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Energy Intensity Forecasting Models for Manufacturing Industries of "Catching Up" Economies: Lithuanian Case

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Abstract: The objective of this research was to construct energy intensity forecasting models for key manufacturing industries, with a particular focus on "catching up" European economies. Future energy intensity values serve as the foundation for energy demand forecasts, which are essential inputs for the analysis of countries' decarbonisation scenarios. The Lithuanian case is analysed in the context of its efforts to reach the economic development level of the most advanced European Union (EU) countries. The scientific literature and energy policy analysis, interdependence (correlation and regression), tendency and case analysis, logical economic reasoning, and graphical representation methods have been applied. The energy intensity forecasts until 2050 were based on historical statistical data of value added and final energy consumption of EU countries from 2000 to 2021. The analysis of historical trends revealed a remarkable decrease in industrial energy intensity in most EU countries, including Lithuania. Given the rapid pace of decline in historical energy intensity, the values observed in individual Lithuanian industries have already reached levels comparable to the most economically advanced EU countries. Four econometric trendlines were employed to construct forecasting models for energy intensity. The results for Lithuania demonstrated that the selected trendlines exhibited a high degree of fit with historical energy intensity data from the EU, as evidenced by their R^2 values. Furthermore, the forecasts were shown to be highly accurate, with their MAPEs remaining below 10% in most cases. Nevertheless, the logarithmic trendline was found to be the most accurate for forecasting energy intensity in total manufacturing (MAPE = 4.0%), non-metallic minerals (MAPE = 3.5%), and food, beverages, and tobacco (MAPE = 4.1%) industries, with the exponential trendline in the chemical industry (MAPE = 8.7%) and the moving average in the total manufacturing industry (MAPE = 4.0%), food industries (MAPE = 4.0%), and remaining aggregate industries (MAPE = 14.5%). It is forecasted that energy intensity could decline by 8 to 16% to 1.10–1.20 kWh/EUR in Lithuania's manufacturing industries by 2050.

Keywords: energy intensity; time series techniques; manufacturing industries; case study

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1. Introduction

The Paris Agreement stipulates that the global average temperature rise should be limited to below 2 °C and even below 1.5 °C [1]. The European Union (EU) aims to become the world's first climate-neutral economy by 2050. According to the European Climate Law, the EU is committed to reducing net greenhouse gas (GHG) emissions by at least 55% by 2030 [2]. The "Fit for 55" legislative package ensures that all sectors of the EU's economy would be able to meet this target. The industry represents Lithuania's third most significant source of GHG emissions, following transport and agriculture. In 2021, the industry accounted for approximately 20% of Lithuania's total GHG emissions, of which 6.4% resulted from fuel combustion and 13.6% from industrial processes [3]. Consequently, the manufacturing industry is of vital importance to achieve GHG reduction goals and the 2 °C target.

To achieve these goals, the National Climate Change Management Agenda [4] calls upon EU-ETS-covered industrial enterprises in Lithuania to improve energy efficiency by replacing polluting technologies, to reduce energy consumption in industrial processes, to utilise renewable energy sources (RES) and become prosumers, to produce green hydrogen, and to finally achieve a 100% reduction in GHG emissions by 2050. With regard to the non-ETS industry, the policy aims to reduce GHG emissions by at least 19% by 2030 in comparison to 2005 and to phase out fossil fuels by 2040. This objective is to be achieved by a number of measures, including the utilisation of RES and alternative fuels, as well as the improvement in energy efficiency. The Law on Energy Efficiency [5] stipulates that Lithuanian economic sectors must reduce energy consumption by 0.8% annually (based on the average of 2016–2018) until 2030. Furthermore, it emphasises that it is mandatory to save 5.45 TWh in the industrial sector. The National Energy Independence Strategy [6] anticipates a reduction in primary and final energy intensity by a factor of 1.5 in 2030 and by a factor of 2.4 in 2050 in comparison to 2017. Historically, approximately 30 financial support measures have been in place to promote industries that improve efficiency in energy consumption and production [7].

To assess the potential of the economy achieving full decarbonisation in the long term, it is necessary to prepare a reasonable forecast of final energy consumption. The forecast of energy demand constitutes one of the critical inputs for the analysis of decarbonisation options applying techno-economic system development modelling tools such as TIMES, MESSAGE, or similar. Therefore, to enable the utilisation of these models, a forecast of the final energy demand of the sector under analysis is generated in advance through the application of various forecasting methodologies. In principle, the energy demand forecast and analysis of decarbonisation scenarios represent distinct processes.

A variety of methods are employed to forecast final energy demand. This paper focuses on the preparation of data required to forecast energy demand using the Model for Analysis of Energy Demand (MAED). Based on the bottom-up scenario approach, the MAED model provides a systematic framework for mapping trends and anticipating changes in energy demand, particularly concerning alternative scenarios for technological, socio-economic, and demographic development [8]. It considers different energy forms in all economic sectors at the end-use level. The final energy demand for producing various goods and services is identified based on the corresponding social, economic, and technological factors that affect this demand. In this methodology, the energy demand of the industrial sector is driven by two key factors: the level of economic activity in terms of its value added and the energy intensity of each energy form. Consequently, the MAED model requires a detailed understanding of energy intensity as a key input for forecasting energy demand.

The main objective of this study is to analyse the historical evolution of the energy intensity of the manufacturing industry in the EU countries and to forecast this indicator for the crucial Lithuanian manufacturing industries.

To achieve the objective, the following tasks have been defined:

1. To prepare the methodological guidelines for the energy intensity research;
2. To analyse the historical developments in energy intensity of the manufacturing industries in the EU countries;
3. To construct reliable energy intensity forecasting models for crucial manufacturing industries;
4. To prepare accurate energy intensity forecasts up to 2050;
5. To analyse the effect of energy intensity on final energy consumption in the Lithuanian manufacturing industries.

The study was conducted using the following methods: a scientific literature review, comparative tendency analysis, time series techniques, and decomposition analysis.

The novelty of the study lies in the adaptation of fundamental time series techniques to develop energy intensity forecasting models for pivotal manufacturing industries in "catching up economies" and their application in addressing final energy demand forecasting tasks within the context of manufacturing industry decarbonisation. The study makes a significant contribution to the literature on sustainable development as it characterises the long-term dynamics in the level of efficiency of energy consumption and establishes a basis for the assessment of energy consumption and its environmental impact resulting from economic growth.

The remainder of the paper is organised as follows. Section 2 outlines the concept of energy intensity and provides an overview of the research in the field. Section 3 introduces methodological guidelines for the construction of energy intensity forecasting models and the preparation of energy intensity forecasts. Section 4 presents historical energy and fuel consumption, value added, and energy intensity in the manufacturing industries in EU countries, along with energy intensity forecasting models for those industries. Section 5 provides a discussion of the results and reveals the implications. Section 6 concludes the paper.

2. Literature Review

Energy intensity is defined as the amount of energy used to produce a given output level. It is calculated as units of energy per unit of gross domestic product (GDP) or some other measure of economic output. Energy intensity is one of the key indicators of sustainable development. Its dynamics characterise the level of energy efficiency. Namely, it measures the capability to "achieve more with little" to produce more output using fewer resources [9]. In addition, the energy intensity indicator is a measure of the extent to which economic growth is decoupled from energy consumption [10]. Reducing energy intensity is an important strategy for mitigating climate change on a global scale [11].

