, however, accelerated investments in alternative renewable energy (biomass), resulting in a more rapid transition from expensive gas to biomass. This is a significant positive aspect. An early study showed (Simanavičienė & Žemaitis, 2015) that the main ways to reduce heat prices are by fostering competition in the market and introducing technologies that allow the use of biofuel in DH. State intervention is crucial, as regulation ensures consumer protection while enabling private producers to enter the centralised heat supply system, which in Kaunas reduced prices during summer periods and later seasons. Only liberalisation and stronger competition can ensure that cost savings are reflected in consumer prices. However, as revealed by this research, liberalisation and stronger competition with government support solve one problem (high heat price, air pollution) and create a new one (overproduction, high concentration of IHP), which requires regulation and financial support. At the same time, continued state support within the same market, including support for waste-to-energy plants competing with existing biomass-based IHPs, contributed to market distortion. As a result, earlier biomass technologies became less competitive despite their initial role in reducing costs. From a system perspective, excessive support led to financial saturation of the market with competing capacities, intensifying competition beyond sustainable levels.

In the context of the developed model and financial saturation, the results of this system research can be summarised as follows: the identified productive bubble exhibits only limited indications of positive feedback, and the Saturation Paradox that was incorporated into the model did not manifest itself. External factors determined the high expectations that attracted capital to the system. In addition, the Saturation Paradox was restricted by the system's strict legal regulation (VERT), the biomass exchange, and the heat purchase auctions, which constrained self-reinforcing price dynamics and supported market-based price formation. The identified significant economic structural imbalances indicate a higher level of financial saturation than indicated by the model results, which is another critical factor to consider. This may be linked to the market's actual capacity being lower than the estimated potential capacity or the specific characteristics of the market (system) in

terms of regulation and promotion. This would necessitate additional research and analysis, which would involve the evaluation of various market capacity sizes and the identification and separation of the impact of market specifics on the calculation results, while also accounting for other external factors and continued unbalanced support.

Having tested the model in a regional system based on installed capacity, the analysis proceeds to renewable energy-related financial market indices, where saturation is assessed using price and accumulated capital indicators.

3.3 Renewable Energy Financial Market Indices for Saturation Assessment

The systems analysed in this section are equity-based renewable energy indices. Depending on data availability and structural characteristics, the application of the research framework is conducted either in terms of index price dynamics or in terms of aggregate net fund flows, which are transformed into accumulated capital. This distinction allows for the assessment of financial saturation from both a market valuation and capital accumulation perspective.

Renewable energy index values are treated as price proxies representing aggregated market valuation and are therefore referred to as ‘price’. In this context, index price is expressed in index points, representing a normalised value rather than a physical measurement unit. Accumulated capital data retain their monetary units in the system description and input data discussion. However, in the model calculation tables, the transformed variables P_p , P_0 , P_{max} , K_p , K_0 , and K_{max} are treated as model input values expressed on the same scale as the corresponding source series. Since the calculation of saturation level, logistic growth rate and elasticity are based on ratios between variables of the same scale, the resulting indicators are interpreted as relative model indicators. Therefore, measurement units are not repeated in the calculation and summary tables.

The following indices are analysed by price:

- European Renewable Energy Price Index (ERIXP);
- MSCI ACWI IMI Clean Energy Infrastructure Index (MXACICEI).

The following indices are measured by aggregate net funds flow or accumulated capital:

- NASDAQ Clean Edge Green Energy Index (CELS);
- S&P Global Clean Energy Index (SPGTCD).

The analysis begins with price-based indices, as they provide the most direct and functionally transparent representation of investment-based capital dynamics within the model framework. All data for this subsection is taken from Bloomberg terminal (Bloomberg Finance L.P., 2024).

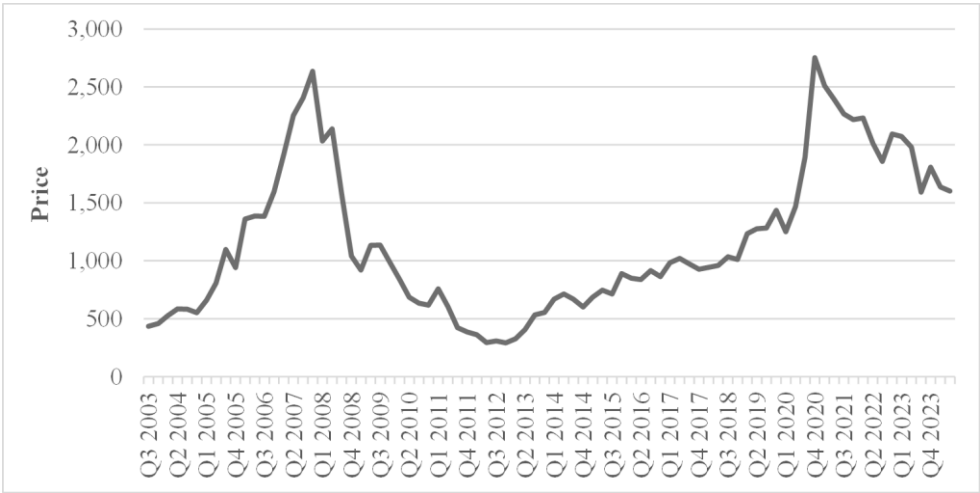
3.3.1 Price-based saturation indicators

In price-based analysis, index price is treated as a direct indicator of market valuation and investment expectations. Therefore, price dynamics allow the assessment of whether rapid index growth is associated with market saturation, the Bifurcation Point, and signs of bubble formation. In this case, two model systems are

evaluated: the European Renewable Energy Price Index and the MSCI ACWI IMI Clean Energy Infrastructure Index.

3.3.1.1 European Renewable Energy Price Index

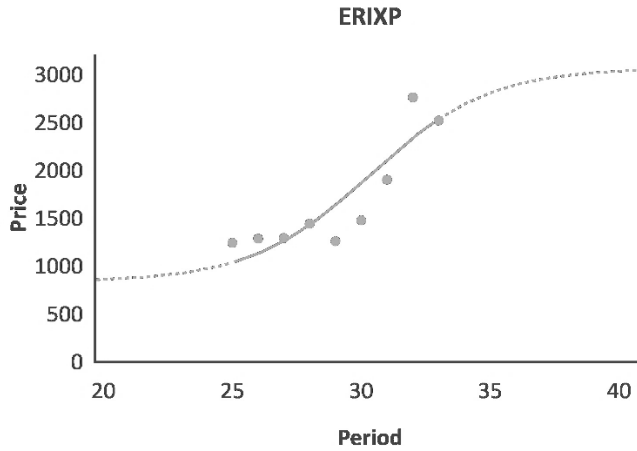
The European Renewable Energy Price Index (ERIXP) is a financial benchmark that tracks the performance of companies within Europe’s renewable energy sector. It reflects the market valuation of firms engaged in the production and development of renewable energy sources, such as wind, solar, and hydroelectric power. Investors and analysts utilise this index to assess the financial health and growth trends of the European renewable energy industry. Data from the Bloomberg terminal reveals the quarterly dynamics of important indicators for the calculations. Fig. 22 shows the ERIXP index value from the beginning of Q3 2003 to Q1 2024. The stocks index price changes identified a possible bubble period when price growth was particularly intense. The second growth period from Q1 2019 to Q1 2021 was chosen and used for the analysis of bubble formation. During this period, the equity index recorded the highest gains and a potential bubble formation.



Source: created by the author based on Bloomberg Finance L.P. (2024)

Fig. 22. ERIXP price dynamics and identification of a potential bubble period

Following the definition of the system and its parameters (ERIXP price in quarters, period from Q1 2019 to Q1 2021), the system capacity was calculated using the Loglet Lab software package. Based on the logistic growth model for the selected period, the price-based market capacity (P_p) is estimated at 3,061. The resulting logistic curve for the analysis period, based on the specified model parameters, is presented in Fig. 23.



Source: author's calculations using Loglet Lab, based on Bloomberg Finance L.P. (2024)

Fig. 23. Logistic growth curve fitting and capacity estimation for ERIXP price

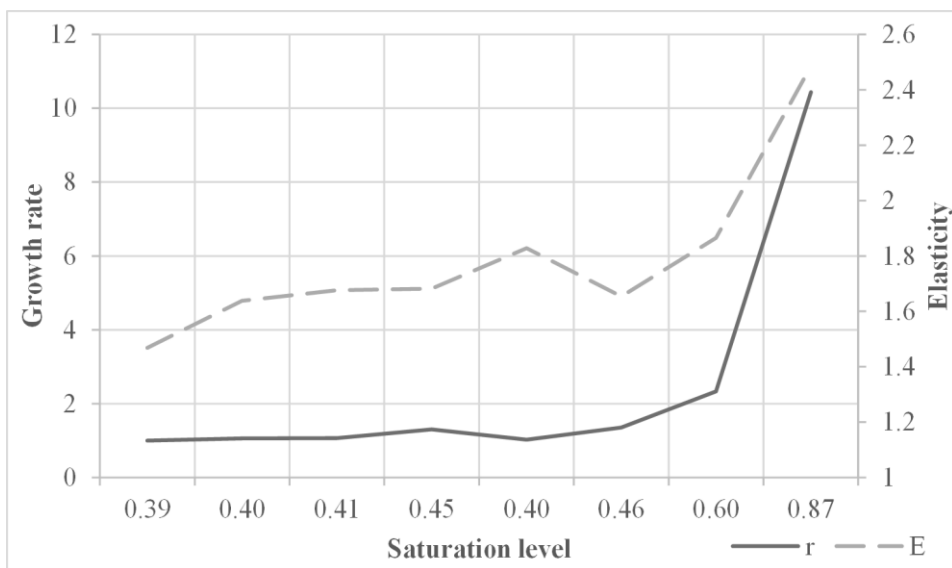
In the figure above, period 25 corresponds to Q1 2019, while period 33 shows the end of the period under analysis (Q1 2021). The dots in the graph represent the actual values of the period on which the logistic growth curve is plotted. The dashed line on the curve shows the projected growth trajectory (see Appendix 4).

Once the potential price level (P_p) of the system has been determined for the period under consideration, the logistic growth rate, the saturation level and the elasticity of the system are calculated. Formula (18) for the logistic growth rate is used for the calculations, with the constant variables shown in Table 15.

Table 15. Input parameters for ERIXP price-based calculations

P_p	P_0	Formula
3,061	1,233	$r = \frac{P_p - P_0}{P_0} \cdot \frac{P_a / P_p}{1 - P_a / P_p}$

The results of the calculation (see Appendix 5) according to the saturation level of the dynamics P_a are shown in Fig. 24. The graphical representation clearly shows the Saturation Paradox with increasing saturation level. The elasticity of the logistic growth rate function with regard to the saturation level is shown in parallel for the analysis period (Q1 2019 to Q1 2021).



Source: author's calculations based on Bloomberg Finance L.P. (2024)

Fig. 24. Growth rate, saturation level and elasticity of ERIXP price

As can be observed from the graph, bifurcation occurs at the last point in the research period, where the saturation level reaches 0.87. The elasticity, which had been fluctuating between 1.5 and 1.8, rises to between 1.86 and 2.49 at the end of the period. According to the research model, the Bifurcation Point has been reached, and the saturation level indicates the formation of a bubble in the ERIXP system.

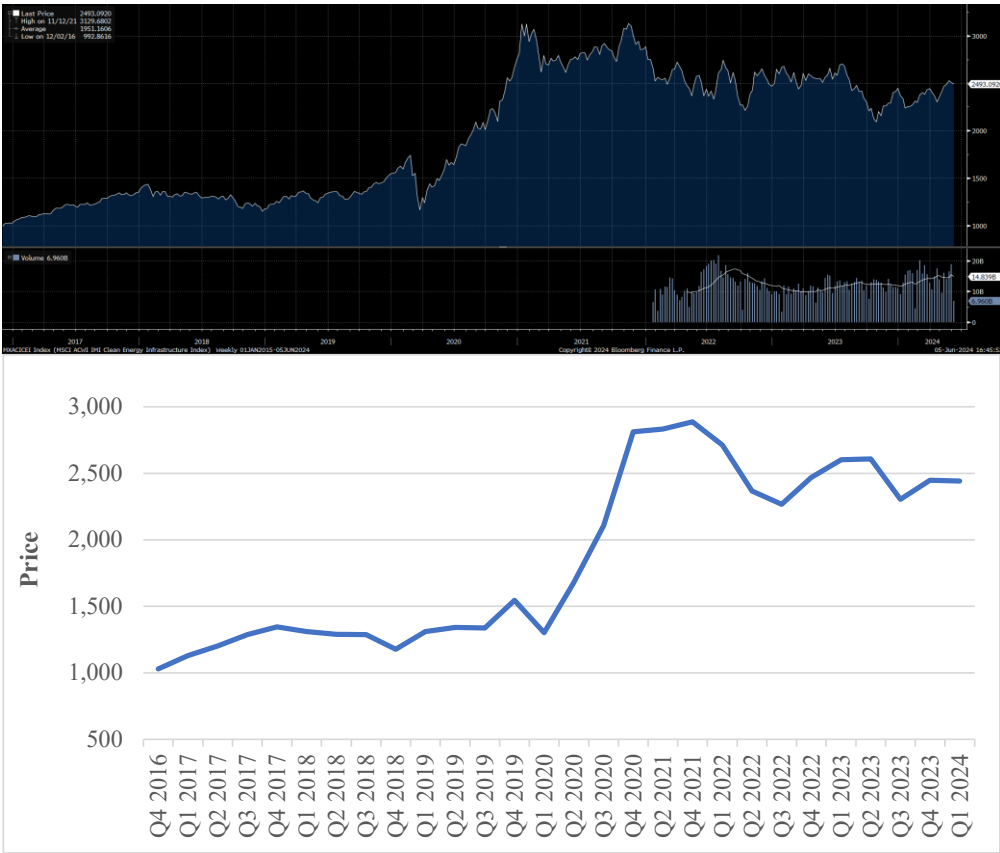
The maximum saturation level (0.869) and elasticity (2.49) indicate the formation of a bubble; however, the saturation level does not reach the threshold (90% and above) associated with overheating or Stage III. Positive feedback is present in the system (elasticity of 2.49), but it is not sufficiently strong. Therefore, according to the calculated saturation and elasticity indicators, ERIXP is classified as a productive bubble. However, since the saturation level is close to the overheating threshold, the subsequent dynamics of the index are also considered in the comparative assessment below.

3.3.1.2 Clean Energy Infrastructure Index

The MSCI ACWI IMI Clean Energy Infrastructure Index (MXACICEI) is derived from the MSCI ACWI Investable Market Index and includes large, mid, and small-cap companies from both developed and emerging markets. It is designed to reflect the performance of companies involved in products and services related to clean energy infrastructure, including batteries, smart grids, future fuels and technologies, alternative energy, and energy efficiency (MSCI, 2025).

Data from the Bloomberg terminal presents the quarterly dynamics of MXACICEI value for the calculations. Fig. 25 shows the MXACICEI index price from Q4 2016 to Q1 2024. The stocks index price changes identified a possible bubble period when price growth were particularly intense. The growth period from Q1 2019

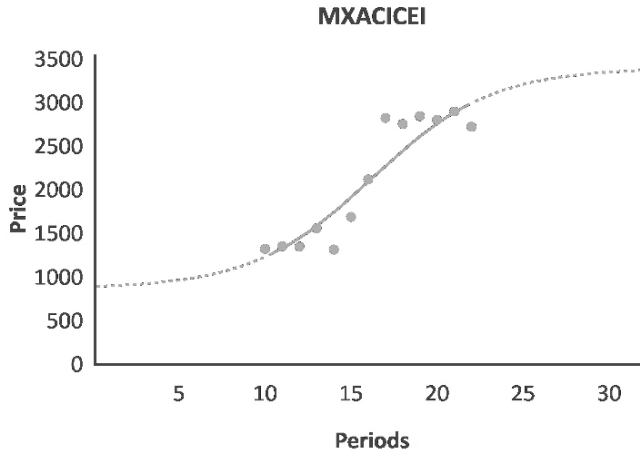
to Q1 2022 was chosen and used for the analysis of bubble formation. During this period, equity index recorded the highest gains and a potential bubble formation.



Source: created by the author based on Bloomberg Finance L.P. (2024)

Fig. 25. MXACICEI price dynamics and identification of a potential bubble period

Following the definition of the system and its parameters (MXACICEI price in quarters, period from Q1 2019 to Q1 2022), the system capacity was calculated using the Loglet Lab software. According to the logistic growth function for that period, the system price-based capacity is calculated to $P_p = 3,386$. The resulting logistic curve for the analysis period, based on the specified model parameters, is presented in Fig. 26.



Source: author's calculations using the Loglet Lab, based on Bloomberg Finance L.P. (2024)

Fig. 26. Logistic growth curve fitting and capacity estimation for MXACICEI price

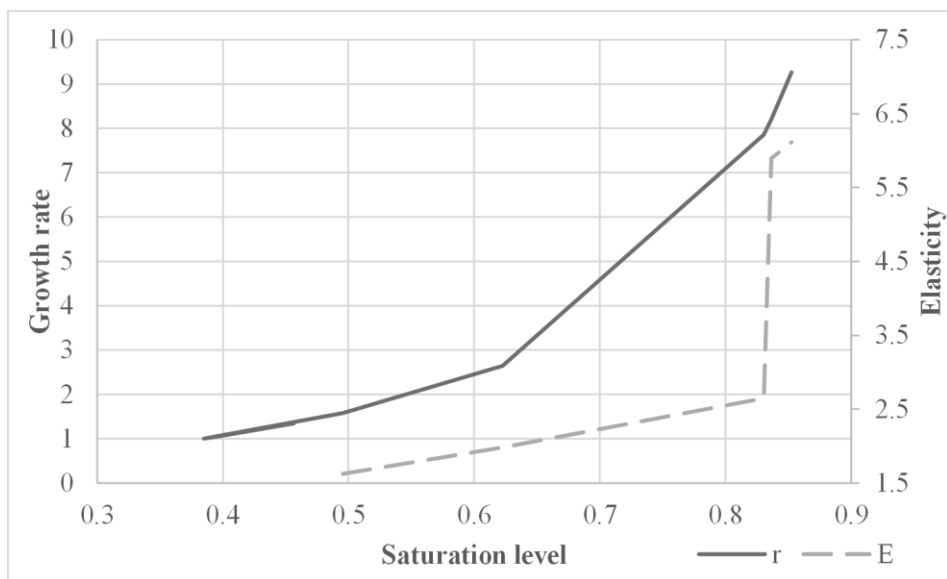
In the provided graph, period 10 corresponds to Q1 2019, while the last statistical period 22 shows the end of the period under analysis (Q1 2022). The dots in the graph represent the actual values of the period on which the logistic growth curve is plotted. The dashed line on the curve shows the projected growth trajectory (see Appendix 6).

Once the potential price level (P_p) of the system has been determined for the period under consideration, the logistic growth rate, the saturation level and the elasticity of the system are calculated. Formula (18) for the logistic growth rate is used for the calculations, with the constant variables shown in Table 16.

Table 16. Input parameters for MXACICEI price-based calculations

P_p	P_0	Formula
3,386	1,300	$r = \frac{P_p - P_0}{P_0} \cdot \frac{P_a / P_p}{1 - P_a / P_p}$

The results of the calculation (see Appendix 7) according to the saturation level of dynamic P_a are shown in Fig. 27. The graphical representation clearly shows the Bifurcation Point and the Saturation Paradox with an increasing saturation level. The elasticity of the logistic growth rate function with regard to the saturation level is shown in parallel for the analysis period (Q1 2019 to Q1 2022).



Source: author's calculations based on Bloomberg Finance L.P. (2024)

Fig. 27. Growth rate, saturation level, and elasticity of MXACICEI price

As can be observed in the graph, a bifurcation occurs in the system under analysis, with a saturation level above 0.7, and a significant increase in the feedback, as reflected by the elasticity of the growth rate with respect to saturation level. The highest saturation level is found to be 0.85, while the elasticity, which was between 1.6 and 1.8, increases to 6.8 during the rapid growth stage. These results indicate that the MXACICEI system reached the Bifurcation Point and entered the heating stage. According to the research model, the observed saturation level and elasticity dynamics indicate the formation of a bubble in the analysed system.

The maximum saturation level (0.85) and elasticity (6.8) found are indicative of bubble formation and are close to the overheating saturation level of the system (~ 0.9 and above), with significant feedback in the system (maximum elasticity 6.8). The values found indicate that the overheating threshold is approaching. However, the subsequent dynamics of the index show only a limited correction (see Fig. 25). Therefore, the bubble identified in the analysed period is interpreted as a productive bubble without clear destructive signs. The summary of the price-based saturation and bubble analysis of equity indices is presented in Table 17.

Table 17. Summary of price-based saturation and bubble analysis of equity indices

Index	P_p	P_{max}	r_{max}	Max saturation	Max elasticity	Bifurcation/ bubble	Heating, quarters	Overheating, quarters	Bubble type
ERIXP	3,061	2,753	10.44	0.87	2.48	Yes	1	-	Productive
MXACICEI	3,386	2,886	9.27	0.85	6.77	Yes	5	-	Productive

Source: author's calculations based on Bloomberg Finance L.P. (2024)

Based on the results obtained, it is possible to summarise the analysis of financial bubbles in the MXACICEI and ERIXP indices:

- Productive bubbles are identified in both equity indices. In both systems, the saturation level reaches the Bifurcation Point as elasticity values clearly confirm bifurcation. Both growth periods enter the heating stage (Stage II) and approach the overheating stage (Stage III), but neither system reaches the overheating stage.

- In the case of ERIXP, although no overheating is detected in the calculated data, the saturation level was close to the overheating threshold. Therefore, together with the subsequent 40.5% price correction (from Q4 2020 to Q1 2024), this case may be interpreted as a productive bubble with possible destructive signs within the margin of error.

- The analysis of the MXACICEI index confirms the formation of a productive bubble. Although the maximum saturation level is close to the overheating stage, the subsequent dynamics of the index show only a limited correction, indicating that the market was able to adjust to the investment-driven price increase.

- The growth of the MXACICEI index, with slight fluctuations, covered 12 quarters, five of which were identified as Stage II. This relatively long and gradual growth period allowed the system to adjust to the investment-driven price increase. Slower and more prolonged growth enables the market to adapt more effectively and may contribute to changes in system capacity over time. This suggests that the capacity of the system may increase over time. Therefore, if changes in system capacity were accounted for, the estimated saturation level and the sensitivity of the growth rate to saturation could be lower.

Since index price reflects market valuation and investor expectations, the following subsection extends the analysis to accumulated capital in order to assess whether capital inflows show similar saturation and bubble dynamics.

3.3.2 Capital-based saturation indicators

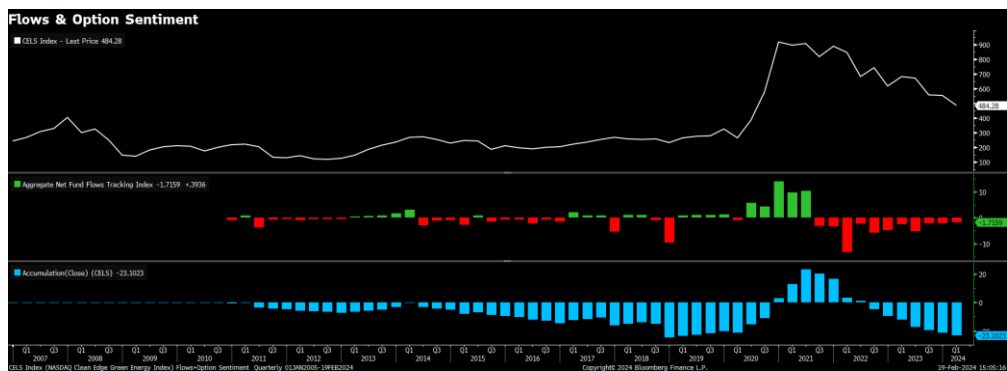
The case study presented below, together with parts of the discussion of general limitations in this subsection, builds on and extends the analysis published in Karaša and Girdzijauskas (2024). The original data framework and the main capital-saturation results are retained, while the dissertation extends the analysis by incorporating elasticity, bifurcation assessment, bubble classification, comparison with other renewable energy systems, and a broader discussion of methodological limitations. The same capital-based analytical procedure is then applied to the S&P Global Clean Energy Index.

The following analysis focuses on RE equity indices using accumulated capital as the main saturation indicator. In this part of the research, capital saturation is assessed through accumulated capital derived from market capitalisation and aggregate net fund flows, while index price is used as an additional indicator for comparing market valuation dynamics. In this case, two model systems are evaluated: the NASDAQ Clean Edge Green Energy Index and the S&P Global Clean Energy Index.

3.3.2.1 Clean Edge Green Energy Index

The NASDAQ Clean Edge Green Energy (CELS) Index is a modified market capitalisation-weighted index designed to track the performance of US-listed companies involved in the clean energy sector, including renewable energy generation, energy storage, energy efficiency, and enabling technologies. Developed by NASDAQ in collaboration with Clean Edge, Inc., the index includes companies that are significantly engaged in areas, such as solar, wind, biofuels, advanced batteries, smart grid technologies, and electric vehicles. To ensure diversification and to mitigate concentration risk, the index employs a two-stage capping process whereby no individual company exceeds 8% of the index's weight, and smaller constituents are further limited to 4%. The index serves as a benchmark for institutional and retail investors seeking exposure to the rapidly evolving clean energy market, and its composition is rebalanced quarterly to reflect industry shifts and maintain compliance with eligibility requirements (Clean Edge, n.d.).

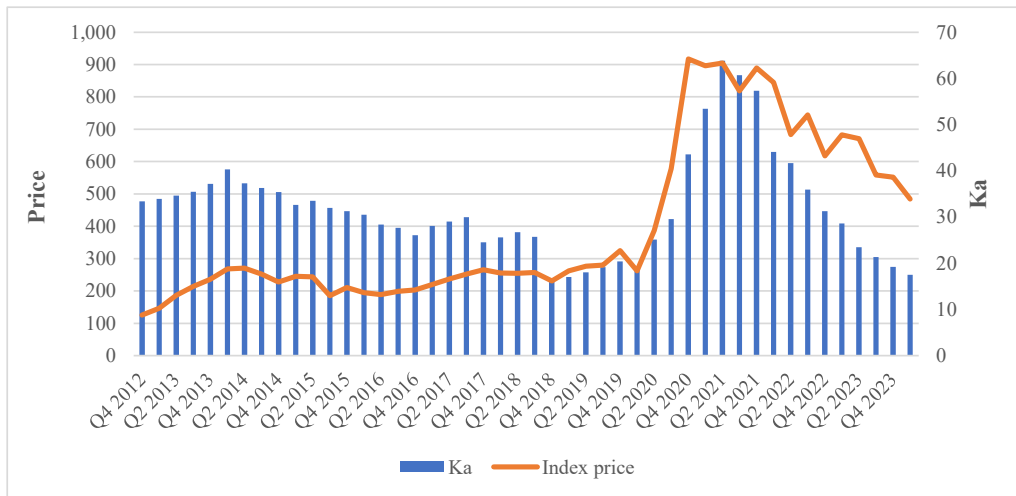
Data from the Bloomberg terminal reveals the quarterly dynamics of important indicators for the calculations. Fig. 28 shows the CELS index value, aggregate net fund flows, and accumulated capital values in quarters from Q1 2007 to Q1 2024.



Source: adapted from Karaša and Girdzijauskas (2024), based on Bloomberg Finance L.P. (2024)

Fig. 28. CELS price and capital flow dynamics and identification of a potential bubble period

Historically, equity index capitalisations are reported from Q4 2012. At the end of this quarter, the CELS Index had a market capitalisation of USD 33.9 billion. After performing additional calculations based on the accumulated capital formula (17), the dynamics of the price of the CELS index and the accumulated capital (K_a) during the considered period were obtained (see Fig. 29).

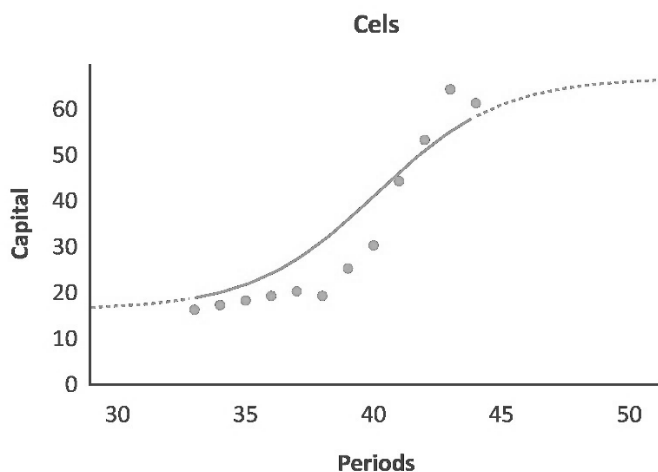


Source: adapted from Karaša and Girdzijauskas (2024), based on Bloomberg Finance L.P. (2024)

Fig. 29. CELS price and accumulated capital dynamics and identification of a potential bubble period

The capital market and the stock index price changes identified a possible bubble period when capital and price growth were particularly intense. The period between Q4 2018 and Q3 2021 was chosen and used for the analysis of bubble. During this period, the value of the equity and accumulated capital recorded the highest gains and a potential bubble formation. Looking at quarterly data, the value of this index has increased almost four times during the research period, precisely from 230 to 917. Meanwhile, the aggregate net fund flows have been gradually increasing their accumulated capital since Q1 2019. With the slight exception of Q1 2020, the market capital increased until Q2 2021. During this period, the accumulated capital on the market increased more than 3.5 times. In 2020 alone (a period of rapid index appreciation), the accumulated capital grew more than double. The developed model is applied to analyse this period of intensive growth.

According to the definition of the system and its parameters (CELS price and accumulated capital in quarters, period from Q4 2018 and Q3 2021), the system capital-based capacity was calculated using the Loglet Lab software. According to the logistic growth function for that period, the system capital-based capacity is calculated to $K_p = 66.5$. The resulting logistic curve for the analysis period, based on the specified model parameters, is presented in Fig. 30.



Source: adapted from Karaša and Girdzijauskas (2024), based on calculations using Loglet Lab and Bloomberg Finance L.P. (2024)

Fig. 30. Logistic growth curve fitting and capacity estimation for CELS accumulated capital

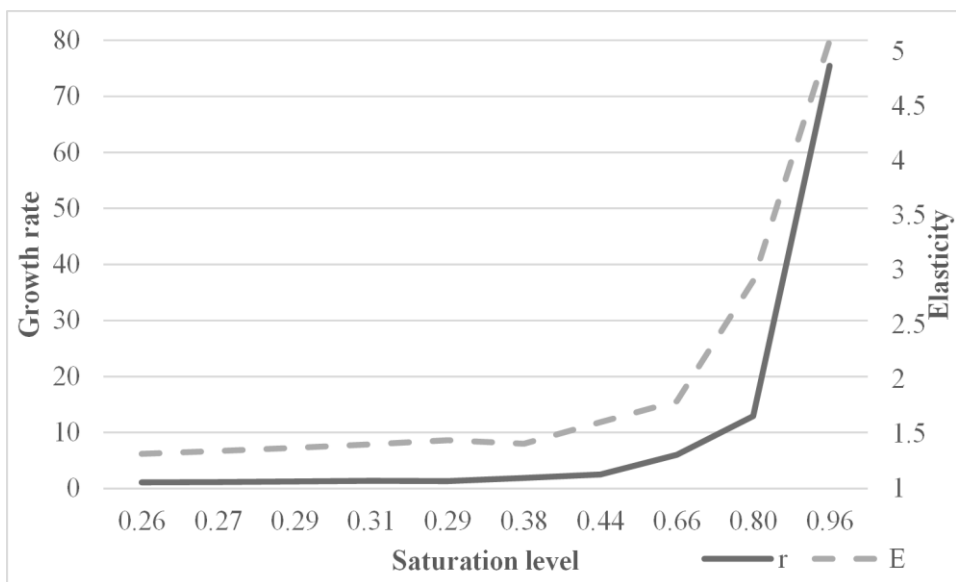
In the analysis, the 33rd period (see Fig. 30) corresponds to Q4 2018; and 44th period, to Q3 2021. The dots on the graph represent the actual values for the period on which the logistic growth curve is based. The dashed line on the curve shows the projected growth trajectory (see Appendix 8).

Once the potential capital capacity (K_p) of the system has been determined for the period under analysis, the logistic growth rate, the saturation level and the elasticity of the system are calculated. Formula (16) for the logistic growth rate is used for the calculations, the expression, and the constant variables of which are given in Table 18.

Table 18. Input parameters for CELS accumulated capital-based calculations

K_p	K_0	Formula
66.55	16	$r = \frac{K_p - K_0}{K_0} \cdot \frac{K_a / K_p}{1 - K_a / K_p}$

The results of the calculation (see Appendix 9), based on the saturation level (K_a), are presented in Fig. 31. The graphical representation clearly illustrates the Saturation Paradox as the saturation level increases. The elasticity of the logistic growth rate function with respect to the saturation level is shown alongside the saturation curve for the actual analysis period (Q1 2019 to Q2 2021). Both curves exhibit a hyperbolic growth pattern.



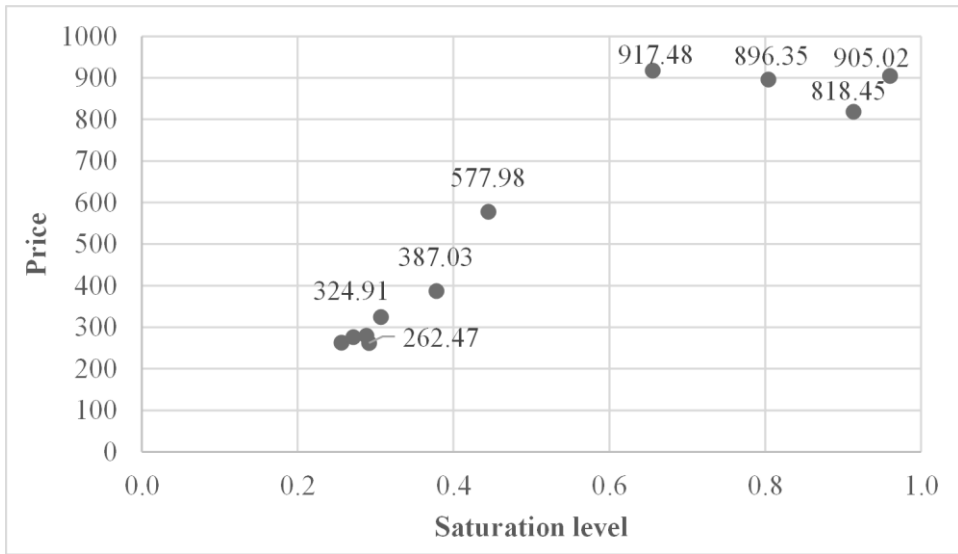
Source: developed by the author by extending Karaša and Girdzijauskas (2024), based on Bloomberg Finance L.P. (2024)

Fig. 31. Growth rate, saturation level and elasticity of CELS accumulated capital

The calculation results show that bifurcation occurred in the system under investigation, with saturation level above 0.7. The feedback, reflected by the elasticity of the growth rate with regard to the saturation level, increases significantly. The highest saturation level is estimated to be 0.96, while the elasticity, which ranges between 1.3 and 1.6, increases to 5.1 during the rapid growth stage. These are significant indications of heating in Stage II and, according to the methodological model, the Bifurcation Point is reached and the saturation level indicates the formation of a bubble in the CELS system.

The maximum saturation level (0.96), the elasticity (5.1) and the logistic growth rate (75.5) reveal the formation of a bubble, with a peak above the system's moderate growth threshold (~ 0.9 and above) and reaching Stage III. It also shows significant positive feedback in the system (maximum elasticity 5.1). The values indicate the formation of a destructive bubble. This interpretation is confirmed by the further dynamics of accumulated capital, as accumulated capital decreased by 72.6% over the 12 quarters after the peak. A high level of financial saturation, a high growth rate, and transition to Stage III indicate overheating and destructive bubble formation according to the Financial Saturation Theory and the developed model.

Since capital accumulation and its dynamics do not directly signal the formation of a bubble in prices, the correlation between capital saturation and the price of the CELS index is explored below. A scatter diagram of these quantities is presented in Fig. 32.



