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SĄRYŠIS TARP ENERGIJOS VARTOJIMO IR EKONOMIKOS AUGIMO: BALTIJOS ŠALIŲ ANALIZĖ	THE ENERGY CONSUMPTION–ECONOMIC GROWTH NEXUS: EVIDENCE FROM THE BALTIC STATES

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LIST OF ABBREVIATIONS

ADF – Augmented Dickey–Fuller

ARDL – Autoregressive Distributed Lag

DOLS – Dynamic Ordinary Least Squares Estimator

FMOLS – Fully Modified Ordinary Least Squares

GDP – Gross Domestic Product

GFCF – Gross Fixed Capital Formation

GMM – Generalized method of moments

IMS – Im, Pesaran, and Shin

KLEC – Capital, Labor, Energy, Creativity

KLEM – Capital, Labor, Energy, Materials

LLC – Levin, Lin, and Chu

OPEC – Organization of the Petroleum Exporting Countries

PP – Phillips–Perron

PVECM – Panel Vector Error Correction Method

R&D – Research and Development

REXS – Resource-EXergy-Service

SNA – System of National Accounts

LIST OF TABLES AND FIGURES

CONTENTS

INTRODUCTION

The relevance of the topic. Economic growth and the exploration of its drivers remain among the most persistently studied topics in modern econometric research. From capital accumulation (Solow, 1956) to institutional quality (Acemoglu et al., 2001) , globalization (Dreher, 2005) to inequality (Kuznets, 1955), the list of potential contributing factors, as does academic interest, continues to expand. The popularity of growth-focused research reflects the theoretical importance of the subject and its significant policy relevance. Understanding growth's mechanisms and principal determinants is essential for designing effective economic policy. In that sense, studying growth is a form of reverse-engineering: breaking down past development to identify which conditions and inputs are worth replicating, and which should be avoided.

While scholars and policymakers continue to puzzle over the drivers of modern economic growth, one fundamental prerequisite remains clear: the extensive use of energy. Throughout most of human history, civilizations relied almost entirely on solar energy, whether in the form of biomass or the muscle power of humans and animals. Population growth and economic output were therefore constrained by agricultural yields and the limits of biological energy. This dynamic changed dramatically with the Industrial Revolution, when societies began to harness fossil fuels — unlocking a surge of productivity that transformed Western Europe and, eventually, the global economy (Wrigley, 2013). In the 21st century, despite the rise of renewables and gains in energy efficiency, global growth remains tightly linked to energy input, especially due to rapid development in emerging economies. Global electricity demand reflects this continued linkage: in the IEA's Stated Policies Scenario (STEPS), total final energy consumption rises from 445 exajoules (EJ) in 2023 to 499 EJ by 2035 and reaches 533 EJ by 2050, with clean energy sources accounting for nearly all of that growth. (World Energy Outlook, 2024). Given this reality, energy concerns remain a central issue in economic policy and strategic decision-making.

The level of exploration of the topic and research gap. The literature on the relationship between energy consumption and economic growth can broadly be grouped as theoretically and empirically driven. While both have developed simultaneously and often intersect, they differ in focus and methodological approach. Theoretical literature is primarily concerned with energy's conceptual and structural role in the production process. These studies often build upon or modify neoclassical growth models, introducing energy as an explicit factor of production alongside labor and capital. The core assumption underpinning this strand is that energy consumption is a fundamental driver of economic growth, and the objective is to incorporate it into growth theory formally. Empirical literature as surveyed by Payne (2010) and Ahmad et al. (2020), by contrast, takes a different stance. Rather than assuming a specific direction of causality, it focuses on statistical testing, often applying time series or panel data techniques to evaluate whether a causal relationship exists between energy use and GDP. These studies emphasize the relationship's presence, direction, and strength, but do not engage deeply with the underlying mechanisms.

Both strands have their advantages and limitations. Theoretical literature offers a well-developed rationale for its essential assumptions and provides a structured approach to modeling economic growth. However, it often lacks sufficient empirical validation across different contexts. Empirical literature presents the opposite case; it has a wide range of applications and country-specific studies, but frequently lacks a strong theoretical foundation, and many studies report statistical results without offering meaningful interpretation or explanation. This thesis adopts a combined approach, aiming to draw on the strengths of both traditions. It begins with a theoretical justification for selecting variables and underlying assumptions, while deliberately avoiding any prior statement of causality.

While the literature is extensive, studies focusing specifically on Estonia, Latvia, and Lithuania remain limited. Given their transition from centrally planned economies to market-oriented systems and rapid integration into the European Union, the Baltic States present an interesting and underexplored context within the energy–growth nexus. The Baltics are united not only by their geopolitical history but by a shared energy profile: limited natural fuel reserves, relatively modest hydropower, and equal opportunity to pursue renewables (IAEA, 2007). Examining this region offers valuable insight into how institutional and structural economic shifts influence the relationship between energy consumption and economic growth.

The aim of the paper. This thesis seeks to address this gap by asking whether energy consumption has a statistically significant long-run and short-run causal relationship with economic growth in the Baltic States: Estonia, Latvia, and Lithuania over the period 1998–2023. The aim is to determine the **presence**, **direction**, and **strength** of the relationship between energy use and GDP per capita, while controlling for labor and capital inputs.

To achieve this aim, **the following research objectives are pursued**:

1. To review the theoretical foundations and empirical literature surrounding the energy–growth nexus;

2. To collect and structure panel data for Estonia, Latvia, and Lithuania for the period 1998–2023;

3. To assess the presence of long-run cointegration among GDP, energy consumption, labor, and capital;

4. To estimate long-run output elasticities;

5. To test for short- and long-run Granger causality using a panel vector error correction model (PVECM);

6. To interpret the results in light of energy-augmented growth theory and recent empirical findings in the European context.

Scope of the study and methods used. A systematic literature review was conducted to explore and synthesize existing research on the energy–growth nexus, with particular attention to production function-based and empirical causality frameworks. In the empirical part, the study employs a panel regression framework using a log-linear Cobb-Douglas production function augmented with energy input. Unit root tests (LLC) assess variable stationarity, followed by Pedroni and Kao cointegration tests to evaluate long-run relationships. For estimation, FMOLS and DOLS regressions are applied to obtain long-run elasticities, while a Panel Vector Error Correction Model (PVECM) is used to explore short-run dynamics and causality.

The structure of the thesis is as follows: Chapter 1 presents the theoretical background on economic growth. Chapter 2 reviews the empirical literature on the energy–growth nexus. Together, these two chapters establish the conceptual framework of the study. Chapter 3 outlines the methodology, including data sources and analytical techniques. Chapter 4 presents the empirical analysis and findings.

1. THEORETICAL FOUNDATIONS OF ECONOMIC GROWTH

1.1 Neoclassical Growth Models

Over the past century, two main schools of thought have emerged to explain economic growth: exogenous and endogenous growth models. Exogenous models, like the neoclassical Solow-Swan model, treat technological progress as an external driver, while endogenous models incorporate innovation, knowledge, or human capital as internal outcomes of the economic system. The key distinction lies in whether long-term growth is explained by factors outside the model or generated by mechanisms within it.

1.1.1 Foundations of Growth Modelling

The Cobb-Douglas production function is a foundational structure in economic growth theory, expressing output as a function of capital and labor inputs. Developed by Charles Cobb and Paul Douglas (1928), it was initially an empirical fit for US manufacturing data but quickly became a central theoretical tool (Vergés, 2024). The Cobb-Douglas function assumes constant returns to scale and diminishing marginal returns to each input individually but increasing both inputs proportionally leads to proportional increases in output. This made it perfect for models like Solow's, where smooth substitution between capital and labor is needed for balanced growth paths. The Cobb-Douglas production function is widely used for its simplicity and ease of integration into growth models, but mounting empirical evidence shows the function itself poorly reflects real-world production dynamics. A large-scale meta-analysis finds the capital-labor substitution elasticity is closer to 0.3 and not the assumed value of 1, indicating that Cobb-Douglas significantly oversimplifies the true relationship between inputs (Gechert et al., 2021). Nevertheless, Cobb-Douglas remains a "default setting" in growth economics, acting as the basic stage upon which more complex theories are constructed (Vergés, 2024).

While a production function describes the static relationship between inputs and output at a given point in time, a growth function extends this framework by modeling how output and inputs evolve dynamically over time. Roy Harrod (1939) developed the first formal growth model in the late 1930s. Harrod's framework aimed to understand how an economy could maintain steady growth without prolonged unemployment or inflation. In his model, he distinguished three types of economic growth: the warranted growth rate, which is driven by the economy's propensity to save and the capital-output ratio; the actual growth rate, determined by the real-time changes in output; and the natural growth rate, which reflects the maximum sustainable growth given exogenous factors such as population growth, capital accumulation, and technological progress. Harrod highlighted the instability in economic growth and that deviations from the warranted rate could lead to cumulative cycles of boom or stagnation. His ideas were important for further dynamic growth models, including Domar's and Solow's."

Evsey Domar, working around the same time as Harrod, independently developed a similar growth model but approached the instability problem from a different angle. Domar (1946) focused more directly on the productivity of investment rather than on saving behavior alone. He argued that investment creates demand (through spending) and expands productive capacity (by adding capital). For growth to be balanced and sustainable, the rate at which new investment creates capacity must match the rate at which it creates demand. Domar introduced the concept of an "investment productivity coefficient," showing that unless investment leads to enough new income (and thus demand), the economy could fall into underemployment. While Harrod stressed the knife-edge balance between "natural" and "warranted" growth rates based on savings and labor growth, Domar emphasized the link between investment, output, and demand expansion. His approach made instability feel slightly less terrifying (from theoretical perspective), not purely a labor force problem but an issue of whether investment generated enough demand for itself. Domar's insights later fed into Keynesian thinking and influenced how economists modeled growth and demand-driven expansions, even as later models (like Solow's) would move toward more supply-side focus (Petersen, 1963).

1.1.2 Exogenous growth models

Solow and Swan independently published seminal papers on exogenous growth theory in 1956 (Solow, 1956; Swan, 1956). Their model focused on long-term economic growth and explained it through capital accumulation, labor (or population) growth, and technological progress, which was treated as something that happened outside the model. In fact, technology (though not explained within the model) was considered the main driver of productivity over time. At the heart of the Solow-Swan model is a neoclassical production function, often a form of the Cobb-Douglas function. This framework allowed Solow to separate short-run growth (caused by adding more capital) from long-run growth (driven by population and technology). One of the principal contributions of this model was the ability to show that economies tend to move toward a stable growth path over time, replacing earlier models that assumed growth was unstable. This made it easier for economists to test the model using real-world data. However, the model has been criticized. One major issue is that the Cobb–Douglas function, as adopted by Solow, treats capital as a single, homogeneous input, which drew strong criticism from Cambridge (UK) economists who argued that capital is inherently heterogeneous and cannot be meaningfully aggregated without reference to prices and distribution.

(Felipe, 2005). The part of the model that represents everything not explained by capital and labor, the so-called Solow residual or total factor productivity has faced much pushback. Critics, especially those from the endogenous growth theory camp, argue that it hides too much under the label of "technological progress" (Frankel, 1962; Lucas, 1988; Romer, 1990).

Tjalling Koopmans (1965) refined Frank Ramsey's (1928) earlier ideas about how societies should optimally allocate consumption and savings over time. In Koopmans' model, economic agents maximize their lifetime utility by choosing a consumption path subject to production and resource constraints. The key contribution was to frame growth as an intertemporal optimization problem, introducing complex mathematical techniques (like dynamic programming) to solve it. Koopmans assumed a representative agent who lived forever (or thought dynastically), cared about current and future consumption, and discounted future utility at a constant rate. The agent's optimal choice between immediate consumption and investment (saving) determines the economy's growth path, which then fuels capital accumulation and future output. Unlike Solow, where savings rates are exogenous, savings are chosen optimally based on preferences and technology. This model highlighted trade-offs between current well-being and future prosperity, adding ethical and philosophical dimensions to the mathematics of economic growth.