The International Energy Agency (IEA) [12] has reported a 36% reduction in global energy intensity between 1990 and 2021. In 2022, the global energy intensity declined by 1.2%, which was slower than the historical trend (−1.9% per year between 2010 and 2019), and it is insufficient compared with the annual 3.5% decrease required to achieve the 2 °C scenario [13]. Energy intensity levels vary considerably across the world's regions, as these differences are strongly influenced by the structure of the economy and implemented energy efficiency policies. It is of critical importance to direct research and development efforts towards the most energy-intensive sectors of the economy, with particular emphasis on the industry.

In the manufacturing industries, energy is utilised for a multitude of purposes. This encompasses the generation of heat in the form of steam and hot water for industrial processes, space heating, and electricity generation. Additionally, the manufacturing industries use electricity for various industrial equipment (machinery, motors, etc.), lighting, heating, refrigerating, cooling, and other purposes. The substantial energy consumption in the manufacturing industries results in varying energy intensity levels and trends across sectors. In general terms, the energy intensity can be reduced through the implementation of energy-saving measures or by installing energy-efficient technologies.

A substantial share of previous research has been conducted to investigate the key determinants of energy intensity reduction. Most of this research analysis has been conducted in Asian regions, especially in China. Technological progress and structural changes have been identified as the main factors contributing most to the decline in energy intensity [14–16]. Lin et al. [14] stated that the effect of technological progress was the primary contributor to the decline in energy intensity, with a cumulative reduction of 72.32% observed in China's metallurgical industry.

The literature also discusses the influence of other variables on energy intensity, such as the cost of materials or products, technology diffusion, R&D activities, innovation capacity, and waste recycling [17–22]. Fisher-Vanden et al. [17] concluded that rising energy costs significantly reduce energy intensity based on the analysis of China's most energy-intensive large- and medium-sized enterprises from 1999 to 2004. Bhadbhade et al. [18] demonstrated that higher energy prices increase energy efficiency by 12%, while for low prices, it dropped to 9% in the Swiss metal sector. Huang et al. [19] stated that R&D activities performed by industrial enterprises can reduce energy intensity, and the main positive effect is from R&D activities.

Researchers have analysed the impact of economic globalisation on energy intensity [23,24]. Jin et al. [24] investigated how industries' participation in global value chains affects their energy intensity. The panel data of 56 industries in 42 countries from 2000 to 2014 were used for empirical tests. The results showed that promoting industries' global value chain position has significantly reduced their energy intensity. Moreover, for developed countries, the deepening of the global value chain's participation degree has been found to reduce energy intensity in manufacturing industries. For developing countries, the opposite effect has been observed, with an increase in energy intensity.

Digitalisation is driving a new technological revolution and industrial transformation; therefore, it has attracted scientific attention to the effects of digitalisation on the environment concerning energy intensity [25–27]. Based on the STIRPAT modelling approach and regression techniques, Liu et al. [25] concluded that the use of industrial robots reduced the energy intensity of Chinese industry sectors. Huang et al. [26] also concluded that the development of the digital economy reduces energy intensity in China. Matthess et al. [27] investigated the relationship between digital technologies and manufacturing energy intensity using panel data covering 15 European countries and 8 manufacturing sectors or clusters from 2012 to 2020. The results showed mixed effects on the energy intensity of manufacturing sectors: an increase in robot density is associated with a decrease in energy intensity, but digital capital intensity is positively associated with energy intensity. According to the researchers, this may indicate the differing effects of varying types of digital capital. The study's results justify the importance of further research on the impact of digitalisation on energy intensity.

Much empirical research has been conducted on the observed decline in energy intensity in developed and developing countries. The majority of this research has focused on the factors driving this decline, with relatively little attention being paid to energy intensity projections for the long-term perspective. In many cases, the forecast of energy intensities is based on a time series analysis. Sánchez-Durán et al. [28] state that only time series trends are relevant for long-term forecasting. Therefore, linear regression is one of the most frequently employed forecasting techniques. To determine the long-term energy demand in Spain, the authors applied time series methods to prepare long-term forecasts for each component. In energy intensity forecasting, the linear regression method was used by [28]. Rehman et al. [29] used the linear forecasting function for energy intensity projections and its integration into the Long-range Energy Alternate Planning (LEAP) model for energy demand forecasting in Pakistan. Chen et al. [30] employed a similar approach, applying a hybrid LEAP model for energy demand forecasting in Hunan province, China. The average growth method was used to determine the variations in energy intensity. According to Eder et al. [31], an exponential trend can best describe the time series of energy intensity across the majority of global regions. The authors concluded that the exponent provides an accurate representation of the time series of energy intensity over the entire period from 1980 to 2015 for developed countries.

To the best of our knowledge, an energy intensity analysis and its forecasting have not been performed for Lithuanian industries. Therefore, we aim to address this research gap. Over the past two decades, Lithuania has made a significant advancement towards the most advanced countries in terms of the energy intensity indicator. The indicator has decreased in most industries and EU countries, although there is a notable disparity in the rate of energy intensity reduction. The Lithuanian industry is distinguished by a more rapid rate of decrease in energy intensity compared to the most economically developed EU Member States (MS) (see Section 4). It is also noteworthy that Lithuania achieved this in parallel with significant economic development, which resulted in increased final energy consumption. This indicates a high rate of intake of energy-efficient technologies. These circumstances make Lithuania a prime example of a "catching up" economy and necessitate further research in this field.

3. Methodology

The EUROSTAT database was used to collect relevant data for the EU MS at the level of the manufacturing sector. Specifically, final energy consumption (GWh) and gross value added in chain-linked volume (2015, EUR million) were collected for the period from 2000 to 2021. The forecast period begins with the first year of missing data and extends to 2050, aligning with the EU's goal of achieving net-zero GHG emissions by that year.

The research question was addressed in three phases of analysis. In the pre-research phase, preparatory work was carried out. This included the selection of relevant EU MS and manufacturing industries based on analysis of economic and energy indicators, the preparation of methodology for research, etc. In the research phase, the historical values of energy intensity in manufacturing industries were analysed, forecasting models were chosen, and long-term forecasts were prepared. The implications phase included forecasts of final energy consumption for key Lithuanian manufacturing industries.

The criterion of "the highest share of final energy consumed" was employed to identify individual manufacturing industries in Lithuania whose energy intensities are relevant for analysis (Figure 1). Based on these data, energy-intensive manufacturing industries were identified for analysis. As Figure 1 illustrates, there has been a modest shift in the structure of final energy consumption in Lithuanian manufacturing industries from 2000 to 2021. The chemical and petrochemical, non-metallic minerals, and food, beverages, and tobacco industries were the leading energy and fuel consumers, accounting for approximately 60% from 2000 to 2021. The chemicals industry experienced the most pronounced rise in energy consumption share from 22.1% to 34.9%.