Source: adapted from Karaša and Girdzijauskas (2024), based on Bloomberg Finance L.P. (2024)

Fig. 32. Scatter plot of CELS price and accumulated capital saturation level

Distribution CELS Index price and capital saturation level are measured from the period when stable capital growth in the market started, i.e. when the preconditions for the formation of a bubble emerged. In the analysis, this corresponds to Q4 2018, when capital started flowing into the market. The analysis concludes with the last available data in Q1 2024 when there was a strong negative net capital flow. A scatter diagram visually depicts the relationship between the CELS Index price and capital saturation level. It provides insights into how two variables affect each other when they are plotted over a graph.

Firstly, the diagram clearly shows the bifurcation, with the points on the left side being before the market bifurcation in fundamental market, and the points on the right side being after the market bifurcation in deficit market. If we do not consider the time lag between capital and price, according to the index value, the bifurcation occurred when the saturation with capital reached ~0.7 of the potential level. In the fundamental market, the points are located up to the 0.4 saturation level.

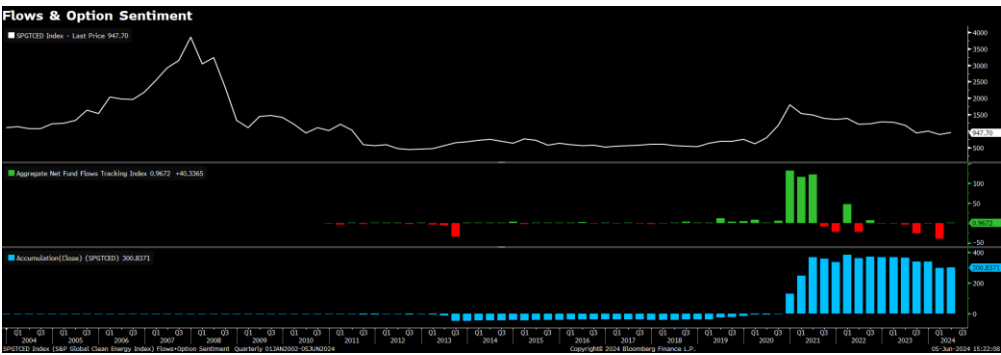
When assessing the time lag, the most relevant points have values of 577.98 (saturation level 0.44) and 917.48 (saturation level 0.66). These points are closest to the saturation level of the Bifurcation Point and reflect the time lag. As shown in Fig. 29, the index value starts to grow first, followed by accumulated capital. This time lag is most evident when the index value reaches its peak (917.48) and capital saturation has just begun (0.66). These points introduce some distortion into the distribution, although not to a significant degree.

3.3.2.2 Global Clean Energy Index

The S&P Global Clean Energy (SPGTCED) index is a benchmark designed to measure the performance of global companies involved in the clean energy sector. It includes firms primarily focused on renewable energy production, such as wind, solar,

and hydroelectric power, as well as related technologies, such as energy storage and clean energy equipment. The index is weighted to ensure diverse geographical and sectoral representation, promoting a comprehensive view of the clean energy industry's growth and investment opportunities.

Data from the Bloomberg terminal reveals the quarterly dynamics of important indicators for the calculations. Fig. 33 illustrates the SPGTCED index value, aggregate net fund flows, and accumulated capital values in quarters from Q4 2003 to Q2 2024.



Source: Bloomberg Finance L.P. (2024)

Fig. 33. SPGTCED price and capital flow dynamics and identification of a potential bubble period

System index capitalisations are reported from Q4 2010. At the end of this quarter, the SPGTCED index had a market capitalisation of USD 78.9 billion. After performing additional calculations based on accumulated capital formula (17), the dynamics of the price of the SPGTCED index and the accumulated capital K_a during the considered period were calculated (see Fig. 34).

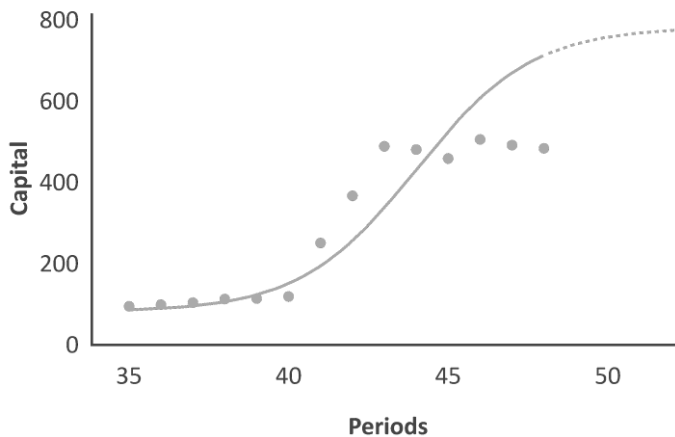


Source: created by the author based on Bloomberg Finance L.P. (2024)

Fig. 34. SPGTCED price and accumulated capital dynamics and identification of a potential bubble period

The capital market and the stock index price changes identified a possible bubble period when capital and price growth were particularly intense. The period between Q2 2019 and Q3 2022 was chosen and used for the analysis of the bubble. During this period, the value of the equity and accumulated capital recorded the highest gains and a potential bubble formation. Looking at quarterly data, the value of this index has doubled during the research period, precisely from 681 to 1,377 in peak. Meanwhile, the aggregate net fund flows have been gradually increasing their accumulated capital since Q2 2019. With the slight exception of Q3 and Q4 in 2021, the market capital increased until Q1 2022. During this period, accumulated capital increased almost 5.5 times, from USD 92 billion to USD 503 billion. This period and data were used to apply the model in SPGTCED index system.

According to the definition of the system and its parameters (SPGTCED price and accumulated capital in quarters, period from Q2 2019 and Q3 2022), the system capacity was calculated using the Loglet Lab software. According to logistic growth function for that period, the system capital-based capacity is calculated to $K_p = 780$. The resulting logistic curve for the analysis period, based on the specified model parameters, is presented in Fig. 35.



Source: author's calculations using Loglet Lab, based on Bloomberg Finance L.P. (2024)

Fig. 35. Logistic growth curve fitting and capacity estimation for SPGTCED accumulated capital

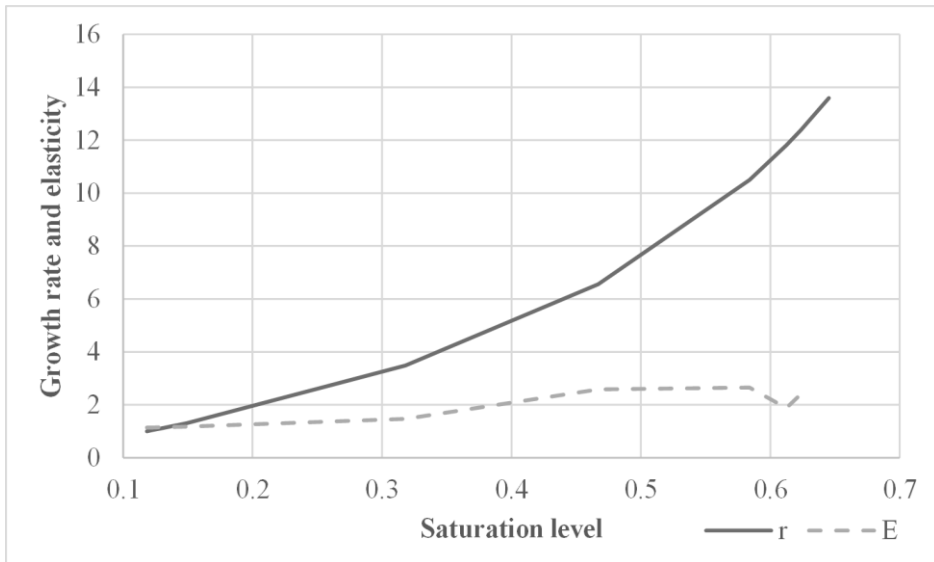
In the analysis, the 35th period (see Fig. 35) corresponds to Q2 2019; and 48th period, to Q3 2022. The points on the graph represent the actual values for the period, based on which the logistic growth curve is drawn. The dotted line on the curve shows the predicted growth trajectory (see Appendix 10).

After determining the potential capital capacity (K_p) of the system for the period under review, the logistic growth rate, the saturation level of the system, and its elasticity are calculated. The calculations use the logistic growth rate formula (16), with its expression and constant variables presented in Table 19.

Table 19. Input parameters for SPGTCED accumulated capital-based calculations

K_p	K_0	Formula
780	92	$r = \frac{K_p - K_0}{K_0} \cdot \frac{K_a/K_p}{1 - K_a/K_p}$

The calculation results (see Appendix 11) according to the saturation level dynamics are presented in Fig. 36. The graphical representation shows the beginnings of the Saturation Paradox as the level of saturation increases. The elasticity of the logistic growth rate function with regard to the saturation level is shown in parallel for the analysis period (Q2 2019 to Q3 2022).

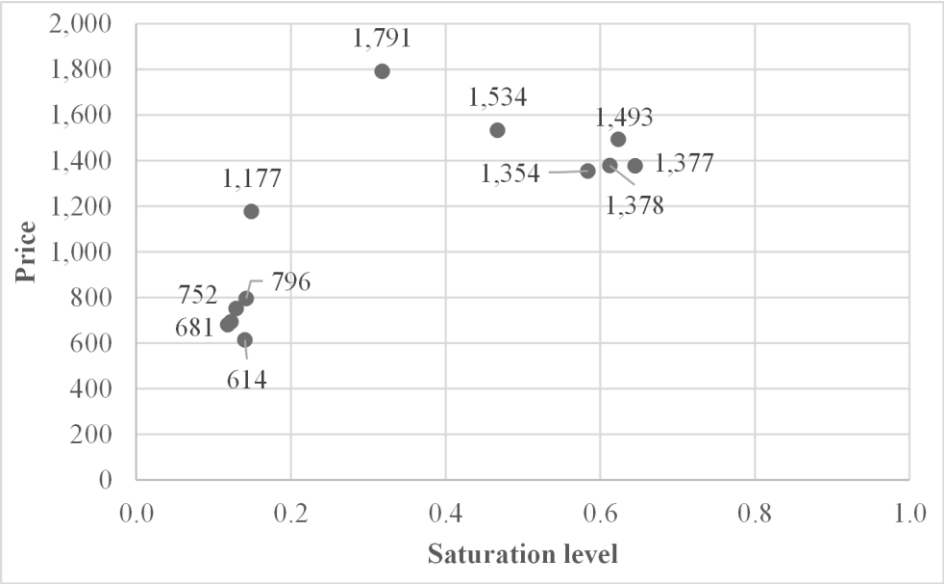


Source: author's calculations based on Bloomberg Finance L.P. (2024)

Fig. 36. Growth rate, saturation level and elasticity of SPGTCED accumulated capital

Based on the calculation results shown in the graph, the system approaches but does not reach the Bifurcation Point. The calculated maximum saturation level reaches 0.65, while elasticity, which fluctuated between 1.15 and 1.17, increases to 2.65 during the period of faster growth. Considering that the saturation level does not reach the 0.7 saturation characteristic of the Bifurcation Point, and the feedback (elasticity) does not become significantly high, it is not definitive to state that the Bifurcation Point has been reached in the system. Taking into account the dynamics of accumulated capital in the periods, it can be concluded that no bubble was formed in the SPGTCED index system during the period under review. This is confirmed by the further dynamics of accumulated capital, when during the eight periods (quarters) following the peak after growth, the index lost 20.5% of accumulated capital. The saturation level and growth rate indicate Stage I, which is characterised by moderate growth and saturation level below the bifurcation threshold of approximately 0.7–0.75.

As in the case of the CELS system, the SPGTCED index allows for a comparison of value and accumulated capital data and indicators calculated according to the model. Since the accumulated capital and its dynamics do not indicate the formation of a bubble, the distribution between capital saturation level and the SPGTCED index price is reviewed below. The scatter plot of these values is shown in Fig. 37.



Source: author’s calculations based on Bloomberg Finance L.P. (2024)

Fig. 37. Scatter plot of SPGTCED price and accumulated capital saturation level

The distribution of SPGTCED index price (value) and capital saturation level are measured from the period when capital growth in the market started, i.e. when the preconditions for the formation of a bubble emerged. The scatter analysis period is the same as all SPGTCED system periods. A scatter diagram visually depicts the relationship between the SPGTCED Index price and capital saturation level. It provides insights into how two variables affect each other when they are plotted over a graph.

Firstly, the diagram shows an approach toward bifurcation, where the points on the left side reflect low prices with low capital saturation level. On the right side, the points reflect increased prices with growing accumulated capital. These points are approaching bifurcation but do not reach the required level. The saturation levels, around which the clusters of points are located, are 0.2 and 0.6, respectively. However, the three points with prices of 1,177, 1,791, and 1,534 do not belong to either cluster. These points most characteristically reflect the time lag between the change in the accumulated capital and the index price. In the distribution diagram, these three points show that in the system under analysis, prices began to rise first, and only then accumulated capital increase. As shown in Fig. 34, the index value begins to grow first, followed by the accumulated capital. It is this time lag that is most characteristic

of the points around the peak of accumulated capital. These time lag points distort the distribution to some extent.

When assessing the further behaviour of the system after the end of the study period (Q3 2022), there is a clear divergence between the trends in accumulated capital and index prices (see Fig. 34). As mentioned earlier, if no bubble forms, the system (market) is able to absorb and retain incoming capital, resulting in no significant decline in accumulated capital after the peak period. However, when evaluating the system index price, it corrected by approximately 35% over eight periods, from the price peak of 1,377 to an index value of 893 in Q1 2024. The research model does not cover the impact of external factors, so these price changes likely caused by external factors are not analysed in detail in the research.

A summary of the research, where system saturation is assessed based on accumulated capital, is presented in Table 20.

Table 20. Summary of capital-based saturation and bubble analysis of equity indices

Index	K_p	K_{max}	r_{max}	Max saturation	Max elasticity	Bifurcation/ bubble	Heating, quarters	Overheating, quarters	Bubble type
CELS	66.5	64	75.46	0.96	5.09	Yes	3	1	Destructive
SPGTCED	780	503	13.59	0.65	2.65	No	-	-	-

Source: author's calculations based on Bloomberg Finance L.P. (2024)

Based on the results achieved, it is possible to summarise the bubble analysis and financial saturation in terms of the accumulated capital in the CELS and SPGTCED index systems:

— A destructive bubble was identified in the CELS index. The saturation level and elasticity in this system clearly indicate that the Bifurcation Point was reached, the system entered heating Stage II, and transitioned to overheating Stage III in the last quarter of the research period. In the case of the SPGTCED index, no Bifurcation Point was identified, and the saturation level and elasticity indicators show moderate growth corresponding to Stage I.

— In the case of the CELS system, the destructive bubble identified is confirmed by the further dynamics of accumulated capital. From the highest K_a point, accumulated capital decreased by 72.6% over 12 periods (quarters). In the case of the SPGTCED system, the accumulated capital decreased by only 20.5% over eight periods (quarters), and no significant correction was recorded, indicating that most of the accumulated capital remained in the system.

After summarising the capital-based results, the analysis can be extended to all four renewable energy-related equity index systems examined in Subsection 3.3. Considering all equity index systems analysed in this subsection, the results show differences in maximum logistic growth rate, saturation level, elasticity, and the duration of heating or overheating stages. Based on the financial saturation limits (Stages), it was assessed how many quarters there were heating or overheating stages.

The SPGTCED index did not reach the Bifurcation Point. Of the remaining three indices, ERIXP, MXACICEI and CELS reached bifurcation and Stage II – the heating stage, while only the CELS index entered Stage III – the overheating stage, exceeding the 0.9 threshold and reaching 0.96.

When assessing the duration of the heating Stage II or overheating Stage III of the indices (how long Stage II and III lasted), the most characteristic is MXACICEI index, whose heating period lasted five quarters. It was close to overheating Stage III, but did not reach it. The shortest heating period was identified in the ERIXP index, lasting one quarter. The CELS index remained in Stage II for three quarters and additionally entered overheating Stage III for one quarter. It should be noted that each index analysed has its own characteristic and unique growth rate due to the different initial capital or price (P_0 or K_0) at the beginning of the period, as well as the dynamics characteristic of that stock index.

The transformation of the accumulated capital growth rate into a stock price requires the assessment of a time lag. Based on the scatter distribution between capital saturation and index prices, prices begin to increase earlier than the capital saturation level. This is reflected in the uneven distribution of the CELS and SPGTCED index values and saturation levels. During correction periods, the timing and magnitude of changes in accumulated capital and index price may also differ. Part of this price dynamics may reflect narrative-driven expectations, where investor beliefs about future clean energy growth affect market valuations before corresponding changes in accumulated capital or real sector capacity become visible. According to Shiller (2015, 2020), a strong increase in stock prices may reinforce investor confidence and create expectations of further price growth or market rebound. This may help explain why price dynamics and accumulated capital dynamics do not fully coincide in time. At a later stage, however, the observed dynamics become consistent with the effects of the Saturation Paradox described by the developed model.

Based on the Financial Saturation Theory, the observed equity index dynamics can be interpreted as a saturation-based bubble formation process. External shocks, including the expected effects of the COVID-19 period, increased liquidity, and strong expectations related to renewable energy development, may have increased demand for equity investments. When investment demand exceeded the available supply of attractive renewable energy-related assets, a deficit market structure was formed. Rising index prices strengthened optimistic expectations and created a positive feedback loop, where further investment increased market saturation and supported additional price growth. In this interpretation, the peak of capital-based saturation reflects the closure of this short-term investment cycle. This short-term investment cycle closed at the peak of capital-based saturation.

The stock index systems analysed in this section allow the following general conclusions to be drawn:

— Three bubbles were identified across the analysed systems: two productive and one destructive. The systems exhibit different growth rates, elasticity values and post-growth dynamics, which serve as additional indicators for assessing bifurcation and the type of bubble formation. In some cases, the bubble formation threshold is not fully unambiguous. Therefore, the interpretation requires additional

assessment of dynamics after the growth period.

— A time lag is observed between price changes and subsequent adjustments in accumulated capital. This confirms that price and capital dynamics do not fully coincide in time and that external factors may initially stimulate market valuation before capital saturation becomes visible. At a later stage, the observed dynamics are consistent with the effects of the Saturation Paradox, as described by the developed model.

— The identified productive and destructive bubbles cannot be considered indicators of the entire renewable energy sector or evidence of a general green bubble. The results should be interpreted as characteristic of the specific systems under review, since the analysed indices differ in composition, regional coverage, market structure, liquidity and sector specialisation. Therefore, broader aggregate market analysis would be required to assess bubble dynamics across the entire renewable energy sector.

Specific limitations of the research of equity indices systems. The discrepancies in the dynamics of index price and accumulated capital in the market over time require a more detailed examination. This requires additional research on the time lag between the growth rate of accumulated capital and the index value. The question is whether the observed time lag between the rate of change of capital (r) and the index price allows for a direct simple transformation of the growth rate into a price, as proposed in the theoretical framework of Financial Saturation Theory.

The stock index bubble formation analysis model consists of five variables, and K_p , K_0 , and t are treated as constant parameters. This assumption simplifies the calculations and allows the relationship between the accumulated capital and the growth rate to be assessed more clearly, but it also limits the model's ability to capture changes in market capacity over time. It is likely that the potential capital capacity of the market (K_p) is not stable and varies over time. This leads to different saturation levels in different periods and affects the size of the dependent variable r . Further research is needed to assess how market capacity varies over time and to incorporate this into the estimation model. Changes in market capacity over time may explain the discrepancy between the capital-based growth rate and the price dynamics over time.

The analysis shows that the logistic growth rate increases as accumulated capital approaches K_p . However, the determination of K_p is more likely to be based on historical data than on accurate forecasting. The capital-based growth rate could be used to predict that the market is approaching a growth opportunity frontier (potential level), followed by a correction/crash or market capacity change. Further research and analysis are needed to identify a dangerous growth rate that would indicate a market changing and approaching saturation.

Slight, small price/market corrections are inevitable and beneficial to the market. However, significant, large corrections are detrimental, reducing the sustainability of the market. The degree of market saturation is likely to help assess the potential magnitude of market correction, but this requires further extensive research and analysis.

3.4 Global Solar, Wind, and Battery Storage Systems: Installed Capacity Analysis

The previous parts of the empirical analysis examined a regional biomass-based district heating system and renewable energy-related financial market indices based on price and accumulated capital. This subsection extends the analysis to global total renewable energy, solar, wind and battery storage systems.

The following analysis is an updated and extended version of the study published in Mikalauskas and Karaša (2025). The dissertation retains the main data framework and saturation results, while extending the analysis through elasticity assessment, indicative bubble classification, and a broader interpretation of installed capacity-based saturation risks.

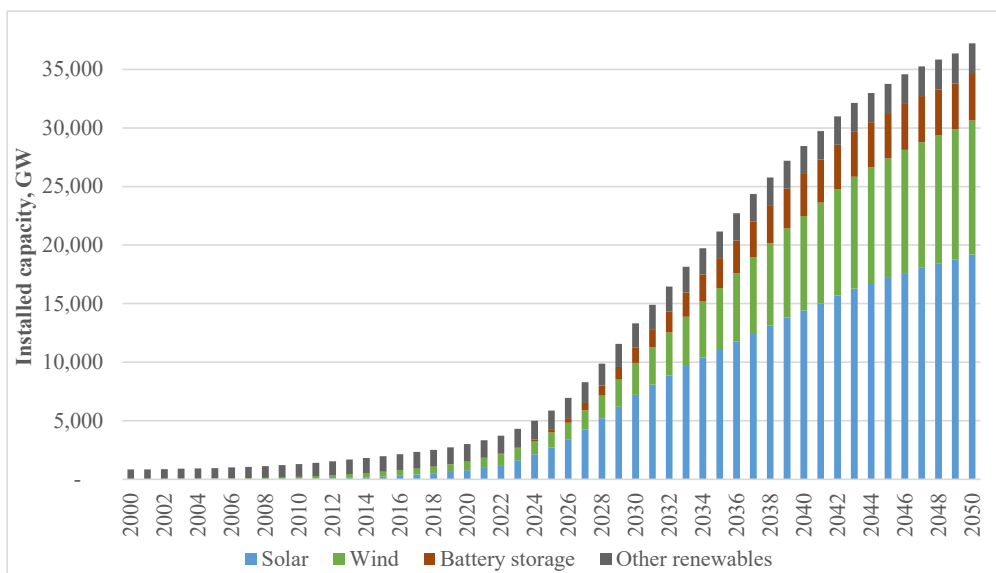
In this part of the research, installed capacity is used as a proxy for physical and technological system saturation. This makes it possible to assess how projected capacity expansion is related to saturation level, logistic growth rate, elasticity, the Bifurcation Point, and potential bubble formation risks. However, installed capacity is not interpreted as direct evidence of a financial bubble. It is treated as an indirect indicator of saturation risks that may be transmitted to related financial, technology, equipment, construction or resource markets.

The analysis is based on forecast data from Bloomberg's New Energy Outlook 2024 (BloombergNEF, 2024b). Therefore, the results depend on the assumptions and projected installed capacity trajectories provided in this source. The dissertation does not assess the accuracy or reliability of the forecasts themselves. The results are interpreted as a scenario-based assessment of saturation and bubble formation risks, rather than as a direct forecast of future outcomes. Accordingly, the analysis considers two alternative development scenarios:

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

The analysis identifies Bifurcation Points, heating and overheating stages, elasticity dynamics and sectoral differences across total renewable energy, solar, wind, and battery storage systems.

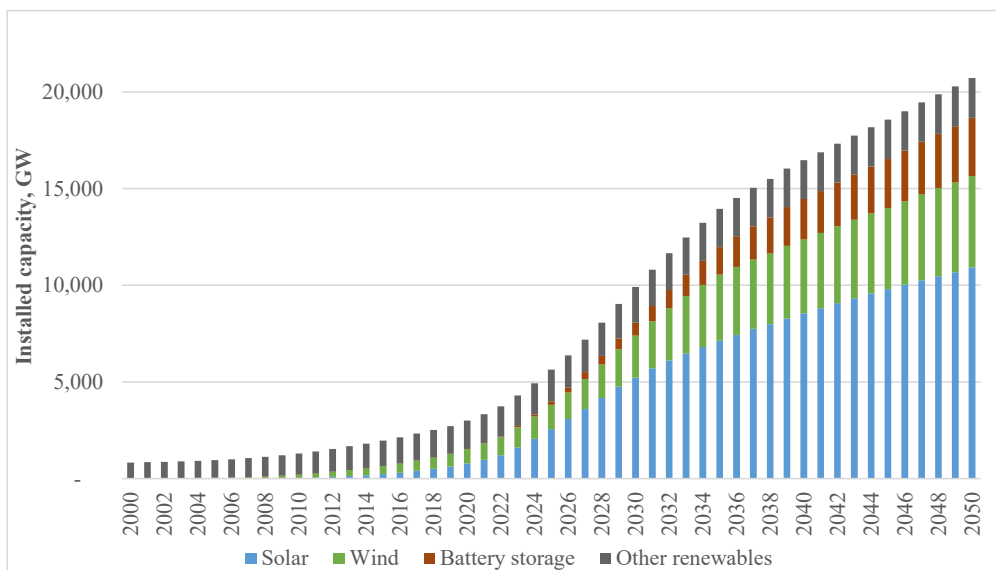
The graphs provided below illustrate the projected market installed capacity trajectories under the Net Zero Scenario (see Fig. 38) and the Economic Transition Scenario (see Fig. 39).



Source: adapted from Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

Fig. 38. Renewable energy installed capacity projections under the Net Zero Scenario

The Net Zero Scenario reflects an accelerated transition to renewable energy, with aggressive deployment targets and strong policy support.



Source: adapted from Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

Fig. 39. Renewable energy installed capacity projections under the Economic Transition Scenario

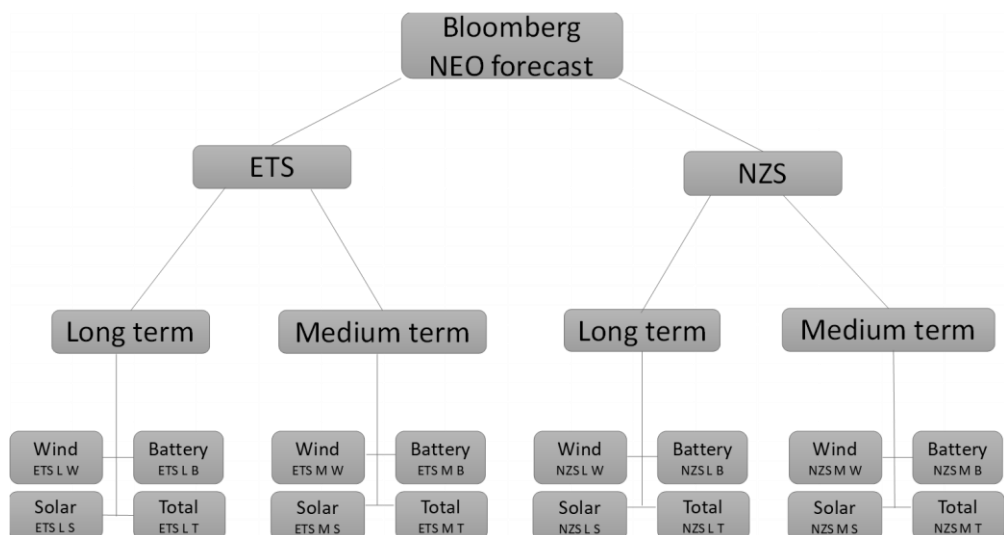
The Economic Transition Scenario is more conservative and assumes a gradual shift to renewables, providing a baseline for assessing risks in a less aggressive market expansion environment. Compared to the NZS, the ETS produces a more measured expansion, thereby lowering speculative risks but potentially postponing the achievement of climate targets.

Using forecast data, there is a continuous growth period, likewise to logistic growth. In this case, it is complicated to emphasise the analysis period. Additional assumption is made according to business cycles. This defines the duration of system evolution in two scenarios for medium-term and long-term periods:

— *Medium-Term Scenario (10–12 years)*. The Juglar cycle refers to an economic cycle characterised 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 (Grinin et al., 2010; Shirazi & Shirazi, 2012).

— *Long-Term Scenario (25–30 years)*. 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 urbanisation, demographic shifts, and infrastructure investment. This timeframe, according to the Kuznets cycle, examines 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 (Bordo & Jeanne, 2004; Selivanova, 2018).

Based on these assumptions, the medium term is assessed for the period 2020–2031, while the long term is assessed for the period 2020–2050. The system analysis structure covers different scenarios based on NZS and ETS scenarios in forecasting, long and medium-term cyclicity, and RE generation capacities in total and separately by solar, wind, and battery system (market) capacity types. This results in $4 \times 4 = 16$ different scenarios, for which saturation and logistic growth rates, elasticity, and bubble formation stages are assessed (see Fig. 40).



Source developed by the author based on Mikalauskas and Karaša (2025)

Fig. 40. Scenario structure based on NZS/ETS, analysis period, and RE system types

Fig. 40 demonstrates the distribution of scenarios, and each scenario is accompanied by a conditional abbreviation for further analysis, where the first three-letter abbreviation indicates the distribution according to ETS and NZS scenarios, the next letter indicates the duration of the period (L – long term, and M – medium term), and the last letter indicates the type of RE generation or storage system (T – total, W – wind, S – solar, B – battery storage).

According to the definition of the system and its parameters (scenario, period, installed capacity), the system capacities for each scenario were calculated using the Loglet Lab software. The essential results of the Loglet analysis under the scenario parameters are presented in Table 21.

Table 21. Input parameters for installed capacity-based scenarios calculations

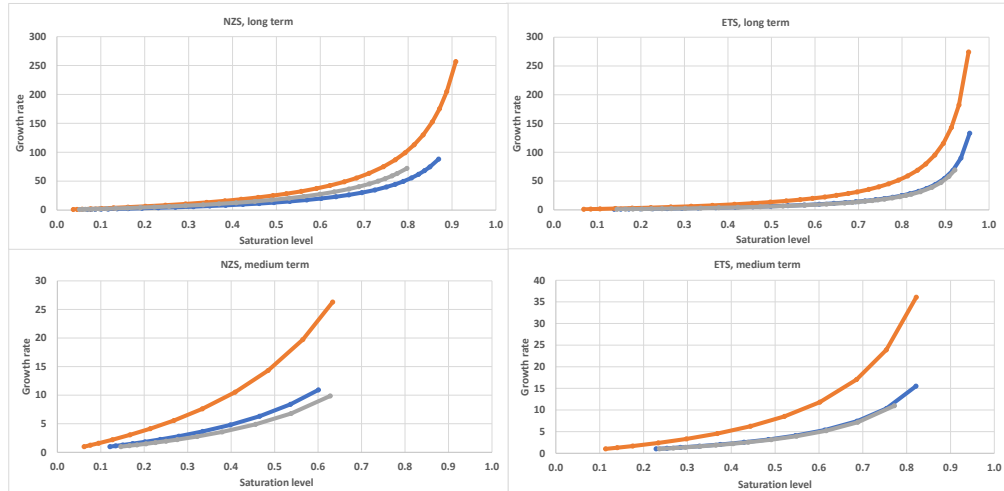
Scenarios	C_p	C_0	Scenarios	C_p	C_0
ETS L T	21,686	3,005	NZS L T	42,804	3,005
ETS L S	11,463	787	NZS L S	21,117	787
ETS L W	5119	742	NZS L W	14,358	742
ETS L B	3,100	13	NZS L B	4,488	13
ETS M T	13,155	3,005	NZS M T	24,815	3,005
ETS M S	6,937	787	NZS M S	12,752	787
ETS M W	3,145	742	NZS M W	5,075	742
ETS M B	1,160	13	NZS M B	1,916	13

Source: developed by the author by consolidating the results of Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

As shown in the table, regardless of the scenario, the initial data for the total market, wind, solar, and battery systems coincide. This is because the initial dataset, based on historical data, is independent of the scenario and remains unchanged. Having analysed for systems capacity, the logistic growth rate, system saturation level,

and elasticity are calculated. The calculations use the logistic growth rate formula (19) already described in the methodology subsection.

The calculation results (see Appendix 12) according to C_a and the change in saturation level (total, solar, wind) are presented in Fig. 41, while the calculation results for the battery storage system are presented in Fig. 42. The graphical representation shows the Saturation Paradox: the saturation level increases as Bifurcation Point is reached in the system. The elasticity of the logistic growth rate function from the saturation level is calculated and displayed in parallel. Battery storage is displayed separately due to its individual growth rate dynamics.



Source: developed by the author by consolidating the results of Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

Note: blue line represents total RE; orange line represents solar; grey line represents wind

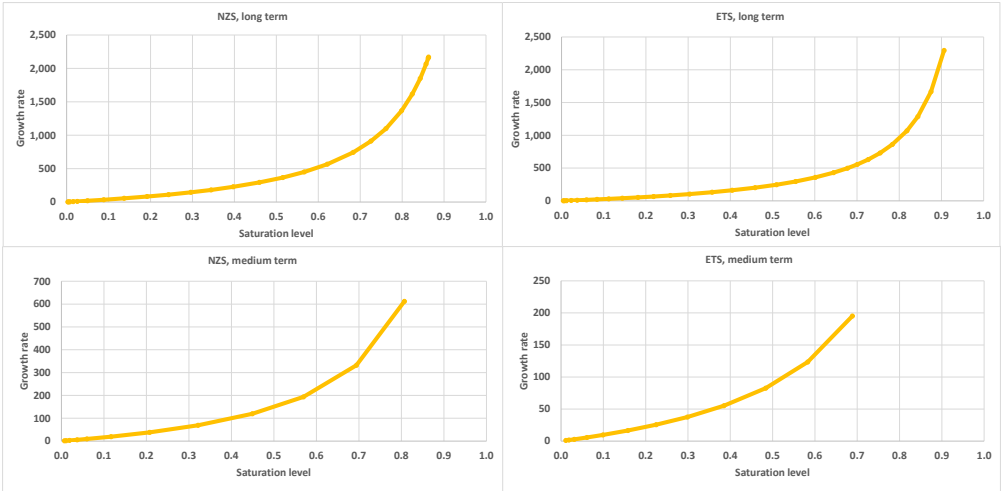
Fig. 41. Growth rate and saturation level of total RE, solar, and wind scenarios

The results of this part of the study (reflected in the graphs) show the phenomenon of the Saturation Paradox: as the system approaches saturation based on installed capacity, the logistic growth rate increases accordingly, and in some cases (at saturation level exceeding 0.9), it reaches almost hyperbolic growth. When evaluating the results, it should be taken into account that in the calculations, the independent variable C_a is a predicted value, which also has signs of logistic growth. However, the analysis does not include the validity of the forecasting assumptions, the forecasting methodology itself. The study is based on data provided by Bloomberg (BloombergNEF, 2024b).

According to the graphs (see Fig. 41), the logistic growth rate of solar installed capacity is higher in all scenarios. However, the saturation level does not differ significantly in different scenarios. The wind sector characteristically reflects the growth trends of the entire RE. Depending on the sector, period length, and scenario, the logistic growth rate is different and unique, except for a few cases where the general RE and wind growth curves usually coincide in periods and scenarios. This can be explained by the different initial capital (installed capacity, C_0) at the beginning of the period in 2020 and different forecasting results C_a or the estimated market

(sector) potential capacity (C_p). The results of batteries are particularly different from the results of solar, wind, and total installed RE capacity (which is why the graphical representation is distinguished). The uniqueness of the battery sector is that the accumulated capital (installed capacity) at the beginning of the period in 2020 is close to zero, which is why the growth rate is significantly higher. Therefore, the battery storage saturation level and growth rate curves have a different shape than the curves of the remaining analysed systems.

The results of battery capacity are presented separately (see Fig. 42).