Exogenous growth models explain long-term economic growth through capital, labor, and technology, but treat technological progress as an external factor. These models show how economies move toward stable growth over time, but face criticism for oversimplifying capital and hiding unexplained growth under "technology" without clarifying where it actually comes from.

1.1.3 Endogenous growth models

The endogenous growth model differs from the exogenous growth model in that it suggests that forces within the economic system create an atmosphere for technological progress. Frankel (1962) proposed the first endogenous model, which is now known as the AK model. The AK model is one of the simplest forms of endogenous growth theory, designed to show how economies can experience sustained long-run growth without relying on exogenous technological progress. Unlike in a typical Cobb-Douglas setup where capital exhibits diminishing marginal returns, the AK model assumes constant marginal returns to capital, meaning that every additional unit of capital leads to a proportional increase in output (Frankel, 1962). This key feature allows the growth rate to be endogenously determined by the savings rate and productivity, making continuous growth possible through pure capital accumulation. The AK model highlights how policies that increase savings, investment, or capital efficiency can permanently raise economic growth rates. It strips the growth process to its essentials, abstracting away from the complexities of labor dynamics and technological shocks. However, critics argue that assuming constant returns to capital is unrealistic over the very long term (Solow, 1994). Despite its simplicity, the AK model laid the groundwork for richer endogenous growth frameworks by showing that internal economic mechanisms could drive sustainable growth.

Robert Lucas (1988) advanced endogenous growth theory by emphasizing the role of human capital accumulation as the engine of long-term growth. Lucas argued that individuals invest in their education and skills, and this self-reinforcing accumulation of knowledge drives sustained productivity increases. In his model, human capital grows through formal education and on-the-job learning, and critically, knowledge spillovers mean that one person's education raises the productivity of others. This mechanism introduced increasing returns to scale at the economy level, even though individual firms face diminishing returns. Lucas' key insight was that economic development differences across countries could largely be explained by differences in human capital accumulation, not just physical capital or exogenous technology shocks. His work formalized how micro-level decisions (individuals choosing how much to learn) aggregate into macro-level outcomes (national growth rates). Lucas also strongly rejected the idea that growth should be treated as a purely exogenous process — instead, he showed that policy, education, and incentives matter deeply in shaping growth paths.

Romer's (1990) growth model introduced the idea that technological change is endogenous, created by economic activity, and not just handed down like in Solow's model. In Romer's world, firms invest in research and development (R&D) to produce new ideas, and ideas are complementary: one firm's use of an idea does not diminish its availability to others. This trait increases returns to scale (at the aggregate level), a key break from traditional neoclassical models. The so-called accumulation of knowledge drives growth. Policies encouraging innovation, like subsidies for R&D or education, can permanently raise growth rates. In Romer's setup, the production function for final goods depends on capital, labor, and a stock of ideas. The R&D sector produces new ideas, and its productivity depends on the research sector's size and the existing stock of knowledge ("standing on the shoulders of giants" effect). This model provided a clear economic rationale for why richer countries continue to grow: knowledge builds on itself, and planned investment decisions sustain growth. However, Romer's model assumes firms invest in R&D because of monopoly profits from innovation, not pure altruism, explaining innovation incentives by economic rewards.

Endogenous growth models explain how growth can continue through internal factors like capital accumulation, education, and innovation, rather than relying on external technological progress. They share the idea that increasing returns, whether from more capital, better skills, or new ideas, can sustain long-run growth. The key differences lie in what drives that growth: some focus on physical capital, others on human capital or knowledge creation through research and development.

Since the creation of the concept of economic growth, scholars have been occupied with the question: What makes economies grow? Exogenous models like Solow-Swan claimed growth comes from outside mysterious "technological progress". These models, built on the Cobb-Douglas function, assumed smooth balance and constant returns but could not explain the "residual" driving most growth. Then, the endogenous direction emerged, Frankel, Lucas, and Romer arguing that innovation, knowledge, and learning rose from within the model. Capital, especially the human one, took center stage. Three traits define the models reviewed here: the source of growth (external vs. internal), returns to scale (constant, diminishing, or increasing), and the role of innovation (exogenous gift/luck or endogenous product). However, both strands share one blind spot: they often ignore the physical world that makes all this possible: energy, materials, and thermodynamic constraints. New models were created where growth was impossible without energy, adding the laws of thermodynamics to an economic core.

1.2 Energy-Augmented Growth Theories

The 1970s marked a watershed decade for academic energy and economic growth discourse. The decade opened with the publication of Nicholas Georgescu-Roegen's seminal *The Entropy Law and the Economic Process* (1971), which introduced the not-so-obvious back-then idea that all natural resources are subject to irreversible degradation, a direct challenge to the sustainability of perpetual economic growth. Soon after, *The Limits to Growth* by Meadows et al. (1972) attracted widespread academic and public debate by warning of industrial civilization's ecological and resource constraints. Together, these works disrupted the long-standing assumption that continuous growth was natural and guaranteed.

The second defining event of the decade was geopolitical: the Yom Kippur War and the subsequent oil embargo imposed by OPEC countries in retaliation against Western support for Israel. The resulting oil crisis led to a dramatic spike in energy prices, particularly hitting the United States and much of Europe. In response, energy conservation quickly emerged as a top policy priority. This period of uncertainty and resource vulnerability spurred a surge in energy-economy research, laying the foundation for the energy-growth literature that would evolve over the following decades.

1.2.1 Kümmel's Energy-Intensive Production Functions

In a series of pioneering works, German econophysicist Reiner Kümmel reoriented the theoretical landscape of growth economics by insisting on the central role of energy in industrial production. Kümmel developed a critique of equilibrium-based neoclassical growth models, introduced alternative production functions based on thermodynamic realities, and offered a new framework for understanding technological progress. His research not only anticipated many contemporary concerns about sustainability and energy dependence but also provided a rigorous empirical basis for rethinking how economies grow.

In his seminal article, Kümmel (1982) critically examined the neoclassical assumption that economic output is driven solely by capital and labor, arguing instead that energy plays an underappreciated role in production. Instead, he argued that energy is a fundamental factor of production, on par with capital and labor, due to its role in enabling both work performance and information processing as foundations of industrial output. This new conceptualization led him to define new measurement units: ATON, representing the productive capacity of capital in terms of its ability to perform work and process information, and ENIN, a unit of industrial output reflecting these same physical functions. While conceptually powerful, these units were not directly used in the empirical part of the paper.

Kümmel's growth model was formalized as an energy-augmented production function where capital (K), labor (L), and energy flow (E) were treated as independent inputs normalized to a base year. This model was tested using data from West Germany and the US (1960–1978), with remarkably accurate results. It not only reproduced actual industrial output but also captured economic downturns during the energy crisis of the mid-1970s. The analysis basically showed that energy and capital, rather than labor, were the primary contributors to output growth, undermining the neoclassical presumption that labor plays the dominant role. The production elasticity of energy consistently exceeded its cost share, introducing what Kümmel called the cost-share problem, a central theme across his later works. He meant by this term that neoclassical models, which assume elasticities align with cost shares under equilibrium, systematically underestimate energy's significance.

Kümmel, Gossner, and Strassl's (1985) paper challenged a foundational assumption of classical and neoclassical thought: that energy is not a primary factor of production but the result of labor, capital, and land. The authors emphasized that energy becomes economically meaningful only when it is liberated from carriers through irreversible processes. This thermodynamic insight was key to reinterpreting the concept of technical progress. Rather than attributing unexplained growth to a so-called "Solow residual," the authors proposed that technical progress is largely energy-embodied and should be captured directly by the energy input variable. By doing so, they dispensed with the need for an ad hoc time-dependent multiplier, treating growth instead as a physical transformation driven by innovation in energy use.

Empirical validation again played a significant role. Using the same LINEX (linear and exponential) production function structure, the model was calibrated against data from the US and West Germany. The results were consistent with the previous work: energy had a production elasticity far exceeding its cost share, while labor's contribution remained minor. Importantly, the model revealed that disembodied technical progress, such as improvements in energy efficiency, only became relevant after 1976. This strengthened Kümmel's argument that energy drives much economic growth.

Kümmel, Henn, and Lindenberger (2002) introduced a dynamic refinement to the energy-augmented model by incorporating creativity as a fourth input, resulting in the KLEC model (Capital, Labor, Energy, Creativity). This extension recognized that innovation and diffusion of technology do not occur instantaneously but evolve over time, driven by human creativity. Unlike traditional models that treat technical progress as an unexplained residual, the KLEC model endogenizes it through time-varying technology parameters. This framework provided a more realistic dynamic structure for understanding long-term economic evolution.

Kümmel's critique of equilibrium-based neoclassical economics reached its most refined form in this work. The cost-share problem was again highlighted once more: the elasticity of production for energy remained an order of magnitude above its cost share, while labor's contribution continued to be overstated in conventional models. The model's empirical application to the US, Germany, and Japan, including industrial sectors and total economies confirmed these patterns. It also revealed that post-crisis improvements in energy efficiency and capital automation could be effectively traced and quantified.

One interesting conceptual innovation in the 2002 paper was the explicit differentiation between raw materials and energy. Raw materials, the authors argued, do not actively contribute to value creation, as they neither perform work nor process information. They are merely rearranged by capital, labor, and energy, thus justifying their exclusion from value-added statistics. This distinction reinforced the unique role of energy as an active, transformational input in the production process.

In sum, across these three works, Kümmel advanced a profound and empirically grounded critique of conventional growth theory. He exposed the shortcomings of equilibrium assumptions, challenged the marginalist view of input productivity, and reasserted the centrality of energy in economic life. His models not only offer a better fit for historical data but also provide critical tools for anticipating the future, especially in the context of innovation and energy transition.

1.2.2 Ayres' Exergy and Thermodynamic Models

Robert U. Ayres' contributions to growth theory represent a critique of the neoclassical tradition and a bold attempt to root economic analysis in physical and thermodynamic reality. Like Reiner Kümmel, Ayres consistently challenged the Solow model's reliance on exogenous technological progress and its restrictive equilibrium assumptions. He argued that the primary drivers of growth, like energy and resource flows, have been systematically overlooked.

In *Towards a Disequilibrium Theory of Endogenous Economic Growth* (Ayres, 1998), the Cobb-Douglas production function is critiqued as mathematically elegant but economically misleading. He observes that its assumption of constant returns to scale and interpretation of factor elasticities as cost shares fails when more than two inputs are considered. The share theorem must be abandoned when introducing material and energy inputs, or the model becomes internally inconsistent. Kümmel, in contrast, chose to retain constant returns to scale but explicitly rejected the share theorem, demonstrating empirically that energy's elasticity often far exceeds its cost share.

Ayres mentioned the KLEM framework (Capital, Labor, Energy, Materials) and argued that the System of National Accounts (SNA) fails to recognize payments to natural capital. He proposes replacing separate E and M inputs with a thermodynamically justified measure: exergy, or usable energy. Exergy, unlike energy, degrades during use and reflects inputs' quality and transformative potential. To capture how effectively exergy is used, Ayres introduces three types of efficiency: technical efficiency, exergy delivery efficiency, and service delivery efficiency, a nuance Kümmel only implicitly touched on.