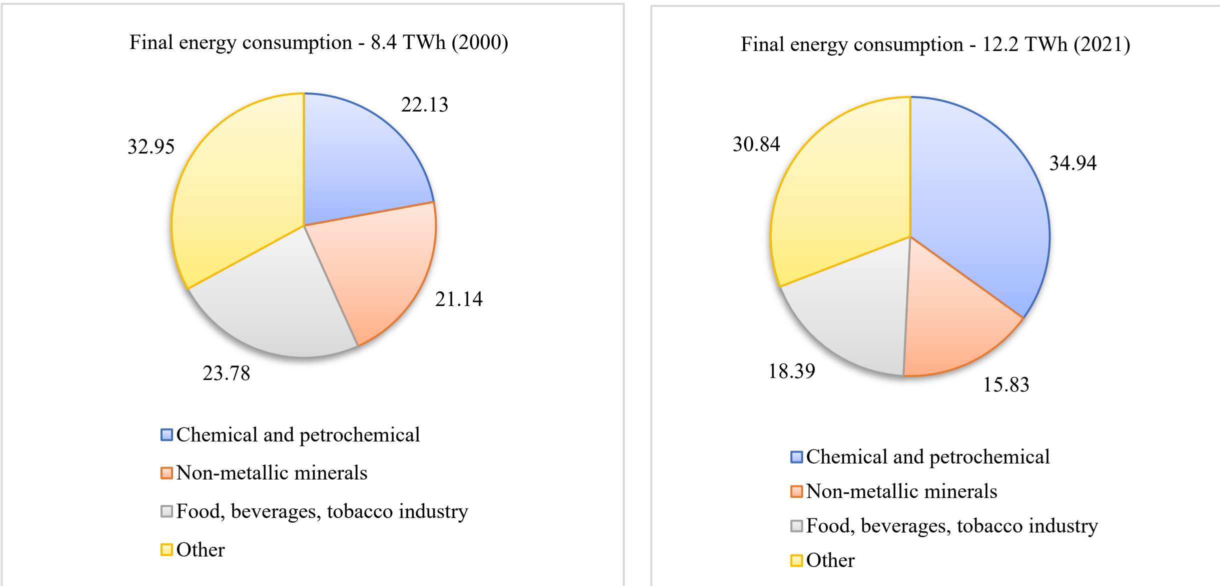


Figure 1. Structure of final energy consumption in Lithuanian manufacturing industries in 2000 and 2021, % [32].

The next step involved the identification and selection of the 10 EU MS as the basis for the energy intensity benchmarking and forecasting. The selection was based on the following criteria: manufacturing industries, on average, consumed the most final energy (in TWh), created value added (in billion EUR) during the period from 2000 to 2021, and joined the EU before 2004 (Figure 2). To provide a clear illustration of average energy intensities, a thematic map of EU countries (Figure 3) has been included.

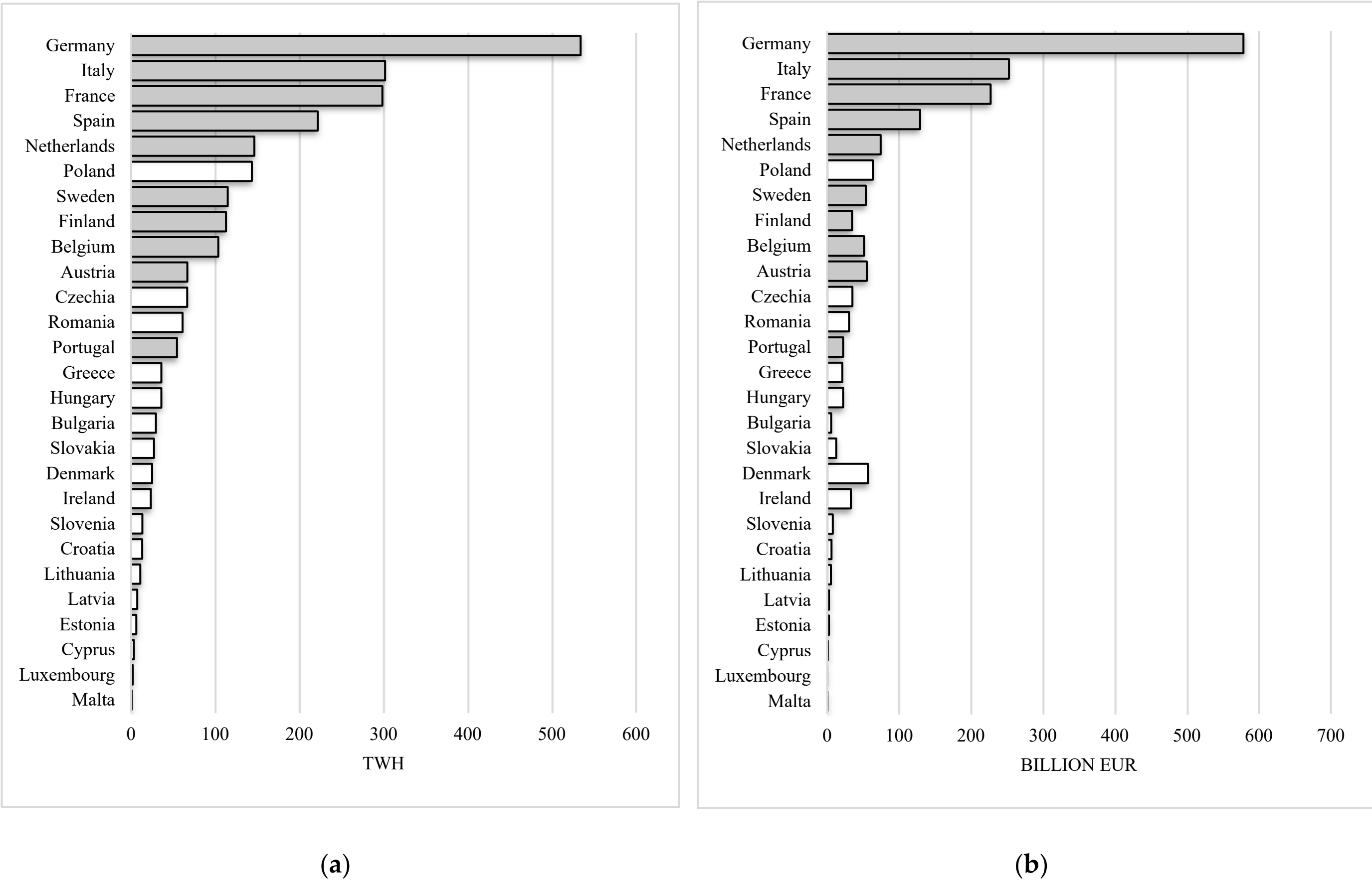


Figure 2. EU MS in accordance with the average energy and economic indicators in manufacturing industries during 2000–2021 [32]. (**a**) Energy and fuel consumption; (**b**) gross value added. The grey colour denotes the countries that meet the above criteria and are suitable for analysis.