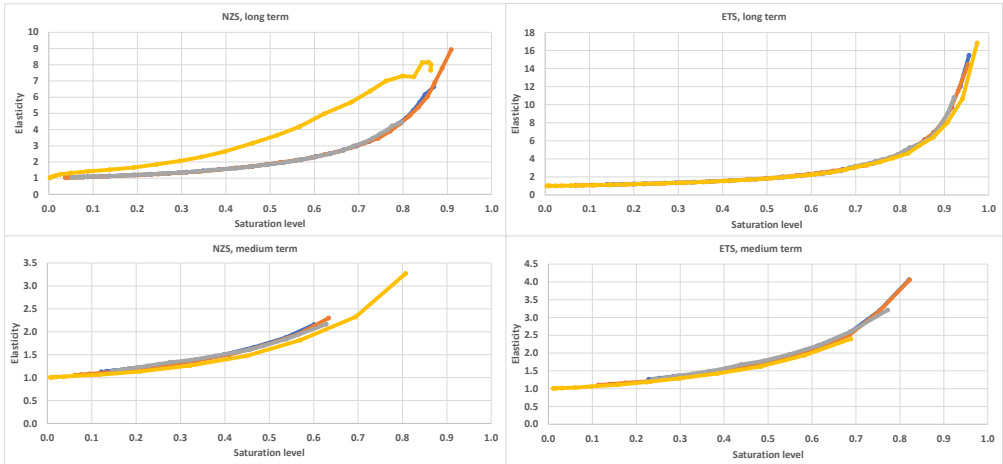


Source: developed by the author by consolidating the results of Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

Fig. 42. Growth rate and saturation level of battery storage scenarios

The battery storage scenarios show the highest sensitivity to changes in saturation and growth rate. The Bifurcation Point is reached in all battery storage scenarios, except for the ETS medium-term scenario (ETS M B). This indicates that battery storage is one of the most sensitive systems in the forecast data, because low initial installed capacity and a rapid projected expansion lead to a high logistic growth rate and a rapid increase in saturation level.

If the growth rates across different systems cannot be directly compared, the elasticity of the growth rate with respect to the saturation level provides a basis for such comparison. The elasticity provides an opportunity to assess objectively the sensitivity of growth rate to installed capacity. A comparison of elasticities by scenarios is presented in Fig. 43.



Source: developed by the author by extending Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

Note: blue line represents total RE; orange line represents solar; grey line represents wind; yellow line represents battery storage

Fig. 43. Elasticity dynamics across all scenarios

In the ETS long-term scenarios, the elasticity almost coincides in all solar, wind, battery capacity, and total RE systems. In the ETS medium-term and NZS medium-term scenarios, the trajectory of the elasticity change in the systems coincides, but the starting and ending points differ due to the different saturation levels in the period under consideration. In the NZS long-term case, the elasticity of the battery capacity system is significantly higher and fundamentally different from the remaining systems.

As described earlier, elasticity, together with the saturation level, helps to identify the Bifurcation Point, beyond which positive feedback becomes increasingly significant. In the previous sections, significant positive feedback was assumed when the elasticity of the growth rate reached approximately 2. However, because this part of the study is based on forecast data and covers a substantially longer time horizon, a more conservative threshold is applied. Accordingly, significant positive feedback is considered to occur when elasticity reaches approximately 2.5.

The summarised results of the scenarios calculations (see Table 22) are presented below, and the bubble formation and its type are determined. It should be noted that when analysing forecast data, the bubble type is interpreted indicatively on the basis of saturation stages. Without historical data after the potential bubble-formation stage, it is not possible to directly assess the actual beneficial or harmful effects of the bubble. Therefore, the classification in Table 22 should be understood as a scenario-based interpretation of potential bubble dynamics.

Table 22. Summary of installed capacity-based saturation and bubble analysis across scenarios

Scenario	C_p	C_{max}	r_{max}	Max saturation	Max elasticity	Bifurcation/ bubble	Heating, year	Overheating, year	Bubble type
ETS L T	21,686	20,719	133.18	0.96	15.46	Yes	10	3	Destructive
ETS L S	11,463	10,923	274.28	0.95	14.43	Yes	9	3	Destructive
ETS L W	5,119	4,717	69.16	0.92	10.81	Yes	11	2	Destructive
ETS L B	3,100	3,018	8,779.9	0.97	16.83	Yes	6	3	Destructive
ETS M T	13,155	10,802	15.5	0.82	4.06	Yes	2	-	Productive
ETS M S	6,937	5,701	36.06	0.82	4.06	Yes	2	-	Productive
ETS M W	3,145	2,428	10.97	0.77	3.21	Yes	1	-	Productive
ETS M B	1,160	799	195.1	0.69	2.4	No	-	-	-
NZS L T	42,804	37,216	88.22	0.87	6.64	Yes	9	-	Productive
NZS L S	21,117	19,187	256.81	0.91	8.93	Yes	9	1	Destructive
NZS L W	14,358	11,447	72.16	0.8	4.44	Yes	6	-	Productive
NZS L B	4,488	3,983	2,715.14	0.89	8.16	Yes	13	-	Productive
NZS M T	24,815	14,909	10.92	0.6	2.16	No	-	-	-
NZS M S	12,752	8,079	26.29	0.63	2.3	No	-	-	-
NZS M W	5,075	3,187	9.86	0.63	2.16	No	-	-	-
NZS M B	1,916	1,546	611.92	0.81	3.27	Yes	1	-	Productive

Source: adapted from Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

In the long-term scenarios, saturation levels and logistic growth rates are generally higher than in the medium-term scenarios. This reflects the longer period of installed capacity expansion, during which the systems move closer to their estimated capacity limits. In the medium-term scenarios, saturation levels and growth rates remain lower in most systems, because the forecast period is shorter and the systems have less time to approach their potential capacity.

Comparing the ETS and NZS scenarios shows that higher absolute installed capacity does not necessarily imply higher relative saturation level. In several cases, the ETS scenario reaches a higher saturation level and logistic growth rate than the NZS scenario because the estimated system capacity is lower. Therefore, a slower projected expansion path may lead to faster relative saturation when the system capacity limit is more restricted. In the medium-term, the same trend is observed between the ETS and NZS scenarios as in the long term, although both the saturation level and growth rate are significantly lower.

Based on the saturation level and elasticity, the timing of the Bifurcation Point, heating Stage II and overheating Stage III are estimated for each scenario. These

timing results are summarised in Table 23 and should be interpreted as indicative, because they are based on forecast data and the assumptions defined in the study.

Table 23. Timeline of saturation stages and bubble formation across scenarios

ETS								
	Long term				Medium term			
	Total RE	Solar	Wind	Battery	Total	Solar	Wind	Battery
Heating Stage II; Bifurcation Point, in year	2038	2039	2038	2042	2030	2030	2031	-
Overheating Stage III, in year	2048	2048	2049	2048	-	-	-	-

NZS								
	Long term				Medium term			
	Total RE	Solar	Wind	Battery	Total	Solar	Wind	Battery
Heating Stage II; Bifurcation Point, in year	2042	2041	2045	2038	-	-	-	2031
Overheating Stage III, in year	-	2050	-	-	-	-	-	-

Source: adapted from Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

While all the analysed renewable energy systems are subject to saturation based on installed capacity, the intensity of associated risks varies across systems, depending on their growth dynamics, capacity expansion, initial installed capacity, and structural characteristics:

- Battery storage is the most vulnerable sector, with bifurcation (0.7) expected by 2031 (NZS, medium term) and by 2038 (NZS) and 2042 (ETS) for long term, and overheating (0.9) by 2048 (ETS, long term). Rapid technological development and strong expectations regarding future deployment may increase the risk of overheating in related financial, technology, equipment, and infrastructure markets.

- Solar energy follows, with its bifurcation expected around 2041 (NZS) and 2039 (ETS) for long term and 2030 (ETS) for medium term, and overheating (0.9 saturation) expected in long term by 2048 (ETS) and 2050 (NZS). Policy-driven deployment targets and investment expectations may increase saturation-related risks in related markets.

- Wind energy is the least vulnerable, with a longer development cycle and more stable projected expansion, delaying saturation-related overheating risks.

- Total renewable energy follows, with its bifurcation expected around 2042 (NZS) and 2038 (ETS) for long term and 2030 (ETS) for medium term, and overheating (0.9 saturation level) expected in long term by 2048 (ETS).

This finding is also consistent with Hirth's (2013) analysis of variable renewable energy, which shows that an increase in solar and wind penetration does not automatically translate into proportional economic value. As the share of variable renewable generation increases, its market value may decline if system flexibility, storage capacity, grid infrastructure, and demand-side response do not expand accordingly (Hirth et al., 2015). Therefore, installed capacity growth should not be interpreted as an isolated indicator of sectoral success, but as a process that must be assessed together with the system's ability to absorb, balance and economically value additional generation.

Bubbles cannot form directly on the basis of installed capacity alone. However, the installed capacity saturation level may indicate physical or technological oversaturation, which can be transmitted to financial, resource, technology, construction, and other related markets where speculative capital flows may emerge. Therefore, the installed capacity saturation is interpreted as an indirect and time-lagged signal of potential bubble-formation risks, rather than as direct evidence of a financial bubble. This time lag arises because capital inflows, investment decisions, and speculative expectations may emerge before the corresponding physical capacity is installed and reflected in the installed capacity data. The oversaturation of the installed capacity may lead to several related risks: overcapacity and overproduction; system instability, where small changes in installed capacity may cause disproportionate changes in system dynamics; pressure on grids, supply chains, equipment and construction markets; and the formation of speculative dynamics in related financial, technology, resource or infrastructure markets.

When a certain saturation level based on installed capacity is reached, the risk of bubble formation becomes relevant mainly in those related markets where speculative capital behaviour is possible. The identified periods therefore indicate the sectors and time intervals in which saturation may create favourable conditions for bubble formation. However, since this part of the research is based on forecast data, the specific type of bubble and its consequences cannot be determined directly. They can only be interpreted indicatively through the logic of business cycle theory. In this context, the business cycle theory is used not to determine the exact future outcome, but to classify the possible type of saturation-related bubble dynamics according to the duration and nature of the forecast period.

In the long-term scenarios, the Kuznets infrastructure cycle is used as a reference point, because long-term renewable energy expansion is closely related to investment in infrastructure, equipment, construction, and other productive assets. In the medium-term scenarios, the Juglar investment cycle is more relevant, as it reflects fluctuations in fixed capital investment and the lifecycle of technologies. Since the analysed data are forecast-based, it is not possible to determine with certainty which cycle will dominate. Therefore, Schumpeter's interpretation of economic cycles (Girdzijauskas, 2024; Schumpeter, 1983) is used as a broader theoretical framework for explaining how innovation waves, investment growth, and production expansion may interact with saturation and potential bubble formation (see Fig. 44).

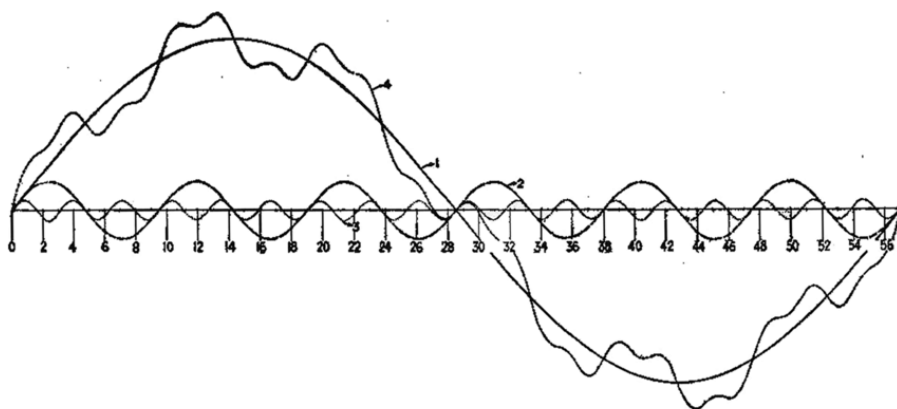


CHART I.—Curve 1, long cycle; curve 2, intermediate cycle; curve 3, short cycle; sum of 1–3.

Source: Gutiérrez-Barbarrusa (2019), Schumpeter (1983)

Fig. 44. Schumpeter's three-cycle model of economic development

Taking into consideration the *ceteris paribus* forecasting approach and the broad assumptions used in this part of the research, the identified stages of bubble formation should be interpreted as indicative rather than deterministic. During the analysed period, market capacity, investment expectations, technological change, renewable energy policy, system flexibility, and capital inflows may change substantially. Therefore, the estimated Bifurcation Point, heating Stage II, and overheating Stage III indicate possible periods of increased saturation risk rather than exact future outcomes. These stages may be associated with productive bubble dynamics if investment growth supports technological development and implementation. However, after the Bifurcation Point, positive feedback in deficit markets may also cause rapid growth to become unstable and lead to overheating. For this reason, the results of this subsection provide a basis for later recommendations on monitoring saturation risks, maintaining system stability during Stage II, and reducing the likelihood of transition to destructive overheating in Stage III.

3.5 Synthesis of Empirical Results

The empirical research clarified the applicability of the developed model to different types of renewable energy-related systems. The model was applied at three empirical levels: a regional biomass-based district heating system, renewable energy-related financial market indices, and global installed capacity scenarios. The results reveal that the model can be used to assess saturation level, logistic growth rate, elasticity, the Bifurcation Point, and potential bubble formation under different empirical conditions. However, due to the assumptions, simplifications, and static elements used in the model, the obtained results should be interpreted as indicative rather than fully predictive.

The empirical part applied three different forms of saturation measurement: installed capacity, price, and accumulated capital. These variables are not identical and represent different dimensions of saturation under specific assumptions and limitations. Installed capacity mainly reflects physical or technological saturation and

may indicate potential bubble risks in related financial, resource or technology markets, where speculative behaviour can emerge. This is especially important in the case of variable renewable energy, where the expansion of installed solar and wind capacity does not necessarily generate proportional economic value if system flexibility, storage, grid infrastructure, and demand-side response do not expand accordingly.

Price-based assessment provides the most direct market valuation, since price is one of the central indicators in bubble analysis. The accumulated capital, in turn, reflects the financial concentration of investments. It is related to price dynamics, although the empirical analysis shows that this relationship may involve a time lag. Another important distinction concerns the nature of the data used. Most systems were analysed using historical data, while part of the research was based on forecast data. Historical data allow for more precise assessment of investment effects on system stability, because turning points and corrections are already observable and system capacity can be estimated more reliably. Forecast data, by contrast, do not directly reveal such turning points. Therefore, additional assumptions regarding business cycles and scenario duration are required. In the installed capacity scenario analysis, these assumptions are especially important because the estimated timing of bifurcation, heating and overheating stages depends on the selected forecast period, business cycle interpretation and estimated system capacity.

The empirical analysis also allowed productive and destructive bubbles to be distinguished. The results indicate that the type of bubble depends not only on rapid growth, saturation level and elasticity, but also on the subsequent dynamics of the system. In some cases, the application of the model does not produce a fully unambiguous classification of the bubble type at the moment of growth. However, historical data after the peak or correction period help to verify and refine the interpretation. Productive bubbles are associated with heating and capital absorption without severe system correction, whereas destructive bubbles are linked to higher saturation, stronger elasticity, overheating, and significant correction after the growth period. Thus, the empirical results support the use of saturation level, elasticity, the Bifurcation Point and subsequent system dynamics as complementary criteria for identifying the nature of bubble formation.

The main limitation of the model is related to the estimation of system capacity and its possible change over time. In this research, capacity is estimated from historical or forecast data and treated as fixed within the analysed period. This simplifies the empirical application but limits the model's ability to account for technological progress, policy support, infrastructure development, and changes in market absorption conditions. Another limitation concerns the relationship between accumulated capital, price and installed capacity. The empirical results show that these variables may not move simultaneously and that time lags may occur between financial market reactions, capital accumulation and real sector development.

External factors also remain important. The model focuses on saturation, elasticity, feedback, and growth limits, while external triggers of bubble formation are not directly modelled. However, the empirical cases show that policy changes, regulation, technological expectations, financial support, liquidity conditions and

market narratives can initiate or strengthen capital flows. For this reason, the results should not be generalised as evidence of a single green bubble in the entire renewable energy sector. They should be interpreted as system-specific findings. Similarly, growth rates and elasticity values cannot be directly compared across different empirical systems without additional balancing or normalisation coefficients, because the analysed systems differ in scale, structure, data type and market characteristics.

CONCLUSIONS

1. The dissertation established a conceptual and theoretical framework linking renewable energy development, investment processes, financial bubbles, and logistic economic growth. The developed framework is based on the idea that renewable energy expansion, investment growth, and bubble formation should be analysed together through the perspective of limited growth. Logistic growth models and marginalism provide the theoretical basis for explaining the importance of growth limits and the necessity of evaluating system capacity.

The analysis showed that renewable energy development cannot be assessed only as a technological or environmental transition. Renewable energy systems require large-scale investments, policy support, subsidies, and legal regulation in order to compete with conventional energy systems. However, the research also revealed that intensive promotion, high expectations, and rapid investment inflows may create conditions for speculative dynamics. In this context, investment flows become not only a source of renewable energy expansion, but also a mechanism increasing the probability of saturation and bubble formation.

The dissertation showed that traditional growth approaches based on assumptions of unlimited expansion are insufficient for explaining overheating and bubble formation in renewable energy markets. Marginalism introduces the concept of diminishing marginal utility and the importance of limits into economic analysis. This provides the theoretical justification for evaluating renewable energy development through logistic growth and Financial Saturation Theory.

The developed framework also indicated that bubbles should not be interpreted only as destructive phenomena. Productive bubbles may support technological development and system expansion, while destructive bubbles lead to instability, inefficient allocation of capital and harmful economic corrections. This distinction allows bubbles to be evaluated through their economic impact rather than only through normative interpretation.

The findings justify the need to analyse renewable energy investment dynamics through a limited-growth perspective. The review of growth models and marginalism shows that renewable energy expansion should be assessed not only through deployment targets and investment volumes, but also through system limits, marginal effects and the risks created by excessive growth expectations.

2. The analysis of Financial Saturation Theory systematised and refined the main theoretical elements necessary for explaining bubble formation under conditions of limited growth. The dissertation showed that bubbles can be interpreted not only as speculative or psychological phenomena, but also as structural outcomes of investment-driven market saturation, logistic growth, and feedback mechanisms. In this context, Shiller's behavioural and narrative interpretation of bubbles is linked with the structural logic of Financial Saturation Theory. Collective expectations, narratives and investor psychology may initiate or amplify speculative investment waves, while financial saturation explains the conditions under which these waves become structurally unstable. The dissertation therefore interprets bubble formation as a behavioural-structural process, in which narrative-driven expectations interact

with saturation, elasticity, positive feedback and limited market capacity. The developed framework integrates the Bifurcation Point, elasticity, feedback polarity, Market Duality, and growth stages into a unified explanation of bubble formation.

The analysis clarified that growth stages defined according to saturation level are essential for identifying bubble formation in economic systems. The dissertation showed that before bifurcation, negative feedback and relative inelasticity dominate, while after bifurcation, increasing elasticity activates positive feedback and creates conditions for accelerated growth and speculative dynamics.

The Saturation Paradox was interpreted as a mechanism through which increasing saturation may lead to rising profitability or growth intensity, while simultaneously reducing system stability and increasing sensitivity to shocks. The analysis further demonstrated that under high saturation and post-bifurcation conditions, the Saturation Paradox contradicts the classical principle of diminishing returns.

The dissertation refined the concept of Market Duality by distinguishing between the remaining fundamental market and the deficit market formed after bifurcation. This distinction explains why, after bifurcation, positive feedback and increasing returns may dominate instead of classical self-regulating market mechanisms. Under these conditions, productive and destructive bubbles become possible. The analysis also showed that productive bubbles are associated with the heating stage (Stage II), while destructive bubbles are associated with the overheating stage (Stage III), although their final classification also depends on subsequent system dynamics. This links bubble classification with saturation-based growth stages.

The phenomenological analysis of market mechanisms and schemes, such as Ponzi dynamics, pump and dump schemes; scarcity and abundance economies confirmed the broader applicability of the developed framework. These phenomena can be interpreted as extreme manifestations of positive feedback, deficit market dynamics, and saturation-based growth.

The dissertation demonstrated that financial bubbles may emerge as structurally conditioned outcomes of investment-driven saturation, bifurcation, and positive feedback in systems approaching growth limits. External shocks and stochastic factors may initiate market transitions, but subsequent bubble dynamics can be primarily explained through the internal mechanisms of financial saturation.

3. A methodological model based on Financial Saturation Theory was developed for assessing market saturation dynamics and bubble formation in the context of renewable energy investments. The model operationalises the theoretical principles of Financial Saturation Theory by transforming bubble formation into a measurable analytical framework based on market or system capacity, saturation level, logistic growth rate, elasticity, and bifurcation indicators.

The model evaluates investment-driven saturation through three empirical proxies: price dynamics, accumulated capital, and installed capacity. This proxy structure allows the model to be applied across different types of renewable energy systems. In this framework, investments are interpreted as an important driver of saturation dynamics, while price dynamics, accumulated capital, and installed capacity are treated as different empirical indicators for assessing saturation.

The developed methodological approach integrates a structured process for identifying and classifying bubbles through the relationship between saturation level, elasticity, and the Bifurcation Point, distinguishing between productive and destructive bubble types. The final classification of the bubble type is additionally linked to the subsequent dynamics of the analysed variable, assessing whether a significant correction, stabilisation or further system expansion occurs after the growth peak.

The dissertation demonstrated that the logistic growth framework can be adapted for the analysis of renewable energy investments through the transformation of variables into capital, price, and installed capacity expressions. In contrast to classical demand and supply models, saturation level and accumulated capital are treated as independent variables influencing the logistic growth rate. This reversed causality forms one of the main methodological distinctions of the model.

The developed model also revealed several important assumptions and limitations. It is deterministic and assumes fixed market or system capacity, homogeneous agents, *ceteris paribus* conditions, and limited consideration of time lag effects. External shocks, policy changes, stochastic fluctuations, and post-collapse dynamics are not directly modelled and are treated as external conditions influencing the system. These limitations define the scope of applicability of the model and indicate directions for further methodological development.

4. The empirical application showed that the developed model can be applied across different renewable energy systems and analytical levels, including regional energy systems, renewable energy financial indices, and global installed capacity projections. Across these levels, the model identified saturation dynamics, Bifurcation Points, elasticity changes and bubble formation stages using price dynamics, accumulated capital and installed capacity growth as empirical indicators.

In the biomass-based district heating system of Kaunas, the model identified a productive bubble related to biomass installed capacity expansion. Strong policy support, market liberalisation, and high investment expectations accelerated renewable energy development and reduced heat prices for consumers, but also created structural imbalances, stronger competition pressure, and overcapacity risks for producers. The case showed that policy intervention and investment stimulation may solve one market problem while simultaneously creating another.

In renewable energy financial indices, the model identified both productive and destructive bubbles. The results also showed that different index systems have unique growth rates, elasticity structures, and saturation dynamics, which limit direct comparability and prevent generalisation of results to the entire renewable energy sector. The analysis additionally revealed time lag effects between capital accumulation and price dynamics, showing that investment expectations may temporarily distort the relationship between saturation and market valuation.

The analysis of global renewable energy installed capacity projections revealed different saturation and bubble risks across renewable energy sectors. Battery storage systems appeared to be the most vulnerable to overheating, while wind systems showed lower saturation sensitivity. The comparison between NZS and ETS scenarios also showed that slower installed capacity growth may still lead to faster saturation

under more constrained capacity conditions. These results should be interpreted as a scenario-based assessment of physical and technological saturation risks, because installed capacity saturation is not direct evidence of a financial bubble, but an indirect signal of possible risks in related financial, technology, resource or infrastructure markets.

The empirical application also confirmed important limitations of the developed model. The framework relies on deterministic assumptions, fixed or estimated market capacity, simplified time relationships, and limited consideration of external shocks and stochastic factors. These assumptions make the results more theoretical and limit the direct application of the model to complex real-world economic processes.

5. The theoretical and empirical analysis demonstrated that renewable energy investments should be evaluated not only through expansion targets and technological development, but also through market saturation dynamics, system stability, and bubble formation risks. The dissertation showed that the main risk in renewable energy markets may arise not only from scarcity, but also from excessive investment concentration and growth that exceeds the system's ability to absorb capital efficiently. As systems approach saturation limits, expectations, and positive feedback increasingly dominate over rational valuation, increasing systemic instability and the probability of destructive bubbles.

The dissertation demonstrated that Financial Saturation Theory provides a framework for transforming bubble formation into a measurable analytical system through saturation level, elasticity, logistic growth, and bifurcation indicators. Investment flows are treated as the main driver of saturation, while price dynamics, accumulated capital, and installed capacity act as empirical proxies reflecting different forms of investment-driven saturation.

The empirical results confirmed that productive bubbles may support technological development and market transition, while destructive bubbles emerge when investment growth becomes detached from the system's ability to absorb capital and maintain stability. The analysis also showed that market capacity and its dynamics are critically important for interpreting saturation and bubble risks. In the developed framework, system potential capacity is estimated from historical or forecast data, but its validity can only be fully evaluated retrospectively through subsequent system development.

The analysis demonstrated that identifying Bifurcation Points requires monitoring not only saturation levels, but also changes in elasticity, accelerating growth rates, divergence between capital inflows and installed capacity growth, and the emergence of self-reinforcing market behaviour. Rapid elasticity growth and increasing divergence between financial growth and real capacity expansion may therefore serve as early warning indicators of overheating and instability in renewable energy systems.

The dissertation also showed that renewable energy policy should not be based only on maximising installed capacity or achieving the fastest possible growth. Excessive promotion and investment stimulation may accelerate renewable energy transition, but may simultaneously create structural imbalances, overcapacity, and destructive competition. Therefore, economic systems should be designed to remain

resilient to saturation by balancing investment growth, market capacity, competition intensity, and system stability.

The results also raise broader questions regarding the long-term objective of achieving fully saturated or near 100% renewable energy systems. The analysis of Financial Saturation Theory, the Saturation Paradox, and increasing instability near saturation limits suggests that excessive concentration of investment may create structural vulnerabilities even in sustainable energy systems. Although this issue requires further research, these tendencies should be considered in long-term renewable energy policy and investment planning.

Based on the theoretical and empirical results, the following recommendations are proposed for renewable energy policymakers and investors:

- Renewable energy investment and support policies should include monitoring of market capacity, saturation level, elasticity, growth acceleration, and divergence between capital inflows and installed capacity growth in order to identify increasing instability before destructive bubbles emerge.
- Saturation levels between approximately 0.7 and 0.9 may indicate intensive but still relatively stable growth conditions, while saturation levels above 0.9 should be treated as potentially speculative and associated with overheating risks.
- Policy measures should aim not only to stimulate renewable energy growth and make effective use of the productive dynamics of Stage II, but also to prevent structural overcapacity and destructive competition through gradual and adaptive support mechanisms.
- Future research and policy analysis should incorporate dynamic market capacity changes, external shocks, technological change, geopolitical conditions, and stochastic factors influencing renewable energy systems.

The dissertation demonstrated that the greatest economic risks may arise not only from scarcity, but also from excess, when investment growth exceeds the system's ability to absorb it sustainably. By linking the behavioural and narrative interpretation of speculative dynamics with the structural logic of Financial Saturation Theory, the dissertation shows that collective expectations, narratives and investor psychology may initiate or amplify investment waves, while financial saturation determines the conditions under which these waves become structurally unstable. The Financial Saturation Theory and the developed model therefore provide a broader analytical framework for understanding how sustainable development itself may become unsustainable when growth approaches structural limits. In this context, the dissertation contributes to the analysis of renewable energy transitions, investment-driven market dynamics and bubble formation under conditions of limited growth. Its main implication is that renewable energy investment should be assessed not only by its contribution to decarbonisation and capacity expansion, but also by its relation to market capacity, saturation level, and system stability, so that sustainable development based on renewable energy can remain sustainable in the long term.

SANTRAUKA

IVADAS

Temos aktualumas

Pasaulinis perėjimas prie atsinaujinančiosios energijos yra viena esminių klimato kaitos švelninimo ir tvarios plėtros sąlygų, paremtas tarptautiniais susitarimais, spartėjančia technologine pažanga, mažėjančiomis sąnaudomis ir stipria politikos parama – subsidijomis ir mokesčių lengvatomis (BloombergNEF, 2024a; International Energy Agency, 2023). Dėl šių ir kitų veiksnių susiformavo precedento neturinčios kapitalo įplaukos į atsinaujinančiosios energetikos sektorių ir spartus šio sektoriaus instaliuotos galios augimas, kurį ateityje daugiausia turėtų lemti saulės ir vėjo energetika.

Vis dėlto, nors tvarumas yra vienas pagrindinių šiuolaikinės energetikos politikos prioritetų, atsinaujinančiosios energetikos sektorius nėra atsparus tam tikroms rizikoms. Didelės investicijos, technologinis pasitikėjimas ir valstybės parama sudaro sąlygas sparčiai rinkos plėtrai, tačiau kartu gali kelti pervertinimo ir spekuliacinės veiklos rizikas. Šią problematiką galima aiškinti remiantis R. J. Shillerio požiūriu, kad finansų rinkas veikia ne tik racionalūs skaičiavimai ir fundamentalieji rodikliai, bet ir kolektyviniai lūkesčiai, investuotojų psichologija, pasitikėjimas, socialinis plitimas bei ekonominiai naratyvai (Akerlof & Shiller, 2009; Shiller, 2015, 2020). Atsinaujinančių energijos išteklių (AEI) rinkose tokie naratyvai gali būti ypač reikšmingi, nes investiciniai lūkesčiai glaudžiai susiję su klimato politikos tikslais, dekarbonizacija, technologiniu optimizmu ir platesniu visuomenės tvarumo poreikiu. Todėl investicijas į AEI gali veikti ne tik fundamentalios rinkos sąlygos, bet ir kolektyviai sustiprinti lūkesčiai dėl būsimo augimo bei technologinės transformacijos. Šioje disertacijoje ši problema nagrinėjama taikant finansinio prisotinimo teoriją, kuri ekonomikos ir investicijų augimą aiškina kaip ribotos talpos sistemose vykstantį prisotinimo procesą.

2025 m. ekonomikos mokslų premija Alfredo Nobelio atminimui išryškino inovacijomis grindžiamo augimo ir kūrybinės destruktijos reikšmę, pabrėžiant, kad ilgalaikis ekonomikos augimas priklauso nuo technologinės pažangos, žinių kaupimo ir pasenusių struktūrų pakeitimo naujomis technologijomis (Aghion & Howitt, 1992; Mokyr, 2016; Nobel Prize, 2025). Atsinaujinančiosios energetikos rinkose ši perspektyva ypač svarbi, nes inovacijos, technologinis pakeičiamumas ir pasenusių energetikos struktūrų keitimas naujomis technologijomis gali formuoti naujus augimo ciklus ir stiprinti lūkesčius dėl būsimos technologinės transformacijos. Kartu ši perspektyva išryškina dinamišką ir ciklišką augimo pobūdį, keliant klausimą, kiek ilgai ir kaip sparčiai AEI sistemos gali plėstis kintančiomis technologinėmis, paramos ir investicinėmis sąlygomis.

Didėjantis finansinis gylis, istoriniai finansinių burbulų pavyzdžiai, augantys lūkesčiai dėl technologinės transformacijos ir stipri politinė parama AEI sektoriui rodo, kad atsinaujinančiąja energetika grindžiamas darnus vystymasis taip pat gali tapti pažeidžiamas dėl nestabilios investicijų dinamikos. Šiame kontekste disertacijos aktualumas grindžiamas poreikiu vertinti ne tik investicijų į AEI augimą, bet ir ribas,

kuriose su AEI susijusios sistemos gali absorbuoti kapitalą, technologijas ir instaliuotą galią nesukurdamos nestabilumo. Inovacijos ir kūrybinė destrukcija gali keisti šias ribas, tačiau jos nepanaikina prisotinimo rizikų. Priešingai, jos daro investicijų intensyvumo, rinkos talpos, sistemos absorbcijos, augimo ciklų ir galimo perkaitimo ryšį dinamiškesnį. Finansinio prisotinimo teorija šiam tikslui gali suteikti tinkamą analitinę perspektyvą, nes leidžia investicijų skatinamą augimą vertinti atsižvelgiant į rinkos talpą, prisotinimo lygį, augimo greitį, grįžamojo ryšio mechanizmus ir burbulų formavimąsi. Jos taikymas investicijų į AEI analizei leidžia susieti šiuolaikinę burbulų dinamiką ir cikliškumą su platesniu riboto augimo taikymu ir įvertinti, ar atsinaujinančiąja energetika grindžiamas darnus vystymasis nepraradęs tvaraus augimo.

Mokslinės problemos ištirtumo lygis

Riboto augimo idėjos moksle atsirado dar ankstyvaisiais laikotarpiais, o XIX a. pradžioje Gomperto ir Verhulsto darbai padėjo pagrindą logistiniams augimo modeliams (Girdzijauskas, 2024; Sterman, 2000). Vėliau šie modeliai plačiai taikyti demografijoje, biologijoje, technologijų sklaidos, inovacijų, energetikos ir infrastruktūros tyrimuose. Logistinio augimo kreivė tapo universaliu įrankiu aiškinant, kaip spartų augimą keičia prisotinimas, lėtėjimas ir artėjimas prie sistemos ribų (Griliches, 1957; Grübler, 1996; Mahajan & Muller, 1979; Mansfield, 1961; May, 1976; Meyer et al., 1999; F. J. Richards, 1959; Rogers, 1976; Sterman, 2000). Logistiniai augimo modeliai taip pat pradėti taikyti ekonomikos, technologijų raidos, energetikos ir vėliau atsinaujinančiosios energetikos tyrimuose, vertinant technologijų sklaidą, instaliuotos galios augimą bei energijos vartojimo struktūrinius pokyčius (R. C. Koo, 2011a; Smirnov & Wang, 2020; Sornette, 2003, 2017; Tsoularis & Wallace, 2002). Tyrimai parodė, kad augimą riboja ištekliai, grįžtamas ryšys ir sistemos talpa (Greiner et al., 2014; Hansen et al., 2017; Karasmanaki et al., 2019; Mohamed & Bodger, 2005; Rypdal, 2018; Wei et al., 2016). Vis dėlto šie modeliai dažniausiai leidžia nustatyti augimo greitį ir ribines asimptotes, tačiau juos sudėtinga transformuoti į ekonomines funkcijas, tokias kaip paklausos, pasiūlos ar bendrojo naudingumo funkcijos. Be to, literatūroje trūksta vertinimų, kurie augimo greičio pokyčius sietų su sukauptu kapitalu, investicijų srautais ir rinkos talpa vertine išraiška. Šią spragą siekia užpildyti finansinio prisotinimo teorija, pasiūliusi naują sprendimą – prisotinimo palūkanas (bendrąsias palūkanas).

Finansinio prisotinimo teorija pradėta vystyti 1997–2002 m. (Girdzijauskas, 1997, 2002), o iki 2020 m. buvo vadinama logistine kapitalo valdymo teorija. Ši teorija išvystyta iš logistinio augimo taikymo kapitalo valdymui ir palaipsniui tapo išplėtotą ekonomikos augimo ribų aiškinimo sistema. Joje augimas suprantamas kaip ribotas procesas, priklausantis nuo rinkos talpos, prisotinimo lygio ir grįžamojo ryšio. Teorija buvo plėtojama analizuojant finansinius būbulus, ekonominius ciklus, krizes, vartotojų elgseną, viešuosius finansus ir tvarų vystymąsi. Ankstesni teorijos taikymai apėmė Baltijos akcijų indeksų, branduolinės energetikos, nekilnojamojo turto rinkos, draudimo, viešųjų finansų ir ekonominių ciklų analizę, dažnai naudojant logistinio modeliavimo programas, tokias kaip „Loglet Lab“ ir „LogMod“. Nepaisant plataus logistinių modelių ir finansinio prisotinimo teorijos taikymo įvairiose srityse, iki šiol trūksta tyrimų, kurie tiesiogiai jungtų AEI investicijas, rinkos prisotinimo dinamiką ir

burbulų formavimąsi finansinio prisotinimo teorijos pagrindu. Todėl ši disertacija siekia užpildyti šią spragą ir pritaikyti finansinio prisotinimo teoriją AEI investicijų poveikiui rinkos prisotinimui ir burbulų formavimuisi vertinti. Šios disertacijos indėlis siejamas su finansinio prisotinimo teorijos susisteminiu AEI investicijų vertinimo kontekste ir jos pritaikymu skirtingoms empirinėms sistemoms.

Mokslinė problema

Kaip finansinio prisotinimo teorija gali būti taikoma vertinant investicijų sukeltą rinkos prisotinimo dinamiką ir burbulų formavimąsi atsinaujinančių energijos išteklių panaudojimo energijos gamybai sektoriuje?

Tyrimo objektas

Investicijų sąlygoti finansinio prisotinimo procesai ir jų raiška atsinaujinančių energijos išteklių panaudojimo energijos gamybai sistemose ir rinkose.

Tyrimo tikslas

Sukurti ir pritaikyti finansinio prisotinimo teoriją pagrįstą modelį, skirtą vertinti investicijų į atsinaujinančių energijos išteklių panaudojimą energijos gamybai poveikį rinkos prisotinimo dinamikai ir burbulų formavimuisi.