Ayres' concept of a dual production model, the transition from so called "cowboy" (resource-abundant) to a "spaceship" (resource-constrained) economy marks an important departure. He formalizes this with a dynamic production function governed by a time-dependent technology parameter, allowing a smooth shift in limiting factors over time. This reflects a more fluid and evolutionary perspective than Kümmel's relatively static LINEX function and lays the foundation for Ayres' later work on feedback-based growth engines.

Ayres and Warr (2005) introduced the REXS model (Resource-EXergy-Service), showing that when raw energy inputs are replaced with useful work, the historical growth of the U.S. economy (1900–1975) can be modeled with high accuracy, and without needing a Solow residual. This distinction between exergy and useful work is critical: the latter reflects actual thermodynamic output rather than just energy availability. Kümmel also argued that energy drives production, but Ayres and Warr's focus on physical work sharpens the empirical relevance and directly connects to observed productivity gains. Importantly, Ayres acknowledges that including energy alone is insufficient to explain growth over long periods without recalibration, introducing limits to explanatory power that Kümmel only partially addressed.

In the same year Ayres & van den Bergh (2005) described three main drivers of economic growth: using more resources and replacing human labor with energy, learning and increasing efficiency through larger production scales, and creating value through innovation. A key idea in their model is the Energy-Growth Feedback (EGF) cycle, a loop where cheaper energy makes it easier to use machines and produce goods on a larger scale. This leads to lower costs, higher demand, and more innovation. By showing how these effects build on each other, Ayres and van den Bergh add a dynamic element to the discussion beyond Kümmel's more stable view of how energy affects growth.

Ayres discusses the rebound effect in detail in his articles: improvements in energy efficiency often led to increased consumption rather than savings. This fact undermines simplistic expectations that technological efficiency will automatically reduce environmental impacts, a nuance missing in much of the endogenous growth literature. Ayres' framework reflects a non-linear, path-dependent vision of economic growth by modeling demand as endogenously responsive to cost and service intensity.

Building on his earlier work, Ayres (2006) asks whether continued exponential growth is plausible given growing resource limits, rising debt, and systemic ecological constraints. He concludes that the only sustainable path forward is increasing technological efficiency but notes that such progress has slowed, especially in energy conversion sectors like electricity and transport. This view resonates with Krugman's (1994) argument that many high-growth economies have expanded through input accumulation rather than genuine productivity gains.

Ayres thus comes full circle, aligning with Kümmel in rejecting the assumptions of the neoclassical paradigm while proposing a more explicitly dynamic and feedback-based growth model. Where Kümmel focused on production functions with adjusted inputs, Ayres emphasized feedback loops and structural shifts. Both reject the cost-share theorem and argue for the primacy of energy in growth. However, Ayres offers a broader critique: not just of production theory but of macroeconomic policy and sometimes unsustainable logic of material expansion.

To sum up, Robert Ayres took the idea of energy-based economic growth further than Kümmel by focusing on how real-world economies are often out of balance and driven by new technologies. He built models using real data, explained how physical limits and laws of thermodynamics, for instance, affect production and gave a strong argument against the theories that rely on exogenous forces and assume everything stays in equilibrium. Ayres and Kümmel offer a robust yet sometimes overlooked interdisciplinary synthesis based on physics, economics, and history. It challenges the assumptions of mainstream growth theory and points toward a more realistic, sustainability-conscious paradigm.

Economic growth theory has historically been shaped by two main schools: exogenous models, like Solow-Swan, which view technological progress as an external force, and endogenous models, such as those by Frankel, Lucas, and Romer, which explain growth through internal factors like capital accumulation, education, and innovation. The widely used Cobb-Douglas production function underpins many of these models but has been criticized for oversimplifying real-world input relationships. Early theorists like Harrod and Domar focused on instability and demand in growth dynamics, while later models, such as Ramsey-Koopmans, introduced intertemporal optimization. Endogenous models allow for sustained growth through mechanisms like human capital and R&D, challenging the idea that technology is a mysterious external driver. However, both strands largely ignore the physical and energy-based foundations of production. This gap led to the development of energy-augmented growth models by scholars like Kümmel and Ayres, who incorporated thermodynamic principles and insisted that energy is not just another input, but a fundamental driver of economic output and technological progress. However, these theoretical foundations relied on strict frameworks and assumed relationships in advance, which led to the rise of more empirically driven research that allowed the data to "speak for itself." This data-centered approach will be explored in the next chapter.

2. REVIEW OF EMPIRICAL STUDIES ON THE ENERGY GROWTH NEXUS

The origins of empirically driven energy-growth nexus research can be closely linked to the 1973 oil crisis. When the US and parts of Europe faced an oil embargo, it triggered widespread economic disruptions and raised questions about energy security and economic stability. In response, scholars and policymakers began seeking a deeper understanding of the relationship between energy consumption and economic performance. This line of econometric research did not emerge merely out of academic curiosity, it developed as a practical response to a pressing global crisis. The goal was to generate insights that could directly inform policy and help manage energy resources more effectively in the face of supply shocks and uncertainty. In this sense, early energy-growth studies were more than theoretical exercises; they were intended as a kind of economic "medicine" to address real world challenges.

Given the vast number of studies on this topic, it becomes essential to adopt a structured way to present the main ideas and findings. To achieve this, a methodological approach has been chosen. The core rationale behind organizing the discussion around methodology rather than by region is that regional comparisons are often difficult and inconsistent, making meaningful synthesis challenging. By focusing on the key econometric methods used in the literature, it becomes easier to trace the evolution of empirical research in a clear and coherent manner. The classification of methodological generations presented in the literature review of Ahmad et al., 2020 was adopted here, with some minor adjustments—most notably, the exclusion of pre-nexus approaches that preceded the formal development of the energy-growth literature.

1st Generation: Causality tests. Sims was one of the first proponents to apply causality testing in econometric research (Sims, 1972). Building on this approach, the first study to examine the energy-growth nexus using causality analysis was conducted by Kraft & Kraft (1978). Their findings showed a unidirectional causal relationship running from gross national product (GNP) to energy consumption, but not the reverse.

2nd Generation: Error Correction Model. These studies started dealing with non-stationary time series data by using cointegration analysis, as developed by Engle and Granger in 1987. Unlike earlier research focused only on short-term effects, Yu & Jin (1992) looked at long-term relationships by conducting cointegration tests. Their paper used cointegration testing to examine whether, in the long run, energy consumption consistently moves together with either output or employment levels.

3rd Generation: Vector Error Correction Models in Causality Tests (VECM). The Johansen cointegration test (Johansen, 1991) was developed to for the number of cointegrating relationships in a system of multiple variables. Masih & Masih (1997) used Johansen's method to test for cointegration between total energy use and real GDP from 1955 to 1990 in countries like India, Pakistan, and others. They applied both VEC and VAR models to understand causal relationships. Similarly, Hondroyiannis & Papapetrou (2002) studied energy use, GDP, and prices in Greece from 1960 to 1996. They found no short-term links but discovered long-term relationships, making the study significant for its use of cointegration, error correction, and a multivariate approach. Oh & Lee (2004) were among the first to apply modern econometric tools for multivariate analysis. They studied South Korea from 1981 to 2004 using the Vector Error Correction Model (VEC) to explore both short- and long-term relationships among energy use, GDP, capital, labor, and prices. They also identified where the causality came from.

4th Generation: Autoregressive Distributed Lag Model. These methods are updated versions of earlier causality tests. They do not require pre-testing for stationarity. The ARDL Bounds Test, introduced by Pesaran et al. in 2001, works well with small sample sizes. One of the first studies using this method for the energy-growth nexus was by Wolde-Rufael (2006), who examined data from 1971 to 2001 to look at the long-term and causal relationship between electricity use and GDP per person in 17 African countries.

5th Generation: Panel Analysis. Lee (2005) looked at the link between GDP and energy use across 18 developing countries from 1975 to 2001 using panel cointegration and error correction methods. The study found one-way causality from energy to GDP in both the short and long term. It was notable for being one of the first to use panel unit root tests, panel cointegration methods, and fully-modified OLS estimations together.

6th Generation: Structural Vector Autoregressive Model. This generation of studies combines traditional econometric or general equilibrium (GE) approaches with time-series data features like stationarity and cointegration. These elements were the main focus in earlier generations, and SVAR models aim to integrate them into a more complete analysis.

2.1 Growth Hypothesis

Energy consumption directly drives GDP growth under what is known as the Growth Hypothesis. This is because energy is considered to be an important parameter for production processes or services, in this sense the absence of an adequate energy supply prevents industries and sectors from operating at their optimal capacity, thus hampering economic growth. An influential paper that backed the hypothesis is Kraft & Kraft (1978), who identified unidirectional causation running from energy consumption to economic growth in the US.

The growth hypothesis has important policy implications by emphasizing the need for a stable energy supply. They might prefer policies that promote production of more energy and more energy consumption (by investing in more energy infrastructure or subsidizing energy costs to encourage higher levels of industrial output and economic growth). Yet those same policies must account for the environmental footprint, and that has led to a greater interest in sustainable energy sources.

Table 1. Summary of Studies Supporting the Growth Hypothesis

Author	Time span	Country or region	Methodology
Stern, 1993	1947-1990	USA	MVAR
Stern, 2000	1948-1994	USA	Cointegration, Granger causality
Paul & Bhattacharya, 2004	1950-1996	India	Granger causality
Lee & Chang, 2005	1954-2003	Taiwan	Cointegration, VECM
Ang, 2007	1960-2000	France	Cointegration, VECM
Ho & Siu, 2007	1966-2002	Hong Kong	Cointegration, VECM

Source: Authors' compilation.

2.2 Neutrality Hypothesis

The Neutrality Hypothesis states that energy consumption does not significantly influence economic growth, suggesting that changes in energy consumption are independent of changes in GDP. This hypothesis relies on studies that find no causal relationship between energy consumption and economic growth, indicating that energy is not a limiting factor for economic expansion in some economies.

Policy implications of the neutrality hypothesis suggest that energy policy may not directly impact economic growth, allowing for more aggressive energy conservation measures without risking economic decline. This can encourage the adoption of energy efficiency initiatives and the transition to renewable energy without the fear of harming economic performance.

Table 2. Summary of Studies Supporting the Neutrality Hypothesis

Author	Time span	Country or region	Methodology
Yu & Hwang, 1984	1947–1979	United States	Sims technique
Yu and Jin, 1992	1974−1990	United States	Cointegration, Granger causality tests.
Fatai et al., 2004	1960−1999	New Zealand	Granger causality, ARDL bounds testing

Altinay & Karagol, 2004	1950−2000	Turkey	Hsiao’s version of Granger Causality
Ghali & El-Sakka, 2004	1961−1997	Canada	Hsiao's version of Granger causality
Jobert & Karanfil, 2007	1960−2003	Turkey	Cointegration and Granger causality test.

Source: Authors’ compilation

2.3 Conservation Hypothesis

The Conservation Hypothesis states that economic growth can lead to reductions in energy consumption, typically through improvements in energy efficiency and technological advancements that make energy use more productive. This hypothesis is supported by studies like those by Sadorsky (2009), who found that economic growth facilitates investments in energy-saving technologies, thus reducing the energy intensity of economic output.

Policy implications of the conservation hypothesis focus on promoting energy efficiency and technological innovation as part of economic policy. Governments might invest in research and development for new technologies that enhance energy efficiency or provide incentives for businesses to adopt more energy-efficient processes.

2.4 Feedback Hypothesis

The Feedback Hypothesis suggests a bidirectional relationship between energy consumption and economic growth, meaning that not only does energy consumption affect economic growth, but economic growth also affects energy consumption.