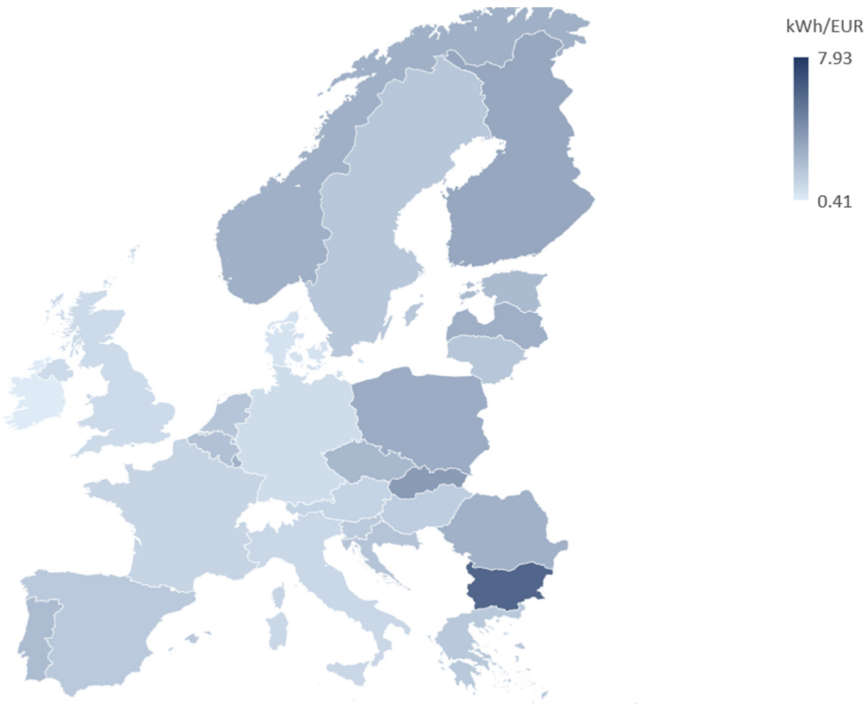


Figure 3. Thematic map of average energy intensity in EU, 2000–2021 (created by authors based on [32]).

As illustrated in Figure 2, selected countries are mature and advanced EU MS. The manufacturing industries of these countries, on average, consumed 79% of energy and fuel and created 87% of gross value added from 2000 to 2021. The selection of large, economically advanced, and stable countries for the study ensures that random and short-term inaccuracies can be avoided, as the development trends of these countries can be treated as reliable and established. This approach was employed to identify the 10 EU MS (Top10) in specific manufacturing industries (Table 1).

Table 1. Selected Top10 EU MS in manufacturing industries (performed by authors).

Manufacturing Industry	EU MS
Chemical and petrochemical industry	Germany, the Netherlands, France, Italy, Spain, Belgium, Austria, Finland, Sweden, and Portugal
Non-metallic mineral industry	Germany, Italy, Spain, France, Portugal, Belgium, Greece, Austria, the Netherlands, and Denmark
Food, beverages, and tobacco industry	France, Germany, Italy, Spain, the Netherlands, Belgium, Denmark, Austria, Ireland, and Greece
Remaining manufacturing industries	Germany, Italy, France, Sweden, Finland, Spain, Austria, Belgium, the Netherlands, and Portugal

Next, the historical energy intensity in manufacturing industries of EU MS was calculated by Equation (1):

$$I_{MI;MS;Y} = \frac{E_{MI;MS;Y}}{VA_{MI;MS;Y}} \times \frac{VA_{total;MS;Y}}{GDP_{MS;Y}} \quad (1)$$

where $I_{MI;MS;Y}$ is an energy intensity in manufacturing industry MI of EU MS in year Y, kWh/EUR; $E_{MI;MS;Y}$ is a final energy consumption in manufacturing industry MI of EU MS in year Y, kWh; $VA_{MI;MS;Y}$ is gross value added in manufacturing industry MI of EU MS in year Y, EUR; $VA_{total;MS;Y}$ is total value added in EU MS in year Y, EUR; and $GDP_{MS;Y}$ is gross domestic product in EU MS in year Y, EUR.

A weighted average method was applied to calculate the historical cumulative energy intensity in the manufacturing industries of selected 10 EU MS (referred to herein as energy intensity of Top10 countries):

$$\overline{I}_{MI;Top10;Y} = \frac{\sum_{Top10=1}^{10} (I_{MI;MS;Y} \times E_{MI;MS;Y})}{\sum_{Top10=1}^{10} E_{MI;MS;Y}} \quad (2)$$

where $\underline{I}_{MI;Top10;Y}$ is a weighted average energy intensity in the manufacturing industry MI of Top10 EU MS in year Y, kWh/EUR.

Four statistical functions were applied to construct energy intensity forecasting models for manufacturing industries in Top10 EU MS. They are represented by Equations (3)–(6):

$$\text{Linear trend} \quad \underline{I}_{MI;Top10;Y} = a \times Y + b \quad (3)$$

$$\text{Exponential trend} \quad \underline{I}_{MI;Top10;Y} = a \times e^{b \times Y} \quad (4)$$

$$\text{Logarithmic trend} \quad \underline{I}_{MI;Top10;Y} = a \times lnY + b \quad (5)$$

$$\text{Moving average} \quad \underline{I}_{MI;Top10;Y} = \frac{I_{MI;MS;Y-1} + I_{MI;MS;Y-2} + I_{MI;MS;Y-3}}{3} \quad (6)$$

Coefficients *a* and *b* were calculated and tested considering the methodology presented by Boguslauskas [33]. In the study, MS Excel was used to derive equations and coefficient of determination (R^2, varying from 0 to 1), which describes the strength of the relationship. The trend is most reliable when its R^2 value is at or near 1. High R^2 values demonstrate an appropriate alignment between the trend and the empirical data. Forecasting models were used to prepare long-term forecasts of energy intensity.

The mean absolute percentage error (MAPE) indicator was applied to measure the accuracy of forecasts. It was calculated by Equation (7):

$$MAPE = \frac{1}{n} \times \sum_{Y=1}^{n} \left| \frac{I_{A;Y} - I_{F;Y}}{I_{A;Y}} \right| \tag{7}$$

where n is number of years; Y is a specific year; $I_{A;Y}$ is actual energy intensity in year Y, kWh/EUR; and $I_{F;Y}$ is forecasted energy intensity in year Y, kWh/EUR. Forecast accuracy was assessed based on Table 2.

Table 2. Forecast accuracy assessment [34].

MAPE Value	Accuracy of Forecast
Less than 10%	Highly accurate forecast
11–20%	Good forecast
21–50%	Reasonable forecast
More than 50%	Inaccurate forecast

The academic literature claims that Lithuania is a "catching-up economy" in the context of advanced EU MS [35], which is characterised by the pursuit of average economic development levels of the EU in recent decades. In line with Bagheri et al. [35], a key assumption was made in the study that energy intensity in identified Lithuanian manufacturing industries will follow the trend of Top10 EU MS in the future and approach its value in the long term. Another study conducted to investigate the developments in energy intensity among 19 European countries [36] observed a negative trend over the 20-year period. A significant and rather strong negative relationship was found between the GDP growth rate and the energy intensity. In particular, it was demonstrated that the energy intensity decreases with the increase in the GDP growth rate, even if the increasing energy and environmental taxes, energy prices, and inertia are taken into account separately. Based on the above observations, a key assumption was formulated that energy intensities in Lithuanian manufacturing industries will decrease and match the level of the most developed Top10 EU MS over a long-term period, as shown by Equation (8):

$$I_{MI;LTU;Y} = \frac{\underline{I}_{MI;Top10;2050} - I_{MI;LTU;2021}}{FH} + I_{MI;LTU;Y-1} \tag{8}$$

where $I_{MI;LTU;Y}$ is energy intensity in manufacturing industry *MI* of Lithuania in forecasting year Y, kWh/EUR; $\underline{I}_{MI;Top10;2050}$ is a weighted average energy intensity in manufacturing industry *MI* of Top10 EU MS in the year *2050*, kWh/EUR; $I_{MI;LTU;2021}$ is energy intensity in the manufacturing industry *MI* of Lithuania in the year *2021*; *FH* is a forecasting horizon, 29 years; and $I_{MI;LTU;Y-1}$ is energy intensity in the manufacturing industry *MI* of Lithuania in forecasting year $Y - 1$; kWh/EUR.