Tyrimo uždaviniai

1. Sukurti konceptualų ir teorinį pagrindą, susiejantį atsinaujinančių energijos išteklių plėtrą, investavimo procesus, burbulų formavimąsi ir logistinį ekonomikos augimą, išryškinant politikos priemonių, išorinių veiksnių ir maržinalizmo reikšmę riboto augimo kontekste.
2. Išanalizuoti finansinio prisotinimo teorijos principus ir ištirti burbulų formavimosi mechanizmus šios teorijos kontekste.
3. Sukurti finansinio prisotinimo teorija paremtą modelį ir metodinį pagrindą, skirtą įvertinti investicijų į atsinaujinančių energijos išteklių panaudojimą energijos gamybai poveikį rinkos prisotinimo dinamikai ir burbulų formavimuisi.
4. Pritaikyti sukurta modelį ir jo analitinius įrankius, siekiant įvertinti investicijų į atsinaujinančių energijos išteklių panaudojimą energijos gamybai poveikį rinkos prisotinimo dinamikai ir burbulų formavimuisi.
5. Apibendrinti teorinės analizės ir empirinio modelio taikymo rezultatus bei suformuluoti išvadas ir praktines rekomendacijas investicijoms į atsinaujinančių energijos išteklių panaudojimą energijos gamybai, atsižvelgiant į rinkos prisotinimo ir burbulų formavimosi rizikas.

Ginamieji teiginiai

— Ekonomikos augimą ir investicijas riboja sistemos talpa, o investicijų ir augimo sąlygojamas didesnis prisotinimo lygis lemia didėjančią pelningumą (soties paradoksas), bet mažesnę sistemos stabilumą (augantį elastingumą).

— Pasiekus aukštą prisotinimo lygį, sistema patiria bifurkaciją, rinka pereina į deficitinę būseną, susidaro teigiamo grįžtamojo ryšio ir burbulų formavimosi sąlygos. Susidarantys burbulai gali būti naudingi (produktyvūs) ir žalingi

(destruktyvūs), jų pobūdį lemia pasiektas prisotinimo lygis ir elastingumas bei vėlesnė sistemos dinamika po spartaus augimo laikotarpio.

— Finansinio prisotinimo teorijos integravimas su logistinio augimo, elastingumo ir bifurkacijos principais sudaro nuoseklią sistemą netiesinei investicijų dinamikai ir burbulų formavimuisi aiškinti.

— Sukurtas finansinio prisotinimo teorija pagrįstas modelis yra taikytinas skirtingo masto ir tipo atsinaujinančiosios energetikos sistemoms ir leidžia nustatyti augimo stadijas, bifurkacijos taškus bei burbulų rizikas ir tipus pagal prisotinimo lygį ir elastingumo dinamiką.

Mokslinis naujumas

— Teorinis indėlis. Disertacijoje finansinio prisotinimo teorija sisteminama ir plėtojama AEI investicijų analizės kontekste kaip nuosekli sistema, paaiškinanti augimą su ribomis ir prisotinimo dinamiką. Investicijų srautai interpretuojami kaip pagrindinis finansinio prisotinimo veiksnys, siejantis kapitalo kaupimą su logistine rinkos dinamika. Į teorinį modelį integruojamas bifurkacijos taškas, elastingumas ir grįžamojo ryšio mechanizmai. Lyginami klasikinės rinkos pusiausvyros ir deficitinės rinkos pusiausvyros modeliai. Suformuojama vieninga teorinė struktūra, integruojanti prisotinimo lygį (su jo stadijomis), elastingumą, soties paradoksą ir grįžamojo ryšio efektus. Sukuriama prisotinimu pagrįsta finansinių burbulų klasifikacija, išskirianti produktyvius ir destruktivius burbulus pagal jų dinamiką ir ekonominius rezultatus. Analizuojami kiti rinkos mechanizmai, pagrįsti prisotinimu ir soties paradoksu.

— Metodologinis indėlis. Sukurtas originalus modelis atsinaujinančiosios energetikos sektoriaus (rinkų), jų bifurkacijos, augimo stadijų ir burbulų formavimosi vertinimui. Modelis pagrįstas logistinio augimo principų transformavimu į paklausos ir pasiūlos funkcijas ir sistemą, susiejančią sukauptą kapitalą, kainų dinamiką ir instaliuotą galią. Į modelį integruojama elastingumo dinamika, soties paradoksas ir burbulų formavimosi mechanizmas. Investicijų srautai laikomi kaip išmatuojamas prisotinimo veiksnys, leidžiantis vertinti kapitalo kaupimo poveikį augimo stadijoms, bifurkacijos taškams ir sistemos stabilumui. Modelis taip pat leidžia nustatyti stabilų ir augimą palaikančių sistemos stadijų ribas bei paaiškina perėjimus į nestabilumo stadijas.

— Empirinis indėlis. Empirinis tyrimas atliktas trimis analitiniais lygiais: regioninės energetikos sistemos, finansų rinkų ir pasaulinių instaliuotos galios projekcijų. Šiose rinkose empiriškai įvertinti prisotinimo lygiai ir elastingumas. Nustatytos augimo stadijos. Aptikti bifurkacijos taškai. Nustatyti burbulų tipai ir su burbulais susijusios prisotinimo rizikos. Rezultatai patvirtina finansinio prisotinimo teorijos taikomumą empirinių ir scenarijais grindžiamų atsinaujinančiosios energetikos sistemų analizei.

— Praktinis indėlis. Pateikiamos rekomendacijos atsinaujinančiosios energetikos politikos formuotojams ir investuotojams dėl investicijų ir kapitalo srautų valdymo, atsižvelgiant į rinkos talpą, prisotinimo stadiją, bifurkacijos dinamiką ir sistemos stabilumą.

Galimos praktinio taikymo kryptys

— Sukurtas modelis leidžia nustatyti sistemos prisotinimo lygį ir identifikuoti potencialiai netvarias būsenas, susijusias su burbulų formavimusi. Modelis taip pat leidžia vertinti sistemos augimo ribų poveikį pelningumo augimo greičiui, sistemos stabilumui ir ilgalaikiam tvarumui.

— Modelis suteikia galimybę vertinti AEI sistemų prisotinimo lygius ir galimas burbulų formavimosi rizikas bei pateikia rekomendacijas dėl šių rizikų valdymo. Taip pat jis leidžia įvertinti, kaip soties paradoksas gali būti panaudojamas spartinant sistemos augimą produktyvių burbulų atvejais ir kaip mažinti nestabilumo bei žalos riziką destruktivių burbulų atveju.

— Sukurtas modelis gali būti taikomas kaip analitinis įrankis rinkos perkaitimo stebėsenai, ankstyvam nestabilumo požymių nustatymui bei investicinių ir politikos sprendimų priėmimui AEI sistemose.

Tyrimo metodai

Šiame darbe naudoti tyrimo metodai: logistinė analizė, mokslo šaltinių teorinė analizė, sintezė ir apibendrinimas. Finansinio prisotinimo teorijos analizė ir tyrimo modelio kūrimas buvo grindžiami mokslo publikacijų, tyrimų ir studijų lyginamąja ir logine analize, remiantis lyginamaisiais, klasifikavimo ir apibendrinimo metodais.

Siekiant empiriškai patikrinti modelį, buvo atliktas empirinis tyrimas, naudojant istorinius ir prognozes duomenis iš atrinktų ekonominių sistemų. Sistemų talpai nustatyti buvo naudojamas logistinio augimo programinės įrangos paketas „Loglet Lab“.

Disertacijos struktūra

Disertacijoje nagrinėjami investicijų, rinkos prisotinimo ir burbulų formavimosi procesai atsinaujinančiosios energetikos sektoriuje.

Pirmojoje darbo dalyje analizuojama AEI samprata, klasifikacija, technologijos ir politika. Taip pat nagrinėjami finansiniai burbulai energetikos sektoriaus kontekste, išskiriant žaliuosius, produktyvius ir destruktivius burbulus. Šioje dalyje aptariami logistinio augimo modeliai ir maržinalizmo reikšmė aiškinant riboto augimo procesus.

Antrojoje darbo dalyje analizuojami finansinių burbulų formavimosi mechanizmai remiantis finansinio prisotinimo teorija. Integruojamos finansinio prisotinimo, soties paradokso, elastingumo, teigiamo grįžtamojo ryšio, bifurkacijos ir rinkos dualumo sąvokos. Šios dalies teorinė analizė sudaro pagrindą metodiniam modeliui, skirtam rinkos prisotinimo dinamikai ir burbulų formavimuisi vertinti.

Trečiojoje darbo dalyje pateikiamas empirinis modelio taikymas trijose sistemose: Kauno regiono biokuru grindžiamo centralizuoto šildymo sistemoje, atsinaujinančiosios ir švarios energetikos akcijų indeksuose bei pasaulinėse AEI (saulės, vėjo ir baterijų kaupimo) instaliuotos galios prognozėse. Tyrime nustatomi prisotinimo lygiai, bifurkacijos taškai, augimo stadijos ir skirtingi finansinių burbulų tipai ir su burbulais susijusios prisotinimo rizikos.

Darbas užbaigiamas išvadomis ir rekomendacijomis.

Ryšys su ankstesnėmis publikacijomis

Dalis disertacijos ir ankstesnės bendraautorinės publikacijos parengtos vykdant tą patį disertacinį tyrimą. Kai kurie teoriniai, metodiniai ir empiriniai tyrimo elementai anksčiau paskelbti Karaša ir Girdzijauskas (2024), Karaša ir kt. (2025) bei Mikalauskas ir Karaša (2025). Disertacijoje ši medžiaga peržiūrėta, išplėsta ir integruota į platesnę teorinę bei empirinę tyrimo struktūrą, apimančią elastingumą, bifurkaciją, burbulų klasifikaciją, papildomus taikymus ir platesnę prisotinimo rizikų interpretaciją.

ATSINAUJINANČIOSIOS ENERGETIKOS INVESTICIJŲ, RINKOS PRISOTINIMO IR BURBULŲ FORMAVIMOSI KONCEPTUALUS PAGRINDAS RIBOTO AUGIMO SĄLYGOMIS

Pirmojoje darbo dalyje formuojamas konceptualusis ir teorinis pagrindas, siejantis atsinaujinančiosios energetikos plėtrą, investicijų procesus, rinkos prisotinimą, burbulų formavimąsi ir riboto ekonomikos augimo logiką. Šioje dalyje analizuojama AEI samprata, technologinė ir institucinė plėtra, investicijų dinamika bei finansinių burbulų formavimosi prielaidos. Taip pat nagrinėjami ekonominio augimo modeliai, logistinio augimo principai ir maržinalizmo reikšmė aiškinant augimo ribas bei prisotinimo procesus.

Disertacijoje terminas „atsinaujinantys energijos ištekliai“ (AEI) vartojamas plačiąja prasme. Jis apima ne tik pačius energijos išteklius, bet ir jų panaudojimą energijos gamybai, susijusias technologijas, infrastruktūrą, rinkas ir investicinius procesus. Siekiant išvengti perteklinio pasikartojimo, toliau darbe vartojami terminai „AEI“, „atsinaujinančioji energetika“ ir „AEI sistemos“, kurie šiame tyrime naudojami artima konceptualia prasme. Trumpesnės formuluotės „investicijos į AEI“ ir „AEI sistemos“ vartojamos kaip sutrumpintos sąvokos, apimančios AEI panaudojimą energijos gamybai, susijusias technologijas, infrastruktūrą, rinkas ir investicinius procesus.

Atsinaujinančioji energetika: samprata, technologijos, politikos priemonės ir išorinių efektų internalizavimas

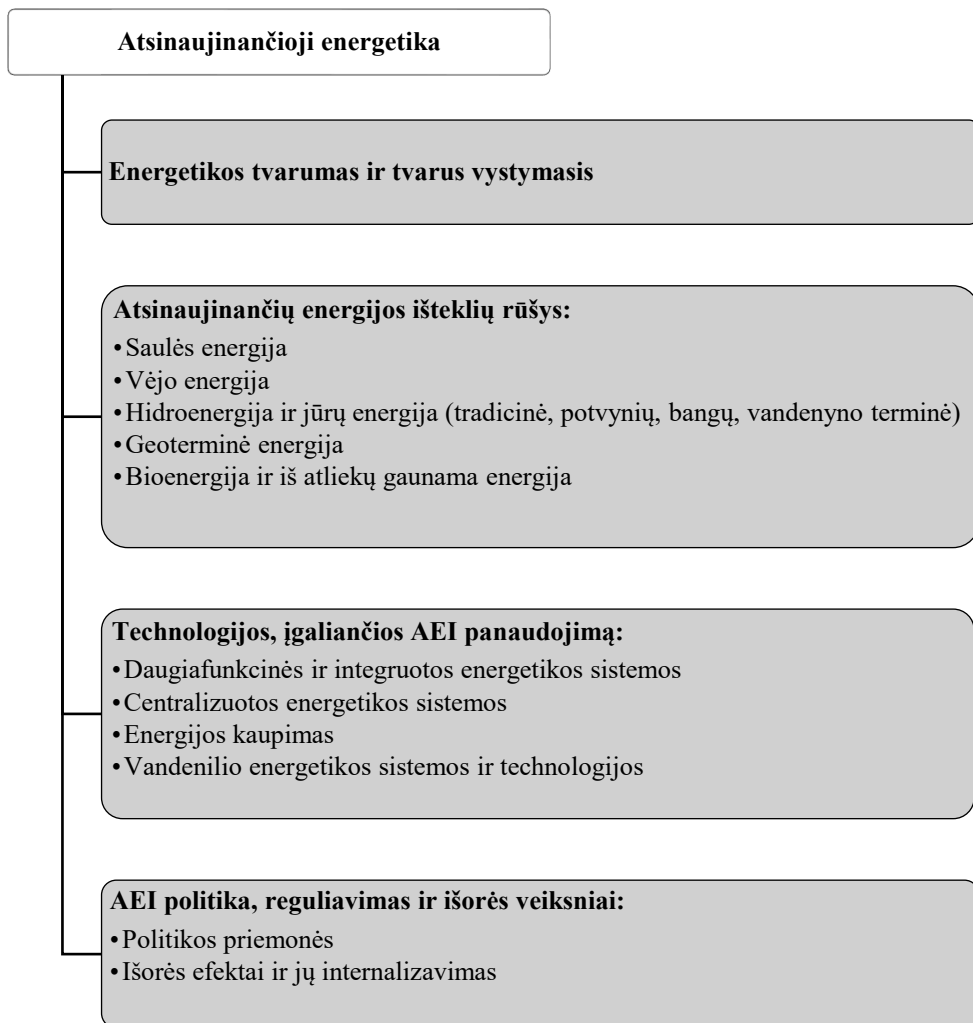
Atsinaujinančiosios energetikos samprata mokslinėje literatūroje apibrėžiama nevienodai. Atsinaujinančiosios energijos apibrėžimai dažniausiai siejami su natūraliai atsinaujinančiais, ilgalaikėje perspektyvoje prieinamais ir santykinai mažą poveikį aplinkai turinčiais energijos ištekliais. Tačiau skirtinguose šaltiniuose šios sąvokos turinys priklauso nuo to, kuris aspektas pabrėžiamas – išteklių atsinaujinamumas, poveikis aplinkai, anglies dioksido emisijų mažinimas, technologinis efektyvumas ar energijos sistemos tvarumas.

Įvairūs autoriai AEI apibrėžia kaip energijos išteklius, kurie mažina poveikį aplinkai, padeda tausoti išteklius ateities kartoms ir prisideda prie energetikos sistemos efektyvumo didinimo. Kartu literatūroje vartojamos ir artimos, bet ne visiškai tapačios sąvokos – „švari energija“, „žalioji energija“ ir „tvarūs energijos ištekliai“. Švari energija gali apimti hidroenergiją, vėjo, saulės, jūrų energiją, biomasę, taip pat kai kuriuos mažai anglies dioksido išmetančius neatsinaujinančius energijos

šaltinius, pavyzdžiui, branduolinę energiją. Žalioji energija paprastai siejama su energija, kurios poveikis aplinkai yra minimalus arba labai mažas, o tvarūs energijos ištekliai siejami su ilgalaikiu išteklių prieinamumu, energijos efektyvumu ir mažu poveikiu aplinkai (G. Boyle, 2004; Jaiswal et al., 2022; Panwar et al., 2011; REN21, n.d.; Twidell & Weir, 2006).

Per pastarąjį dešimtmetį terminai „atsinaujinančioji energija“, „švari energija“ ir „žalioji energija“ vis plačiau vartojami tiek akademiniuose tyrimuose, tiek viešajame diskurse. Kai kuriuose šaltiniuose „žalioji energija“ ir „švari energija“ vartojamos kaip atsinaujinančiosios energijos arba AEI sinonimai, tačiau toks vartojimas gali sukelti terminologinę painiavą. Pavyzdžiui, žalioji energija kai kuriais atvejais laikoma tapačia atsinaujinančiajai energijai, nors šios sąvokos ne visada sutampa (Mavragani et al., 2016). Dėl to disertacijoje šios sąvokos vertinamos plačiame atsinaujinančiosios energetikos kontekste, apimančiame skirtingas technologines, aplinkosaugines ir ekonomines interpretacijas.

Atsinaujinančiosios energetikos samprata visose trijose pagrindinėse interpretacijose (atsinaujinančiosios, žaliosios ir švarios energijos) siejama su energijos gamyba iš natūraliai atsinaujinančių arba mažesnį poveikį aplinkai turinčių išteklių. Nors šios sąvokos nėra visiškai tapačios, disertacijoje daugiausia remiamasi atsinaujinančiosios energetikos samprata. Atsinaujinančioji energetika šiame tyrime nagrinėjama iš keturių pagrindinių perspektyvų (45 pav.).



Šaltinis: sukurta autoriaus remiantis Koohi-Fayegh & Rosen, 2020

45 pav. AEI teminės sritys

AEI yra svarbi darnaus vystymosi dalis dėl augančios pasaulinės energijos paklausos, ribotų iškastinio kuro išteklių ir klimato kaitos problemų. Tokie energijos ištekliai kaip saulės, vėjo ir vandens energija yra mažai anglies dioksido išmetančios, aplinkosauginiu, ekonominiu ir socialiniu požiūriu priimtinos alternatyvos, galinčios didinti energetinį saugumą ir mažinti poveikį aplinkai. Vis dėlto jų plėtra susijusi ir su tam tikrais iššūkiais, tokiais kaip gamybos nepastovumas, tinklų integracijos problemos ir didelės pradinės investicijos. Energetikos tvarumo strategijos paprastai apima energijos paklausos mažinimą, efektyvumo didinimą ir iškastinio kuro pakeitimą atsinaujinančiais energijos iškoliais (Dincer & Acar, 2017; Evans et al., 2009; Varun et al., 2009). Atsinaujinančiosios energetikos plėtra apima perėjimą prie tokių išteklių ir technologijų kaip saulės, vėjo, vandens, geoterminė, bioenergija ir jūrų energetika. Pasauliniu mastu pagal AEI instaliuotą galią dominuoja saulės, vėjo

ir hidroenergijos technologijos (Dincer & Bicer, 2020; Jaiswal et al., 2022; Koohi-Fayegh & Rosen, 2020).

Siekiant įveikti tokius iššūkius kaip energijos gamybos nepastovumas ir aukšti kaštai, patikimam atsinaujinančiosios energijos integravimui būtinos tinklo modernizavimo, skaitmeninimo, paklausos valdymo ir energijos kaupimo technologijos. Atsinaujinančiosios energijos plėtrą taip pat skatina energetikos sistemų integracija, daugiafunkcės bei decentralizuotos energetikos sistemos, o biomasė išlieka svarbiu šildymo energijos šaltiniu regionuose. Energijos kaupimo sprendimai (terminiai, elektrocheminiai, suslėgto oro, vandenilio ir termocheminiai) prisideda prie pasiūlos ir paklausos balansavimo (Algburi et al., 2025; Dincer & Acar, 2018; Dincer & Bicer, 2020; Koohi-Fayegh & Rosen, 2020; Pamfile, 2023; Pérez, 2025). Kartu būtina įvertinti, kad didėjant kintamos AEI generacijos, ypač saulės ir vėjo energetikos, daliai, papildoma instaliuota galia nebūtinai sukuria proporcingą ekonominę vertę. Jos rinkos vertė priklauso nuo gamybos laiko, elektros kainų, tinklų pralaidumo, kaupimo galimybių ir visos sistemos lankstumo (Hirth, 2013; Hirth et al., 2015). Ši aplinkybė yra svarbi disertacijos logikai, nes ji rodo, kad AEI plėtra turi būti vertinama ne tik pagal absoliutų instaliuotos galios ar investicijų augimą, bet ir pagal ribinę šios plėtros naudą.

Nepaisant skirtingų sąvokų interpretacijų, AEI plėtra praktiškai neatsiejama nuo aktyvios politikos, technologinių inovacijų ir kapitalo srautų, kurie formuoja investicijų dinamiką bei rinkos augimo greitį. AEI susiduria su įvairiomis kliūtimis, trukdančiomis visapusiškai išnaudoti savo potencialą. Dėl technologinių, infrastruktūrinių ir rinkos transformacijos iššūkių atsinaujinančioji energetika sunkiai galėtų vystytis vien laisvos rinkos sąlygomis, be išorinio stimulo, paramos ir skatinimo priemonių. Todėl politika tampa vienu pagrindinių atsinaujinančiosios energetikos augimo katalizatorių, formuojančių investicijų srautus, diegimo tempus ir rinkos struktūrą.

AEI plėtros politika gali būti skirstoma į reguliacines, rinkos pagrindu veikiančias, finansines ir įgalinančias priemones (Aldy & Stavins, 2012; Carley, 2009; del Río & Mir-Artigues, 2014a; IRENA, 2019). AEI sistemų diegimas tradiciškai remiasi tokiais mechanizmais kaip elektros energijos supirkimo įstatymai, kvotos su prekybai tinkamais žaliaisiais sertifikatais ir konkursai, o tenkančios išlaidos dažnai perkeliamos vartotojams. Siekiant kurti tvarias energetikos sistemas, taip pat būtina internalizuoti neigiamą iškastinio kuro poveikį, t. y. į energijos kainas įtraukti neįvertintas aplinkos ir sveikatos sąnaudas. Tai gali būti daroma taikant taršos mokesčius, apyvartinių taršos leidimų prekybos sistemas ir kitas aplinkosaugines kainodaros priemones.

Skirtingai nei tradiciniai energijos gamybos ištekliai, AEI sukuria teigiamus išorinius efektus, įskaitant mažesnę taršą, geresnę visuomenės sveikatą ir mažesnę klimato kaitos poveikį. Nepaisant šių privalumų, subalansuota skatinimo politika išlieka būtina, nes ji padeda įveikti rinkos nepakankamumus, kylančius dėl neįvertintų tradicinės energetikos sąnaudų, ir spartina perėjimą prie AEI (Batra, 2023; Bento et al., 2020; Bilan et al., 2020; Dirma et al., 2024; Hoffmann et al., 2022; Jaiswal et al., 2022; Klaassen & Riahi, 2007; Mishchuk et al., 2018; Neverauskienė & Rakauskienė, 2018; Štreimikienė & Ališauskaitė, 2016).

Aptartos technologinės, institucinės ir reguliacinės sąlygos tiesiogiai formuoja investicijų srautus atsinaujinančiosios energetikos sektoriuje, kapitalo koncentraciją ir rinkos kainų dinamiką. Aktyvi AEI skatinimo politika sudaro prielaidas spartesnei sektoriaus plėtrai, tačiau kartu didina perteklinio ir spekuliacinio investavimo riziką. Todėl investicijų srautai tampa vienu svarbiausių rinkos prisotinimo, spartėjančio augimo ir finansinių burbulų formavimosi veiksnių atsinaujinančiosios energetikos sektoriuje.

Investicijų dinamika ir burbulų formavimasis atsinaujinančiosios energetikos rinkose

Skatinanti politika, technologinis naujumas, aukšti augimo lūkesčiai ir dideli kapitalo srautai į AEI sistemas sudaro prielaidas spartėjančiam rinkos prisotinimui ir burbulų formavimosi rizikas. Burbulams būdingas netvarus turto kainų arba vertės augimas, nutolstantis nuo fundamentaliųjų rodiklių ir dažnai grindžiamas optimizmu, spekuliacijomis bei nestabiliais rinkos lūkesčiais. Ši dinamika ypač aktuali atsinaujinančiosios energetikos sektoriuje, kuriame investicijų srautai ir politikos intervencijos gali spartinti tiek sektoriaus plėtrą, tiek finansinio nestabilumo riziką.

Struktūriniai ir elgsenos sąlygoti burbulų formavimosi mechanizmai

Atsinaujinančiosios energetikos sektorius, siejamas su dekarbonizacijos tikslais, technologinėmis inovacijomis ir spartėjančia energetikos transformacija, kartu pasižymi padidėjusia spekuliacine rizika. Dideli investicijų srautai, aukšti augimo lūkesčiai ir priklausomybė nuo valstybės paramos gali skatinti perteklinį optimizmą, turto perversimą ir finansinį nestabilumą. Todėl, vertinant AEI rinkų raidą, svarbu analizuoti ne tik investicijų ir technologinės plėtros naudą, bet ir struktūrinius bei elgsenos veiksnius, kurie gali lemti burbulų formavimąsi. Įvairių autorių pateikti burbulų aspektai apibendrinti 24 lentelėje.

24 lentelė. Pagrindiniai finansinių burbulų aspektai ir formavimosi veiksniai

Burbulų aspektas	Priežastis / sukėlėjai	Autoriai
Apibrėžimas ir atpažinimas	Netvaraus augimo laikotarpiai; greitesnis nei eksponentinis augimas; atpažįstamas pagal specifinius modelius.	Sornette ir Cauwels (2015)
Fazės ir išoriniai sukrėtimai	Pasikartojantis pobūdis; kritinis pokyčio taškas; paspartintas išorinių sukrėtimų, pavyzdžiui, COVID-19 pandemijos.	Ghosh ir kt. (2022)
Istorinė perspektyva	Spartus kainų kilimas, viršijantis vertę, po kurio seka staigus kritimas.	Afilipoei ir Carrero (2023)
Finansinio nestabilumo hipotezė	Perėjimas nuo stabilumo prie euforijos, baigiantis krize dėl nepagrįsto optimizmo.	Minsky (1977)
Racionalus burbulo modelis	Turto pirkimas pagal racionalius lūkesčius, kad jis bus perparduotas už aukštesnę kainą, nors ir žinant, kad galiausiai gali įvykti kritimas.	Blanchard ir Watson (1982)

Struktūriniai ir elgsenos veiksniai	Struktūriniai disbalansai, rinkos likvidumo poveikis, psichologiniai veiksniai, tokie kaip minios instinktas, per didelis pasitikėjimas savimi.	Jlassi ir Bensaïda (2014), Lim (2018), Sathya ir Gayathiri (2024)
Naratyvinė ir elgsenos dinamika	Kolektyviniai lūkesčiai, investuotojų psichologija, pasitikėjimas, socialinis plitimas, manipuliacija ir ekonominiai naratyvai	Akerlof ir Shiller (2009, 2016), Shiller (1989, 2015, 2020)
Investicijų srautai	Ekspansinė pinigų politika, per didelis likvidumas, kapitalo įplaukos į spekuliacines rinkas.	Allen ir Gale (2000), Calvo (2012)
Psichologinė dinamika	Būdingas bandos elgesys, per didelis pasitikėjimas savimi, naujumo šališkumas, vedantis prie spekuliacinių veiksmų, sprendimų neatitikimas pagrindiniams rodikliams.	Andraszewicz (2020), Shiller (2015)
Atsinaujinančiosios energetikos sektorius	Pernelyg dideli investicijų srautai, priklausomybė nuo politikos, technologijų populiarumas ir pervertinimo rizika.	Ghosh ir kt. (2022), Lehnert (2023), Padmavathy (2024)
Technologinės inovacijos	Susidomėjimas naujais technologiniais pasiekimais didina lūkesčius ir gali lemti aukštesnius investicinio turto vertinimus.	Goodrich ir kt. (2012), Hamdan ir kt. (2024)

Apibendrinant skirtingus burbulų formavimosi veiksnus, svarbu išskirti Shillerio indėlį, kuris burbulų analizę papildo elgsenos ir naratyvine dimensija (Shiller, 2020). Šis požiūris rodo, kad finansinių burbulų formavimąsi gali skatinti ne tik struktūriniai disbalansai, likvidumas ar investicijų srautai, bet ir kolektyviniai lūkesčiai, investuotojų psichologija, pasitikėjimas, socialinis plitimas bei ekonominiai naratyvai. Atsinaujinančiosios energetikos rinkose tokie veiksniai ypač reikšmingi, nes investuotojų lūkesčius gali stiprinti žaliosios transformacijos, technologinio proveržio, energetinės nepriklausomybės ir būsimo sektoriaus augimo naratyvai.

Atsinaujinančiosios energetikos sektorius, kaip ir kitos sparčiai augančios bei technologiniu proveržiu grindžiamos rinkos, yra jautrus ateities lūkesčiams. Investuotojų dėmesys dažnai nukreipiamas ne į esamus fundamentalius rodiklius, bet į būsimą sektoriaus potencialą, numatomą technologinę pažangą ir politinės paramos tęstinumą. Dėl to kapitalo srautai gali augti sparčiau nei reali rinkos, infrastruktūros ar technologijų absorbcinė galia. Todėl, siekiant vertinti ilgalaikį AEI sektoriaus finansinį tvarumą, būtina analizuoti rinkos prisotinimo dinamiką, augimo ribas ir sistemos gebėjimą absorbuoti investicijas.

Sparčiai augant investicijoms į atsinaujinančiosios energetikos sektorių, didėja ir žaliųjų burbulų formavimosi reikšmė. Vis daugiau tyrimų identifikuoja sprogstamojo augimo ir perteklinio vertinimo požymius AEI rinkose. Tačiau šiame sektoriaus vystymosi etape žalieji burbulai negali būti vertinami vienareikšmiškai neigiamai, todėl svarbu juos vertinti ne tik pagal kainų augimą ar spekuliacinį pobūdį, bet ir pagal jų ekonomines pasekmes.

Žalieji, produktyvūs ir destruktivyūs burbulai atsinaujinančiosios energetikos rinkose

Žalieji burbulai yra specifinė finansinių burbulų forma, pasireiškianti atsinaujinančiosios energetikos ir kitų aplinkai palankių technologijų sektoriuose. Jie susidaro tuomet, kai investuotojų lūkesčiai ir kapitalo srautai ima augti sparčiau nei fundamentalūs technologiniai, gamybiniai ar pelningumo rodikliai. Tokiam procesui didelę įtaką daro valstybės politika, subsidijos, reguliacinė aplinka, visuomenės ir investuotojų nuotaikos bei technologinis ažiotžas. Dėl šių veiksnių gali susiformuoti perteklinis turto vertinimas ir padidėti staigios kainų korekcijos rizika (Lehnert, 2023; W.-F. Pan, 2020; Shao & Chen, 2022).

Empiriniai tyrimai rodo, kad žaliųjų technologijų ir atsinaujinančiosios energetikos akcijų rinkose gali atsirasti sprogstamojo pobūdžio kainų kilimo fazės, kurios kartais persiduoda ir platesnėms finansų rinkoms. Tačiau tokie burbulai ne visuomet yra vien neigiamas reiškinys. Tam tikromis sąlygomis jie gali paskatinti spartesnę technologinę pažangą, padidinti investicijas į inovacijas ir padėti formuoti naujiems rinkos segmentams, kurie ilgainiui sukuria realią ekonominę vertę (Janeway, 2018).

Atsižvelgiant į paminėtas aplinkybes, burbulai turėtų būti vertinami ne vien normatyviniu požiūriu, bet ir pagal jų ekonomines funkcijas bei pasekmes, skiriant produktyvius ir destruktivius burbulus. Produktyvūs burbulai padeda finansuoti technologinius proveržius, infrastruktūros kūrimą ir naujų sektorių plėtrą. Nors dalis investuotojų tokių burbulų metu patiria nuostolių, ilgalaikė nauda ekonomikai gali viršyti trumpalaikes finansines sąnaudas ar žalas. Istoriškai tokio tipo burbulai buvo susiję su didelėmis technologinėmis revoliucijomis (Perez, 2002; Quinn & Turner, 2020). Tam tikromis rinkos sąlygomis kai kurie destruktivyūs (spekuliaciniai) burbulai gali transformuotis į produktyvius burbulus (Raurich & Seegmuller, 2019).

Priešingai, destruktivyūs burbulai grindžiami perteklinėmis spekuliacijomis, dideliu finansiniu svertu ir kredito plėtra, nesukuria realios pridėtinės vertės ir kelia sisteminę riziką finansų stabilumui (Sornette, 2003; Sornette & Woodard, 2009). Atsinaujinančiosios energetikos investicijos gali įgyti tiek produktyvių, tiek destruktivių burbulų bruožų. Remiantis literatūra, pagrindinis kriterijus, skiriantis produktyvius ir destruktivius burbulus, yra jų ekonominės pasekmės. Produktyvūs burbulai, nepaisant trumpalaikių finansinių nuostolių, prisideda prie technologinės pažangos, infrastruktūros kūrimo ir ilgalaikio produktyvumo augimo, todėl pasižymi teigiama suminio rezultato rinkos dinamika (Clain-Chamosset-Yvrard et al., 2024; Farmer & Schelnast, 2013; Pástor & Veronesi, 2009; Raurich & Seegmuller, 2019, 2022). Tuo tarpu destruktivyūs burbulai grindžiami perteklinėmis spekuliacijomis ir rinkos prisotinimu, sukelia sisteminę riziką, finansinį nestabilumą ir ilgalaikę žalą ekonomikai, nes jų augimas yra neatsiejamas nuo neproduktyvaus (spekuliatyvaus) turto ir neigiamo suminio rinkos persikirstymo (Afilipoaei & Carrero, 2023; Cahuc & Challe, 2012; Corsi & Sornette, 2014; Girdzijauskas, 2024; Otaki, 2016).

Dauguma iki šiol atliktų burbulų tyrimų daugiausia dėmesio skyrė kainų dinamikai, rinkos lūkesčiams ir elgsenos veiksniams. Tačiau sistemų augimo ribos, rinkos prisotinimas ir investicijų skatinamas augimo intensyvėjimas finansinių burbulų analizėje vertinami fragmentiškai, ypač AEI sektoriuje. Atsižvelgiant į

spartėjančią atsinaujinančiosios energetikos plėtrą ir didėjančius kapitalo srautus, sistemos augimo greitis, prisotinimo lygis ir rinkos talpa tampa svarbiais veiksniais vertinant burbulų formavimosi riziką. Kitame poskyryje aptariami ekonomikos augimo modeliai ir maržinalizmo principai sudaro teorinį pagrindą tolesnei finansinio prisotinimo teorijos ir augimo ribomis grindžiamo modelio analizei.

Ekonomikos augimo teorijos, maržinalizmas ir augimo ribos

Siekiant susieti ekonominio augimo, investicijų ir burbulų reiškinius su augimo ribomis ir iš to išplaukiančiu finansiniu prisotiniu, pateikiama platesnė teorinė perspektyva. Ekonomikos augimo modeliai ir maržinalizmo koncepcija suteikia pagrindą, leidžiantį analizuoti augimo ribas ir jų reikšmę šiuolaikinėms investicijų dinamikoms, ypač atsinaujinančiosios energetikos sektoriuje. Istorinė augimo teorijų raida rodo, kad dauguma modelių buvo orientuoti į augimą skatinančius veiksnius: kapitalo kaupimą, technologinę pažangą, žmogiškąjį kapitalą ar inovacijas. Tačiau augimo ribotumo problema dažniausiai liko nepakankamai išplėtotą arba buvo paliekama antrame plane.

Keinsistiniai ir neoklasikiniai augimo modeliai, tokie kaip Harrodo-Domaro ar Solow-Swan modeliai, pabrėžė investicijų, santaupų, darbo ir technologijų svarbą ilgalaikiam augimui, tačiau technologinę pažangą dažnai traktavo kaip išorinį veiksni (Domar, 1946; Harrod, 1939; Solow, 1956). Vėlesni endogeninio ir vieningo augimo modeliai išplėtė augimo aiškinimą, įtraukdami žinias, mokslinius tyrimus, žmogiškąjį kapitalą, demografinius, technologinius ir institucinius veiksnius (Galor, 2011; Galor & Weil, 2000). Inovacijomis grindžiamas Schumpeterio požiūris augimą aiškino kaip kūrybinio naikinimo ir verslumo inovacijų rezultata, pabrėždamas cikliškumą, technologinius lūžius ir ekonominės struktūros kaitą (Aghion & Howitt, 1992; Schumpeter, 1983).