Policy implications under the feedback hypothesis are complex, because they require coordinated energy and economic policies. Ensuring energy supply must go hand in hand with promoting economic growth, and vice versa. Policies aimed at increasing energy efficiency and renewable energy use need to be aligned with broader economic development goals.

Table 3. Summary of Studies Supporting the Feedback Hypothesis

Author	Time span	Country or region	Methodology
Erdal et al., 2008	1970−2006	Turkey	Granger causality test
Odhiambo, 2009	1971–2006	South Africa	Granger causality test
Tang, 2009	1970–2005	Malaysia	Granger causality
Ziramba, 2009	1980−2005	South Africa	ARDL bounds testing approach
Belloumi, 2009	1971−2004	Tunisia	Granger causality tests
Ozturk, 2010	1968–2005	Turkey	Cointegration, VECM

Source: Authors' compilation

2.5. Critique of the Energy Consumption-Economic Growth Nexus

Despite the abundance of literature on this topic, it has also received criticism. Beaudreau (2010) argued that Granger causality tests for the relationship between energy consumption and GDP are largely exploratory and lack a strong theoretical foundation. These tests often involve specifying a reduced-form equation and applying forward and backward lags. This approach brings up several concerns. Moreover, without a structured theoretical framework, there's a risk that such results might be spurious. This shows the necessity for a more rigorous theoretical basis when interpreting causal relationships from Granger causality tests.

Kalimeris et al. (2014) conducted the first meta-analysis that included 158 studies examining the causality between energy and GDP from 1978 to 2011. This was the first application of meta-analysis to explore the direction of causality in the relationship between energy consumption and economic growth. The results of this meta-analysis do not confirm a consistent overarching direction nor do they support the "neutrality hypothesis" in the causal dynamics between energy consumption and economic growth.

Using meta-analysis, (Hajko, 2007) analyzed 104 articles on the topic and concluded that the theory has no basis in principle, and there is no fundamental connection between energy and economic growth.

Liddle & Lung (2015) argues that the four widely discussed hypotheses do not enable predictions; determining which causality outcome will hold for a specific country or group of countries requires conducting the test first, as these hypotheses effectively serve as ex post descriptive categories. Given that energy functions both as a production input and a consumption good, one might expect a bi-directional energy-GDP causality, or feedback hypothesis, to be common across most countries. Yet, no such consistent pattern has been observed. If a test yields a result that deviates from previous findings, it's challenging to determine whether this new result represents true evidence or is merely a reflection of the factors causing variability in the results across the literature.

Understanding the historical development and diverse findings within the energy-growth literature highlights the complexity of the relationship between energy use and economic performance. Over time, numerous empirical studies have tested this nexus using a variety of econometric tools, producing results that support different theoretical perspectives such as the growth, conservation, neutrality, or feedback hypotheses. To navigate this broad and sometimes conflicting body of research, a structured and methodologically driven approach is required. By organizing the literature and empirical analysis around successive generations of econometric methods, the aim is to provide a clearer understanding of how conclusions in this field have developed and how they are shaped by the methodological choices researchers make.

3. METHODOLOGY FOR RESEARCHING ENERGY CONSUMPTION – ECONOMIC GROWTH DYNAMICS IN THE BALTICS (1998–2023)

3.1. Aim, model and hypotheses of the research

Using a production function framework, this study investigates the energy consumption-economic growth nexus in the Baltic States (Estonia, Latvia, Lithuania). Based on this framework, GDP per capita is used as the measure of economic growth, energy consumption as the primary independent variable of interest, while labor and capital are included as additional inputs for a complete assessment. This thesis is guided by the following research questions:

- Do GDP per capita, energy consumption, labor, and capital form a stable long-run cointegrating relationship across the Baltic States?
- Is energy consumption a significant long-run contributor to output in the region?
- Does energy consumption Granger-cause economic growth in the short run or long run?

Research Hypotheses

To empirically answer these questions, the following hypotheses are tested:

H_{01}: There is no long-run cointegrating relationship between GDP per capita, energy consumption, labor, and capital.

H_{02}: Energy consumption has no statistically significant long-run effect on GDP per capita.

H_{03a}: There is no Granger-causal relationship between energy consumption and GDP per capita in the long run.

H_{03b}: There is no Granger-causal relationship between energy consumption and GDP per capita in the short run.

3.1.1. Conceptual Framework and Model Specification

The study uses a Cobb-Douglas production function as a theoretical basis for investigating the relationship between energy consumption and economic growth. In the most general way, a Cobb-Douglas function describes output **Y** as a function of inputs, capital **K** and labor **L** with constant elasticities. Here this framework is extended by including the energy consumption **E** as an additional input of production, which addresses the notion that energy consumption is a key driver of production and economic activity (Stern, 1993; Stern, 2000; Narayan & Smyth, 2008).

In this study, a quite conservative modeling approach was adopted, using a single proxy for energy: total final energy consumption. While recent energy–growth nexus literature shows an obsession with disaggregating renewables and breaking down energy sources by mix, this analysis pursues a different objective. The commonly cited benefits of renewable energy such as technology spillovers, energy independence, and green job creation, are all indirect effects, and their economic impact can vary widely depending on national context.

Moreover, disaggregation by energy type rather than by sectoral consumption says little about how energy is actually used or whether effective conservation measures are in place. While one could argue that countries investing in renewables also tend to use energy more efficiently, such assumptions fall outside the scope of this work. Instead, by focusing on total final energy consumption, this study captures energy's role as a core production input, avoiding overly narrow interpretations and emphasizing its place in economic activity.

The production function will have the following form:

$$\boldsymbol{Y = A \times Labor^{\alpha} \times Capital^{\beta} \times Energy^{\gamma}}$$

where **Y** represents aggregate output, **A** refers to a total factor productivity term, and $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$ are output elasticities of labor, capital, and energy respectively. This relationship can be rewritten in log-linear form for ease of empirical estimation and interpretation:

$$\begin{aligned}&\boldsymbol{ln(GDPper\ capita)}\\&= \boldsymbol{A' + \alpha ln(Labor) + \beta ln(Capital) + \gamma ln(Energy\ Consumption) + \varepsilon,}\end{aligned}$$

This log-linear specification serves as the empirical model. The dependent variable is real GDP per capita (a measure of economic output per person), and the explanatory variables are labor input, capital input, and energy consumption — all expressed in per capita terms (discussed in detail below). The error term ε represents random disturbances.

The purpose of using logarithms is twofold, the first is that it stabilizes the time-series variance (Asiedu et al., 2021) (reduces heteroscedasticity) because proportional changes show less variance over time than absolute changes. Second, the coefficients α, β, γ can be interpreted directly as elasticities, i.e. the percentage change in GDP per capita from a one percent increase in labor, capital or energy use. This interpretation has economic significance in order to analyze the relative importance of each factor. The model specification reflects the hypothesis that energy consumption is not only an input, but a driver of growth. Including labor and capital alongside energy in economic growth models allows for a more comprehensive analysis and enables the use of multivariate Granger causality tests. Unlike bivariate approaches, which can only assess pairwise relationships and are more prone to spurious correlations, multivariate frameworks offer a fuller view of the economic system and provide a more reliable basis for testing causal links between energy use and growth (Stern, 1993).Therefore, the energy–growth nexus is developed based on a multivariate model to provide a theoretically logical and robust framework for this test.

3.1.2. Data Sources and Variables Definitions

The work involves annual panel data for three Baltic States, i.e., Estonia, Latvia, and Lithuania, for the period 1998–2023. This period includes a critical post-transition period when these economies experienced high growth and structural transformation. The sampling period is driven by the availability of data in comparable form from the late-1990s (subsequent to regaining independence and implementing economic reforms) to the 2023. A simple panel of three countries over 26 years provides 78 observations for every variable which, somewhat limited, is nevertheless useful with the application of panel econometrical techniques that exploit the availability of cross-sectional and time-series information.

The main data source is Eurostat, the statistical office of the European Union. All series were extracted from Eurostat's publicly available databases, which guarantees that the data are official, trustworthy and comparable. Harmonized definitions and homogeneous data collection methodologies implemented in member and partner countries make Eurostat an additional source of reliable information to use for comparing of indicators between the Baltic States. The use of Eurostat mitigates the risks of measurement problems. All indicators (except for the employment rate) are per capita (divided by total population), to control for differences in country-size and allow direct comparison across the three countries. Here are the definitions and significance of each variable:

Output (Y): Output is used to measure economic growth. In this paper, the chosen indicator for output is Real Gross Domestic Product per capita in euros (chain-linked volumes, index 2020 = 100, at market prices). This dependent variable captures average economic output per person. By adjusting for population, GDP per capita offers a more accurate representation of living standards and productivity across economies. It is widely used as a proxy for economic growth in cross-country empirical research.

Labor (L): Labor input is proxied by the employment rate for individuals aged 15–64, covering both sexes and all citizenships. This indicator was selected for its ability to reflect the active working-age population, capturing participation from early employment through to retirement age. Labor is one of the core factors of production, and its inclusion in the model controls for changes in workforce utilization that may influence output across countries and over time.

Capital (K): Capital input is proxied by gross fixed capital formation (GFCF) per capita, measured in chain-linked volumes (2020 = 100, at market prices). GFCF captures investment in physical assets such as infrastructure, machinery, and equipment, representing the accumulation of productive capital stock over time. Expressing capital in per capita terms ensures consistency with the output variable and helps mitigate scale-related distortions in cross-country comparisons. While GFCF is a flow indicator rather than a direct measure of capital stock, it is widely used in empirical growth literature as a reliable proxy for long-term capital formation (Bhattacharya, 2016; Magazzino et al., 2020; Ur Rahman et al., 2020).

Energy Consumption (E): Energy consumption in this model is measured as total final energy consumption per capita, reported in kilograms of oil equivalent. This indicator was selected for two main reasons. First, final energy consumption reflects the total energy actually used by end users: such as households, industry, transport, and agriculture, while excluding energy consumed by the energy sector itself (e.g., for deliveries and transformation processes). This approach better captures energy as a direct input into economic activity, rather than including upstream losses or conversion inefficiencies. Second, it focuses on the demand side of energy use, not the overall supply available within a country. Expressing energy use in per capita terms adjusts for population differences and reflects the relative energy intensity of each economy. This variable is central to the research question, as it quantifies the scale of energy consumption that may drive or constrain economic growth.

Given that all the above indicators are derived from secondary data sources collected and reported by Eurostat, a high degree of source reliability is expected. In addition, data from an official source like Eurostat are presumably validated and checked for quality, thereby minimizing the risk of measurement error. The time series for the listed indicators are presented in Figures 1a, 1b, 1c, and 1d.