In case the historical values in energy intensity of the Lithuanian manufacturing industries overcome the ones achieved by the Top10 EU MS, we did not set a requirement to increase the energy intensity. This assumption is relevant for the remaining manufacturing industries, which include dome energy-intensive industries in EU-27, which are absent in Lithuania.

In the implication phase, we aim to calculate final energy and fuel demand by applying energy intensity forecasts prepared for the specified Lithuanian manufacturing industries by Equation (9):

$$FEC_{MI;LT;Y} = I_{MI;LT;Y} \times VA_{MI;LT;Y-1} \times (1 + R_{VA;LT}) \quad (9)$$

where $FEC_{MI;LT;Y}$ is energy and fuel consumption in the Lithuanian manufacturing industry MI in year Y, GWh; $VA_{MI;LT;Y-1}$ is the value added created by the Lithuanian manufacturing industry MI in year $Y-1$, EUR; and $R_{VA;LT}$ is the expected value-added growth rate in Lithuania, %.

Economic growth will be sustained to the extent that is achievable in terms of a climate-neutral economy. The Lithuanian Economic Development Scenario [37] expects that the Lithuanian economy (in terms of VA) will grow by 2.9% annually, while the EU economy will grow by 1.7%. In our calculations, we assume that such growth rates will be maintained until 2050. They represent optimistic and pessimistic scenarios; in between, a realistic scenario was assumed with 2.5% annual growth until 2050.

The utilisation of historical data to predict future outcomes will inevitably be subject to certain limitations, including the inability to predict crises, such as wars or supply chain disruptions. In the case of recent data that are either above or below the prevailing trend, it is always challenging to decide whether these are merely short-term fluctuations or a long-term structural turning point. Furthermore, the limitations of the methodology pertain to the assumptions made about the possible future development of Lithuanian industry and the averaging of energy consumption and intensity data from EU countries. The methodology is not applicable to non-EU countries, as they may exhibit substantially different economic development and trends due to differences in political, economic, and environmental objectives and employed policies.

The research has additional limitations shaping the directions for future research. As the constructed models are single regression models, in which time is selected as an informative factor in energy intensity forecasting, they are limited to explaining correlations between energy intensity and its forming and level-changing factors. To address this, it is necessary to pay greater attention to understanding the factors that form and change the level of efficiency in energy consumption and their reflection in the forecasting models. Therefore, the multiple regression trendlines should be tailored. We have analysed the long-term dynamics in the efficiency of energy consumption by breaking it down by industry sector. Future research should disaggregate it by fuel as well as construct models for all sectors of the economy and reveal the environmental impacts of improvements in energy intensity.

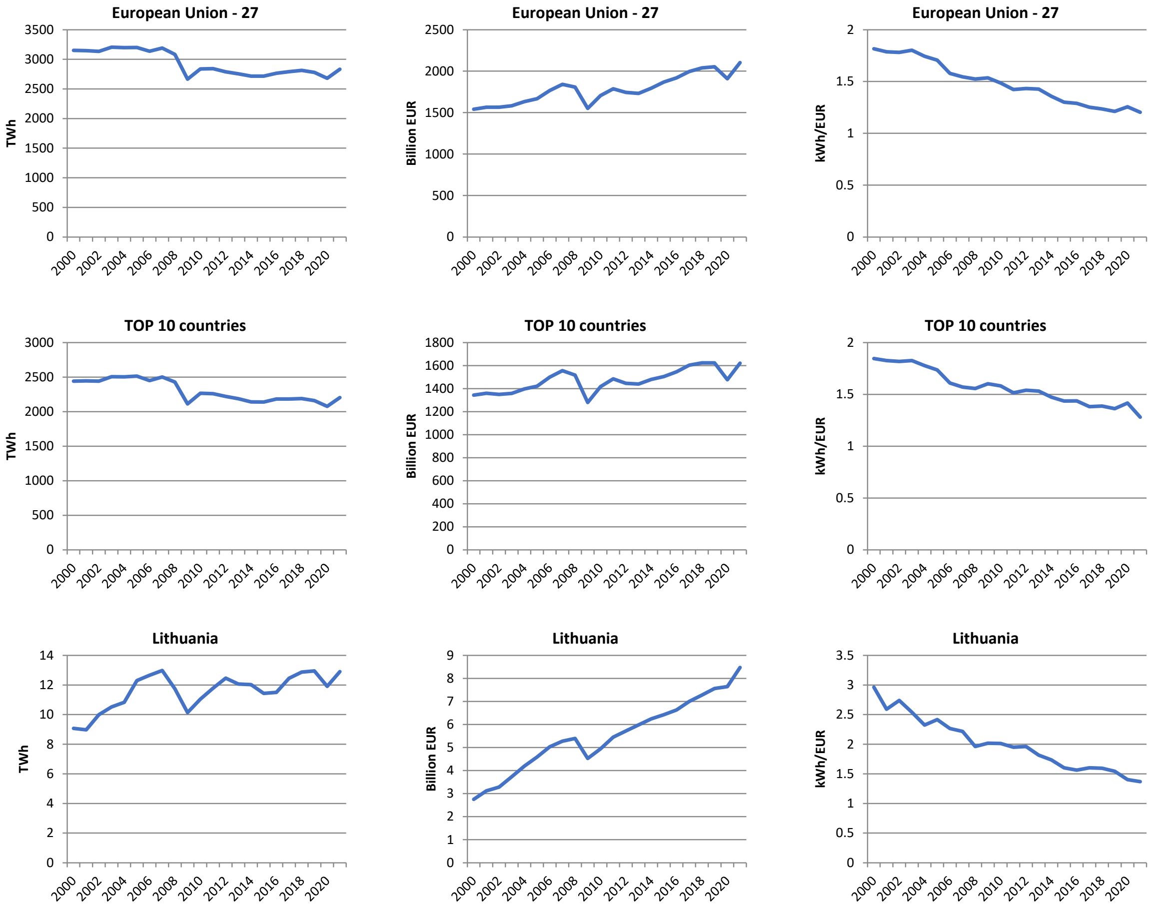
4. Results

4.1. Historical Energy and Fuel Consumption, Value Added, and Energy Intensity in the Manufacturing Industry

This chapter presents a comparison of the long-term historical trends in final energy consumption, value added, and the calculated energy intensity of the manufacturing industries in the EU-27, Top10 EU MS, and Lithuania.

A downward trend in final energy consumption in the EU-27 manufacturing industry is evident between the years 2000 and 2021 (see Figure 4). The overall decrease was 11%, from 3150 TWh in 2000 to 2830 TWh in 2021. The plunge in energy consumption during the economic crisis in 2008 and the pandemic in 2020 is particularly evident. Over the 21 years, the value added of the EU-27 manufacturing industry increased by 36% (with brief variations) from 1541 to 2104 billion EUR. Observed data trends resulted in a notable decline in energy intensity, which decreased from 1.82 kWh/EUR in 2000 to 1.2 kWh/EUR in 2021. Upon analysis of indicators in Lithuania, it becomes evident that there are some distinctions with EU-27 data. Over the 20-year period, final energy consumption increased significantly from 9.1 to 12.9 TWh, corresponding with a substantial rise in GDP. The most pronounced increase in fuel consumption was observed between 2000 and 2007, when it peaked at

13 TWh. Thereafter, the annual values have remained stable, with short-term fluctuations. Between 2000 and 2021, the manufacturing industry experienced a threefold increase in value added, from 2.8 to 8.5 billion EUR. Consequently, the energy intensity of Lithuanian industry has decreased continuously from 2.96 kWh/EUR in 2000 to 1.37 kWh/EUR in 2021. The weighted average trends for energy intensity, final energy consumption, and value added for Top10 EU MS have been added for comparison.