Vis dėlto net ir šie modeliai dažniausiai remiasi prielaida apie tęstinį ar potencialiai neribotą augimą. Ribotų išteklių, rinkos talpos ar prisotinimo poveikis investicijų dinamikai lieka nepakankamai išplėtotas. Šią teorinę spragą padeda užpildyti maržinalizmas, į ekonominę analizę įvedęs mažėjančio ribinio naudingumo ir prisotinimo idėjas (Čiegis, 2006). Istorškai ekonomikos teorijoje matematinė analizė buvo vertinama prieštaringai: viena vertus, ji leido formalizuoti ryšius, kita vertus, pernelyg sudėtingi ir specializuoti modeliai dažnai nutolino nuo realių ekonominių procesų supratimo. Matematinų ir ekonometrinių metodų dominavimas lėmė vadinamųjų „juodosios dėžės“ modelių paplitimą, kuriuose pagrindinis dėmesys skiriamas prognozavimo tikslumui, o ne priežastinių mechanizmų aiškinimui (Betz, 2013; Castañeda, 2010; Gossen, 1854; Leontief, 1986). Tai prisidėjo prie teorinio sąstingio ir ribojimo galimybes analizuoti prisotinimo, perkaitimo, burbulų ar finansinių krizių reiškinius.

Šiame kontekste vėl išryškėja maržinalizmo reikšmė. Maržinalizmas, grindžiamas ribų, mažėjančios ribinės grąžos ir mažėjančio ribinio naudingumo principais, suteikia metodologinį pagrindą ribotam, logistiniam augimui analizuoti. Šis požiūris leidžia sistemiškai vertinti prisotinimo reiškinius, augimo ribas ir jų poveikį rinkų stabilumui (Girdzijauskas, 2024). Todėl atsinaujinančiosios energetikos plėtra darbe vertinama ne tik pagal absoliutų instaliuotos galios ar investicijų

didėjimą, bet ir pagal papildomos instaliuotos galios ar papildomų investicijų ribinį indėlį į sistemos stabilumą, ekonominę vertę ir gebėjimą absorbuoti papildomą augimą. Finansinio prisotinimo teorija remiasi maržinalizmo iškelta augimo ribų logika, tačiau ją išplečia, augimo ribas susiedama su prisotinimu, grįžtamuju ryšiu, bifurkacija ir burbulų formavimosi dinamika. Atsižvelgiant į spartų atsinaujinančiosios energetikos sektoriaus augimą, didelius investicijų srautus ir stiprią politikos įtaką, šis požiūris tampa svarbus vertinant ilgalaikį investicijų tvarumą ir galimas burbulų formavimosi rizikas.

FINANSINIO PRISOTINIMO TEORIJS IR BURBULŲ FORMAVIMOSI ANALIZĖ: METODINIO VERTINIMO MODELIO KŪRIMAS

Antrojoje darbo dalyje analizuojama finansinio prisotinimo teorija ir jos taikymas burbulų formavimosi mechanizmui aiškinti riboto augimo sąlygomis. Šioje dalyje nagrinėjama, kaip logistinio augimo principai gali būti taikomi ekonominių sistemų prisotinimo, perkaitimo ir burbulų formavimosi analizei. Finansinio prisotinimo teorijos analizė remiasi rinkos augimo ribų vertinimu, logistinius modelius taikant burbulų formavimosi priežastims ir pasekmėms nustatyti. Parodoma, kad sistemai artėjant prie maksimalios talpos ribos didėja elastingumas ir stiprėja teigiamas grįžtamas ryšys, o tai sudaro prielaidas bifurkacijai ir finansinių burbulų formavimuisi. Šiame kontekste elgsenos ir naratyviniai burbulų veiksniai, tokie kaip kolektyviniai lūkesčiai, investuotojų psichologija ir augimo naratyvai, gali būti vertinami kaip investicinių bangų inicijavimo ar stiprinimo veiksniai, o finansinio prisotinimo teorija paaiškina sąlygas, kuriomis šios bangos tampa struktūriškai nestabilios.

Disertacijoje finansinio prisotinimo teorija sisteminama ir plėtojama integruojant elastingumo, grįžtamojo ryšio ir bifurkacijos principus, leidžiančius tiksliau apibrėžti augimo stadijas, rinkos dualumo mechanizmą ir perėjimą iš fundamentalios į deficitinę rinkos būseną. Atlikta paklausos ir pasiūlos transformacijos analizė dualioje sistemoje leidžia analizuoti klasikinės ir deficitinės rinkos pusiausvyros modelius bei išryškinti logistinių augimo modelių prielaidas ir apribojimus.

Remiantis teorine analize, sukuriamas tyrimo modelis, skirtas AEI sistemų prisotinimo kapitalu ir burbulų formavimosi vertinimui. Modelis leidžia paaiškinti finansinių burbulų mechanizmą, jų tipus bei susijusius reiškinius, tokius kaip Ponzi ir „pump and dump“ schemos, taip pat gausos ir stokos ekonomikos procesus.

Finansinio prisotinimo, augimo ribų ir burbulų dinamikos teoriniai pagrindai

Finansinio prisotinimo teorijos analizė pradedama nuo augimo modelių transformacijos, kuri sudaro prielaidas visus palūkanų pagrindu veikiančius augimo modelius integruoti į bendrą teorinę struktūrą. Paprastųjų palūkanų modeliai šiame kontekste transformuojami į sudėtinių arba soties palūkanų modelius, o pastarieji – į bemačius procentinius dydžius, leidžiančius analizuoti augimą nepriklausomai nuo absoliučių matavimo vienetų. Apibrėžus prisotinimo palūkanų sąvoką, prisotinimo lygis kartu su sukaupu kapitalu ir rinkos talpa gali būti toliau transformuojami į

ekonominius kintamuosius, tokius kaip kaina ar kiekis vertės išraiška (Girdzijauskas, 2002, 2024; Girdzijauskas, Moskaliova, et al., 2014; Gryshova et al., 2019).

Augimo modelių taikymas ekonominių sistemų analizei grindžiamas tam tikromis prielaidomis ir apribojimais. Logistiniams augimo modeliams būdingas ekonominių procesų supaprastinimas, išorinių sukrėtimų ir išorinių veiksnių (externalities) neįtraukimas, homogeniškumo prielaida, kuri ne visuomet atspindi heterogenišką investuotojų elgseną, ribotos galimybės modeliuoti staigius struktūrinius pokyčius ar krizes (neigiamą augimą), taip pat aiškiai apibrėžtų grįžtamojo ryšio mechanizmų nebuvimas (Grubb et al., 2015; Grübler, 1990; Shiller, 2015; Sornette, 2003; Sterman, 2000; Wilson & Grubler, 2011). Šios prielaidos ir metodologiniai apribojimai toliau kritiškai vertinami ir sistemiškai integruojami vystant disertacijoje siūlomą modelį.

Vienas pagrindinių finansinio prisotinimo teorijos elementų yra didėjančios gražos fenomenas, arba soties paradoksas. Diskontuojant pinigų srautus prisotinimo procentais, stebimas hiperboliškai intensyvėjantis gražos augimas, kuris pasireiškia ne finansinių resursų trūkumo, o jų pertekliaus sąlygomis. Artėjant prie sistemos talpos ribos, investicijų gražos intensyvumas pavojingai didėja, sukeldamas netikėtą augimo spartą. Tai vyksta iki tol, kol sistema pasiekia kritinį tašką ir destabilizuojasi (Gryshova et al., 2019; Girdzijauskas, Mialik, et al., 2012; Girdzijauskas, Štreimikienė, et al., 2012). Remiantis ankstesniais tyrimais (Gryshova et al., 2019; Karaša & Girdzijauskas, 2024; Mikalauskas & Karaša, 2025) ir disertacijoje atliktu teorijos sisteminimu, augimą galima suskirstyti į tris prisotinimo ir elastingumo stadijas. I-oji stadija apima maždaug 0–0,70/0,75 prisotinimo lygio intervalą ir pasižymi sąlyginai lėtu augimu. II-oji stadija apima maždaug 0,70/0,75–0,90/0,95 prisotinimo lygio intervalą ir pasižymi sparčiu, vis greitėjančiu pelningumo augimu. III-oji stadija, viršijanti 0,90/0,95 prisotinimo lygį, pasižymi ypač sparčiu, hiperboliniu pelningumo augimu ir sprogstamojo didėjimo požymiais.

Elastingumas kiekybiškai išreiškia jautrumą pokyčiams arba grįžtamojo ryšio stiprumą. Elastingumas, mažesnis nei 1, rodo santykinį sistemos stabilumą ir neigiamo grįžtamojo ryšio dominavimą, o elastingumas, didesnis nei 1, siejamas su teigiamu grįžtamojo ryšiu po bifurkacijos taško. Nors žemesnis ir vidutinis prisotinimo lygis (I–II stadijos) gali skatinti investicijas ir inovacijas, per didelis prisotinimo lygis kelia perkaitimo, burbulų susidarymo ir jų sprogo riziką. Todėl būtina valdyti investicijų augimą ir identifikuoti bifurkacijos tašką, ypač tokiuose sektoriuose kaip atsinaujinančioji energetika. Detalesnis stadijų apibūdinimas pagal prisotinimo lygį ir elastingumą pateiktas 25 lentelėje.

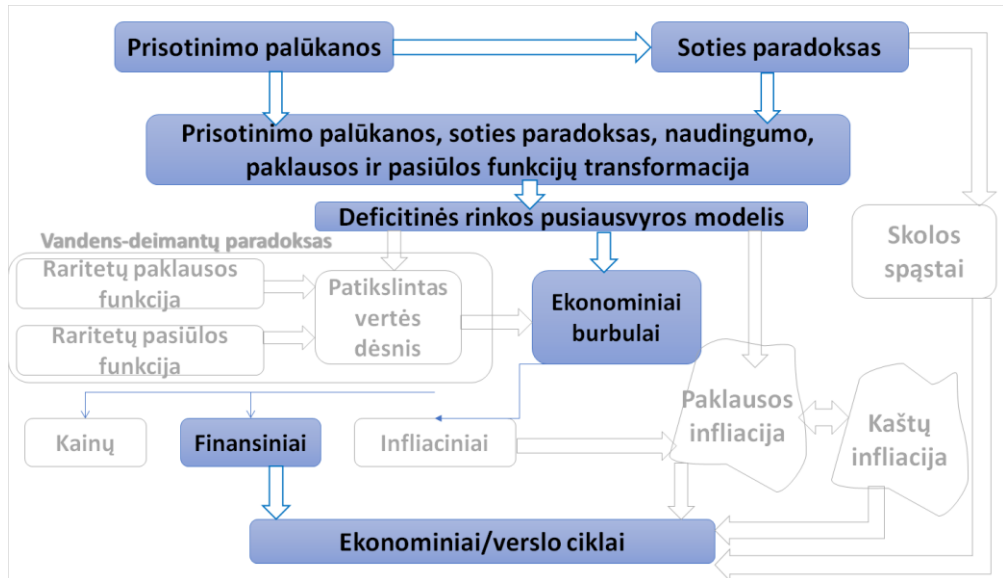
25 lentelė. Augimo stadijų charakteristikos pagal prisotinimo lygį ir elastingumą

Etapas	Prisotinimo lygis	Pelningumo (augimo greičio) dinamika	Elastingumas	Grįžtamojo ryšio tipas	Rinkos charakteristikos
I stadija: nuosaikus (stagnuojantis) augimas	Nuo 0 iki 0,7–0,75	Lėtas, nuolatinis pelningumo augimas	Santykinis neelastingumas	Neigiamas	Subalansuota rinka, stabilumą užtikrina „nematoma ranka“; investicijų rezultatai palankūs, bet riboti
II stadija: spartėjantis augimas (kaitimas)	Nuo 0,7–0,75 iki 0,9–0,95	Spartus, didėjantis pelningumo augimas	Pereinantis į santykinį elastingumą, didėjantis	Pereinantis į teigiamą ir stiprėjantis	Didėja teigiami kapitalo srutai; atsiranda spekuliacinių tendencijų; formuojasi perkaitimo rizika
III stadija: hiperbolinis augimas (perkaitimas)	Daugiau nei 0,9–0,95	Hiperbolinis (sparčiai didėjantis) pelningumas, nežymus prisotinimo pokytis sukelia didelį pelningumo šuolį	Santykinis elastingumas, artėjantis į absoliutų elastingumą	Dominuoja teigiamas stiprus grįžtamasis ryšys	Rinkos nestabilumas, aiški minios elgsena, burbulų susidarymas, sisteminė žlugimo rizika

Finansinio prisotinimo teorija teigia, kad burbulų susidarymas yra rinkos prisotinimo ir grįžtamojo ryšio dinamikos ribotos talpos rinkose rezultatas. Didėjančios investicijos veda prie prisotinimo, o dėl soties paradokso padidėjęs pelningumas skatina optimistinius lūkesčius ir teigiamus grįžtamojo ryšio ciklus, didindamas paklausą ir kainas. Šis mechanizmas, panašus į finansinį rezonansą, tampa nestabilus, kai rinkos priartėja prie ribos, kur nuotaikų pokyčiai gali sukelti susiformavusių burbulų sproginą. Burbulai klasifikuojami į kainų, finansinius rezonansinius ir infliacinius, atspindinčius prisotinimo, elastingumo ir grįžtamojo ryšio pasireiškimus ekonominėse sistemose (Girdzijauskas, 2024).

Remiantis išanalizuota teorija ir papildymais, į modelį įtrauktas sąlyginis burbulų skirstymas: produktyvusis (II augimo stadija po bifurkacijos) ir destruktivusis (III stadija). Logistinis augimas, elastingumas ir rinkos prisotinimo lygis gali padėti sąlygiškai įvertinti, kokią augimo stadiją pasiekė analizuojama sistema ir ar joje susiformavo aukštas spekuliacinis lygis. Burbulo tipą papildomai galima vertinti pagal jo pasekmes po spartaus augimo laikotarpio, nes šios pasekmės nėra tiesiogiai fiksuojamos logistinio augimo modelyje, tačiau gali padėti apibrėžti nustatyto burbulo pobūdį.

Burbulų susidarymo analizės, pagrįstos finansinio prisotinimo teorija, eiga ir apibendrinimai pateikti 46 paveiksle. Paveiksle pateikiama analizei aktuali finansinio prisotinimo teorijos struktūra. Mažiau reikšmingos, tačiau platesniam teoriniam kontekstui svarbios dalys pažymėtos pilka spalva ir tiesiogiai į tolesnę analizę neįtraukiamos.

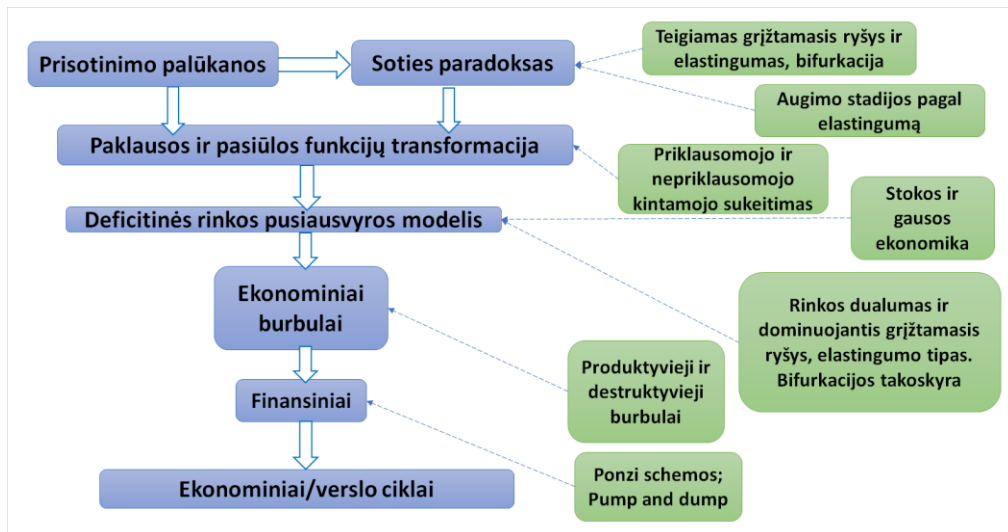


46 pav. Finansinio prisotinimo teorijos analizės struktūra

Prisotinimo palūkanos pagal logistinio augimo modelį atskleidžia soties paradoksą. Kartu šie du elementai leidžia konvertuoti paklausos, pasiūlos ir bendrosios naudingumo funkcijas logistinio augimo modelyje. Transformuotos paklausos ir pasiūlos kreivės sudaro deficitinės rinkos pusiausvyros modelį, kuriame soties paradoksas pasireiškia rinkos bifurkacijos atveju. Po bifurkacijos rinkoje ima dominuoti teigiamas grįžtamasis ryšys, sudarantis sąlygas burbulų formavimuisi. Rinkų, ypač energetikos sektoriaus, kontekste labiausiai aktualūs yra finansiniai burbulai, susidarantys tam tikrose rinkose ir sektoriuose. Analizė pateikia atsakymą į finansinių burbulų susidarymą rinkose ir sektoriuose, remiantis finansiniu prisotinimu ir potencialia (maksimalia) rinkos (sistemos) riba (talpa).

Ekonominių (finansinių) burbulų susidarymo analizė, pagrįsta finansinio prisotinimo teorija, leido atrasti tam tikrus principus ir patobulinti kai kuriuos teorijos elementus, pavaizduotus 47 pav. Remiantis finansinio prisotinimo teorijos analize ir sisteminimu, soties paradoksas buvo papildytas ir išplėstas, įtraukiant teigiamą grįžtamojo ryšio principą jį susiejant su elastingumu. Rinkos bifurkacija yra pagrįsta teigiamu grįžtamoju ryšiu ir elastingumu. Augimo etapai, pagrįsti prisotinimo lygiu, buvo peržiūrėti pagal elastingumą, kuris laikomas vienu pagrindiniu matu, apibūrinančiu burbulų susidarymą. Naujasis rinkos pusiausvyros modelis buvo palygintas su klasikiniu (fundamentaliu) rinkos pusiausvyros modeliu, o skirtumai paaiškinti rinkos dualumu, grįžtamojo ryšio tipu ir elastingumu. Įtrauktas rinkos dualumas papildytas produktyvaus ir destrukttyvaus burbulo sąvokomis, o jų tipas

vertinamas pagal prisotinimo lygį ir rezultatus po burbulų sprogo / korekcijos ar tolesnio vystymosi. Papildomai burbulai ir jų mechanizmas panaudojami aiškinant natūraliojo Ponzi ir „pump and dump“ schemų kontekste.



47 pav. Finansinio prisotinimo teorijos išplėtimas ir autoriaus indėlis

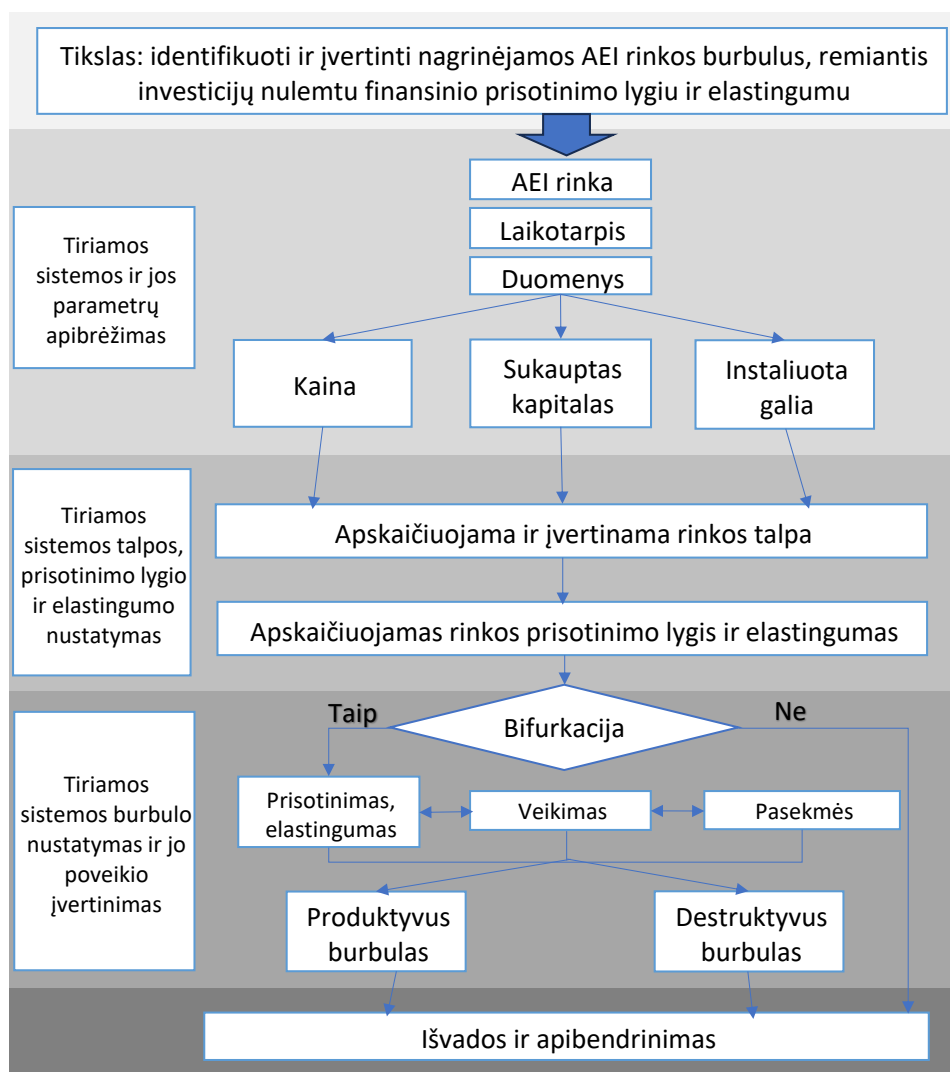
Finansinio prisotinimo teorijos analizė ir jos taikymas burbulų formavimosi mechanizmsms paaiškinti sudaro pagrindą toliau kuriamam vertinimo modeliui. Atliktas teorijos sisteminimas leidžia burbulų formavimąsi aiškinti ne tik kaip spekuliacinį ar elgsenos reiškinį, bet ir kaip struktūrinį procesą, kylantį iš rinkos prisotinimo, ribotos talpos, elastingumo pokyčių, bifurkacijos ir teigiamo grįžtamojo ryšio. Remiantis šiais teorinės analizės rezultatais, toliau plėtojamas finansinio prisotinimo teorija grindžiamas AEI sistemų prisotinimo ir burbulų formavimosi vertinimo modelis.

Finansinio prisotinimo teorija pagrįsto metodinio burbulų analizės modelio kūrimas

Kuriamas finansinio prisotinimo teorija ir logistiniu augimu pagrįstas metodinis burbulų analizės modelis, skirtas vertinti rinkos prisotinimo dinamiką ir burbulų formavimąsi AEI sistemose. Modelyje investicijos traktuojamos kaip pagrindinis prisotinimo dinamikos veiksnys, o jų poveikis vertinamas per tris empirinius pakaitinius rodiklius: kainų dinamiką, sukauptą kapitalą ir instaliuotą galią. Modelis leidžia įvertinti, kaip prisotinimo lygis ir elastingumas veikia augimo greitį, kainų ar kitų sistemos rodiklių dinamiką bei sistemos stabilumą. Naratyvai, investuotojų psichologija ir kolektyviniai lūkesčiai modelyje nėra tiesiogiai modeliuojami, tačiau jie gali būti interpretuojami kaip išoriniai veiksniai, inicijuojantys kapitalo srautus ir paklausos poslinkius. Skirtingai nuo klasikinių ekonominių modelių, šis modelis leidžia vertinti augimą ribotos rinkos arba sistemos talpos sąlygomis. Vienas pagrindinių metodologinių modelio bruožų yra tai, kad prisotinimo lygis ir sukauptas

kapitalas traktuojami kaip nepriklausomi kintamieji, darantys įtaką logistiniam augimo greičiui.

Tyrimo metodika apima kelis etapus: iš pradžių apibrėžiama sistema, jos parametrai ir atrenkamas objektas pagal konkrečias sąlygas, vertinant sistemos dydį ir augimo dinamiką. Antrajame etape remiantis atrinktais statistiniais duomenimis rinkos arba sistemos talpa nustatoma naudojant programinį paketą „Loglet Lab“. Gauti keli galimi talpos dydžiai įvertinami ir atrenkamas tinkamiausias sistemos talpos dydis. Turint visus reikalingus kintamuosius, apskaičiuojamas sistemos prisotinimo lygis, augimo greitis bei santykinis elastingumas nuo prisotinimo lygio. Trečiasis etapas skirtas burbulo identifikavimui įvertinant, ar pasiektas bifurkacijos taškas. Jei nustatyta sistemos bifurkacija, analizė išplečiama iki detalesnio burbulų vertinimo. Pagal apskaičiuotą ir nustatytą prisotinimo lygį, elastingumą, grįžtamojo ryšio pobūdį, augimo dinamiką ir pasekmes po spartaus augimo laikotarpio nustatomas burbulo tipas. Paskutinis etapas apima tyrimo išvadas ir vertinimą platesniu kontekstu. Tyrimo modelis pateikiamas 48 paveiksle.



48 pav. Finansiniu prisotinimu pagrįstas metodinis burbulų analizės modelis

Modelio taikymas grindžiamas keliomis prielaidomis ir ribotumais. Modelis yra deterministinis, remiasi fiksuota arba įvertinta rinkos talpa, homogeniškumo ir *ceteris paribus* prielaidomis, taip pat ribotai įtraukia laiko atotrūkius, išorinius šokus, politikos pokyčius, stochastinius svyravimus ir procesus po burbulo sprogo. Šie ribotumai apibrėžia modelio taikymo sritį ir nurodo tolesnio metodologinio plėtojimo kryptis.

Toliau trečiajame skyriuje sukurtas modelis taikomas empirinėje dalyje analizuojant atrinktas AEI sistemas ir vertinant jų prisotinimo bei burbulų formavimosi dinamiką.

FINANSINIO PRISOTINIMO IR BURBULŲ FORMAVIMOSI EMPIRINIS VERTINIMAS ATSINAUJINANČIOSIOS ENERGETIKOS SISTEMOSE

Trečiojoje darbo dalyje atliekamas empirinis tyrimas, kuriame taikomas sukurtas finansinio prisotinimo teorija pagrįstas modelis. Tyrime analizuojamas prisotinimo lygis, logistinis augimo greitis, elastingumas, bifurkacijos taškas ir iš šių rodiklių kylanti burbulų formavimosi rizika. Modelio funkcionalumui ir pritaikomumui įvertinti atliekama logistinio prisotinimo analizė skirtingose AEI sistemose, kurios skiriasi dydžiu, tipu, duomenų pobūdžiu ir tiriamuoju laikotarpiu. Empiriniu tyrimu siekiama patikrinti modelio tinkamumą vertinti skirtingų AEI sistemų prisotinimo dinamiką, bifurkacijos procesus ir burbulų formavimąsi.

Empirinio tyrimo struktūra ir aprašymas

Tyrime analizuojami logistinio augimo procesai skirtingose AEI sistemose: regioninėje biokuro pagrindu veikiančioje centralizuoto šilumos tiekimo (CŠT) rinkoje, atsinaujinančiosios energetikos akcijų indeksuose ir pasaulinėse AEI instaliuotos galios sistemose. Empiriniame tyrime investicijų poveikis prisotinimo dinamikai vertinamas taikant skirtingus pakaitinius rodiklius: kainą, sukauptą kapitalą ir instaliuotą galią. Remiantis sukurtu tyrimo modeliu (žr. 48 pav.), parengta burbulų analizės modelio taikymo schema (26 lentelė), kuri užtikrina nuoseklų modelio taikymą ir empirinių tyrimų vykdymą pagal bendrą loginę struktūrą.

26 lentelė. Burbulų analizės modelio taikymo schema

Nr.	Etapo pavadinimas	Tikslas	Aprašymas
1	Sistemos ir jos parametrų apibrėžimas	Apibrėžti ir įvertinti sistemą ir nustatyti jos pagrindinius parametrus	Analizuojama pasirinkta sistema, tiriamas laikotarpis, atrenkami duomenys ir nustatomas galimo burbulo susidarymo laikotarpis.
2	Sistemos talpos, prisotinimo lygio ir elastingumo nustatymas	Apskaičiuoti sistemos talpą, prisotinimo lygį, augimo greitį ir elastingumą per nustatytą tiriamąjį laikotarpį	a) Apibrėžto laikotarpio potencialios talpos apskaičiavimas naudojant „Loglet Lab“ b) Logistinio augimo greičio, prisotinimo lygio ir sistemos elastingumo apskaičiavimas remiantis duomenimis ir nustatyta talpa c) Grafikų braižymas
3	Burbulų identifikavimas ir poveikis sistemai	Nustatyti augimo stadijas (etapus) ir identifikuoti burbulo tipą	Remiantis skaičiavimo rezultatais, nustatoma, ar sistema pasiekė bifurkacijos tašką. Jei bifurkacijos taškas pasiektas, vertinama augimo stadija ir burbulo tipas. Kai leidžia duomenys, papildomi analitiniai metodai naudojami burbulo tipo interpretacijai patikslinti.

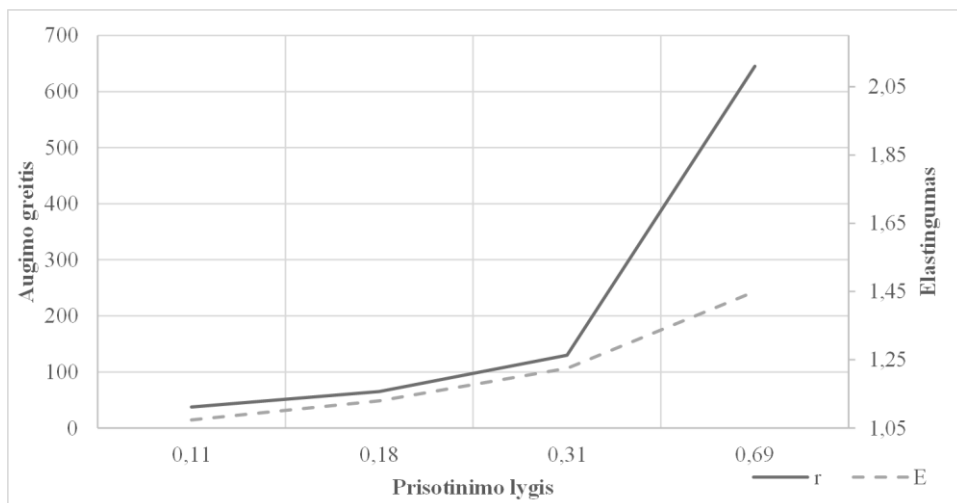
Tollesniuose poskyriuose pateikiami modelio taikymo rezultatai skirtingose AEI sistemose.

Kauno regiono biokuru pagrįstos centralizuoto šilumos tiekimo sistemos instaliuotos galios analizė

Pirmojoje empirinio tyrimo dalyje analizuojama Kauno regiono biokuru pagrįsta CŠT sistema. Šioje analizėje sistemos prisotinimui vertinti naudojama instaliuota biokuro šilumos gamybos galia ir jos dinamika. Instaliuota galia šioje dalyje laikoma fizinio ir technologinio prisotinimo pakaitiniu rodikliu, atspindinčiu investicijų skatinamą šilumos gamybos pajėgumų kaupimąsi ir galimą perteklinės instaliuotos galios susiformavimą.

Kauno CŠT sistema pasirinkta kaip pereinamosios energetikos rinkos pavyzdys. Po 2012 m. rinkos liberalizavimo ir reguliacinių pokyčių Kauno šilumos gamybos rinkoje sparčiai augo investicijos į biokuro technologijas, didėjo nepriklausomų šilumos gamintojų vaidmuo ir stiprėjo konkurencija. Tyrime analizuojami du scenarijai. I scenarijus apima 2012–2016 m. nepriklausomų biokuro šilumos gamintojų plėtrą. II scenarijus apima 2012–2020 m. platesnę šilumos gamybos pajėgumų sistemą, į kurią įtraukiami nepriklausomi biokuro šilumos gamintojai, AB „Kauno energija“ biokuro pajėgumai ir Kauno kogeneracinė jėgainė kaip konkuruojantis šilumos gamybos šaltinis.

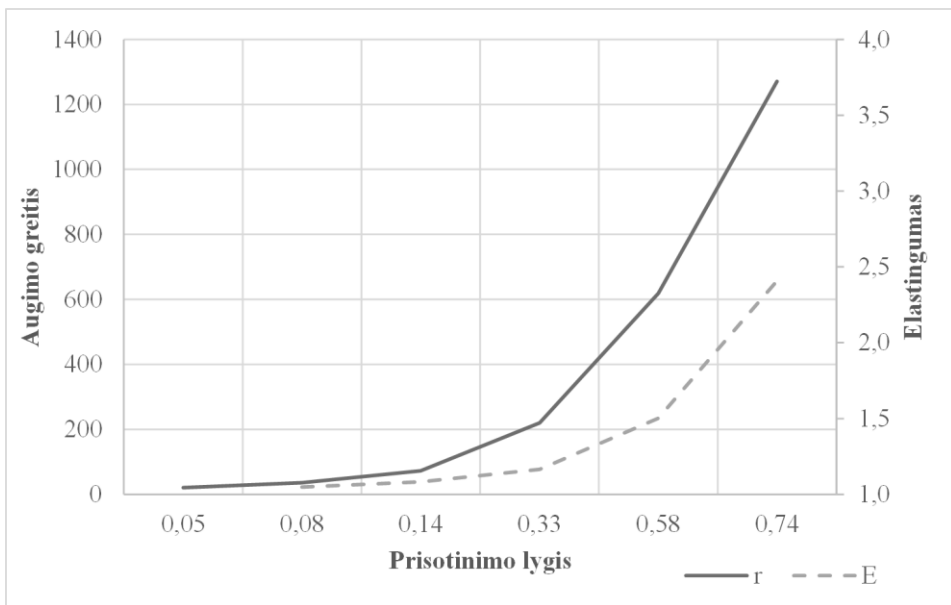
49 paveiksle pateikti I scenarijaus skaičiavimo rezultatai. Šios tyrimo dalies atveju prisotinimo lygis pasiekia 0,69, tačiau neviršija bifurkacijos taško. Nors elastingumas padidėja iki 1,45, šis lygis nerodo sistemos nestabilumo ar aiškaus grįžtamojo ryšio pasireiškimo. Tiriamos sistemos augimas sustoja prieš pereinant į aiškia kaitimo (II) stadiją. Todėl pagal tyrimo modelį I scenarijuje burbulas nenustatomas, o sistema išlieka nuosaikaus augimo stadijoje. Tai rodo, kad nepriklausomų biokuro šilumos gamintojų plėtra reikšmingai padidino instaliuotą galią, tačiau nesukūrė pakankamų sąlygų savaime stiprėjančiam teigiamam grįžtamajam ryšiui.



Šaltinis: autoriaus skaičiavimai pagal Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.) ir Kauno energija, AB (2023)

49 pav. I scenarijus: biokuro instaliuotos galios augimo greitis ir prisotinimo lygis

50 paveiksle pateikti II scenarijaus rezultatai. Šiuo atveju platesnė šilumos gamybos pajėgumų sistema pasiekia 0,74 prisotinimo lygį, o maksimalus elastingumas padidėja iki 2,41. Tai rodo, kad sistema pasiekia bifurkacijos tašką ir pereina į II augimo stadiją, susijusią su kaitimu ir produktyvaus burbulo formavimusi. Produktyvus burbulas šiuo atveju siejamas su sparčia biokuro ir šilumos gamybos pajėgumų plėtra, kuri padėjo mažinti priklausomybę nuo gamtinių dujų, skatino atsinaujinančiosios energetikos plėtrą ir prisidėjo prie mažesnių šilumos kainų vartotojams.