Fig. 1a Real GDP per Capita (EUR)

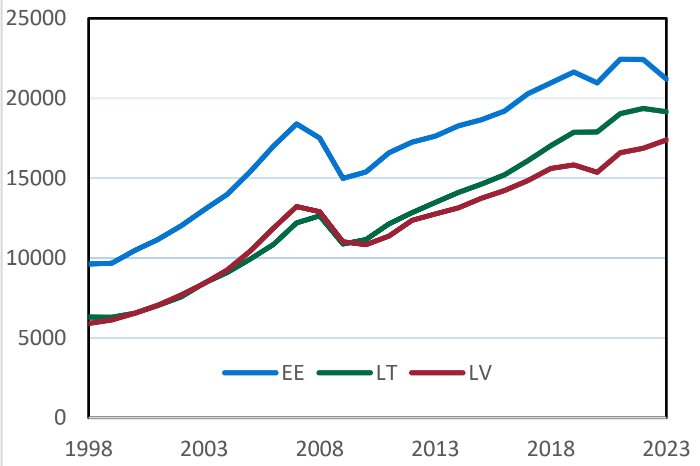


Fig. 1b Gross Fixed Capital Formation per Capita (EUR)

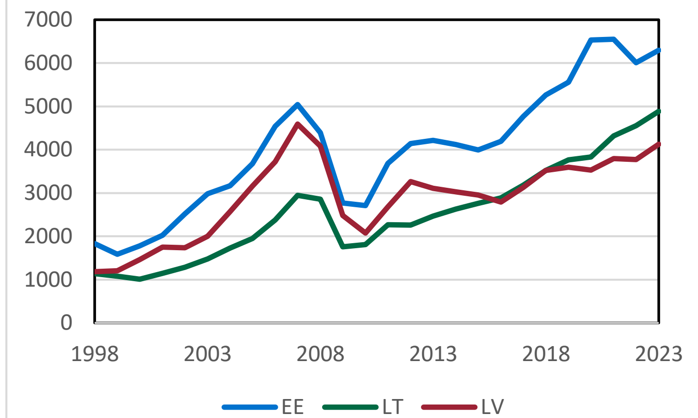


Fig. 1c Employment Rate (15–64 Age Group, % of Total Population)

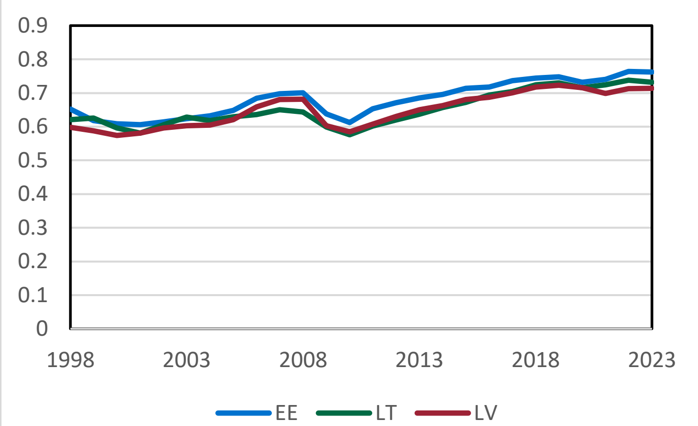
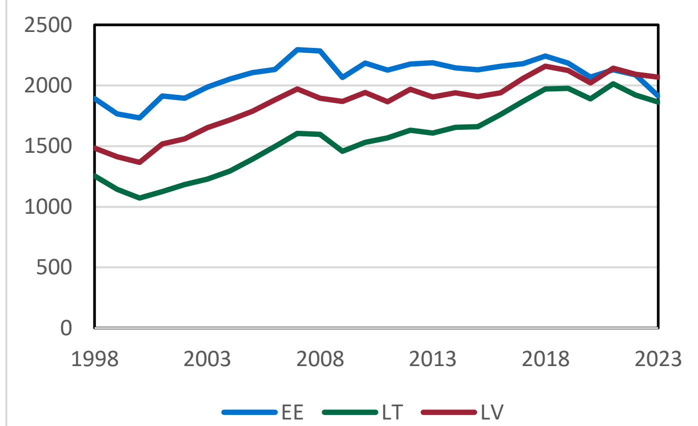


Fig. 1d Final Energy Consumption per Capita (kg of Oil Equivalent)



3.2. Organization and instruments of the research

3.2.1. Panel Data Method and Explanation

Since the analysis is multi-country and multi-temporal, this analysis adopts a panel data approach. Panel data (also called longitudinal data) consists of cross-sectional observations across time, and this research benefits from its use for a number of reasons.

First, unlike cross-sectional data, panel data combines both cross-country and time-series dimensions. This allows researchers to capture differences between countries as well as changes within each country over time. In the context of the Baltic States a panel framework is especially valuable, as it can account for both shared trends and country-specific dynamics.

Second, the panel data strengthens the sample size and variability, hence improves the statistical power of the tests and the efficiency of estimators. Panel data provides more information (Lee & Chang, 2008) and enables identifying effects that pure time-series analyzes would not have detected.

Third, the panel structure allows control for unobserved heterogeneity like country-specific factors like geography, policy environment, etc. (Apergis & Payne, 2009) that do not vary over time can be controlled for with fixed-effects, or random-effects if required.

Thus, I use panel data methodology to get the most information we can from the data and to increase the credibility of causal inference by using both cross-sectional (between countries) and time-series (within countries) variation in the data.

3.2.2. Stationarity and Unit Root Tests

For the purpose of testing the stationarity of the variables, this study employs the Levin-Lin-Chu (LLC) test, which is well-suited for panel data and offers improved power in multivariate contexts. Given that the dataset comprises multiple countries (Estonia, Latvia, and Lithuania) observed over time, standard time-series unit root tests such as the Augmented Dickey-Fuller (ADF) may lack power or reliability in this setting (Im et al., 2003).

The LLC test, specifically designed for panel structures with both cross-sectional and time-series dimensions, enhances the ability to detect stationarity (Levin et al., 2002). It tests the null hypothesis of a unit root in each panel series against the alternative that all panels are stationary. While it assumes a common autoregressive parameter across cross-sections, it allows for individual specific intercepts and time trends, making it a flexible yet structured tool for panel-based stationarity testing (Levin et al., 2002).

However, since panel data often involve heterogeneous dynamics, methods based on group-mean stationarity, such as the Im, Pesaran, and Shin (IPS) test or Fisher-type tests, are considered appropriate (Belke et al., 2011). These approaches allow for individual trend behavior across panel units while assessing overall stationarity at the panel level.

In this study, it is crucial to confirm the order of integration before proceeding to cointegration analysis across countries. The unit root tests contribute to this process by validating the stationarity status of the variables, thereby strengthening the foundation for long-run equilibrium modeling.

3.2.3. Panel Cointegration Testing

In many empirical economic analyses based on non-stationary time series data it is critical to check whether a long-run equilibrium relationship exists between the variables. This is accomplished via cointegration testing, which determines whether non-stationary series move together over time, suggesting a stable and meaningful relationship as opposed to a spurious correlation. Consequently, in this study, panel data from different countries spanning several years is employed, which meant conventional time-series cointegration methods were not suitable. Thus, the Pedroni (1999) and Kao (1999) panel cointegration tests were applied, since both tests are developed for panel data sets.

The Pedroni test is especially useful since it allows for heterogeneity in the cointegrating vector across countries, which in other words means that each of the Baltic states can have different long-run coefficients. It gives statistics across within-between matrix statistic, making it robust.

On the other hand, the Kao test assumes a homogeneous cointegrating relationship for all cross-sections and is structurally similar to the Engle-Granger two-step technique. Using both tests enables the cross-validation of results under different assumptions about cross-sectional behavior. These tests are necessary to ascertain the existence of a long-run equilibrium between energy consumption and economic growth in the long-run for valid estimation of long-run coefficients and causality analysis.

3.2.4. Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) regressions

Once unit root tests confirm that the variables are integrated of order one, and Pedroni and Kao cointegration tests establish the existence of a long-run relationship among them, it becomes appropriate to estimate the long-run coefficients of that relationship. This is where Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) regressions play a crucial role. These methods are specifically designed to provide consistent and unbiased estimates in the presence of cointegration, addressing the limitations of standard Ordinary Least Squares, which may be biased due to issues like endogeneity and serial correlation in the residuals (Ozcan, 2013).

FMOLS adjusts the OLS estimator by applying non-parametric corrections that account for autocorrelation and potential feedback effects among the variables (Pedroni, 2000), while DOLS includes leads and lags of the first-differenced independent variables to directly model short-term dynamics and eliminate endogeneity (Stock & Watson, 1993). Both approaches are particularly useful in panel data settings, where they can incorporate heterogeneity across countries while still estimating a common long-run relationship. Using FMOLS and DOLS after cointegration testing enhances the reliability and interpretability of the long-run elasticities. This step strengthens the empirical analysis and forms a solid foundation for subsequent exploration of short-run dynamics and causality.

3.2.5. Panel Vector Error Correction Model (PVECM) and Causality

To analyze dynamic interactions and causality within the energy–growth relationship, this study employs a Panel Vector Error Correction Model (PVECM). Unlike traditional VAR models, which can only capture short-run relationships and often lose information about long-run dynamics (Lee & Chang, 2008), the PVECM framework is specifically designed to address these limitations. It incorporates both short-run adjustments and a long-run equilibrium component through the error-correction term (ECT). Each equation in the PVECM (e.g., for GDP per capita, energy consumption) includes: (1) lagged changes of the variables, reflecting short-run dynamics, and (2) the ECT, which measures the deviation from long-run equilibrium and the speed at which the system corrects itself.

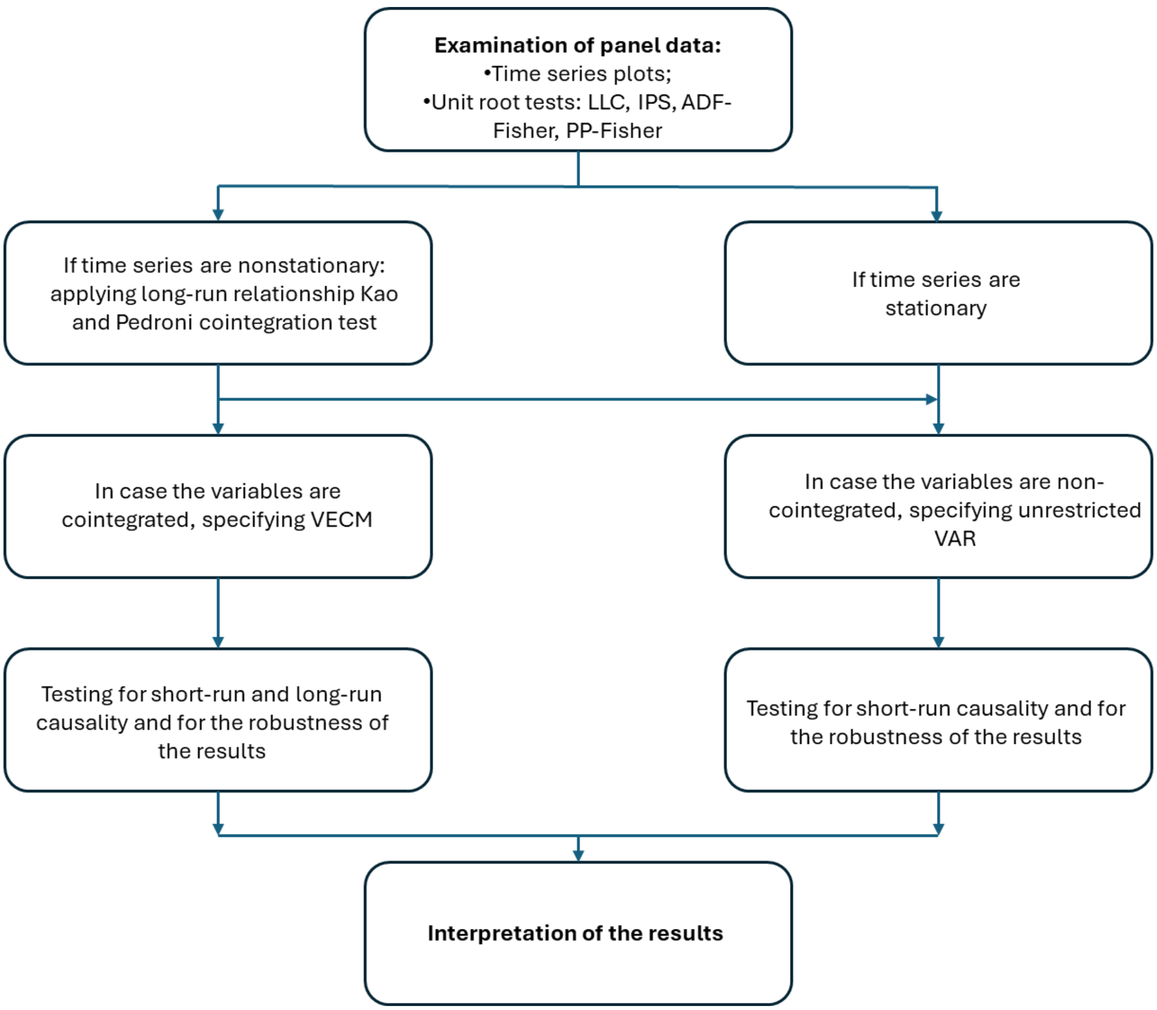
By modeling both short- and long-run components, the PVECM allows for a more accurate identification of causality and avoids spurious results that may arise from models lacking a cointegrated structure. This makes it a superior alternative to the VAR model when cointegration is present, as it distinguishes between transient fluctuations and equilibrium-based relationships across the Baltic States.