(**a**) (**b**) (**c**)

Figure 4. Dynamics of energy intensity and its constituents in the total manufacturing industry in EU-27, Top10 EU MS, and Lithuania from 2000 to 2021 (figures created by authors based on [38,39]). (**a**) Fuel and energy consumption, TWh; (**b**) value added, chain-linked volumes (2015), billion EUR; (**c**) calculated energy intensity, kWh/EUR.

Figure 5 compares the energy intensity of Lithuania's manufacturing industry with a sample of highly developed EU countries having the highest final energy consumption, as well as the EU-27 (average). The illustration demonstrates the advancement of Lithuania's energy intensity value relative to other countries.

In 2000, Lithuania exhibited a higher energy intensity trend than that of virtually all the advanced EU countries. Over the past two decades, Lithuania has demonstrated a consistent and remarkable reduction in energy intensity. The rate of decline has been more pronounced than in the majority of the countries included in the comparison. In 2021, it was approaching the weighted average of the Top10 EU MS, with an industrial intensity value that surpassed countries such as Belgium, Sweden, Spain, and the Netherlands.

To provide a more comprehensive and detailed overview of the indicators analysed, we have identified and distinguished the most energy-intensive industrial sectors within the Lithuanian manufacturing industry.

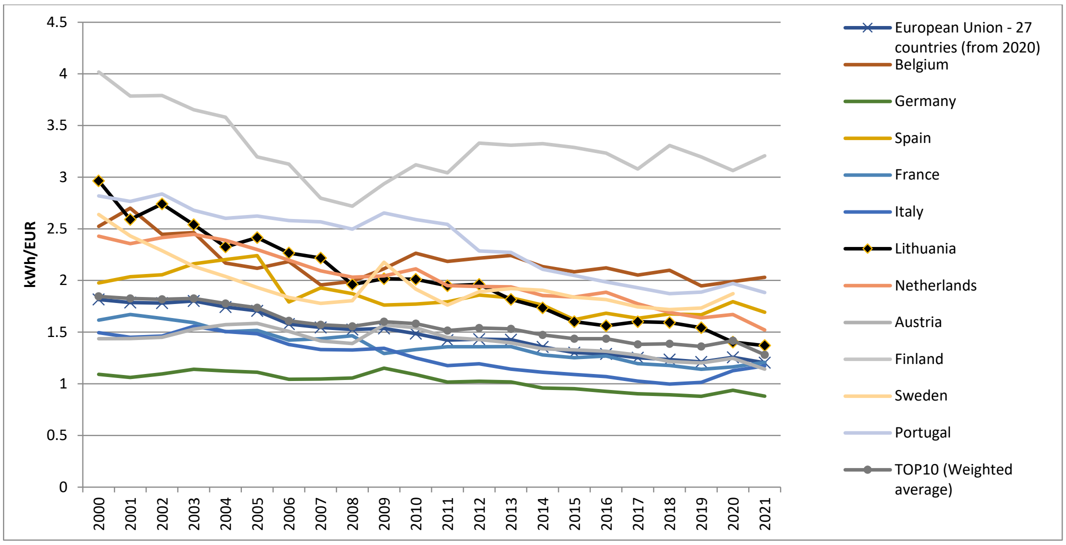


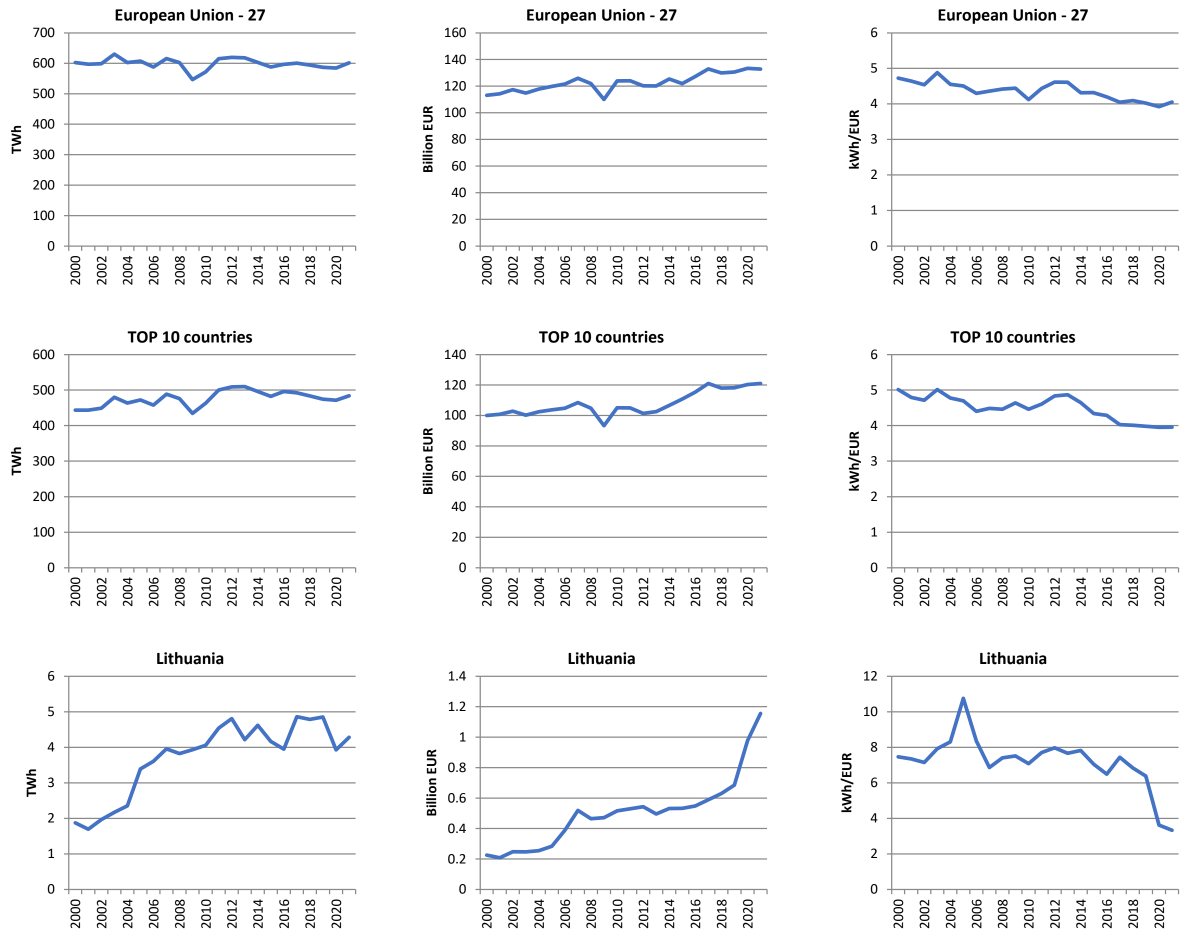
Figure 5. Dynamics of energy intensity in manufacturing industry of Top10 EU MS and Lithuania from 2000 to 2021, kWh/EUR (figure compiled by authors based on [38,39]).