Šaltinis: autoriaus skaičiavimai pagal Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.) ir Kauno energija, AB (2023)

50 pav. II scenarijus: biokuro instaliuotos galios augimo greitis ir prisotinimo lygis

27 lentelėje apibendrinami abiejų scenarijų rezultatai. I scenarijuje maksimalus prisotinimo lygis siekia 0,69, todėl bifurkacijos taškas nepasiekiamas ir burbulas nenustatomas. II scenarijuje maksimalus prisotinimo lygis siekia 0,74, sistema pasiekia bifurkacijos tašką, o nustatyti rodikliai leidžia identifikuoti produktyvų burbulą. Vis dėlto II scenarijuje nenustatoma perėjimo į perkaitimo (III) stadiją, todėl destruktivaus burbulo požymiai nefiksuojami.

27 lentelė. Kauno regiono centralizuoto šildymo biokuru sistemos scenarijų analizės rezultatai

Scenarijus	C_p	C_{max}	r_{max}	Maksimalus prisotinimas	Maksimalus elastingumas	Bifurkacija/ burbulas	Kaitimo stadijos trukmė, metai	Perkaitimo stadijos trukmė, metai	Burbulo tipas
I	290	200	645	0,69	1,45	Ne	-	-	-
II	440	327	1270	0,74	2,41	Taip	1	-	Produktyvus

Šaltinis: autoriaus skaičiavimai pagal Bakas (2018), Valstybinė energetikos reguliavimo taryba (n.d.) ir Kauno energija, AB (2023)

Kauno CŠT atvejo analizė rodo, kad rinkos liberalizavimas, palankus reguliavimas, aukšti atsiperkamumo lūkesčiai, taršos mažinimo įsipareigojimai ir ES parama skatino investicijas į biokuro technologijas bei šilumos gamybos pajėgumų plėtrą. I scenarijuje šis procesas priartino sistemos instaliuotą galią prie bifurkacijos ribos, tačiau tolesnį augimą apribojo konkurencijos stiprėjimas, reguliacinė aplinka, ribotos spekuliacinio investavimo galimybės ir nepakankamai stiprus teigiamas grįžtamasis ryšys šioje rinkoje. II scenarijuje bifurkacijos taškas pasiektas išplėtus analizuojamą pajėgumų sistemą ir į ją įtraukus Kauno kogeneracinę jėgainę, tačiau reguliavimo mechanizmai ir rinkos struktūra neleido susiformuoti tolesnei destruktvyviai spekuliacinei dinamikai (perkaitimui).

Šios dalies empiriniai rezultatai rodo dvejopą instaliuotos galios prisotinimo poveikį. Vartotojams didesnis šilumos gamybos pajėgumų prisotinimo lygis buvo palankus, nes prisidėjo prie šilumos kainų mažėjimo ir priklausomybės nuo gamtinių dujų mažinimo. Tačiau gamintojams padidėjusi instaliuota galia sukūrė struktūrinių disbalansų: sustiprėjo konkurencija, atsirado perteklinių pajėgumų rizika, dalis esamų biokuro jėgainių susidūrė su mažesniu pajėgumų panaudojimu ir sunkumais parduoti pagamintą šilumą. Todėl Kauno CŠT atvejis parodo, kad investicijų skatinama AEI plėtra gali vienu metu spręsti vieną rinkos problemą – mažinti šilumos kainą ir priklausomybę nuo iškastinio kuro – ir kartu sukurti kitą problemą, susijusią su pertekliniais pajėgumais, konkurencijos iškraipymu ir papildomo reguliavimo poreikiu.

Atsinaujinančiosios energetikos finansų rinkų indeksų prisotinimo analizė

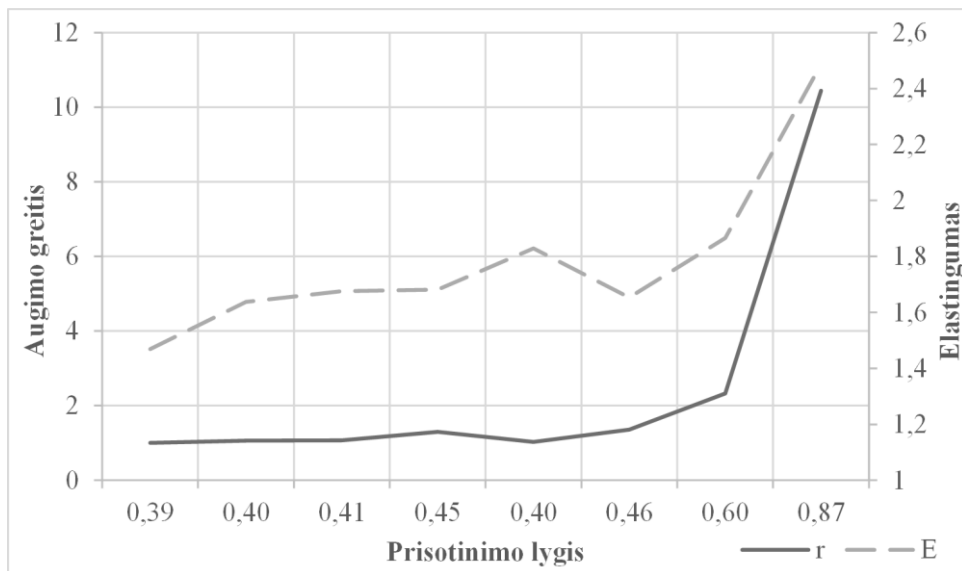
Šiame poskyryje analizuojami atsinaujinančiosios energetikos finansų rinkų indeksai, taikant du vertinimo požiūrius. Pirmuoju atveju prisotinimas vertinamas pagal indekso kainos dinamiką, o antruoju – pagal gryųjų kapitalo srautų pagrindu apskaičiuotą sukaupą kapitalą. Toks skirstymas leidžia vertinti finansinį prisotinimą tiek per rinkos vertinimo, tiek per kapitalo kaupimosi perspektyvą. Pradiniai duomenys šiame poskyryje turi savo matavimo vienetų: indeksų kainos išreiškiamos indekso punktais, o sukauptas kapitalas – piniginiiais vienetais. Tačiau modelio skaičiavimuose P_p , P_0 , P_{max} , K_p , K_0 ir K_{max} naudojami kaip tos pačios skalės įvesties

dydžiai. Kadangi prisotinimo lygis, augimo greitis ir elastingumas apskaičiuojami kaip santykiniai rodikliai, skaičiavimo ir apibendrinimo lentelėse matavimo vienetai papildomai nenurodomi.

Kainos pagrindu atliekamoje analizėje vertinami du indeksai: „European Renewable Energy Price“ indeksas (ERIXP) ir MSCI ACWI IMI „Clean Energy Infrastructure“ indeksas (MXACICEI). Šiuo atveju indekso kaina modelyje traktuojama kaip tiesioginis rinkos vertinimo ir investicijų lūkesčių rodiklis. Todėl kainos dinamika leidžia vertinti, ar spartus indekso augimas susijęs su rinkos prisotinimu, bifurkacijos tašku ir burbulo formavimosi požymiais.

„European Renewable Energy Price“ indeksas

„European Renewable Energy Price“ indeksas (ERIXP) atspindi Europos atsinaujinančiosios energetikos įmonių, veikiančių vėjo, saulės ir hidroenergetikos sektoriuose, rinkos vertės dinamiką. Analizei pasirinktas 2019 m. I ketvirčio–2021 m. I ketvirčio laikotarpis, kuriame fiksuotas ypač spartus indekso kainos augimas ir galimas burbulo formavimosi laikotarpis. Skaičiavimo rezultatai, paremti indekso kainos dinamika, pateikti 51 paveiksle.



Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

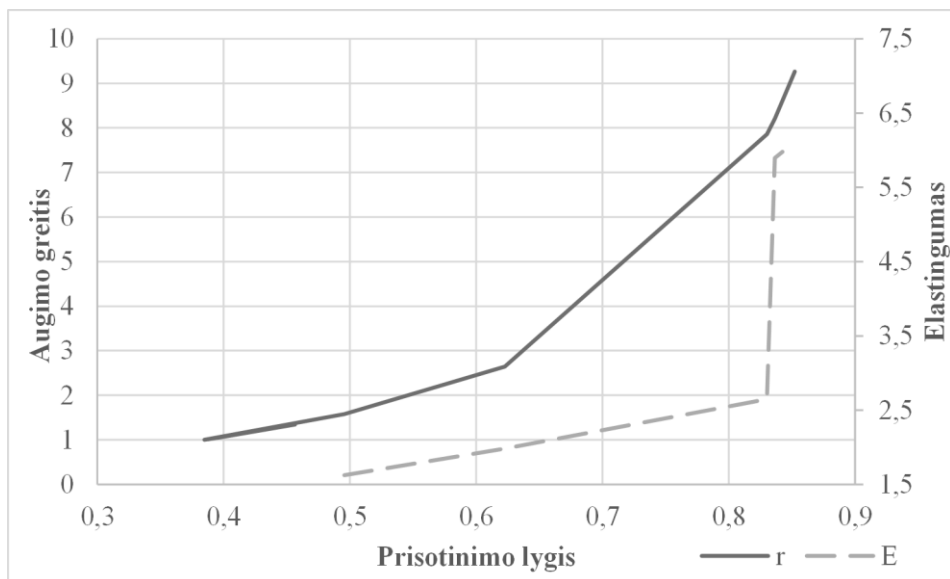
51 pav. ERIXP indekso augimo greitis ir prisotinimo lygis

Iš pateiktų tyrimo rezultatų matyti, kad tyrimo laikotarpio pabaigoje ERIXP sistema pasiekia bifurkacijos tašką. Maksimalus prisotinimo lygis siekia 0,87, o elastingumas, kuris ankstesniais laikotarpiais svyravo apie 1,5–1,8, laikotarpio pabaigoje padidėja iki 2,49. Šie rodikliai rodo, kad sistemoje susiformavo teigiamas grįžtamasis ryšys ir burbulo požymiai. Pikiniu laikotarpiu sistema veikė kaitimo (II augimo) stadijoje. Vis dėlto prisotinimo lygis nepasiekia perkaitimo (III) stadijos ribos, siejamos su 0,9 ir aukštesniu prisotinimo lygiu. Todėl pagal tyrimo modelį ERIXP atveju nustatomas produktyvus burbulas.

Svarbu pažymėti, kad ERIXP atvejis nėra visiškai vienareikšmis. Nors skaičiavimo rezultatai nerodo perėjimo į perkaitimo stadiją, maksimalus prisotinimo lygis yra arti šios ribos, o vėlesnė indekso dinamika rodo reikšmingą kainos korekciją. Todėl šis atvejis gali būti vertinamas kaip produktyvus burbulas su galimais destraktyvus burbulo požymiais paklaidos ribose.

„Clean Energy Infrastructure“ indeksas

MSCI ACWI IMI „Clean Energy Infrastructure“ indeksas (MXACICEI) apima švarios energijos infrastruktūros įmones, susijusias su baterijų kaupimo, pažangiaisiais tinklais, atėties degalais, alternatyviaja energija ir energijos efektyvumu išsivysčiusiose ir besivystančiose rinkose. Analizei pasirinktas 2019 m. I ketvirčio–2022 m. I ketvirčio laikotarpis, kuriame fiksuotas reikšmingas indekso kainos augimas ir galimi burbulo formavimosi požymiai. Skaičiavimo rezultatai, paremti indekso kainos dinamika, pateikti 52 paveiksle.



Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

52 pav. MXACICEI indekso augimo greitis ir prisotinimo lygis

MXACICEI analizė rodo aiškiai pasiektą bifurkacijos tašką. Maksimalus prisotinimo lygis siekia 0,85, o elastingumas spartaus augimo laikotarpiu padidėja nuo maždaug 1,6–1,8 iki 6,77. Tai rodo stiprėjantį teigiamą grįžtamąjį ryšį, nestabilią būseną ir burbulo formavimąsi. Nors prisotinimo lygis artėja prie perkaitimo ribos (III stadijos), sistema jos nepasiekia, todėl pagal tyrimo modelį MXACICEI atveju nustatomas produktyvus burbulas II augimo stadijoje.

Šis atvejis skiriasi nuo ERIXP tuo, kad MXACICEI augimo laikotarpis buvo ilgesnis ir nuoseklesnis. Kaitimo stadija truko 5 ketvirčius, o vėlesnė indekso dinamika rodo tik nedidelę korekciją ir tolesnį rinkos prisitaikymą. Nors MXACICEI, kaip ir ERIXP, buvo arti perkaitimo ribos, siejamos su III augimo stadija, burbulas vertinamas kaip produktyvus be aiškių destraktyvus burbulo požymių, kadangi

spartus augimas vėliau nesukėlė reikšmingos destruktivos korekcijos sistemoje. Analizės, paremtos indeksų kaina, santrauka pateikiama 28 lentelėje.

28 lentelė. Indeksų analizės pagal kainą santrauka

Indeksas	P_p	P_{max}	r_{max}	Maksimalus prisotinimas	Maksimalus elastingumas	Bifurkacija/burbulas	Kaitimo trukmė, ketv.	Perkaitimo trukmė, ketv.	Burbulo tipas
ERIXP	3061	2753	10,44	0,87	2,48	Taip	1	-	Produktyvus
MXACICEI	3386	2886	9,27	0,85	6,77	Taip	5	-	Produktyvus

Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

Indekso kainos pagrindu atlikta ERIXP ir MXACICEI sistemų analizė rodo, kad abiem atvejais buvo pasiektas bifurkacijos taškas, o prisotinimo ir elastingumo rodikliai patvirtina burbulo formavimąsi. Abu indeksai pateko į kaitimo (II augimo) stadiją, tačiau nė vienas nepasiekė perkaitimo (III) stadijos, todėl pagal tyrimo modelį abu burbulai klasifikuojami kaip produktyvūs.

ERIXP atveju burbulas buvo trumpesnis ir intensyvesnis. Nors maksimalus prisotinimo lygis siekė 0,87 ir neperžengė perkaitimo ribos, vėlesnė reikšminga indekso kainos korekcija leidžia daryti prielaidą, kad šis atvejis galėjo turėti destruktivaus burbulo požymių paklaidos ribose. Tai rodo, kad ribiniais atvejais, kai sistema yra arti kaitimo ir perkaitimo stadijų ribos, burbulo tipo nustatymas vien pagal prisotinimo lygį ir elastingumą gali būti nepakankamai tikslus. Tokiais atvejais svarbi tampa ir vėlesnė indekso dinamika po tiriamojo laikotarpio, nes reikšminga kainos korekcija gali parodyti galimus destruktivaus burbulo požymius.

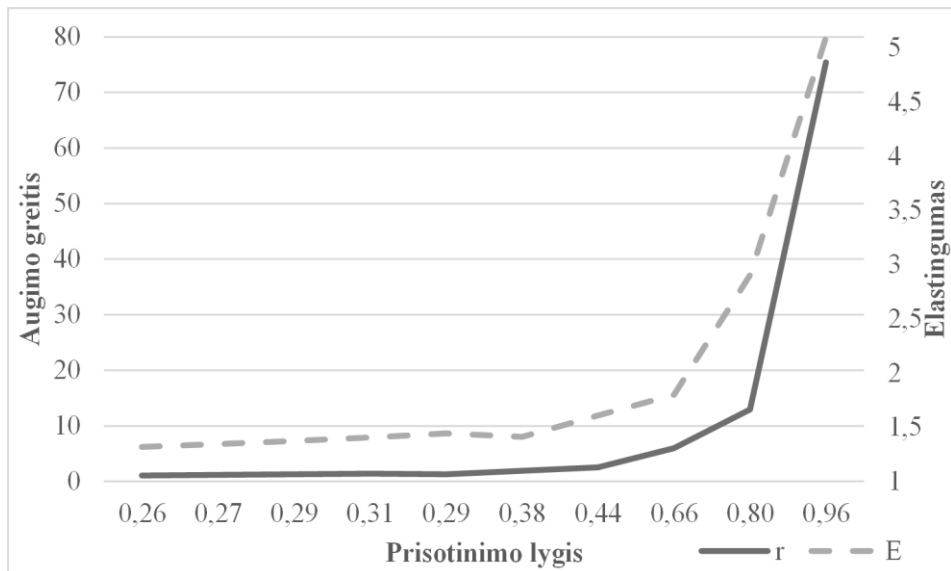
MXACICEI atveju burbulo dinamika buvo nuoseklesnė. Ilgesnis augimo ir kaitimo laikotarpis sudarė sąlygas rinkai prisitaikyti ir absorbuoti kapitalo srautus, todėl aiški destruktivi korekcija sistemoje nepasireiškė. Kartu šis atvejis parodo, kad modelyje nustatyta pastovi rinkos talpa realiose finansų rinkose turi būti interpretuojama atsargiai, nes faktinės rinkos talpos ribos gali kisti bėgant laikui. Todėl tolesniuose tyrimuose svarbu tikslinti augimo stadijų ribas pagal prisotinimo ir elastingumo rodiklius, taip pat įvertinti papildomų rodiklių, išorinių veiksnių ir dinamiškos rinkos talpos įtraukimo galimybes.

Toliau atliekama indeksų analizė, paremta sukaupu kapitalu. Šiuo atveju prisotinimo dinamika vertinama ne pagal indekso kainą, bet pagal grynujų kapitalo srautų pagrindu apskaičiuotą sukaupą kapitalą. Toks požiūris leidžia vertinti, kaip kapitalo įplaukos ir jų kaupimasis finansų rinkoje veikia prisotinimo lygį, augimo greitį, elastingumą ir burbulų formavimosi riziką.

„NASDAQ Clean Edge Green Energy“ indeksas

„NASDAQ Clean Edge Green Energy“ indeksas (CELS) atspindi JAV vertybinių popierių biržų prekybos sąrašuose esančių įmonių, veikiančių atsinaujinančiosios energetikos, energijos kaupimo, energijos vartojimo efektyvumo ir susijusių technologijų sektoriuose, akcijų kainų dinamiką. Indeksas apima tokias sritis kaip saulės, vėjo, biokuro, baterijų kaupimo, pažangiųjų tinklų ir elektromobilių

technologijos. Analizei pasirinktas 2018 m. IV ketvirčio–2021 m. III ketvirčio laikotarpis, kuriame fiksuotas ypač spartus indekso kainos ir sukaupto kapitalo augimas. Per šį laikotarpį indekso vertė padidėjo beveik keturis kartus, o sukauptas kapitalas – daugiau kaip 3,5 karto. Šio laikotarpio prisotinimo lygio ir augimo greičio skaičiavimo rezultatai, paremti sukaupto kapitalo dinamika, pateikti 53 paveiksle.

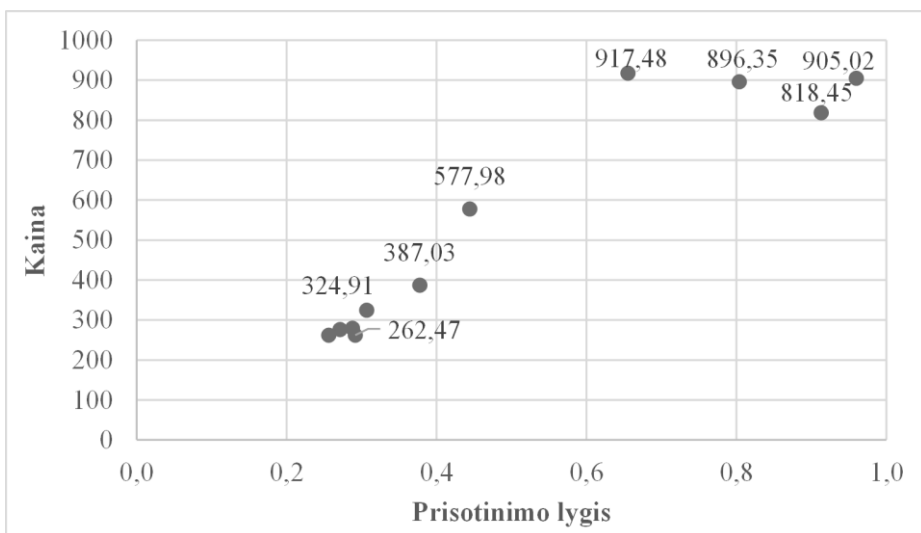


Šaltinis: autoriaus skaičiavimai, išplečiant Karaša ir Girdzijauskas (2024) analizę ir remiantis Bloomberg Finance L.P. (2024) duomenimis

53 pav. CELS indekso augimo greitis ir prisotinimo lygis

Tyrimo rezultatai rodo, kad CELS sistema pasiekia bifurkacijos tašką ir pereina į perkaitimo (III augimo) stadiją. Maksimalus prisotinimo lygis siekia 0,96, o maksimalus elastingumas padidėja iki 5,09. Šie rodikliai rodo stiprų teigiamą grįžtamąjį ryšį, aukštą sistemos jautrumą ir destruktvyvaus burbulo formavimąsi. Pagal tyrimo modelį toks prisotinimo lygis, viršijantis 0,9 ribą, rodo perkaitimo stadiją ir didelę burbulo sprogo ar reikšmingos korekcijos riziką. Šį vertinimą patvirtina ir vėlesnė sukaupto kapitalo dinamika: po pikinės reikšmės CELS sistema per 12 ketvirčių patyrė 72,6 % sukaupto kapitalo korekciją.

CELS sistemos atveju papildomai analizuojamas indekso kainos ir sukaupto kapitalo prisotinimo lygio ryšys. Ši analizė leidžia įvertinti galimą laiko atotrūkį tarp indekso kainos pokyčių ir kapitalo kaupimosi sistemoje (54 pav.).



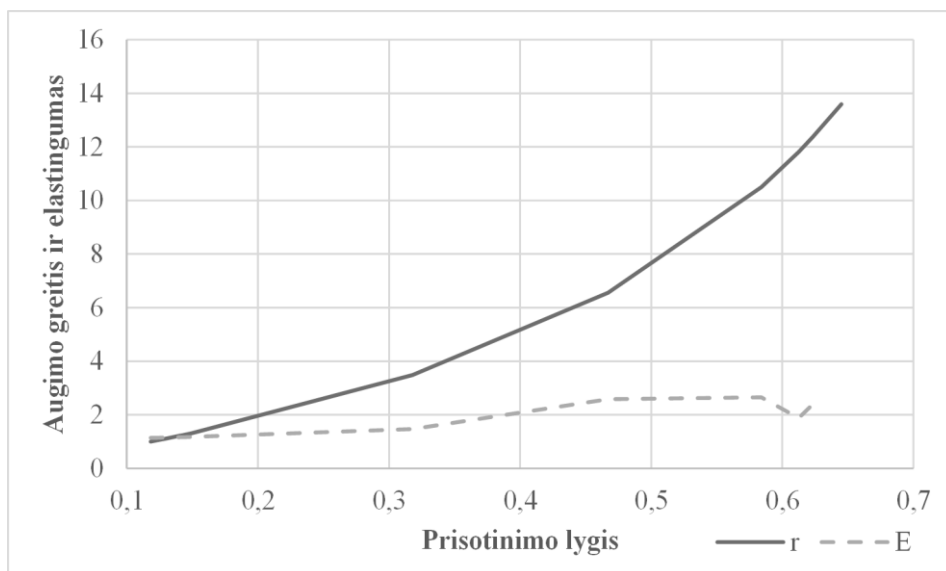
Šaltinis: adaptuota pagal Karaša ir Girdzijauskas (2024), remiantis Bloomberg Finance L.P. (2024) duomenimis

54 pav. CELS indekso vertės ir prisotinimo lygio sklaidos diagrama

54 paveiksle pateikta sklaidos diagrama rodo aiškią bifurkacijos takoskyrą. Apatinėje kairėje diagramos dalyje išsidėstę taškai atspindi laikotarpius iki bifurkacijos, kai indekso vertė ir sukaupto kapitalo prisotinimo lygis buvo santykinai žemi. Tuo tarpu viršutinėje dešinėje dalyje esantys taškai rodo laikotarpius po bifurkacijos, kai didesnis kapitalo prisotinimo lygis siejamas su aukštesne indekso verte. Kartu diagrama atskleidžia ir galimą laiko atotrūkį tarp indekso kainos ir sukaupto kapitalo prisotinimo lygio. Tai ypač matoma ties aukščiausia indekso verte, kai indeksas pasiekė 917,48 punkto, tačiau kapitalo prisotinimo lygis siekė tik 0,66. Kiti artimi laiko atotrūkio taškai taip pat matomi ties 577,98 ir 896,35 indekso reikšmėmis. Tai rodo, kad kainos dinamika CELS atveju galėjo aplenkti kapitalo kaupimosi procesą, o rinkos vertinimas buvo veikiamas ne tik sukaupto kapitalo, bet ir investuotojų lūkesčių bei kitų išorinių veiksnių.

„Global Clean Energy“ indeksas

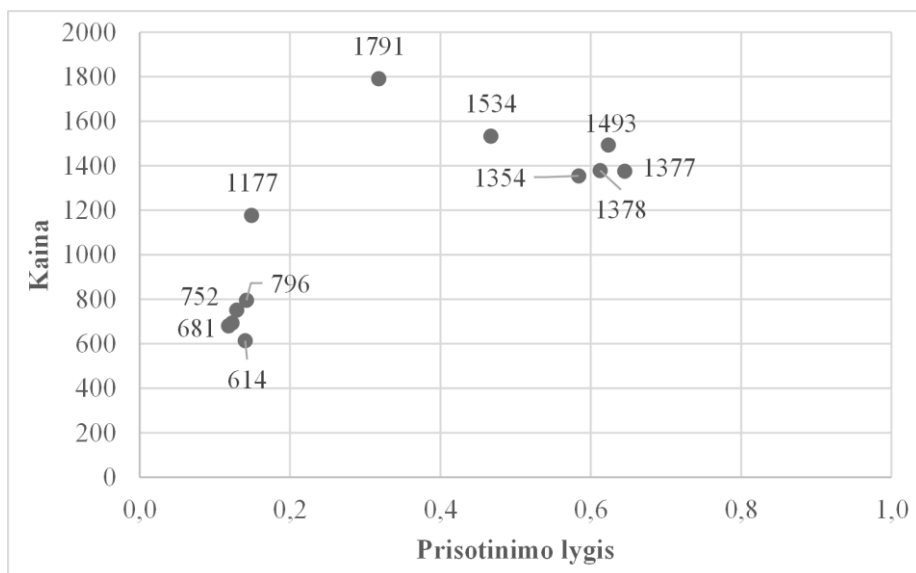
„S&P Global Clean Energy“ indeksas (SPGTCED) atspindi pasaulines švarios energijos įmones, veikiančias atsinaujinančiosios energetikos gamybos ir susijusių technologijų srityse. Indeksas apima įmones, susijusias su vėjo, saulės, hidroenergijos, energijos kaupimo ir švarios energijos įrangos technologijomis. Analizei pasirinktas 2019 m. II ketvirčio–2022 m. III ketvirčio laikotarpis, kuriame indekso vertė padvigubėjo, o sukauptas kapitalas padidėjo maždaug 5,5 karto – nuo 92 iki 503 mlrd. JAV dolerių. Šio laikotarpio prisotinimo lygio ir augimo greičio skaičiavimo rezultatai, paremti sukaupto kapitalo dinamika, pateikti 55 paveiksle.



Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

55 pav. SPGTCED indekso augimo greitis ir prisotinimo lygis

Tyrimo rezultatai rodo, kad SPGTCED sistemoje bifurkacijos taškas nepasiekiamas. Maksimalus prisotinimo lygis siekia 0,65, todėl jis išlieka žemiau 0,7 ribos, kuri tyrimo modelyje siejama su bifurkacijos tašku. Elastingumas spartesnio augimo laikotarpiu padidėja iki 2,65, tačiau šis padidėjimas nėra pakankamas aiškiam teigiamo grįžtamojo ryšio dominavimui ir burbulo formavimuisi patvirtinti. Todėl pagal tyrimo modelį SPGTCED sistema išlieka nuosaikaus augimo (I) stadijoje, o burbulas nenustatomas. Šį vertinimą patvirtina ir vėlesnė sukaupto kapitalo dinamika: po tiriamojo laikotarpio sukauptas kapitalas per 8 ketvirčius sumažėjo tik 20,5 %, todėl didžioji kapitalo dalis liko sistemoje. SPGTCED sistemos atveju taip pat analizuojamas indekso kainos ir sukaupto kapitalo prisotinimo lygio ryšys (56 pav.).



Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

56 pav. SPGTCED indekso vertės ir kapitalo prisotinimo lygio sklaidos diagrama

56 paveiksle pateikta sklaidos diagrama rodo dvi pagrindines taškų grupes. Apatinėje kairėje diagramos dalyje išsidėstę taškai atspindi laikotarpius, kai indekso vertė ir sukaupto kapitalo prisotinimo lygis buvo santykinai žemi. Tuo tarpu viršutinėje dešinėje dalyje esantys taškai rodo laikotarpius, kai indekso vertė buvo didesnė, o kartu didėjo ir sukaupto kapitalo prisotinimo lygis. Vis dėlto, skirtingai nei CELS atveju, šie taškų telkiniai neparodo aiškiai pasiektos bifurkacijos takoskyros, o veikiau rodo sistemos artėjimą prie jos nepasiekiant bifurkacijos taško. Kartu diagrama atskleidžia ir galimą laiko atotrūkį tarp indekso kainos ir sukaupto kapitalo prisotinimo lygio. Tai matyti iš trijų išsiskiriančių taškų, kurių indekso vertės siekia 1177, 1791 ir 1534 punktus, kai indekso vertė jau buvo reikšmingai padidėjusi, tačiau sukaupto kapitalo prisotinimo lygis dar nebuvo aukštas. Tai rodo, kad SPGTCED atveju kainos dinamika taip pat galėjo aplenkti kapitalo kaupimosi procesą, nors bendras sistemos prisotinimo lygis išliko nepakankamas bifurkacijai ir burbulo susidarymui.

Po tiriamojo laikotarpio SPGTCED sistemoje išryškėja skirtumas tarp sukaupto kapitalo ir indekso kainos dinamikos. Sukauptas kapitalas sumažėjo apie 20,5 %, tačiau indekso vertė koregavosi reikšmingiau – apie 54 %. Tai rodo, kad kapitalo srautai ir kainų dinamika gali judėti nevienodai, o indekso kaina gali būti jautresnė išoriniams veiksniams, investuotojų lūkesčiams ir rinkos nuotaikoms. Kadangi tyrimo modelis tiesiogiai neįtraukia išorinių veiksnių poveikio, šis atvejis parodo modelio ribotumą aiškinant kainų korekcijas tais atvejais, kai sukauptas kapitalas išlieka sistemoje. Analizės, paremtos indeksų sukauptu kapitalu, santrauka pateikiama 29 lentelėje.

29 lentelė. Indeksų analizės pagal sukaupą kapitalą santrauka

Indeksas	K_p	K_{max}	r_{max}	Maksimalus prisotinimas	Maksimalus elastingumas	Bifurkacija/burbulas	Kaitimo trukmė, ketv.	Perkaitimo trukmė, ketv.	Burbulo tipas
CELS	66,5	64	75,46	0,96	5,09	Taip	3	1	Destruktyvus
SPGTCED	780	503	13,59	0,65	2,65	Ne	-	-	-

Šaltinis: autoriaus skaičiavimai pagal Bloomberg Finance L.P. (2024)

Sukaupto kapitalo pagrindu atlikta CELS ir SPGTCED sistemų analizė rodo skirtingus finansinio prisotinimo ir burbulų formavimosi rezultatus. CELS atveju nustatytas bifurkacijos taškas, sistema perėjo į perkaitimo (III augimo) stadiją, o aukštas prisotinimo lygis, padidėjęs elastingumas ir vėlesnė reikšminga sukaupto kapitalo korekcija leidžia identifikuoti destruktivų burbulą. SPGTCED atveju bifurkacijos taškas nepasiektas, prisotinimo ir elastingumo rodikliai atitiko nuosaikaus augimo (I) stadiją, todėl burbulas nenustatytas.

Abiejų indeksų sklaidos diagramos rodo galimą laiko atotrūkį tarp indekso kainos ir sukaupto kapitalo prisotinimo lygio. CELS atveju aiškiai matoma takoskyra tarp laikotarpių iki bifurkacijos ir po jos, o kai kurie taškai rodo, kad indekso vertės augimas galėjo aplenkti sukaupto kapitalo prisotinimo didėjimą. SPGTCED atveju bifurkacijos takoskyra nesusiformuoja, tačiau taip pat matomi taškai, kuriuose indekso vertė jau buvo padidėjusi, o sukaupto kapitalo prisotinimo lygis dar nebuvo aukštas. Tai rodo, kad kainos ir kapitalo kaupimosi dinamika finansų rinkose gali nesutapti laike, todėl šis aspektas svarbus vertinant prisotinimo, bifurkacijos ir burbulų formavimosi požymius.

Bendra indeksų analizė rodo, kad iš keturių tirtų atsinaujinančiosios energetikos finansų rinkų indeksų trijuose nustatyti burbulai: du produktyvūs ir vienas destruktivus. ERIXP, MXACICEI ir CELS pasiekė bifurkacijos tašką ir kaitimo (II augimo) stadiją, o CELS vienintelis perėjo į perkaitimo (III augimo) stadiją. SPGTCED atveju bifurkacijos taškas nepasiektas, todėl burbulas nenustatytas. Šie rezultatai rodo, kad prisotinimo lygis, augimo greitis ir elastingumas gali būti naudojami kaip burbulų formavimosi indikatoriai, tačiau finansų rinkų indeksų analizėje būtina atsižvelgti ir į laiko atotrūkį, išorinius veiksnius, kainos ir kapitalo dinamikos neatitikimus bei galimą rinkos talpos kitimą laike.

Pasaulinių saulės, vėjo ir baterijų kaupimo sistemų instaliuotos galios analizė

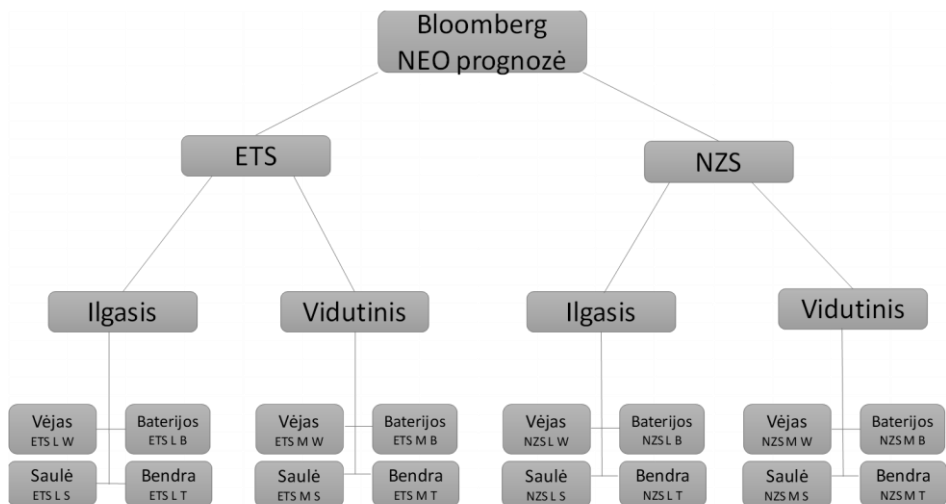
Šioje dalyje nagrinėjamos pasaulinės bendros AEI, saulės, vėjo ir baterijų kaupimo sistemų instaliuotos galios prognozės, remiantis „Bloomberg New Energy Outlook 2024“ duomenis (BloombergNEF, 2024b). Analizėje instaliuota galia naudojama kaip fizinio ir technologinio sistemos prisotinimo pakaitinis rodiklis, leidžiantis vertinti, kaip prognozuojama AEI pajėgumų plėtra susijusi su prisotinimo lygiu, augimo greičiu, elastingumu, bifurkacijos tašku ir galimu burbulų formavimusi.

Svarbu pažymėti, kad ši analizė remiasi prognoziniais duomenimis, todėl jos rezultatai priklauso nuo BloombergNEF (2024b) pateiktų scenarijų prielaidų ir

prognozuojamų instaliuotos galios trajektorijų. Disertacijoje nevertinamas pačių prognozių tikslumas ar patikimumas. Todėl gauti rezultatai interpretuojami kaip scenarijinis finansinio prisotinimo ir burbulų formavimosi rizikos vertinimas, o ne kaip tiesioginė ateities prognozė.