3.3. Methodological Rationale

The choice of methods and data in this analysis is driven in part by theoretical considerations and happens to be consistent with the empirical literature. It involves choosing an energy-augmented Cobb-Douglas production function in a manner consistent with growth theory and acknowledging energy as a factor of production. Following the widely used techniques by Pedroni and Kao for assessing long-run linkages in panel settings. These tests are a robust confirmation that used in this study multivariate model is not spurious. Moreover, Toda & Phillips (1993) stress the importance of unit roots and cointegration for drawing correct conclusions about causality, justifying the use of a VECM for panel data.

In conclusion, the data sources and variables have been selected with care to allow the findings to be reliable and comparable. Using Eurostat as the main data source can enhance the credibility of our analysis since these are official statistics collected within a common framework. Using per capita measures, both for GDP, energy and capital improves cross-country comparability. Therefore, the approach is built on strong ground of economic theory, established econometric methods and good quality data and gives confidence that results will capture the real energy–growth relationship of the Baltic States.

Figure 2. Research process overview



4. EMPIRICAL RESULTS AND INTERPRETATION

Following the procedures outlined in the methodology section, this chapter presents the empirical results. The analysis was conducted using EViews software. To enhance clarity and readability, the main results are summarized in simplified tables within this section. Each set of results is discussed in relation to the underlying theoretical expectations and econometric assumptions.

4.1 Unit Root Testing (Hypothesis 1A Precondition)

First, panel unit root tests were conducted to examine the stationarity properties of the variables. Given the likelihood of heterogeneous dynamics across the three Baltic countries, tests that allow for heterogeneity in autoregressive coefficients, such as the Im, Pesaran, and Shin (IPS) test, and the Fisher-type ADF and Phillips–Perron (PP) tests, were employed alongside the Levin, Lin, and Chu (LLC) test for robustness. This approach helps capture potential differences in how each country adjusts to economic shocks. Accordingly, unit root tests were specified with individual intercepts only, preserving test power without imposing unnecessary trend assumptions. The Akaike Information Criterion (AIC) was used for automatic lag length selection, given its suitability for relatively short panels and frequent use in applied macroeconomic research. At the level, none of the tests (the only exception is lnGDP per capita by LLC) rejected the null hypothesis of a unit root at the 5% significance level ($p > 0.05$), confirming that all series are non-stationary in levels. The detailed results of these tests are provided in the table below.

Table 4. Panel Unit Root Test Results at Level

	ln(EMPRATE)		ln(FEC_PC)		ln(GDP_PC)		ln(GFCF_PC)	
	Stat.	Prob.**	Stat.	Prob.**	Stat.	Prob.**	Stat.	Prob.**
LLC	0.78	0.78	-0.47	0.32	-2.33	0.01	-0.81	0.21
IPS	0.9	0.82	0.45	0.67	-0.63	0.26	-0.59	0.28
ADF-Fisher	1.89	0.93	3.34	0.77	6.3	0.39	6.75	0.34
PP-Fisher	1.32	0.97	3.15	0.79	5.71	0.46	4.23	0.65

**Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Source: Authors' calculations

Non-stationarity is a common feature in time series analysis, particularly for macroeconomic indicators such as GDP, which often exhibit persistent upward trends rather than fluctuating around a constant mean. Variables typically used in the energy consumption–economic growth literature, including GDP, energy use, capital, and labor, are no exception, and non-stationarity at levels has been widely documented. This characteristic can lead to spurious regression results if not properly addressed. A standard approach is to eliminate non-stationarity by differencing the data, thereby transforming the series into stationary processes integrated of order one, I(1). After differencing, stationarity tests were re-applied, and the null hypothesis of a unit root was rejected at the 1% significance level across all variables. The results, presented in the table below, confirm that GDP, energy consumption, labor, and capital stock are all I(1) processes.

Table 5. Panel Unit Root Test Results at First Difference

	ln(EMPRATE)		ln(FEC_PC)		ln(GDP_PC)		ln(GFCF_PC)	
	Stat.	Prob.**	Stat.	Prob.**	Stat.	Prob.**	Stat.	Prob.**
LLC	-6.13	<0.01	-5.87	<0.01	-3.88	<0.01	-5.87	<0.01
IPS	-5.14	<0.01	-6.35	<0.01	-3.44	<0.01	-4.60	<0.01
ADF-Fisher	35.08	<0.01	42.99	<0.01	22.74	<0.01	31.79	<0.01
PP-Fisher	24.57	<0.01	42.98	<0.01	18.74	<0.01	22.83	<0.01

**Probabilities for Fisher tests are computed using an asymptotic Chi-square distribution. All other tests assume asymptotic normality.

Source: Authors' calculations

Since the variables were found to be integrated of order one I(1), it is appropriate to proceed with cointegration testing. Cointegration tests are specifically designed for I(1) variables, and applying them to series with a different order of integration can lead to misleading or invalid results. If the variables were already stationary I(0), cointegration analysis would not be necessary. Verifying the correct order of integration is therefore essential to avoid spurious regression and to ensure that any detected long-run relationships are statistically valid and based on appropriate assumptions.

4.2 Testing for Long-Run Cointegration (Hypothesis 1)

The next step after testing panel stationarity is the exploration of the long-run relationship between the variables using the cointegration test. The key characteristic of cointegrated variables is that although each variable is non-stationary on its own, a specific linear combination of them becomes stationary. This implies the existence of a stable long-run relationship among the variables, where short-term deviations may occur but are ultimately corrected over time.

To assess the presence of a long-run relationship, two panel cointegration tests were employed: the Pedroni and Kao tests. The Pedroni test includes seven individual statistics—panel v-statistic, panel rho-statistic, panel PP-statistic (non-parametric), panel ADF-statistic (parametric t), as well as group rho-, group PP-, and group ADF-statistics. (Pedroni, 2000) The test was conducted under three deterministic specifications: (i) individual intercept only, (ii) individual intercept and trend, and (iii) no intercept or trend. The variation in deterministic assumptions notably influenced the test outcomes. In each case, four out of seven statistics rejected the null hypothesis of no cointegration at 5% significance, indicating partial support for the existence of a long-run equilibrium relationship among the variables.

Table 6. Pedroni Residual-Based Panel Cointegration Test Results

Within dimension						
	Individual intercept		Individual intercept and individual trend		No intercept or trend	
Panel	Statistic	Weighted statistic	Statistic	Weighted statistic	Statistic	Weighted statistic
v-Stat	0.189	0.155	6.196***	5.992***	0.673	0.638
rho-Stat	-0.789	-0.785	0.010	-0.072	-0.899	-0.923
PP-Stat	-2.461***	-2.466***	-2.003**	-2,223**	-2,240**	-2.252**
ADF-Stat	-2.464***	-2.482***	-1.795**	-2,030**	2,345***	-2.373***
Between dimensions						
Group	Statistic		Statistic		Statistic	
rho-Stat	-0.124		0.718		-0.281	
PP-Stat	-2.553***		-1.697**		-2.675***	
ADF-Stat	-2.575***		1.421*		-2.836***	

Asterisks denote statistical significance levels as follows — * indicates significance at the 10% level, ** at the 5% level, and *** at the 1% level.

Source: Authors' calculations

The rho-statistic consistently failed to reject the null hypothesis across all model configurations. This pattern has been observed in several previous studies, including Bhattacharya

(2016), Streimikiene (2016), Adams (2018), Kasperowicz (2020), and Leitão (2020). As noted by Adams (2018), the panel v- and rho-statistics are prone to under- or over-rejection in small samples, particularly when the time dimension (T) is limited. In contrast, the PP- and ADF-statistics provided stronger and more consistent evidence of cointegration across specifications. Notably, the inclusion of both individual intercept and trend significantly increased the panel v-statistic, suggesting that deterministic components can strongly influence test outcomes.

To confirm the robustness of the cointegration results, the Kao test was also employed. In contrast to the Pedroni test, the Kao test assumes homogeneous dynamics across panel units. The null hypothesis of no cointegration was rejected at the 1% significance level, providing additional evidence of a stable long-run relationship among the variables.

Table 7. Kao Residual-Based Panel Cointegration Test Results

Test	t-Statistic	p-Value
ADF	-4.156	0.000

Source: Authors' calculations

Pedroni allows for heterogeneity in autoregressive dynamics across panel units, while Kao assumes a homogeneous cointegrating relationship. The cointegration test results indicate that four out of seven Pedroni statistics consistently reject the null hypothesis of no cointegration at the 5% significance level across various model specifications. Therefore, the **null hypothesis (H_{01})** is rejected, suggesting the presence of a long-run cointegrating relationship among the variables.

4.3 Estimating Long-Run Output Elasticities (Hypothesis 2)

To estimate the long-run relationship between the dependent and independent variables, Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS) techniques were applied. These estimators are well-suited for cointegrated panel data and correct for potential endogeneity and serial correlation (Kasman, 2015; Bhattacharya, 2016), providing robust coefficient estimates. The models were estimated using logged per capita variables, as justified in the methodology section. Although cointegration test results were somewhat mixed, the theoretical foundation supported the use of long-run estimation methods.

The FMOLS and DOLS estimations provide consistent and statistically significant evidence of long-run elasticities between GDP and its key determinants. Across both methods, energy consumption and capital formation show positive effects on economic growth, while labor displays varying significance. These findings are aligned with theoretical expectations under a log-linear

Cobb–Douglas production framework and suggest a stable long-run relationship among the selected variables.

Table 8. Fully Modified Ordinary Least Squares (FMOLS) Estimation Results

	Coefficient	Prob.
ln(EMPRATE)	0.987 (3.729)	<0.01
ln(FEC_PC)	0.912 (6.481)	<0.01
ln(GFCF_PC)	0.292 (4.328)	<0.01
R-squared	0.967	
Adjusted R-squared	0.965	
Standard error of regression	0.063	
Long-run variance	0.0072	

Coefficients are reported with *t*-statistics in parentheses.

Source: Authors' calculations

The FMOLS estimation results reveal statistically significant and positive long-run relationships between GDP per capita and the selected explanatory variables: employment rate, energy consumption per capita, and gross fixed capital formation per capita. To focus on the Baltic region as a whole, this study adopts the specification without heterogeneous long-run coefficients. This approach simplifies interpretation and aligns with the goal of identifying common regional dynamics. A 1% increase in employment rate is associated with a 0.99% increase in GDP per capita, while a 1% rise in energy use leads to a 0.91% increase in GDP. Similarly, capital formation contributes positively, though to a smaller extent, with a 0.29% increase in GDP per 1% rise in GFCF. All coefficients are significant at the 1% level, and the model demonstrates a strong overall fit (Adjusted R^2 = 0.965), indicating robust long-run relationships consistent with theoretical expectations. The standard error of regression is low (0.063), indicating that the FMOLS model closely tracks the actual data with minimal unexplained variation. Additionally, the long-run variance is small (0.0072), suggesting that the residuals are stable over time and the estimated long-run relationship is robust.