4.2. Chemical and Petrochemical Industry

The chemical industry is among the most energy-intensive manufacturing industries. Figures 6 and 7 present a comparison of the long-term trends in final energy consumption, sectoral value added, and estimated energy intensity of the chemical and petrochemical industry in the EU-27, Top10 EU MS, and Lithuania.

The indicator patterns vary by country. While fuel consumption has remained relatively constant in the EU-27 and Top10 EU MS since 2000, Lithuania has experienced growth in this area. At the same time, value added has experienced limited growth at the EU level. This has resulted in a slight but steady reduction in energy intensity. The indicators of the Lithuanian chemical sector stand out from the EU-27 context, especially in the most recent years. Following a period of moderate growth, the value added generated by the Lithuanian chemical industry experienced a sudden surge after 2020. Over a long period, the energy intensity indicator was at least 1.5 times higher than in the advanced EU economies. However, a sudden decline was observed, as illustrated in Figure 7. Further clarification is therefore necessary concerning this indicator.

The chemical industry is a significant contributor to the Lithuanian economy. It is dominated by fertiliser production facilities, with a concentration of activity in a few large enterprises. The industry manufactures a range of products, including ammonia, sulphuric acid, ammonium nitrate, urea, diammonium phosphate, and others. From 2000 to 2021, the chemicals industry consumed an average of 32% of the final energy in the manufacturing industry (the primary fuel used is natural gas). Ammonia (NH_3) is a crucial product in Lithuania's chemical industry, as it is used to produce fertilisers. The production of NH_3 is subject to annual fluctuations, which are influenced by a variety of factors, including natural gas prices, fertiliser market conditions, and technical aspects. In general, the price of the chemical commodities (ammonia) is closely correlated to the price of the feedstocks (natural gas). For instance, the production of ammonia was temporarily halted in 2022 due to the extremely high natural gas prices. The plant reported that 995 kt of NH_3 were produced in 2020, 869 kt in 2021, and 522 kt in 2022. Despite this, the sales revenue of the NH_3 producer increased from 374 million EUR in 2020 to 937 million EUR in 2022 [42]. This could be explained by the fact that the price of NH_3, the main source of nitrogen fertiliser, increased sixfold on global markets between mid-2020 and mid-2022 [43,44]. The high price of fertiliser remained throughout 2022 but has since shown a downward trend in 2023 [45]. The global ammonia market is highly interconnected, with the Lithuanian market prices closely following international ammonia prices.



(**a**) (**b**) (**c**)

Figure 6. Dynamics of energy intensity and its constituents in the chemicals industry in the EU-27, Top10 EU MS, and Lithuania from 2000 to 2021 (figures created by authors based on [40,41]). (**a**) Final energy consumption, TWh; (**b**) value added, chain-linked volumes (2015), billion EUR; (**c**) calculated energy intensity, kWh/EUR.

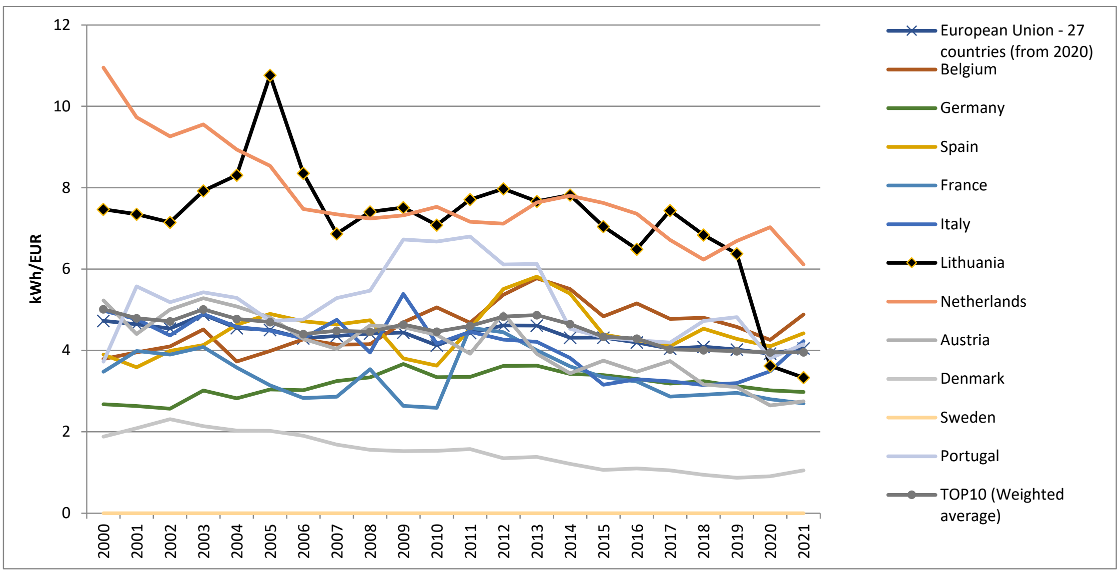


Figure 7. Dynamics of energy intensity in the chemicals industry of Top10 EU MS and Lithuania from 2000 to 2021, kWh/EUR (Figure compiled by authors based on [40,41]).

As a result, the sharp decline in energy intensity observed from 2020 to 2021 is predominantly attributable to the high value added. Technological breakthroughs have not had a significant impact in this regard, as fertiliser industrial complexes are constrained in their ability to promptly improve energy efficiency due to the extensive heat demand for high-temperature processes.

4.3. Non-Metallic Minerals Industry

The non-metallic minerals industry represents another significant sector in Lithuania in terms of final energy consumption. In the EU-27 and Top10 EU MS, there is a downward trend in energy consumption and value added (Figure 8). This decline was most pronounced during the global financial crisis of 2008–2009. However, the Lithuanian case demonstrates different patterns. While fuel consumption is relatively stable over time, it exhibits considerable annual fluctuations, while value added is on the rise. This resulted in a significant reduction in energy intensity in Lithuania, from 13.3 kWh/EUR in 2000 to 7.6 kWh/EUR in 2010 and to 5.74 kWh/EUR in 2021. Given the accelerated rate of decline, the energy intensity value nearly reached the value of the weighted average of Top10 EU MS in 2021 (Figure 9).