Analizei taikomi du pagrindiniai scenarijai. Economic Transition Scenario (ETS) atspindi nuoseklesnę energetikos transformaciją, labiau grindžiamą esamomis ekonomikos, rinkos ir politikos sąlygomis. Net Zero Scenario (NZS) numato spartesnę dekarbonizaciją ir intensyvesnę AEI diegimą siekiant nulinės emisijos tikslų. Disertacijos modelio požiūriu šie scenarijai leidžia palyginti, kaip skirtingas instaliuotos galios augimo greitis ir prognozuojama sistemos talpa veikia prisotinimo lygį, bifurkaciją ir galimą perėjimą į kaitimo ar perkaitimo stadijas.

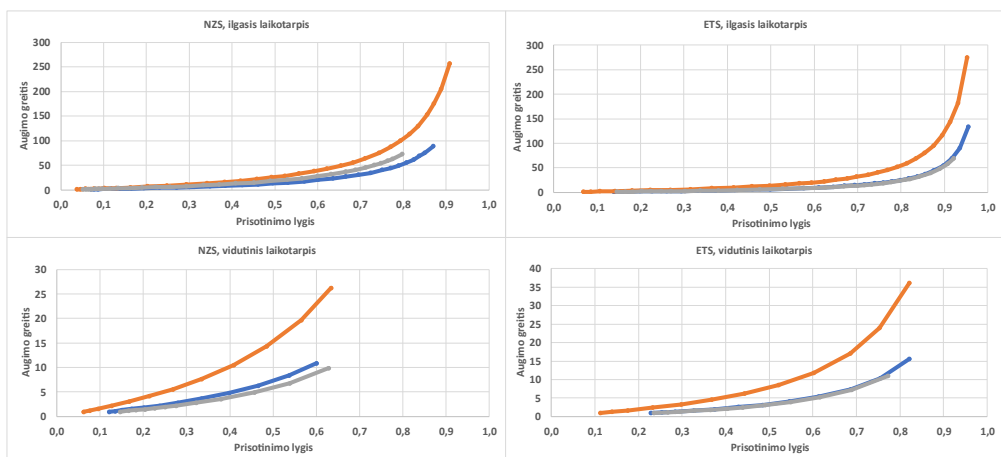
Kadangi naudojami prognoziniai duomenys rodo nuoseklų instaliuotos galios augimą iki 2050 m., analizės laikotarpiai apibrėžiami tyrimo modelio taikymo tikslais. Remiantis ekonominių ciklų teorijomis, išskiriamas vidutinės trukmės laikotarpis (2020–2031 m.), siejamas su Juglar investiciniu ciklu, ir ilgalaikis laikotarpis (2020–2050 m.), siejamas su Kuznets infrastruktūros ciklu (Gutiérrez-Barbarrusa, 2019; Schumpeter, 1983). Taip sudaroma 16 scenarijų struktūra, apimanti du scenarijus (ETS ir NZS), du laikotarpius (vidutinės trukmės ir ilgąjį) ir keturias sistemas: bendrą AEI, saulės, vėjo ir baterijų kaupimo sistemas (57 pav.).



Šaltinis: sudaryta autoriaus pagal Mikalauskas ir Karaša (2025)

57 pav. Scenarijų struktūra pagal NZS/ETS scenarijus, laikotarpį ir AEI sistemų tipus

AEI (bendras, saulės, vėjo) prisotinimo lygių ir logistinių augimo greičių skaičiavimo rezultatai pateikti 58 paveiksle, o baterijų kaupimo sistemos rezultatai – 59 paveiksle. Baterijų kaupimo sistema pateikiama atskirai, nes jos augimo greičio dinamika reikšmingai skiriasi nuo bendros AEI, saulės ir vėjo sistemų.

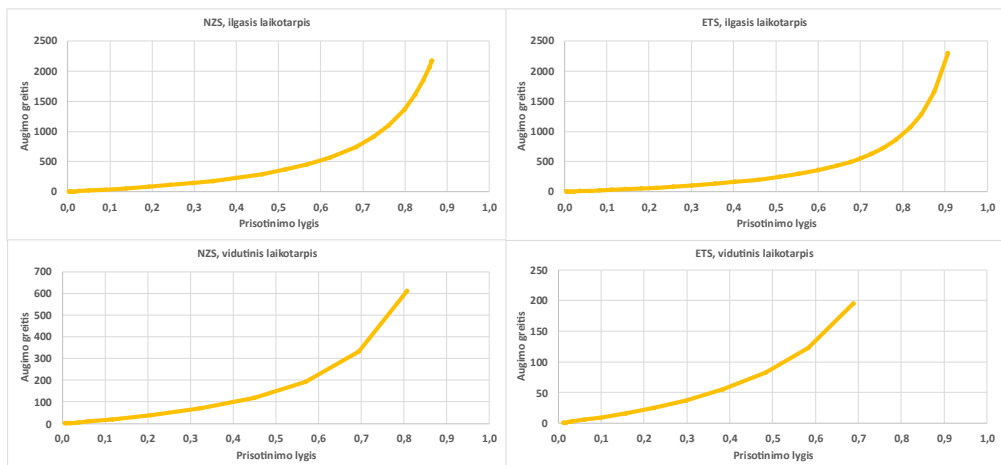


Šaltinis: autoriaus skaičiavimai, išplečiant Mikalauskas ir Karaša (2025) analizę ir remiantis BloombergNEF (2024b) duomenimis

Pastaba: mėlyna linija žymi bendrą AEI, oranžinė – saulės energiją, pilka – vėjo energiją.

58 pav. Bendros AEI, saulės ir vėjo instaliuotos galios scenarijų augimo greitis ir prisotinimo lygis

Išanalizavus prognozinčius duomenis pagal skirtingus scenarijus matyti, kad saulės energetikos instaliuota galia daugelyje scenarijų pasižymi didesniu logistiniu augimo greičiu nei vėjo energetika ar bendra AEI sistema, net kai pasiekiamas panašus prisotinimo lygis. Vėjo energetikos sistema pasižymi stabilesne dinamika ir labiau atitinka bendros AEI sistemos tendencijas. Augimo greičio skirtumus lemia skirtinga pradinė instaliuota galia, prognozuojamas plėtros mastas ir skirtingos sistemų augimo trajektorijos. Baterijų kaupimo sistema išsiskiria dideliais augimo greičiais ir specifine augimo kreivės forma. Tai siejama su žema pradine instaliuota galia 2020 m. ir prognozuojamu sparčiu šios technologijos plėtros tempu.



Šaltinis: autoriaus skaičiavimai, išplečiant Mikalauskas ir Karaša (2025) analizę ir remiantis BloombergNEF (2024b) duomenimis

59 pav. Baterijų kaupimo scenarijų augimo greitis ir prisotinimo lygis

Baterijų kaupimo sistemos analizė rodo didžiausią jautrumą prisotinimo ir augimo greičio pokyčiams. Bifurkacijos taškas nustatomas visuose baterijų kaupimo scenarijuose, išskyrus ETS vidutinės trukmės scenarijuose. Tai rodo, kad baterijų kaupimo technologijos pagal prognozinis duomenis yra viena jautriausių AEI sistemų, nes žema pradinė instaliuota galia ir spartus prognozuojamas augimas lemia didelį logistinio augimo greitį bei spartų prisotinimo lygio didėjimą.

Apibendrinti visų 16 scenarijų rezultatai pateikti 30 lentelėje.

30 lentelė. Scenarijų pagal instaliuotą galią analizės santrauka

Scenarijai	C_p	C_{max}	r_{max}	Maksimalus prisotinimas	Maksimalus elastingumas	Bifurkacija/ burbulas	Kaitimo trukmė, metais	Perkaitimo trukmė, metais	Burbulo tipas
ETS L T	21686	20719	133,18	0,96	15,46	Taip	10	3	Destruktyvus
ETS L S	11463	10923	274,28	0,95	14,43	Taip	9	3	Destruktyvus
ETS L W	5119	4717	69,16	0,92	10,81	Taip	11	2	Destruktyvus
ETS L B	3100	3018	8779,9	0,97	16,83	Taip	6	3	Destruktyvus
ETS M T	13155	10802	15,5	0,82	4,06	Taip	2	-	Produktyvus
ETS M S	6937	5701	36,06	0,82	4,06	Taip	2	-	Produktyvus
ETS M W	3145	2428	10,97	0,77	3,21	Taip	1	-	Produktyvus
ETS M B	1160	799	195,1	0,69	2,4	Ne	-	-	-
NZS L T	42804	37216	88,22	0,87	6,64	Taip	9	-	Produktyvus
NZS L S	21117	19187	256,81	0,91	8,93	Taip	9	1	Destruktyvus
NZS L W	14358	11447	72,16	0,8	4,44	Taip	6	-	Produktyvus
NZS L B	4488	3983	2715,14	0,89	8,16	Taip	13	-	Produktyvus
NZS M T	24815	14909	10,92	0,6	2,16	Ne	-	-	-
NZS M S	12752	8079	26,29	0,63	2,3	Ne	-	-	-
NZS M W	5075	3187	9,86	0,63	2,16	Ne	-	-	-
NZS M B	1916	1546	611,92	0,81	3,27	Taip	1	-	Produktyvus

Šaltinis: autoriaus skaičiavimai, išplečiant Mikalauskas ir Karaša (2025) analizę ir remiantis BloombergNEF (2024b) duomenimis

Tyrimo rezultatai rodo, kad ilgalaikiuose scenarijuose prisotinimo lygis ir logistinis augimo greitis dažniausiai yra didesni nei vidutinės trukmės scenarijuose, nes instaliuota galia kaupiama ilgesnį laikotarpį. Pagal tyrimo modelį ilgalaikiuose scenarijuose dažniau identifikuojami perkaitimo (III stadija) ir destruktivių burbulų požymiai, o vidutinės trukmės scenarijuose rezultatai nuosaikesni ir dažniau atitinka kaitimo (II) arba nuosaikaus augimo (I) stadijas. Svarbu pažymėti, kad aukštesnis prisotinimo lygis ne visada reiškia didesnę absoliutų instaliuotos galios kiekį: kai kuriais atvejais ETS scenarijus rodo aukštesnį prisotinimą nei NZS scenarijus, nes

prisotinimo lygis priklauso nuo santykio tarp pasiektos instaliuotos galios ir įvertintos sistemos talpos. NZS scenarijuje prognozuojama didesnė sistemos talpa, todėl net didesnis absoliutus instaliuotos galios augimas gali reikšti žemesnį santykinį prisotinimą.

Analizės rezultatus susiejus su laiko dinamika, nustatoma, kada skirtingose sistemose pagal scenarijus pasiekiamos kaitimo ir perkaitimo stadijos (31 lentelė). Šios datos nėra tiesioginė ateities prognozė, o modelio taikymo prognoziniais duomenimis rezultatas, priklausantis nuo pasirinkto scenarijaus, laikotarpio, įvertintos sistemos talpos ir modelio prielaidų.

31 lentelė. Prisotinimo stadijų ir burbulų formavimosi dinamika

ETS								
Stadija	Ilgasis				Vidutinis			
	Bendra	Saulė	Vėjas	Baterijos	Bendra	Saulė	Vėjas	Baterijos
Kaitimas (II)	2038	2039	2038	2042	2030	2030	2031	-
Perkaitimas (III)	2048	2048	2049	2048	-	-	-	-
NZS								
Stadija	Ilgasis				Vidutinis			
	Bendra	Saulė	Vėjas	Baterijos	Bendra	Saulė	Vėjas	Baterijos
Kaitimas (II)	2042	2041	2045	2038	-	-	-	2031
Perkaitimas (III)	-	2050	-	-	-	-	-	-

Šaltinis: autoriaus adaptuota pagal Mikalauskas ir Karaša (2025), remiantis BloombergNEF (2024b) duomenimis

Apibendrinti ir su laiku susieti rezultatai rodo, kada pagal skirtingus scenarijus analizuojamos sistemos pasiekia kaitimo ir perkaitimo stadijas. Ilgalaikiuose scenarijuose kaitimo stadija dažniausiai nustatoma 2038–2045 m., o perkaitimo stadija – tik kai kuriose sistemose: ETS scenarijuje apie 2048–2049 m., o NZS scenarijuje tik saulės energetikos sistemoje 2050 m. Vidutinės trukmės scenarijuose kaitimo stadija pasiekama anksčiau, tačiau ne visose sistemose: pagal ETS scenarijų ji nustatoma bendroje AEI, saulės ir vėjo sistemose 2030–2031 m., o pagal NZS scenarijų – tik baterijų kaupimo sistemoje 2031 m. Tai rodo, kad prisotinimo stadijų pasireiškimo laikas priklauso ne tik nuo scenarijaus ambicingumo, bet ir nuo sistemos tipo, pradinės instaliuotos galios bei įvertintos sistemos talpos.

Apibendrinant šį poskyrį, pažymėtina, kad scenarijų trukmė leidžia rezultatus interpretuoti per verslo ciklą logiką. Vidutinės trukmės scenarijai siejami su Juglar investiciniu ciklu, todėl juose nustatytos kaitimo stadijos labiau rodo investicijų aktyvumo, technologijų diegimo ir kapitalo kaupimo ciklišumą. Ilgalaikiai scenarijai siejami su Kuznets infrastruktūros ciklu, nes ilgalaikė AEI plėtra priklauso nuo infrastruktūros, įrangos, statybos ir kitų produktyvių aktyvų kaupimo. Šiuo požiūriu Schumpeterio ekonominių ciklų (Gutiérrez-Barbarrusa, 2019; Schumpeter, 1983) interpretacija leidžia scenarijų rezultatus vertinti kaip galimas inovacijų, investicijų ir

gamybinių pajėgumų plėtros bangas, kurios, artėjant prie sistemos talpos ribų, gali pereiti į kaitimo ar perkaitimo stadijas.

Pažymėtina, kad instaliuotos galios augimas neturėtų būti vertinamas kaip izoliuotas sektoriaus sėkmės rodiklis. Didėjanti saulės ir vėjo energetikos skverbtis nebūtinai sukuria proporcingą ekonominę vertę, jeigu kartu neauga sistemos lankstumas, kaupimo galimybės, tinklų infrastruktūra ir paklausos valdymas (Hirth, 2013; Hirth et al., 2015). Todėl instaliuotos galios prisotinimas šioje analizėje laikomas ne tiesioginiu finansinio burbulo įrodymu, o fizinio ir technologinio prisotinimo signalu, galinčiu rodyti perteklinių pajėgumų, sistemos nestabilumo ir spekuliacinės dinamikos riziką susijusiose rinkose.

Kadangi analizė pagrįsta prognoziniais duomenimis, nustatytos bifurkacijos, kaitimo ir perkaitimo stadijos interpretuojamos kaip scenarijinis prisotinimo rizikos vertinimas. Todėl nustatytos datos ir burbulų tipai rodo galimus padidėjusios rizikos laikotarpius, o ne tiesioginę ateities prognozę.

Empirinių tyrimų rezultatų sintezė

Empirinis tyrimas parodė, kad finansinio prisotinimo teorija pagrįstas modelis gali būti taikomas skirtingo pobūdžio AEI sistemoms: regioninei biokuru pagrįstai CŠT sistemai, atsinaujinančiosios energetikos finansų rinkų indeksams ir pasaulinėms AEI instaliuotos galios prognozėms. Šiose sistemose buvo vertinami tie patys pagrindiniai rodikliai: prisotinimo lygis, logistinis augimo greitis, elastingumas, bifurkacijos taškas ir burbulų formavimosi rizika.

Tyrimė taikytos trys prisotinimo vertinimo formos: instaliuota galia, indekso kaina ir sukauptas kapitalas. Šie rodikliai nėra tapatūs ir gali nesutapti laike. Kainų dinamika kai kuriais atvejais gali aplenksti kapitalo kaupimąsi, o instaliuotos galios prisotinimas gali būti vėluojantis fizinio ir technologinio sistemos prisotinimo rodiklis, susijęs su ankstesniais investiciniais ir finansiniais procesais. Todėl skirtingi prisotinimo rodikliai turėtų būti vertinami kaip papildantys, o ne tiesiogiai vienas kitą pakeičiantys matavimo būdai.

Empiriniai rezultatai parodė, kad prisotinimo poveikis priklauso nuo analizuojamos sistemos pobūdžio. Kauno CŠT atveju instaliuotos galios prisotinimas buvo susijęs ir su vartotojams palankiais rezultatais, ir su perteklinių pajėgumų bei reguliavimo poreikio rizika gamintojams. Finansų rinkų indeksų analizė atskleidė produktyvių ir destruktivių burbulų skirtumus bei parodė, kad burbulo tipui nustatyti svarbi ir vėlesnė sistemos dinamika. Pasaulinių instaliuotos galios scenarijų analizė parodė, kad baterijų kaupimo ir saulės energetikos sistemos yra jautresnės spartaus augimo ir prisotinimo rizikai, o vėjo energetikos sistema pasižymi stabilesne dinamika.

Šie rezultatai rodo, kad modelio taikymo rezultatai turi būti interpretuojami konkrečios sistemos kontekste. Jie neturėtų būti apibendrinami kaip vieno bendro „žaliojo burbulo“ visame AEI sektoriuje įrodymas. Vis dėlto empirinė analizė parodė, kad modelis leidžia sistemiskai vertinti investicijų ir pajėgumų plėtros skatinamą augimą ribotos sistemos talpos sąlygomis ir identifikuoti laikotarpius, kuriuose AEI sistemų plėtra gali pereiti iš stabilaus augimo į kaitimo ar perkaitimo stadijas.

IŠVADOS

1. Disertacijoje sukurtas konceptualus ir teorinis pagrindas, susiejantis atsinaujinančiosios energetikos plėtrą, investavimo procesus, finansinius burbulus ir logistinį ekonomikos augimą. Šis pagrindas grindžiamas idėja, kad AEI plėtra, investicijų augimas ir burbulų formavimasis turi būti analizuojami kartu kaip kompleksinis procesas, remiantis riboto augimo perspektyva. Logistinio augimo modeliai ir maržinalizmas suteikia teorinį pagrindą augimo ribų svarbai ir sistemos talpos vertinimo būtinumui paaiškinti.

Analizė parodė, kad AEI plėtra negali būti vertinama vien kaip technologinis ar aplinkosauginis perėjimas nuo tradicinės energetikos. AEI sistemoms reikalingos didelės investicijos, politikos parama, subsidijos ir teisinis reguliavimas, siekiant konkuruoti su tradicinėmis energetikos sistemomis. Tyrimas taip pat atskleidė, kad agresyvus plėtros skatinimas, aukšti lūkesčiai ir intensyvūs investicijų srautai gali sudaryti prielaidas burbulų formavimuisi AEI sektoriuje. Šiame kontekste investicijų srautai tampa ne tik AEI plėtros šaltiniu, bet ir mechanizmu, didinančiu prisotinimo bei burbulų formavimosi tikimybę.

Disertacijoje parodyta, kad tradiciniai augimo požūriai, grindžiami neribotos plėtros prielaidomis, yra nepakankami aiškinant perkaitimą ir burbulų formavimąsi AEI rinkose. Maržinalizmas į ekonominę analizę įveda mažėjančio ribinio naudingumo ir ribų svarbos sampratą. Tai suteikia teorinį pagrindą vertinti AEI plėtrą remiantis logistiniu augimu ir Finansinio prisotinimo teorija.

Sukurtas konceptualus pagrindas taip pat parodė, kad burbulai neturėtų būti interpretuojami vien kaip destruktivūs reiškiniai. Produktivūs burbulai gali skatinti technologinę plėtrą ir sistemų vystymąsi, o destruktivūs burbulai lemia nestabilumą, neefektyvų kapitalo paskirstymą ir žalingas ekonomikos korekcijas. Toks skirstymas leidžia burbulus vertinti ne tik normatyviniu, bet ir ekonominio poveikio požiūriu.

Šios išvalgos pagrindžia poreikį AEI investicijų dinamiką analizuoti riboto augimo perspektyvoje. Augimo modelių ir maržinalizmo apžvalga parodė, kad AEI plėtra turėtų būti vertinama ne tik pagal diegimo tikslus ir investicijų apimtį, bet ir pagal sistemos ribas, ribinius efektus bei rizikas, kylančias dėl perteklinių augimo lūkesčių.

2. Finansinio prisotinimo teorijos analizė susistemino ir patikslino pagrindinius teorinius elementus, būtinus burbulų formavimuisi aiškinti riboto augimo sąlygomis. Disertacijoje parodyta, kad burbulai gali būti interpretuojami ne tik kaip spekuliaciniai ar psichologiniai reiškiniai, bet ir kaip struktūrinės investicijų sąlygoto rinkos prisotinimo, logistinio augimo ir grįžamojo ryšio pasekmės. Šiame kontekste elgseninė ir naratyvinė burbulų interpretacija susiejama su finansinio prisotinimo teorijos struktūrine logika. Sukurtas teorinis pagrindas integruoja bifurkacijos tašką, elastingumą, grįžamojo ryšio poliškumą, rinkos dualumą ir augimo stadijas į vientisą burbulų formavimosi mechanizmo paaiškinimą.

Analizė atskleidė, kad pagal prisotinimo lygį apibrėžtos augimo stadijos yra esminės identifikuojant burbulų formavimąsi ekonominėse sistemose. Šios stadijos papildytos elastingumu kaip grįžamojo ryšio intensyvumo ir sistemos stabilumo indikatoriumi. Disertacijoje parodyta, kad iki bifurkacijos taško dominuoja neigiamas

grįžtamasis ryšys ir santykinis neelastingumas, o po bifurkacijos taško egzistuoja didėjantis elastingumas ir jis aktyvuoja teigiamą grįžtamąjį ryšį. Tai sudaro sąlygas spartėjančiam augimui bei spekuliacinei dinamikai – soties paradokso pasireiškimui.

Soties paradoksas interpretuotas kaip mechanizmas, per kurį didėjantis prisotinimas gali lemti didesnį pelningumą arba augimo intensyvumą, tačiau kartu mažina sistemos stabilumą ir didina jautrumą išorės sukrėtimams. Analizė taip pat parodė, kad šis reiškinys prieštarauja klasikiniam mažėjančio ribinio naudingumo principui.

Disertacijoje patikslinta rinkos dualumo samprata, išskiriant fundamentalią rinką iki bifurkacijos taško ir deficitinę rinką, susiformuojančią po bifurkacijos taško. Toks skirstymas paaiškina, kodėl po bifurkacijos gali dominuoti teigiamas grįžtamasis ryšys ir didėjanti grąža, o ne klasikiniai save koreguojantys rinkos pusiausvyros mechanizmai. Šiomis prisotinimo (deficitinės rinkos) sąlygomis galimi produktyvūs ir destruktivūs burbulai. Darbas toliau atskleidė, kad produktyvūs burbulai siejami su kaitimo stadija (II stadija), o destruktivūs burbulai – su perkaitimo stadija (III stadija), tačiau galutinis jų vertinimas taip pat priklauso nuo vėlesnės sistemos dinamikos. Tai leidžia burbulų klasifikavimą susieti su prisotinimu pagrįstomis augimo stadijomis.

Fenomenologinė rinkos mechanizmų ir schemų, tokių kaip Ponzi dinamika, „pump and dump“ schemos bei stokos ir gausos ekonomikos, analizė patvirtino platesnį vystomo teorinio pagrindo taikomumą. Šie reiškiniai gali būti interpretuojami kaip kraštutinės teigiamo grįžtamojo ryšio, deficitinės rinkos dinamikos ir prisotinimu paremto augimo išraiškos ekonomikoje, rinkose.

Apibendrinant, disertacijoje parodyta, kad finansiniai burbulai gali susiformuoti kaip struktūriškai sąlygoti investicijų sukkelto prisotinimo, bifurkacijos ir teigiamo grįžtamojo ryšio rezultatai sistemoms artėjant prie augimo ribų. Išoriniai sukrėtimai ir stochastiniai veiksniai gali inicijuoti rinkos pokyčius, tačiau tolesnė burbulų dinamika gali būti pirmiausia paaiškinama vidiniais investicijų sukeltais finansinio prisotinimo mechanizmais.

3. Sukurtas finansinio prisotinimo teorija pagrįstas metodologinis modelis, skirtas rinkos prisotinimo dinamikai ir burbulų formavimuisi vertinti AEI rinkų kontekste. Modelis pritaiko finansinio prisotinimo teorijos principus, transformuodamas burbulų formavimąsi į išmatuojamą analitinę sistemą, pagrįstą rinkos talpa, prisotinimo lygiu, logistinio augimo greičiu, elastingumu ir bifurkacijos indikatoriais.

Modelis investicijų sąlygotą prisotinimą vertina pasitelkdamas tris empirinius rodiklius: kainų dinamiką, sukauptą kapitalą ir instaliuotą galią. Tokia rodiklių struktūra leidžia modelį taikyti skirtingų tipų AEI sistemoms, įskaitant finansų rinkas, regionines energetikos sistemas ir pasaulines instaliuotos galios prognozes. Šiame kontekste investicijos interpretuojamos kaip svarbus prisotinimo dinamikos veiksnys, o kainų dinamika, sukauptas kapitalas ir instaliuota galia laikomi skirtingais empiriniais prisotinimo vertinimo rodikliais.

Sukurtas metodologinis požiūris integruoja struktūrizuotą burbulų identifikavimo ir klasifikavimo procesą, grindžiamą prisotinimo lygio, elastingumo ir bifurkacijos taško ryšiu, atskiriant produktyvius ir destruktivius burbulų tipus. Galutinis burbulo tipo vertinimas papildomai siejamas su vėlesne analizuojamo

kintamojo dinamika, vertinant, ar po augimo piko pasireiškia reikšminga korekcija, stabilizacija ar tolesnė sistemos plėtra.

Disertacijoje parodyta, kad logistinio augimo sistema gali būti pritaikyta AEI investicijų analizei transformuojant kintamuosius į kapitalo, kainos ir instaliuotos galios išraiškas. Skirtingai nei klasikiniuose paklausos ir pasiūlos modeliuose, prisotinimo lygis ir sukauptas kapitalas šiame modelyje traktuojami kaip nepriklausomi kintamieji, veikiantys logistinio augimo greitį. Toks priežastingumo apvertimas sudaro vieną pagrindinių metodologinių modelio išskirtinumų.

Potenciali rinkos arba sistemos talpa modelyje vertinama remiantis istoriniais arba prognoziniais duomenimis ir traktuojama kaip struktūrinis sistemos parametras.

Sukurtas modelis taip pat atskleidė svarbias prielaidas ir ribotumus. Modelis yra deterministinis ir grindžiamas fiksuotos rinkos talpos, homogeniškų agentų, *ceteris paribus* sąlygų bei riboto laiko atotrūkio vertinimo prielaidomis. Išoriniai sukrėtimai, politikos pokyčiai, stochastiniai svyravimai nėra tiesiogiai modeliuojami ir traktuojami kaip išorinės sąlygos, veikiančios sistemą. Šie ribotumai apibrėžia modelio taikomumo ribas ir nurodo tolesnio metodologinio vystymo kryptis.

4. Empirinis taikymas patvirtino, kad sukurtas modelis gali būti taikomas skirtingoms AEI sistemoms ir įvairiais analitiniais lygmenimis, įskaitant regionines energetikos sistemas, atsinaujinančiosios energetikos finansinius akcijų indeksus ir pasaulines instaliuotos galios prognozes. Tai patvirtina modelio metodologinį lankstumą ir suteikia trianguliaciją tarp skirtingų sistemų, empirinių pakaitinių rodiklių ir analitinių lygmenų.

Empirinė analizė patvirtino, kad modelis gali identifikuoti prisotinimo dinamiką, bifurkacijos taškus, elastingumo pokyčius ir tuo paremtas skirtingas burbulų formavimosi stadijas. Investicijų sąlygotas prisotinimas buvo identifikuotas per skirtingas empirines formas, įskaitant kainų dinamiką, sukauptą kapitalą ir instaliuotos galios augimą.

Kauno biokuru paremtos centralizuoto šildymo sistemos analizėje modelis identifikavo produktyvų burbulą, susijusį su sparčia biokuro instaliuotos galios plėtra. Stipri politikos parama, liberalizavimas ir aukšti investiciniai lūkesčiai spartino AEI plėtrą ir mažino šilumos kainas vartotojams, tačiau kartu sukūrė struktūrinius disbalansus, didesnę konkurencinį spaudimą ir perteklinės instaliuotos galios riziką gamintojams. Šis atvejis parodė, kad politikos intervencija ir investicijų skatinimas gali vienu metu spręsti vieną rinkos problemą ir kartu kurti kitą.

Atsinaujinančiosios energetikos finansų rinkų indeksų analizėje modelis identifikavo tiek produktyvius, tiek destruktivius burbulus. Rezultatai taip pat parodė, kad skirtingos indeksų sistemos pasižymi unikaliais augimo greičiais, elastingumo struktūromis ir prisotinimo dinamika, todėl jų negalima tiesiogiai lyginti ar apibendrinti visam AEI sektoriui. Analizė papildomai atskleidė laiko atotrūkį tarp kapitalo kaupimo ir kainų dinamikos, parodydama, kad investuotojų lūkesčiai gali laikinai iškreipti ryšį tarp prisotinimo ir rinkos vertinimo.

Prisotinimo ir burbulų rizikos skiriasi tarp atsinaujinančiosios energetikos technologinių sistemų. Baterijų kaupimo sistemos pasirodė esančios jautriausios dėl labai žemos pradinės instaliuotos galios ir spartaus prognozuojamo augimo, tuo tarpu vėjo energetikos sistemos pasižymėjo mažesniu jautrumu prisotinimui. NZS ir ETS

scenarijų palyginimas taip pat parodė, kad lėtesnis instaliuotos galios augimas gali lemti spartesnį santykinį prisotinimą esant labiau apribotoms sistemos talpos sąlygoms. Kartu šie rezultatai turi būti interpretuojami kaip scenarijinis fizinio ir technologinio prisotinimo rizikos vertinimas, nes instaliuotos galios prisotinimas nėra tiesioginis finansinio burbulo įrodymas, o veikiau galimas netiesioginis signalas apie rizikas susijusiose finansų, technologijų, išteklių ar infrastruktūros rinkose.

Empirinis taikymas taip pat atskleidė svarbius sukurto modelio ribotumus. Modelis remiasi deterministinėmis prielaidomis, fiksuota rinkos arba sistemos talpa, ribotu laiko atotrūkiu, išorinių sukrėtimų ir stochastinių veiksmų vertinimu. Todėl gauti rezultatai turi būti interpretuojami kaip konkrečių sistemų prisotinimo ir burbulų formavimosi požymių vertinimas, o ne kaip universalus ar tiesiogiai prognozuojantis viso AEI sektoriaus modelis.

5. Teorinė ir empirinė analizė parodė, kad investicijos į AEI turėtų būti vertinamos ne tik per plėtros tikslų ir technologinio vystymosi perspektyvą, bet ir per rinkos prisotinimo dinamiką, sistemos stabilumą ir burbulų formavimosi rizikas. Disertacijoje parodyta, kad pagrindinė rizika AEI rinkose gali kilti ne tik dėl stokos, bet ir dėl perteklinės investicijų koncentracijos bei augimo, viršijančio sistemos gebėjimą efektyviai absorbuoti kapitalą. Sistemoms artėjant prie prisotinimo ribų, lūkesčiai ir teigiamas grįžtamasis ryšys vis labiau pradeda dominuoti prieš racionalų vertinimą, didindami sisteminių nestabilumą ir destruktivių burbulų tikimybę.

Disertacijoje parodyta, kad finansinio prisotinimo teorija suteikia pagrindą transformuoti burbulų formavimąsi į išmatuojamą analitinę sistemą, pagrįstą prisotinimo lygiu, elastingumu, logistiniu augimu ir bifurkacijos indikatoriais. Investicijų srautai traktuojami kaip pagrindinis prisotinimo veiksnys, o kainų dinamika, sukauptas kapitalas ir instaliuota galia veikia kaip empiriniai pakaitiniai rodikliai, atspindintys skirtingas investicijų sąlygoto prisotinimo formas.

Empiriniai rezultatai patvirtino, kad produktyvūs burbulai gali skatinti technologinę plėtrą ir rinkos transformaciją, tuo tarpu destruktiviūs burbulai formuojasi tada, kai investicijų augimas atsiskiria nuo sistemos gebėjimo absorbuoti kapitalą ir išlaikyti stabilumą. Analizė taip pat parodė, kad rinkos talpa ir jos dinamika yra kritiškai svarbios interpretuojant prisotinimo ir burbulų rizikas. Sukurtame modelyje sistemos potenciali talpa vertinama remiantis istoriniais arba prognoziniais duomenimis, tačiau jos pagrįstumas gali būti pilnai įvertintas tik retrospektyviai, stebint tolimesnį sistemos vystymąsi.

Bifurkacijos taškų identifikavimas reikalauja stebėti ne tik prisotinimo lygį, bet ir elastingumo pokyčius, spartėjančius augimo greičius, skirtumus tarp kapitalo įplaukų ir instaliuotos galios augimo bei save stiprinančios rinkos elgsenos atsiradimą.

Disertacijoje taip pat parodyta, kad AEI politika neturėtų būti grindžiama vien maksimalios instaliuotos galios siekiu ar kuo spartesniu šios galios didinimu. Perteklinis skatinimas ir investicijų stimuliavimas gali spartinti AEI plėtrą, tačiau kartu kurti struktūrinius disbalansus, perteklinę instaliuotą galią ir destruktivių konkurenciją. Todėl ekonominės sistemos turėtų būti skatinamos derinant investicijų augimą, rinkos talpą, konkurencijos intensyvumą ir sistemos stabilumą.

Rezultatai taip pat kelia platesnius klausimus dėl ilgalaikio tikslo pasiekti visiškai prisotintas arba beveik 100 proc. siekiančias AEI sistemas. Finansinio

prisotinimo teorijos, kurios paradokso ir didėjančio nestabilumo artėjant prie prisotinimo ribų analizė rodo, kad perteklinė investicijų ir instaliuotos galios koncentracija gali sukurti struktūrinius pažeidžiamumus net ir tvariose energetikos sistemose. Nors šiam klausimui reikalingi tolimesni tyrimai, į šias tendencijas būtina atsižvelgti ilgalaikėje AEI politikoje ir investicijų planavime.

Remiantis teoriniais ir empiriniais rezultatais, pateikiamos šios rekomendacijos AEI politikos formuotojams ir investuotojams:

- AEI investicijų ir paramos politika turėtų apimti rinkos talpos, prisotinimo lygio, elastingumo, augimo spartėjimo bei skirtumų tarp kapitalo įplaukų ir instaliuotos galios augimo stebėseną, siekiant identifikuoti didėjančią nestabilumą dar prieš susiformuojant destruktiviems burbulams. Esminis taškas, parodantis, nuo kada sistema turi būti stebima, yra bifurkacijos taškas.

- Prisotinimo lygiai tarp maždaug 0,7 ir 0,9 gali rodyti intensyvaus, tačiau dar santykinai stabilaus augimo sąlygas (II stadija), tuo tarpu prisotinimo lygiai didesni nei 0,9 turėtų būti vertinami kaip potencialiai spekuliaciniai ir susiję su perkaitimo rizika.

- Politikos priemonės turėtų būti orientuotos ne tik į AEI augimo skatinimą, bet ir į struktūrinės perteklinės pasiūlos bei destruktivios konkurencijos prevenciją, taikant laipsniškus ir adaptyviuos paramos mechanizmus.

- Ateities tyrimai ir politikos analizė turėtų įtraukti dinamišką rinkos talpą, išorinius sukrėtimus, technologinius pokyčius, geopolitines sąlygas ir stochastinius veiksmus, darančius įtaką AEI sistemų plėtrai.

Apibendrinant, disertacijoje parodyta, kad didžiausios ekonominės rizikos gali kilti ne tik dėl stokos, bet ir dėl pertekliaus, kai investicijų augimas viršija sistemos gebėjimą jį tvariai absorbuoti. Susiejant elgsenos ir naratyvinę dinamikos interpretaciją su finansinio prisotinimo teorijos struktūrine logika, parodoma, kad kolektyviniai lūkesčiai, naratyvai ir investuotojų psichologija gali inicijuoti ar sustiprinti investicines bangas, o finansinis prisotinimas lemia sąlygas, kuriomis šios bangos tampa struktūriškai nestabilios. Finansinio prisotinimo teorija ir sukurtas modelis suteikia platesnį analitinį pagrindą suprasti, kaip pats tvarus vystymasis gali tapti netvarus sistemoms artėjant prie augimo ribų. Šiame kontekste disertacija prisideda prie atsinaujinančiosios energetikos transformacijos, investicijų sąlygotos rinkos dinamikos ir burbulų formavimosi analizės, parodydama, kad tvarus vystymasis gali tapti netvarus tada, kai investicijų skatinama plėtra pradeda viršyti sistemos gebėjimą stabiliai absorbuoti kapitalą, technologijas ir instaliuotą galią.