Table 9. Dynamic Ordinary Least Squares (DOLS) Estimation Results

	Coefficient	Prob.
ln(EMPRATE)	1.248 (5.679)	<0.01
ln(FEC_PC)	0.874 (5.612)	<0.01
ln(GFCF_PC)	0.203 (2.929)	<0.01
R-squared	0.992	
Adjusted R-squared	0.985	
Standard error of regression	0.039	
Long-run variance	0.0014	

Source: Authors' calculations

The DOLS estimation results align with those of FMOLS, confirming a statistically significant long-run relationship between GDP per capita and the selected explanatory variables. All coefficients are positive and significant at the 1% level. A 1% increase in the employment rate is associated with a 1.25% increase in GDP per capita, while energy use contributes 0.87%, and capital formation 0.20%. The adjusted R^2 of 0.985 indicates excellent model fit, and the results are consistent with economic theory and the previously estimated FMOLS model, reinforcing the robustness of the findings.

The empirical results of this study are consistent with and supported by a previous literature exploring the energy–growth nexus and the role of capital and labor in economic development. Drawing on studies that applied similar methodologies and regional scopes, the findings affirm the existence of stable long-run relationships among the selected variables.

The use of FMOLS and DOLS estimators to examine long-run relationships between GDP per capita, employment, energy consumption, and gross fixed capital formation was employed by Streimikiene and Kasperowicz (2016) in their study of EU countries. Their results demonstrated a positive and significant relationship between energy consumption and economic growth using both FMOLS and DOLS, with capital formation also playing a reinforcing role. Similarly, this study found energy consumption to have a statistically significant elasticity with respect to GDP, particularly in the FMOLS specification. The consistent positive signs and significance levels across both estimation methods indicate a long-run equilibrium, similar to the conclusions of Streimikiene and Kasperowicz.

Kasperowicz et al. (2020) analyzed renewable energy consumption across 29 European countries and found a significant positive relationship with GDP, reporting elasticities of renewable energy consumption of approximately 0.16 using both FMOLS and DOLS estimators. In comparison, the present analysis focused on total energy consumption and similarly identified a significant long-run contribution to economic growth, suggesting that total energy use plays a comparably important role. While capital remained a significant driver of GDP in both studies, labor was found to be statistically insignificant in the former. These findings underscore the relevance of energy inputs, whether renewable or aggregate, as key components of long-run economic performance.

The further use of additional sources to illustrate similarities or differences in regression analysis results is not viable due to three key factors. First, most recent studies employing modern econometric techniques focus primarily on renewable energy, often adopting a distinct theoretical framework. Second, other studies typically investigate entirely different regional contexts, rendering direct comparisons methodologically inappropriate. Third, many earlier papers lack key robustness checks that are now considered standard practice in empirical research, reducing their applicability to the present analysis.

The FMOLS and DOLS estimation results both reveal relatively strong, positive, and statistically significant long-run relationships between GDP per capita and the selected explanatory variables: employment rate, energy consumption per capita, and gross fixed capital formation per capita. The consistency in coefficient signs, magnitudes, and significance across both methods confirms the robustness of the findings. Employment and energy consumption have the largest long-run elasticities, while capital formation shows a moderate but still positive effect. High adjusted R-squared values in both models indicate strong explanatory power.

The **null hypothesis (H_{02})** that energy consumption has no statistically significant long-run effect on GDP per capita is rejected, as both the FMOLS and DOLS estimations indicate that energy consumption per capita exerts a positive and statistically significant effect on GDP per capita at the 1% level.

4.4 Causality Analysis Using PVECM (Hypothesis 3)

To explore both short-run dynamics and long-run equilibrium relationships among the core macroeconomic variables, a Panel Vector Error Correction Model (PVECM) was estimated. The initial specification used a lag structure of one period for both the error correction and differenced terms (1,1). The model captures not only how variables co-move over time but also how deviations from equilibrium are corrected in subsequent periods.

To interpret the long-run relationship captured by the cointegrating vector, the error correction term (ECT) was derived from the estimated PVECM. This term represents the extent of deviation from the long-run equilibrium path in each period and serves as the key mechanism through which the system adjusts over time. Specifically, the ECT is defined as follows:

$$\boldsymbol{ECT_t = ln(GDP\_PC_{t-1}) - (2.13 \cdot ln(EMPRATE_{t-1}) + 0.193 \cdot ln(FEC\_PC_{t-1}) + 0.016 \cdot ln(GFCF\_PC_{t-1}) + 8.80)}$$

To simplify interpretation, the cointegrating equation was rearranged from the perspective of GDP per capita as the dependent variable. This transformation allows the coefficients to directly reflect long-run elasticities, showing how percentage changes in employment rate, energy consumption, and capital formation per capita impact GDP per capita. By expressing the relationship in this log-linear form, it becomes easier to understand the relative contribution of each factor to economic growth within an augmented Cobb-Douglas framework.

$$\boldsymbol{ln(GDP\_PC_{t-1}) = 2.13 \cdot ln(EMPRATE_{t-1}) + 0.193 \cdot ln(FEC\_PC_{t-1}) + 0.016 \cdot ln(GFCF\_PC_{t-1}) + 8.80 + ECT_t}$$

The coefficient for ln($EMPRATE_{t-1}$) is statistically significant at the 1% level (t-statistic = -3.72). This suggests that, in the long run, a one-unit increase in the employment rate is associated with a 2.13-unit increase in GDP per capita, holding other factors constant. Given the log-log specification, this implies that a 1% increase in the employment rate leads to approximately a 2.13% increase in GDP per capita. This strong elasticity highlights the critical role of labor market conditions in driving long-term economic growth.

Table 10. Panel Vector Error Correction Model (PVECM) – Long-Run Coefficients

Variable	Coefficient	Standard Error	t-Statistic
ln(GDP_PC)	1		
ln(EMPRATE)	-2.13	0.572	-3.723
ln(FEC_PC)	-0.193	0.265	-0.729
ln(GFCF_PC)	-0.016	0.157	-0.100
Constant	-8.804		

Source: Authors' calculations

The coefficients for energy consumption and capital formation are both **statistically insignificant**. This means that, within this long-run framework, energy use and investment do not exhibit a robust and statistically detectable influence on GDP per capita across the panel. However, their inclusion remains theoretically justified, as they are essential components of the production process and are strongly supported by the empirical growth literature. Moreover, the lack of statistical significance for these variables in the cointegration equation does not invalidate the overall presence of a long-run relationship among the variables.

The short-run dynamics of the system are captured by the panel vector error correction model (PVECM), where the first-differenced variables represent short-term fluctuations. Each equation estimates how a dependent variable responds to both its own lags and the lags of other variables in the system. Statistical significance is indicated with standard asterisk notation.

Table 11. Panel Vector Error Correction Model (PVECM) – Short-Run Dynamics

Regressor	D(ln(GDP_PC))	D(ln(EMPRATE))	D(ln(FEC_PC))	D(ln(GFCF_PC))
CointEq1	-0.051 (-1.325)	0.058 (2.936)***	-0.037 (-1.083)	0.032 (0.293)
D(ln(GDP_PC)(-1))	0.332 (1.175)	0.252 (1.759)*	0.054 (0.222)	1.241 (1.579)
D(ln(EMPRATE)(-1))	-0.665 (-2.407)**	-0.197 (-1.406)	-0.469 (-1.948)*	-1.889 (-2.453)**
D(ln(FEC_PC)(-1))	0.008 (0.047)	0.015 (1.630)	-0.050 (-0.353)	-0.031 (-0.378)
D(ln(GFCF_PC)(-1))	0.127 (1.497)	0.033 (0.776)	0.113 (1.534)	0.241 (1.020)

Source: Authors' calculations

The short-run dynamics of the PVECM reveal several statistically significant relationships among the macroeconomic variables. Most notably, the employment rate exhibits a positive and statistically significant response to deviations from long-run equilibrium, as indicated by the significant coefficient on the error correction term (t-stat = 2.94). This suggests that employment plays a key role in adjusting the system back toward its long-run path when GDP per capita deviates from equilibrium. Additionally, capital formation is significantly and negatively affected by changes in employment (t-stat = –2.45), indicating a potential short-run trade-off between labor and investment, possibly reflecting labor-substituting capital adjustments.

By contrast, short-run effects from energy consumption and GDP per capita are generally statistically insignificant across equations. This implies a lack of strong short-term interdependencies among these variables, consistent with the view that their relationships unfold more gradually and are more appropriately captured in a long-run framework. Furthermore, other potential short-run causal links also fail to reach statistical significance, reinforcing the dominance of long-run dynamics in this system.

The **null hypothesis (H_{03a})** that there is no long-run Granger-causal relationship between energy consumption and GDP per capita is not rejected. In the panel VECM, the coefficient on energy consumption in the long-run cointegrating equation is statistically insignificant (t = –0.729), indicating that energy consumption does not have a statistically detectable long-run impact on GDP per capita at conventional significance levels.

The **null hypothesis (H_{03b})** that there is no short-run Granger-causal relationship between energy consumption and GDP per capita is not rejected. In the short-run dynamics of the PVECM, the lagged difference of energy consumption (D(ln(FEC_PC)(-1))) has a statistically insignificant effect on GDP per capita (t = 0.047), suggesting no evidence of short-run causality running from energy use to economic output.

4.4.1 Discussion of Results in the Context of Energy-Augmented Growth Theory

The empirical results of this thesis, while not confirming a statistically significant causal relationship between energy consumption and GDP, align with the theoretical critiques developed in the energy-augmented growth paradigm, particularly by Reiner Kümmel and Robert Ayres. Both scholars challenged the neoclassical tradition by asserting that energy is not merely an intermediate input but a fundamental driver of economic growth. Kümmel, in particular, emphasized that capital and labor are not productive in isolation, they require energy to operate, perform work, and process information. His empirical studies revealed that energy's elasticity of output often exceeds its cost share, contradicting the neoclassical assumption that factor elasticities mirror income shares.

In light of these insights, the absence of short-run or long-run causality between energy and GDP in this study does not cancel energy's role as a production input. Rather, it may reflect a form of relative decoupling, where energy's contribution is embodied in technological systems and infrastructure but does not manifest through direct changes in consumption. The long-run cointegration established among GDP, labor, capital, and energy validates Kümmel's core claim that energy should be treated as a core production factor. The lack of statistical significance in energy's coefficient does not invalidate this relationship; it merely highlights that energy's effect may be mediated through efficiency gains, structural change, or other factors not captured in aggregate consumption data.

Ayres' contributions further contextualize these findings. His emphasis on exergy and useful work suggests that raw energy consumption is a limited proxy for economic productivity. The absence of causality in this thesis may stem from the aggregate data's inability to distinguish between energy quantity and energy quality. Similarly, the rebound effect, where efficiency gains lead to higher overall consumption may obscure the direct relationship between energy use and output in small and open economies like the Baltics.

In sum, while the findings do not statistically confirm energy consumption as a driver of GDP, they are not inconsistent with the broader energy-augmented growth paradigm. Instead, they initiate the broader discussion that energy plays a foundational but complex role in economic dynamics, one that may require more consumer-disaggregated, or quality-adjusted data to fully uncover.

4.4.1 Discussion of Results in Light of Empirical Literature on the Energy–Growth Nexus

Across the body of empirical research on the energy–growth nexus in Europe, a wide range of causality directions have been proposed—often reflecting regional structural differences, energy mixes, and methodological choices. While the prevailing literature tends to confirm some form of causal relationship between energy consumption and economic output, the results for the Baltic States depart notably from this trend.

Ciarreta and Zarraga (2009) stand out as an early study that, much like the Baltic panel analysis, identified no short-run causality in either direction between electricity consumption and GDP across 12 European countries. Their conclusion supports what is often termed the **neutrality hypothesis**, suggesting that energy use and economic performance may evolve independently under certain conditions—especially in more service-oriented or energy-efficient economies.

In contrast, several later studies present stronger interaction between the two variables. Marinas et al. (2018), focusing on Central and Eastern Europe, found long-run bidirectional causality between renewable energy and GDP in the panel as a whole, though short-run effects remained inconsistent across individual countries. Similarly, Armeanu et al. (2019) observed short-run causality flowing from GDP to renewable energy, and long-run causality in the opposite direction, lending empirical support to both the conservation and growth hypotheses. These findings suggest an ongoing feedback process between output and energy use—something that does not emerge clearly in the Baltic results.

Asiedu et al. (2021) reported perhaps the strongest case for a feedback mechanism, confirming bidirectional causality between renewable energy and GDP across 26 European countries. Their findings imply a mutually reinforcing loop between energy policy and economic growth, a dynamic absent in the Baltic case. Likewise, Leitão and Lorente (2020), applying Dumitrescu–Hurlin panel causality tests, detected a robust effect of renewable energy on growth across EU-28, further reinforcing the role of energy as a growth enabler.

Taken together, the Baltic results, showing no significant causality in either direction—stand out. They reinforce the idea of relative decoupling: a structural shift where energy consumption and

GDP become less tightly linked, possibly due to technological efficiency, diversification of energy sources, or the post-transition economic restructuring unique to the region.

CONCLUSIONS

This thesis investigated the causal relationship between energy consumption and economic growth in the Baltic States over the period 1998–2023. The study drew on the theoretical foundations of energy-augmented growth models, particularly those of Kümmel and Ayres, and empirically applied cointegration and causality testing techniques within a panel data framework. The major findings and contributions are summarized below:

1. The research began by grounding the analysis in classical and neoclassical growth theories and then progressed toward energy-augmented growth models. The key insight of these models is the inclusion of energy as an independent, essential factor of production. The theoretical synthesis formed a strong basis for treating energy as a key driver of economic output and justified the empirical specification using a Cobb-Douglas production function augmented with energy consumption alongside capital and labor.
2. Methodologically, the study employed a panel econometric framework including Pedroni and Kao tests for panel cointegration, Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) for long-run elasticity estimation, and a Panel Vector Error Correction Model (PVECM) to test for both short- and long-run Granger causality. Data was collected from Eurostat and included per capita figures for GDP, final energy consumption, gross fixed capital formation, and employment.
3. The cointegration tests provide partial support for the rejection of the **null hypothesis (H_{01})** of no long-run cointegrating relationship among GDP per capita, energy consumption, labor, and capital. This suggests the presence of a shared long-run equilibrium across the Baltic countries, despite their economic differences.
4. The regression results from FMOLS and DOLS estimations show that energy consumption has a statistically significant and positive long-run effect on GDP per capita for the panel as a whole, leading to the rejection of the **null hypothesis (H_{02})**. This indicates that energy use plays a meaningful role in economic growth across the Baltic States.
5. Results from the PVECM analysis do not provide sufficient evidence to reject the null hypotheses of no Granger-causal relationship between energy consumption and GDP per capita, either in the short run **(H_{03b})** or the long run **(H_{03a}).** This outcome supports the neutrality hypothesis for the Baltic region, indicating a lack of dynamic causal interaction between energy use and economic output. One plausible explanation lies in the Baltics' relatively high energy efficiency and post-industrial economic structure, which may have decoupled economic growth from energy consumption.

6. While causality is absent, the findings do not invalidate the foundational importance of energy as theorized in energy-augmented growth frameworks. Rather, they may indicate that energy's role is more subtle, especially in small, efficient, and service-oriented economies. The divergence from previous panel studies across Europe suggests regional uniqueness rather than contradiction.

7. Comparative assessment with existing European studies shows that while many confirm unidirectional or bidirectional causality, some examples such as Ciarreta and Zarraga (2009) also report null results, aligning more closely with this study. Therefore, the findings contribute to a better understanding of energy–growth dynamics in post-transition economies.

RECOMMENDATIONS

Based on the empirical findings and broader theoretical implications, several recommendations for policy and future research can be offered:

1. Policymakers should avoid assuming a straightforward linkage between increased energy consumption and economic growth. The absence of causality suggests that energy policy should focus more on sustainability, security, and efficiency, rather than GDP stimulation alone.
2. Future research should attempt to disaggregate energy consumption by sector (industry, services, households). The lack of significance in causality might stem from the use of aggregate data.
3. While the 1998–2023 time frame is sufficient, extending the dataset in future updates or integrating additional post-2023 data may help capture delayed effects, especially considering the energy transition and digital transformation of recent years.
4. Quarterly data or firm-level datasets could allow researchers to test the relationship between energy and growth at micro levels. Moreover, testing alternative estimation strategies may strengthen the robustness of conclusions.

In summary, the thesis confirms a long-run association between GDP, energy, labor, and capital in the Baltics but finds no causal directionality from energy to growth or vice versa.

LIMITATIONS

The study relies on annual panel data covering the period from 1998 to 2023 for Estonia, Latvia, and Lithuania. While the time span is relatively long for a post-transition context, annual frequency reduces the number of effective observations, particularly for dynamic models like the Panel Vector Error Correction Model (PVECM). Quarterly data could have provided greater resolution and potentially revealed more nuanced short-run interactions.

The use of aggregate energy consumption as a proxy may obscure the effects of energy quality, efficiency, and structural composition. Similarly, employment rate and gross fixed capital formation are used as proxies for labor and capital, respectively, though they may not fully reflect the productivity or technological intensity of these inputs.

The cointegration and causality framework assumes linear relationships. However, the economic structure of the Baltic States has undergone significant transformation over the period studied, including EU accession, energy diversification, and digitalization. These structural breaks are not explicitly modeled, potentially affecting the stability and interpretation of long-run relationships.

Finally, the focus on the three Baltic countries enhances internal consistency but limits external generalizability. While comparisons with broader European literature were made, caution is warranted when extrapolating these findings to larger or more resource-intensive economies.

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SUMMARY IN LITHUANIAN

SĄRYŠIS TARP ENERGIJOS VARTOJIMO IR EKONOMIKOS AUGIMO: BALTIJOS ŠALIŲ ANALIZĖ

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SANTRAUKA

62 puslapiai, 5 paveikslai, 11 lentelių ir 87 šaltiniai.

Šio magistro darbo pagrindinis tikslas – ištirti, ar energijos vartojimas turi statistiškai reikšmingą ilgalaikį ar trumpalaikį priežastinį ryšį su ekonomikos augimu Baltijos šalyse 1998–2023 metų laikotarpiu. Tyrimas remiasi energija papildyta ekonominio augimo teorija ir siekia nustatyti energijos vartojimo bei vienam gyventojui tenkančio BVP ryšio kryptį, egzistavimą ir stiprumą, atsižvelgiant į darbo ir kapitalo veiksnius.

Darbas susideda iš keturių pagrindinių dalių. Pirmoje dalyje pateikiamas teorinis pagrindas – klasikinės bei energija papildytos ekonominio augimo teorijų apžvalga. Antroje – analizuojami pagrindiniai sąryšio tarp energijos vartojimo ir ekonomikos augimo literatūros empiriniai rezultatai bei hipotezės. Trečioje dalyje aprašoma tyrimo metodologija: duomenų rinkimas, kintamųjų pasirinkimas bei taikyta ekonometrinė strategija. Ketvirtoji dalis skirta empirinei analizei, rezultatų interpretacijai bei išvadoms ir rekomendacijoms.

Empirinėje dalyje taikytas tvirtas panelinių duomenų analizės pagrindas. Pirmiausia atlikti vienetinės šaknies testai siekiant įvertinti stacionarumą, vėliau Pedroni ir Kao kointegracijos testais tikrintas ilgalaikis ryšys tarp kintamųjų. Trumpalaikis ir ilgalaikis priežastingumas tirtas naudojant panelinių duomenų vektorinį paklaidų korekcijos modelį (PVECM), leidžiantį įvertinti ir laikinę, ir struktūrinę sąveiką tarp energijos ir ekonomikos augimo.

Rezultatai patvirtina ilgalaikę kointegraciją tarp BVP, energijos vartojimo, darbo ir kapitalo visose trijose Baltijos šalyse, tai rodo stabilų ilgalaikį ryšį tarp šių veiksnių. Visgi Grangerio priežastingumo testai neatskleidė statistiškai reikšmingo priežastinio ryšio tarp energijos ir augimo abiem kryptimis – tai patvirtina neutralumo hipotezę.

Šie rezultatai leidžia teigti, kad energijos vartojimas Baltijos regione neveikia kaip tiesioginis ekonomikos augimą skatinantis veiksnys. Todėl energijos politika neturėtų būti orientuota vien į BVP skatinimą, bet turėtų fokusuotis į tvarumą, energetinį saugumą ir efektyvų išteklių naudojimą.

Tyrimas rekomenduoja būsimus tyrimus atlikti pagal ekonomikos sektorius, taip pat naudoti didesnio periodiškumo duomenis, kurie galėtų atskleisti užslėptus ar uždelstus efektus, nematomus metiniuose apibendrintuose duomenyse.

SUMMARY IN ENGLISH

THE ENERGY CONSUMPTION–ECONOMIC GROWTH NEXUS: EVIDENCE FROM THE BALTIC STATES

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Master thesis

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SUMMARY

62 Pages, 5 Figures, 11 Tables and 87 sources.

The main purpose of this Master's thesis is to examine whether energy consumption has a statistically significant long- or short-run causal relationship with economic growth in the Baltic States—Estonia, Latvia, and Lithuania—over the period 1998–2023. The work is grounded in energy-augmented growth theory and explores the direction, presence, and strength of the relationship between energy use and GDP per capita, while controlling for labor and capital inputs.

The thesis is structured into four main parts. The first part presents the theoretical background, offering a critical review of classical and energy-augmented economic growth models, the second one summarizes key empirical findings and hypotheses from international energy–growth literature. The third part outlines the research methodology, detailing data collection, variable selection, and the econometric strategy employed. The fourth part focuses on empirical analysis, interpretation of results, and formulation of conclusions and recommendations.

Empirically, the study applies a robust panel data framework. It begins by testing for stationarity using panel unit root tests and then evaluates long-run relationships among variables through Pedroni and Kao cointegration tests. To estimate the long-run elasticities of output with respect to capital, labor, and energy, both Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) estimators are used. Short- and long-run causality dynamics are assessed using a Panel Vector Error Correction Model (PVECM), allowing for both temporal and structural insights into the energy–growth nexus.

The findings confirm the existence of long-run cointegration between GDP, energy use, labor, and capital across the three Baltic states, indicating a stable long-term association. However, Granger-causality tests reveal no statistically significant causal link from energy to growth or vice versa, thus supporting the neutrality hypothesis.

These results suggest that energy consumption in the Baltic region does not act as a direct driver of economic growth. Accordingly, energy policy should not be centered solely on stimulating GDP but

should instead emphasize goals such as sustainability, energy security, and resource efficiency. The study recommends future research to disaggregate energy data by sector and explore higher-frequency datasets to detect potential hidden or delayed effects that may not be visible in aggregate annual data.