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CURRICULUM VITAE AND DESCRIPTION OF CREATIVE ACTIVITIES (CV)

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Education

- Since 2020** Lithuanian Energy Institute, Kaunas University of Technology. PhD candidate in Economics, Social Sciences.
- 2007–2009** Kaunas University of Technology, Faculty of Economics and Management. Master's degree in Economics, specialization in International Trade and Economics.
- 2003–2007** Kaunas University of Technology, Faculty of Economics and Management. Bachelor's degree in Economics, specialization in International Trade and Economics.

Professional Experience

- Since 2013** Lecturer. Main topics: entrepreneurship, finance and planning, financial literacy, business development, business plan preparation.
- Since 2009** Head of “Verslo iniciatyva”, a non-governmental organization. Responsible for scientific, educational and entrepreneurship skills development projects, research, training programmes and their implementation.
- 2015–2023** Vilnius University, Kaunas Faculty, Project Specialist. Responsible for faculty projects, R&D activities and commercialization of research activities, training development and research implementation.
- 2018–2020** Kauno kolegija, Lecturer. Main teaching topics/courses: fundamentals of business organization, microeconomics, finance.

Project Activities

- 2019–2023** Erasmus+ KA2 project “Future Competences Pathways for Marketing and ICT Education”. Project researcher and project administrator.
- 2017–2020** Erasmus+ KA2 project “New Pathways of Youth to Labour Market through Lifestyle Self-Employment”. Project researcher, responsible for methodology development and structuring of training material.
- 2018–2020** Erasmus+ KA2 project “BlockChain Network Online Education for Interdisciplinary European Competence Transfer”. Project coordinator/administrator.

LIST OF SCIENTIFIC PAPERS AND SCIENTIFIC CONFERENCES

Articles in peer-reviewed scientific journals:

1. Karaša, D., Drabavičius, Ž., Girdzijauskas, S., & Mikalauskas, I. (2025). Deconstructing the Enron Bubble: The Context of Natural Ponzi Schemes and the Financial Saturation Hypothesis. *Journal of Risk and Financial Management*, 18(8), 454. <https://doi.org/10.3390/jrfm18080454>
2. Karaša, D., & Girdzijauskas, S. (2024). Analysis of the green stock market bubble based on Financial Saturation Theory. *Transformations in Business & Economics*, 23(63A). <http://www.transformations.knf.vu.lt/63a/article/anals>
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Presentation of research results at conferences:

1. Karaša D., Drabavičius Z. ENRON natural Ponzis as a result of financial saturation phenomenon In: CYSENT' 2024: 20th international conference of young scientists on energy and natural sciences issues, 21–23 May, 2024 [proceedings]. Kaunas: Lietuvos energetikos institutas, 2024, pp. 47–47. ISSN 2783-6339
2. Karaša D., Girdzijauskas S. Prerequisites for the Formation of the Theory of Financial Saturation: The Return of Marginalism In: 19th Prof. Vladas Gronskas International Scientific Conference Abstract Book 29th of November, 2024. Vilnius: Vilnius University Press, 2024, pp. 14–14

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APPENDICES

Appendix 1. Calculation of growth rate elasticity based on saturation interest

K_p	K/K_p	i	E
100	0.011	0.101	
10	0.110	0.112	0.11
5	0.220	0.128	0.25
3	0.367	0.158	0.47
1.74	0.633	0.273	1.00
1.67	0.659	0.293	1.80
1.65	0.667	0.300	1.95
1.5	0.733	0.375	2.20
1.46	0.753	0.406	2.83
1.3	0.846	0.650	3.43
1.25	0.880	0.833	5.72
1.22	0.902	1.017	7.51
1.2	0.917	1.200	9.32
1.18	0.932	1.475	11.19
1.16	0.948	1.933	13.99
1.15	0.957	2.300	18.49
1.14	0.965	2.850	22.19
1.13	0.973	3.767	27.74
1.12	0.982	5.600	36.99
1.11	0.991	11.100	55.50

Appendix 2. Example of Loglet Lab calculation on index

Parameters							
k	271.53						
d	0						
t_m	35.61						
a	55.63						
x	cumulative	y_data0	y_model0	yfp_data0	yfp_model0	ys_data0	ys_model0
7	25.656	17.93	25.656	-1.151	-0.982	2.633	2.291
14	41.692	36.36	41.692	-0.811	-0.741	3.559	2.817
21	65.097	67.76	65.097	-0.478	-0.501	4.41	3.889
28	96.144	98.1	96.144	-0.247	-0.261	4.517	4.814
35	132.495	131	132.495	-0.03	-0.021	5.1	5.227
42	169.321	169.5	169.321	0.22	0.219	5.321	4.932
49	201.545	205.5	201.545	0.493	0.459	4.2	4.072
56	226.322	228.3	226.322	0.723	0.7	2.971	3
63	243.545	247.1	243.545	1.005	0.94	1.586	2.027
70	254.695	250.5	254.695	1.076	1.18	0.479	1.288
77	261.584	253.8	261.584	1.156	1.42	0.286	0.787
84	265.718	254.5	265.718	1.174	1.66	0.1	0.591

Appendix 3. Calculations for the biomass-based DH system in the Kaunas region

Scenario I					
Period	Date	K_a	K/K_p	r	E
1	2012	20.00	0.07	21.41	
2	2013	33.30	0.11	37.49	1.07
3	2014	53.30	0.18	65.08	1.13
4	2015	90.00	0.31	130.05	1.23
5	2016	200.28	0.69	645.13	1.45
Scenario II					
Period	Date	K_a	K/K_p	r	E
1	2012	20.00	0.05	20.90	
2	2013	33.30	0.08	35.94	1.05
3	2014	62.30	0.14	72.41	1.08
4	2015	147.00	0.33	220.25	1.16
5	2016	257.28	0.58	618.14	1.50
6	2020	327.00	0.74	1,270.38	2.41

Source: author's calculations based on Bakas (2018) and Valstybinė energetikos reguliavimo taryba

Appendix 4. ERIXP Loglet Lab calculation

Parameters							
k	3,061						
d	826						
t m	30.34						
a	10.15						
x	cumulati ve	y_ data0	y_ model0	yfp_ data0	yfp_ model0	ys_ data0	ys_ model0
25	1,027.49	1,233.00	1,027.49	-0.65	-1.00	44.00	94.70
26	1,122.19	1,277.00	1,122.19	-0.60	-0.82	25.50	112.30
27	1,252.08	1,284.00	1,252.08	-0.59	-0.63	78.50	149.62
28	1,421.44	1,434.00	1,421.44	-0.43	-0.44	-16.50	188.09
29	1,628.26	1,251.00	1,628.26	-0.63	-0.25	17.50	220.06
30	1,861.57	1,469.00	1,861.57	-0.39	-0.06	321.00	237.01
31	2,102.29	1,893.00	2,102.29	-0.04	0.12	642.00	233.66
32	2,328.88	2,753.00	2,328.88	0.80	0.31	309.00	211.08
33	2,524.45	2,511.00	2,524.45	0.49	0.50	-242.00	195.58

Source: author’s calculations using Loglet Lab, based on Bloomberg Finance L.P. (2024)

Appendix 5. ERIXP growth rate and saturation level calculation

Date	Period	P			
Q1 2013	1	327.54			
Q2 2013	2	406.75			
Q3 2013	3	533.74			
Q4 2013	4	553.84			
Q1 2014	5	670.23			
Q2 2014	6	712.65			
Q3 2014	7	669.85			
Q4 2014	8	600.61			
Q1 2015	9	685.88			
Q2 2015	10	747.28			
Q3 2015	11	713.36			
Q4 2015	12	888.60			
Q1 2016	13	850.43			
Q2 2016	14	838.73			
Q3 2016	15	916.25			
Q4 2016	16	863.82			
Q1 2017	17	983.40			
Q2 2017	18	1,020.18			
Q3 2017	19	972.98			
Q4 2017	20	926.15			
Q1 2018	21	944.52			
Q2 2018	22	958.96			
Q3 2018	23	1,035.30			
Q4 2018	24	1,010.37	P/P_p	r	E
Q1 2019	25	1,233.20	0.39	1.00	1.47
Q2 2019	26	1,276.88	0.40	1.06	1.64
Q3 2019	27	1,283.71	0.41	1.07	1.68
Q4 2019	28	1,434.48	0.45	1.30	1.68
Q1 2020	29	1,251.27	0.40	1.02	1.83
Q2 2020	30	1,468.81	0.46	1.36	1.65
Q3 2020	31	1,892.64	0.60	2.33	1.87
Q4 2020	32	2,752.64	0.87	10.44	2.49
Q1 2021	33	2,511.07	0.79	6.01	7.66

Q2 2021	34	2,393.47
Q3 2021	35	2,267.77
Q4 2021	36	2,216.63
Q1 2022	37	2,232.79
Q2 2022	38	2,013.84
Q3 2022	39	1,857.94
Q4 2022	40	2,093.38
Q1 2023	41	2,073.44
Q2 2023	42	1,980.31
Q3 2023	43	1,591.31
Q4 2023	44	1,808.14
Q1 2024	45	1,637.39

Source: author's calculations based on Bloomberg Finance L.P. (2024)

Appendix 6. MXACICEI Loglet Lab calculation

Parameters							
k	3,386						
d	854						
t_m	16.22						
a	15.32						
x	cumulati ve	y_ data0	y_ model0	yfp_ data0	yfp_ model0	ys_ data0	ys_ model0
10	1,218.13	1,310.00	1,218.13	-0.66	-0.78	31.00	98.85
11	1,316.98	1,341.00	1,316.98	-0.62	-0.65	13.50	108.67
12	1,435.48	1,337.00	1,435.48	-0.63	-0.53	102.50	128.38
13	1,573.75	1,546.00	1,573.75	-0.43	-0.40	-17.00	147.33
14	1,730.14	1,303.00	1,730.14	-0.67	-0.28	66.00	163.56
15	1,900.88	1,678.00	1,900.88	-0.32	-0.15	402.50	175.06
16	2,080.26	2,108.00	2,080.26	-0.01	-0.03	567.00	180.19
17	2,261.26	2,812.00	2,261.26	0.53	0.10	317.50	178.17
18	2,436.60	2,743.00	2,436.60	0.47	0.22	10.00	169.32
19	2,599.89	2,832.00	2,599.89	0.55	0.35	23.50	154.93
20	2,746.46	2,790.00	2,746.46	0.51	0.47	27.00	136.92
21	2,873.73	2,886.00	2,873.73	0.61	0.60	-39.50	117.33
22	2,981.12	2,711.00	2,981.12	0.44	0.72	-175.00	107.38

Source: author's calculations using Loglet Lab, based on Bloomberg Finance L.P. (2024)

Appendix 7. MXACICEI growth rate and saturation level calculation

Date	Period	P			
Q4 2016	1	1,030.40			
Q1 2017	2	1,128.81			
Q2 2017	3	1,202.52			
Q3 2017	4	1,288.32			
Q4 2017	5	1,346.50			
Q1 2018	6	1,310.81			
Q2 2018	7	1,290.64			
Q3 2018	8	1,288.62			
Q4 2018	9	1,176.92	P/P_p	r	E
Q1 2019	10	1,310.37	0.39	1.01	1.53
Q2 2019	11	1,341.15	0.40	1.05	1.63
Q3 2019	12	1,337.48	0.40	1.05	1.66
Q4 2019	13	1,545.76	0.46	1.35	1.65
Q1 2020	14	1,303.10	0.38	1.00	1.84
Q2 2020	15	1,678.14	0.50	1.58	1.63
Q3 2020	16	2,108.01	0.62	2.65	1.98
Q4 2020	17	2,811.65	0.83	7.86	2.65
Q1 2021	18	2,742.73	0.81	6.84	5.90
Q2 2021	19	2,832.09	0.84	8.20	5.26
Q3 2021	20	2,789.55	0.82	7.50	6.11
Q4 2021	21	2,886.18	0.85	9.27	5.68
Q1 2022	22	2,711.39	0.80	6.45	6.77
Q2 2022	23	2,366.77			
Q3 2022	24	2,267.63			
Q4 2022	25	2,468.10			
Q1 2023	26	2,602.44			
Q2 2023	27	2,607.83			
Q3 2023	28	2,303.57			
Q4 2023	29	2,449.04			
Q1 2024	30	2,441.05			

Source: author's calculations based on Bloomberg Finance L.P. (2024)

Appendix 8. CELS Loglet Lab calculation

Parameters							
k	66.55						
d	16						
t_m	40.11						
a	10.65						
x	cumulative	y_data0	y_model0	yfp_data0	yfp_model0	ys_data0	ys_model0
33	18.55	16.00	18.55	-inf	-1.27	1.00	1.21
34	19.76	17.00	19.76	-1.70	-1.10	1.00	1.46
35	21.47	18.00	21.47	-1.39	-0.92	1.00	2.04
36	23.84	19.00	23.84	-1.20	-0.74	1.00	2.75
37	26.97	20.00	26.97	-1.07	-0.56	0.00	3.54
38	30.92	19.00	30.92	-1.20	-0.38	2.50	4.31
39	35.59	25.00	35.59	-0.66	-0.20	5.50	4.89
40	40.70	30.00	40.70	-0.42	-0.02	9.50	5.14
41	45.86	44.00	45.86	0.09	0.16	11.50	4.98
42	50.66	53.00	50.66	0.44	0.34	10.00	4.46
43	54.78	64.00	54.78	1.28	0.52	4.00	3.72
44	58.10	61.00	58.10	0.91	0.70	-3.00	3.31

Source: adapted from Karaša and Girdzijauskas (2024), based on calculations using Loglet Lab and Bloomberg Finance L.P. (2024)

Appendix 9. CELS growth rate and saturation level calculation

Date	Period	P	Accumulation	Aggregate Net Fund Flows Tracking Index	K_a
Q4 2010	1	216.22	-0.82		39.78
Q1 2011	2	222.47	0.05	0.88	40.65
Q2 2011	3	201.60	-3.62	-3.67	36.98
Q3 2011	4	131.99	-4.31	-0.69	36.29
Q4 2011	5	127.41	-4.79	-0.48	35.81
Q1 2012	6	142.06	-5.79	-1.00	34.81
Q2 2012	7	122.82	-6.23	-0.45	34.37
Q3 2012	8	117.67	-6.73	-0.49	33.87
Q4 2012	9	125.15	-7.20	-0.47	33.40
Q1 2013	10	146.25	-6.65	0.55	33.95
Q2 2013	11	186.37	-5.94	0.71	34.66
Q3 2013	12	214.48	-5.14	0.80	35.46
Q4 2013	13	236.18	-3.40	1.74	37.20
Q1 2014	14	267.73	-0.29	3.12	40.31
Q2 2014	15	271.03	-3.31	-3.02	37.29
Q3 2014	16	251.71	-4.33	-1.02	36.27
Q4 2014	17	227.58	-5.20	-0.86	35.40
Q1 2015	18	244.94	-7.98	-2.78	32.62
Q2 2015	19	243.36	-7.10	0.88	33.50
Q3 2015	20	185.34	-8.61	-1.51	31.99
Q4 2015	21	210.95	-9.36	-0.76	31.24
Q1 2016	22	194.78	-10.09	-0.72	30.51
Q2 2016	23	188.91	-12.22	-2.13	28.38
Q3 2016	24	198.85	-12.96	-0.75	27.64
Q4 2016	25	203.32	-14.53	-1.57	26.07
Q1 2017	26	219.79	-12.50	2.03	28.10
Q2 2017	27	236.89	-11.60	0.90	29.00
Q3 2017	28	252.12	-10.64	0.95	29.96
Q4 2017	29	265.91	-16.04	-5.40	24.56

Q1 2018	30	255.39	-15.02	1.02	25.58			
Q2 2018	31	254.93	-13.88	1.14	26.72			
Q3 2018	32	257.32	-14.89	-1.01	25.71	K/K_p	r	E
Q4 2018	33	230.89	-24.57	-9.68	16.03	0.24	1.00	1.63
Q1 2019	34	262.57	-23.57	1.00	17.03	0.26	1.09	1.32
Q2 2019	35	276.27	-22.55	1.02	18.05	0.27	1.18	1.34
Q3 2019	36	279.54	-21.44	1.11	19.16	0.29	1.28	1.37
Q4 2019	37	324.91	-20.20	1.24	20.40	0.31	1.40	1.40
Q1 2020	38	262.47	-21.21	-1.01	19.39	0.29	1.30	1.44
Q2 2020	39	387.03	-15.47	5.74	25.13	0.38	1.92	1.41
Q3 2020	40	577.98	-11.05	4.42	29.55	0.44	2.52	1.61
Q4 2020	41	917.48	2.98	14.03	43.58	0.66	6.00	1.80
Q1 2021	42	896.35	12.85	9.87	53.45	0.80	12.93	2.90
Q2 2021	43	905.02	23.23	10.38	63.83	0.96	75.46	5.10
Q3 2021	44	818.45	20.12	-3.11	60.72			
Q4 2021	45	889.43	16.71	-3.41	57.31			
Q1 2022	46	844.99	3.47	-13.24	44.07			
Q2 2022	47	683.06	1.04	10.41	41.64			
Q3 2022	48	744.13	-4.64	-8.11	35.96			
Q4 2022	49	617.40	-9.36	-4.72	31.24			
Q1 2023	50	682.67	-11.97	-13.02	28.63			
Q2 2023	51	670.73	-17.14	-5.17	23.46			
Q3 2023	52	558.25	-19.28	-2.13	21.32			
Q4 2023	53	552.08	-21.39	-2.11	19.21			
Q1 2024	54	484.28	-23.10	-1.72	17.50			

Source: developed by the author by extending Karaša and Girdzijauskas (2024) based on Bloomberg Finance L.P. (2024)

Appendix 10. SPGTCED Loglet Lab calculation

Parameters							
<i>k</i>	780.00						
<i>d</i>	44						
<i>t_m</i>	78						
<i>a</i>	7.99						
<i>x</i>	cumulative	y_data0	y_model0	yfp_data0	yfp_model0	ys_data0	ys_model0
35	82.94	92.00	82.94	-1.69	-2.15	4.00	3.58
36	86.52	96.00	86.52	-1.58	-1.91	4.50	4.85
37	92.63	101.00	92.63	-1.47	-1.67	7.00	8.23
38	102.97	110.00	102.97	-1.32	-1.43	5.00	13.78
39	120.18	111.00	120.18	-1.31	-1.19	3.00	22.53
40	148.03	116.00	148.03	-1.24	-0.96	68.50	35.46
41	191.10	248.00	191.10	-0.50	-0.72	124.00	52.65
42	253.32	364.00	253.32	-0.16	-0.48	119.00	71.87
43	334.84	486.00	334.84	0.14	-0.24	57.00	87.84
44	429.00	478.00	429.00	0.12	0.00	-15.00	94.16
45	523.16	456.00	523.16	0.07	0.24	12.50	87.84
46	604.68	503.00	604.68	0.19	0.48	16.50	71.87
47	666.90	489.00	666.90	0.15	0.72	-11.00	52.65
48	709.97	481.00	709.97	0.13	0.96	-8.00	43.07

Source: author’s calculations using Loglet Lab, based on Bloomberg Finance L.P. (2024)

Appendix 11. SPGTCED growth rate and saturation level calculation

Date	Period	P	Accumulation	Aggregate Net Fund Flows Tracking Index	K_a
Q4 2010	1	1,014	-2		116
Q1 2011	2	1,199	-5	-4	113
Q2 2011	3	1,033	-4	1	113
Q3 2011	4	591	-7	-2	111
Q4 2011	5	556	-6	1	112
Q1 2012	6	581	-5	1	113
Q2 2012	7	463	-4	1	114
Q3 2012	8	436	-6	-3	111
Q4 2012	9	457	-5	1	113
Q1 2013	10	472	-9	-3	109
Q2 2013	11	555	-14	-6	103
Q3 2013	12	648	-49	-34	69
Q4 2013	13	667	-48	1	70
Q1 2014	14	714	-47	1	71
Q2 2014	15	754	-46	1	72
Q3 2014	16	688	-45	1	72
Q4 2014	17	625	-42	3	75
Q1 2015	18	755	-45	-2	73
Q2 2015	19	723	-43	1	74
Q3 2015	20	575	-42	1	75
Q4 2015	21	626	-42	1	76
Q1 2016	22	588	-41	1	77
Q2 2016	23	558	-39	2	79
Q3 2016	24	575	-40	-1	78
Q4 2016	25	507	-39	1	79
Q1 2017	26	545	-40	-1	78
Q2 2017	27	548	-39	1	79
Q3 2017	28	570	-40	-1	78
Q4 2017	29	599	-43	-3	75

Q1 2018	30	606	-44	-1	74			
Q2 2018	31	561	-43	1	75			
Q3 2018	32	547	-40	3	78			
Q4 2018	33	531	-39	0	79			
Q1 2019	34	625	-38	1	80	K/K_p	r	E
Q2 2019	35	681	-26	12	92	0.12	1.00	1.11
Q3 2019	36	694	-22	3	96	0.12	1.05	1.13
Q4 2019	37	752	-17	5	101	0.13	1.11	1.14
Q1 2020	38	614	-8	9	110	0.14	1.22	1.15
Q2 2020	39	796	-7	1	111	0.14	1.24	1.16
Q3 2020	40	1,177	-2	5	116	0.15	1.31	1.17
Q4 2020	41	1,791	130	132	248	0.32	3.49	1.17
Q1 2021	42	1,534	246	116	364	0.47	6.55	1.47
Q2 2021	43	1,493	369	122	486	0.62	12.39	1.88
Q3 2021	44	1,378	360	-9	478	0.61	11.82	2.66
Q4 2021	45	1,354	338	-22	456	0.58	10.50	2.58
Q1 2022	46	1,377	385	48	503	0.65	13.59	2.40
Q2 2022	47	1,273	371	0	489			
Q3 2022	48	1,212	363	-22	481			
Q4 2022	49	1,226	371	8	489			
Q1 2023	50	1,261	371	0	489			
Q2 2023	51	1,172	367	-4	485			
Q3 2023	52	932	341	-25	459			
Q4 2023	53	1,000	339	-2	457			
Q1 2024	54	893	300	-39	418			

Source: author's calculations based on Bloomberg Finance L.P. (2024)

	Total				Solar				Wind				Battery			
	K_a GW	K/K_p	r	E	K_a GW	K/K_p	r	E	K_a GW	K/K_p	r	E	K_a GW	K/K_p	r	E
NZS Medium term																
2020	3,005	0.12	1.00	1.12	787	0.06	1.00	1.05	742	0.15	1.00	1.15	13	0.01	1.02	1.00
2021	3,332	0.13	1.13	1.14	969	0.08	1.25	1.07	843	0.17	1.16	1.17	21	0.01	1.65	1.01
2022	3,734	0.15	1.29	1.16	1,215	0.10	1.60	1.08	930	0.18	1.31	1.20	36	0.02	2.82	1.01
2023	4,305	0.17	1.52	1.18	1,619	0.13	2.21	1.11	1,035	0.20	1.50	1.22	71	0.04	5.64	1.02
2024	4,998	0.20	1.83	1.21	2,133	0.17	3.05	1.15	1,147	0.23	1.71	1.26	115	0.06	9.33	1.04
2025	5,878	0.24	2.25	1.25	2,727	0.21	4.14	1.20	1,271	0.25	1.95	1.29	224	0.12	19.35	1.06
2026	6,941	0.28	2.82	1.31	3,421	0.27	5.57	1.27	1,400	0.28	2.22	1.33	398	0.21	38.32	1.13
2027	8,304	0.33	3.65	1.39	4,258	0.33	7.62	1.37	1,634	0.32	2.77	1.38	616	0.32	69.39	1.26
2028	9,884	0.40	4.80	1.50	5,219	0.41	10.53	1.50	1,926	0.38	3.57	1.47	861	0.45	119.38	1.47
2029	11,554	0.47	6.32	1.66	6,185	0.48	14.32	1.69	2,316	0.46	4.90	1.61	1,091	0.57	193.60	1.82
2030	13,309	0.54	8.40	1.87	7,203	0.56	19.73	1.94	2,730	0.54	6.80	1.84	1,330	0.69	332.28	2.32
2031	14,909	0.60	10.92	2.16	8,079	0.63	26.29	2.30	3,187	0.63	9.86	2.16	1,546	0.81	611.92	3.27
ETS Medium term																
2020	3,005	0.23	1.00	1.26	787	0.11	1.00	1.10	742	0.24	1.00	1.26	13	0.01	1.02	1.01
2021	3,332	0.25	1.15	1.30	969	0.14	1.27	1.13	843	0.27	1.19	1.31	21	0.02	1.66	1.01
2022	3,734	0.28	1.34	1.34	1,215	0.18	1.66	1.16	930	0.30	1.36	1.37	36	0.03	2.84	1.02
2023	4,305	0.33	1.64	1.40	1,619	0.23	2.38	1.21	1,035	0.33	1.59	1.42	71	0.06	5.76	1.03
2024	4,930	0.37	2.02	1.49	2,064	0.30	3.31	1.30	1,147	0.36	1.86	1.49	115	0.10	9.70	1.07
2025	5,644	0.43	2.54	1.60	2,554	0.37	4.55	1.42	1,271	0.40	2.20	1.57	183	0.16	16.56	1.11

2026	6,377	0.48	3.18	1.75	3,078	0.44	6.23	1.58	1,380	0.44	2.53	1.68	261	0.22	25.57	1.19
2027	7,189	0.55	4.07	1.94	3,615	0.52	8.50	1.80	1,544	0.49	3.12	1.78	347	0.30	37.60	1.29
2028	8,068	0.61	5.36	2.21	4,175	0.60	11.81	2.09	1,726	0.55	3.94	1.96	446	0.38	55.19	1.43
2029	9,036	0.69	7.41	2.59	4,756	0.69	17.04	2.51	1,939	0.62	5.20	2.22	561	0.48	82.71	1.63
2030	9,916	0.75	10.34	3.19	5,227	0.75	23.89	3.18	2,165	0.69	7.16	2.61	676	0.58	123.36	1.94
2031	10,802	0.82	15.50	4.06	5,701	0.82	36.06	4.06	2,428	0.77	10.97	3.21	799	0.69	195.10	2.40
NZS Long term																
2020	3,005	0.07	1.00	1.07	787	0.04	1.00	1.03	742	0.05	1.00	1.05	13	0.00	1.02	1.00
2021	3,332	0.08	1.12	1.08	969	0.05	1.24	1.04	843	0.06	1.14	1.05	21	0.00	1.65	1.00
2022	3,734	0.09	1.27	1.08	1,215	0.06	1.58	1.05	930	0.06	1.27	1.06	36	0.01	2.80	1.00
2023	4,305	0.10	1.48	1.10	1,619	0.08	2.14	1.06	1,035	0.07	1.43	1.07	71	0.02	5.54	1.01
2024	4,998	0.12	1.75	1.11	2,133	0.10	2.90	1.08	1,147	0.08	1.59	1.08	115	0.03	9.04	1.02
2025	5,878	0.14	2.11	1.13	2,727	0.13	3.83	1.11	1,271	0.09	1.78	1.09	224	0.05	18.06	1.03
2026	6,941	0.16	2.56	1.16	3,421	0.16	4.99	1.15	1,400	0.10	1.98	1.10	398	0.09	33.45	1.05
2027	8,304	0.19	3.19	1.19	4,258	0.20	6.52	1.19	1,634	0.11	2.36	1.11	616	0.14	54.78	1.10
2028	9,884	0.23	3.98	1.24	5,219	0.25	8.48	1.25	1,926	0.13	2.84	1.13	861	0.19	81.67	1.16
2029	11,554	0.27	4.90	1.30	6,185	0.29	10.70	1.33	2,316	0.16	3.53	1.15	1,091	0.24	110.56	1.24
2030	13,309	0.31	5.98	1.37	7,203	0.34	13.37	1.41	2,730	0.19	4.31	1.19	1,330	0.30	144.98	1.32
2031	14,909	0.35	7.08	1.45	8,079	0.38	16.01	1.52	3,187	0.22	5.24	1.23	1,546	0.34	180.91	1.42
2032	16,460	0.38	8.28	1.53	8,865	0.42	18.69	1.62	3,666	0.26	6.29	1.29	1,783	0.40	226.94	1.53
2033	18,142	0.42	9.74	1.62	9,680	0.46	21.86	1.72	4,202	0.29	7.59	1.34	2,064	0.46	293.03	1.66
2034	19,731	0.46	11.33	1.74	10,395	0.49	25.04	1.85	4,781	0.33	9.16	1.41	2,314	0.52	366.28	1.85
2035	21,163	0.49	12.95	1.86	11,036	0.52	28.28	1.97	5,301	0.37	10.74	1.50	2,543	0.57	450.13	2.06
2036	22,714	0.53	14.97	1.98	11,753	0.56	32.42	2.09	5,862	0.41	12.66	1.59	2,790	0.62	565.64	2.31
2037	24,360	0.57	17.49	2.13	12,489	0.59	37.39	2.26	6,473	0.45	15.06	1.69	3,066	0.68	742.13	2.64

2038	25,763	0.60	20.02	2.32	13,131	0.62	42.48	2.45	7,020	0.49	17.56	1.82	3,257	0.73	910.87	3.16
2039	27,210	0.64	23.11	2.51	13,822	0.65	48.94	2.64	7,598	0.53	20.63	1.96	3,417	0.76	1,098.65	3.65
2040	28,466	0.67	26.29	2.74	14,413	0.68	55.54	2.89	8,074	0.56	23.58	2.12	3,585	0.80	1,366.48	4.19
2041	29,735	0.69	30.13	2.99	15,013	0.71	63.54	3.15	8,606	0.60	27.46	2.28	3,700	0.82	1,615.22	4.97
2042	30,999	0.72	34.78	3.28	15,707	0.74	75.00	3.46	9,070	0.63	31.48	2.50	3,784	0.84	1,850.18	5.69
2043	32,136	0.75	39.90	3.63	16,281	0.77	86.96	3.90	9,550	0.67	36.45	2.72	3,847	0.86	2,064.68	6.37
2044	32,977	0.77	44.44	4.01	16,750	0.79	99.09	4.37	9,876	0.69	40.43	2.99	3,873	0.86	2,169.65	7.00
2045	33,772	0.79	49.52	4.36	17,185	0.81	112.91	4.84	10,220	0.71	45.32	3.20	3,869	0.86	2,152.82	7.30
2046	34,578	0.81	55.68	4.74	17,615	0.83	129.94	5.37	10,509	0.73	50.10	3.47	3,936	0.88	2,452.77	7.25
2047	35,264	0.82	61.95	5.20	18,057	0.86	152.45	6.03	10,733	0.75	54.34	3.73	3,938	0.88	2,463.49	8.13
2048	35,846	0.84	68.23	5.68	18,404	0.87	175.22	6.90	10,960	0.76	59.19	3.96	3,928	0.88	2,412.29	8.16
2049	36,360	0.85	74.73	6.15	18,752	0.89	204.80	7.78	11,128	0.78	63.22	4.23	3,902	0.87	2,292.95	8.01
2050	37,216	0.87	88.22	6.64	19,187	0.91	256.81	8.93	11,447	0.80	72.16	4.44	3,983	0.89	2,715.14	7.66
ETS Long term																
2020	3,005	0.14	1.00	1.14	787	0.07	1.00	1.06	742	0.15	1.00	1.14	13	0.00	1.02	1.00
2021	3,332	0.15	1.13	1.16	969	0.08	1.25	1.07	843	0.16	1.16	1.17	21	0.01	1.65	1.00
2022	3,734	0.17	1.29	1.18	1,215	0.11	1.61	1.09	930	0.18	1.31	1.20	36	0.01	2.81	1.01
2023	4,305	0.20	1.54	1.21	1,619	0.14	2.23	1.12	1,035	0.20	1.50	1.22	71	0.02	5.57	1.01
2024	4,930	0.23	1.83	1.25	2,064	0.18	2.98	1.16	1,147	0.22	1.70	1.25	115	0.04	9.14	1.02
2025	5,644	0.26	2.19	1.29	2,554	0.22	3.89	1.22	1,271	0.25	1.95	1.29	183	0.06	14.92	1.04
2026	6,377	0.29	2.59	1.35	3,078	0.27	4.98	1.29	1,380	0.27	2.18	1.33	261	0.08	21.80	1.06
2027	7,189	0.33	3.08	1.42	3,615	0.32	6.25	1.37	1,544	0.30	2.55	1.37	347	0.11	29.90	1.09
2028	8,068	0.37	3.68	1.50	4,175	0.36	7.77	1.46	1,726	0.34	3.00	1.43	446	0.14	39.94	1.13
2029	9,036	0.42	4.44	1.59	4,756	0.41	9.62	1.57	1,939	0.38	3.60	1.51	561	0.18	52.50	1.17
2030	9,916	0.46	5.24	1.71	5,227	0.46	11.37	1.71	2,165	0.42	4.32	1.61	676	0.22	66.26	1.22

2031	10,802	0.50	6.17	1.84	5,701	0.50	13.42	1.84	2,428	0.47	5.32	1.73	799	0.26	82.42	1.28
2032	11,656	0.54	7.22	1.99	6,118	0.53	15.53	1.99	2,694	0.53	6.56	1.90	941	0.30	103.44	1.35
2033	12,472	0.58	8.41	2.16	6,485	0.57	17.67	2.14	2,953	0.58	8.04	2.11	1,106	0.36	131.69	1.44
2034	13,224	0.61	9.72	2.35	6,812	0.59	19.87	2.30	3,206	0.63	9.88	2.36	1,253	0.40	161.11	1.55
2035	13,953	0.64	11.22	2.56	7,135	0.62	22.37	2.46	3,419	0.67	11.87	2.68	1,421	0.46	200.99	1.68
2036	14,514	0.67	12.58	2.80	7,442	0.65	25.11	2.65	3,511	0.69	12.88	3.01	1,578	0.51	246.32	1.85
2037	15,040	0.69	14.07	3.02	7,752	0.68	28.34	2.85	3,582	0.70	13.74	3.18	1,719	0.55	295.57	2.04
2038	15,502	0.71	15.58	3.26	7,988	0.70	31.18	3.09	3,660	0.71	14.79	3.33	1,864	0.60	358.03	2.24
2039	16,033	0.74	17.63	3.51	8,295	0.72	35.52	3.30	3,745	0.73	16.09	3.51	1,998	0.64	430.39	2.51
2040	16,466	0.76	19.61	3.84	8,557	0.75	39.94	3.62	3,810	0.74	17.17	3.73	2,099	0.68	497.98	2.81
2041	16,879	0.78	21.83	4.15	8,816	0.77	45.17	3.94	3,888	0.76	18.63	3.91	2,171	0.70	554.56	3.10
2042	17,318	0.80	24.65	4.51	9,076	0.79	51.58	4.33	3,981	0.78	20.63	4.16	2,252	0.73	630.12	3.34
2043	17,742	0.82	27.97	4.97	9,319	0.81	58.97	4.80	4,068	0.79	22.83	4.50	2,340	0.75	730.59	3.65
2044	18,166	0.84	32.09	5.50	9,575	0.84	68.79	5.35	4,142	0.81	24.99	4.87	2,429	0.78	859.74	4.08
2045	18,559	0.86	36.90	6.16	9,793	0.85	79.55	6.07	4,203	0.82	27.08	5.24	2,536	0.82	1,068.39	4.62
2046	18,994	0.88	43.86	6.94	10,033	0.88	95.16	6.86	4,311	0.84	31.49	5.59	2,616	0.84	1,284.51	5.50
2047	19,457	0.90	54.26	8.05	10,258	0.89	115.45	8.01	4,447	0.87	39.07	6.34	2,713	0.88	1,664.86	6.41
2048	19,877	0.92	68.32	9.73	10,469	0.91	142.92	9.51	4,553	0.89	47.44	7.62	2,809	0.91	2,295.25	8.01
2049	20,284	0.94	89.91	11.99	10,669	0.93	182.23	11.54	4,645	0.91	57.86	9.04	2,916	0.94	3,759.45	10.67
2050	20,719	0.96	133.18	15.46	10,923	0.95	274.28	14.43	4,717	0.92	69.16	10.81	3,018	0.97	8,779.90	16.83

Source: developed by the author by consolidating the results of Mikalauskas and Karaša (2025), based on BloombergNEF (2024b)

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