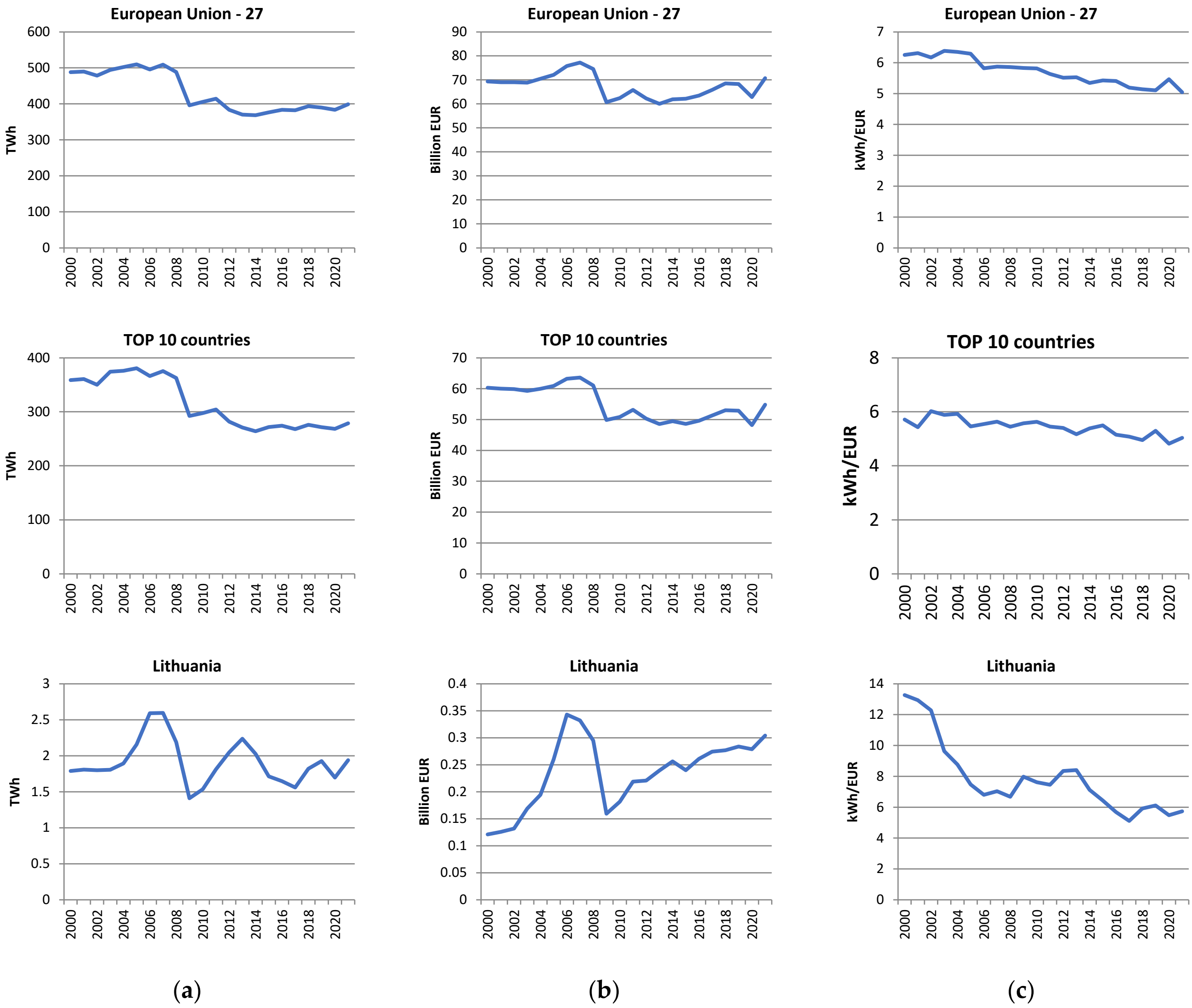


Figure 8. Dynamics of energy intensity and its constituents in the non-metallic minerals industry in the EU-27, Top10 EU MS, and Lithuania from 2000 to 2021 (figures created by authors based on [46,47]). (**a**) Final energy consumption, TWh; (**b**) value added, chain-linked volumes (2015), billion EUR; (**c**) calculated energy intensity, kWh/EUR.

The cement manufacturing accounts for the largest share of final energy consumption within the Lithuanian non-metallic minerals industry. In 2014, the Lithuanian cement production company, known as AB Akmenės cementas, underwent a comprehensive modernisation process that involved the installation of a new dry clinker production line. The new technological line has resulted in a significant decline in fuel consumption per unit of clinker production. This is evidenced by the energy intensity values of this industry after 2014 (Figure 9). In general, the Lithuanian cement plant has implemented well-established energy efficiency solutions that have reduced fuel consumption and emissions. In theory, future steps for efficiency improvement and decarbonisation could be the implementation of innovative technologies, such as the electrification of cement kilns or the use of carbon capture and storage. However, such developments would necessitate significant further investments, which are not envisaged for the medium term.

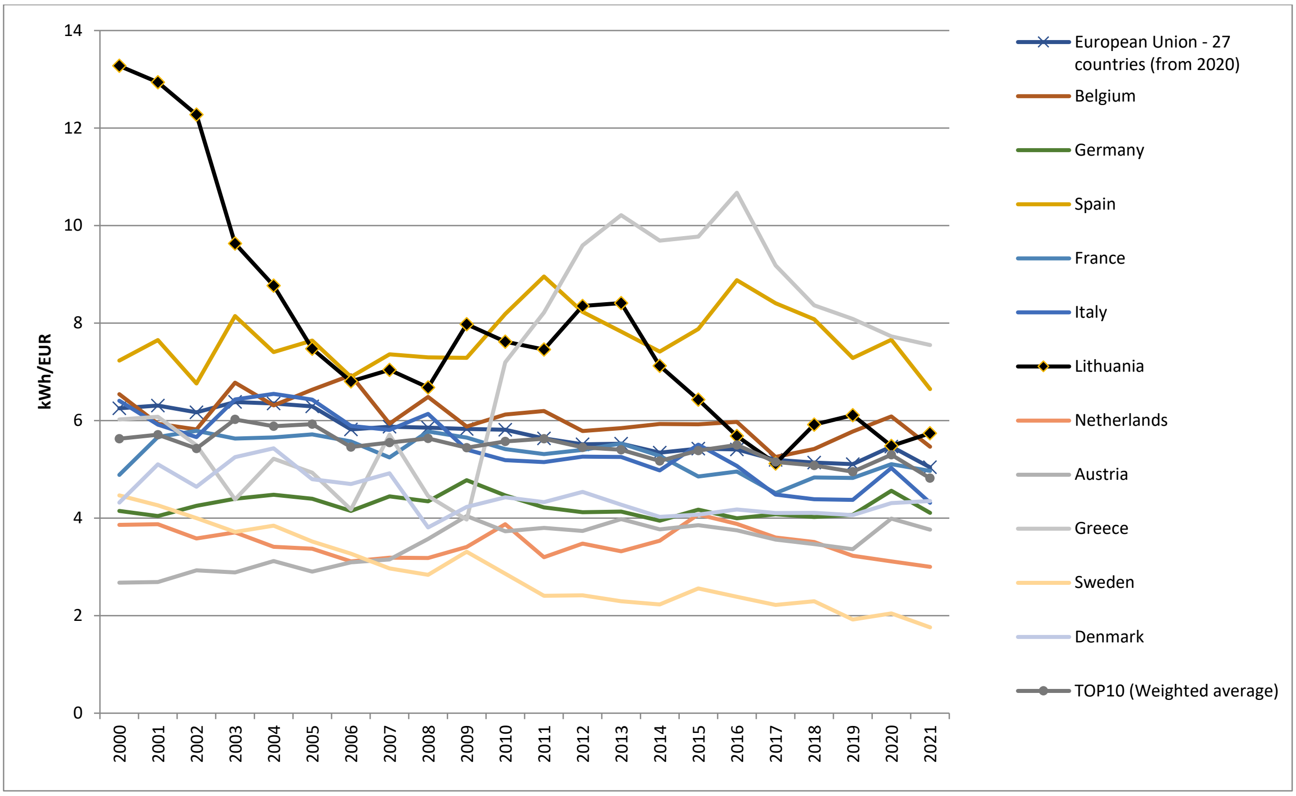
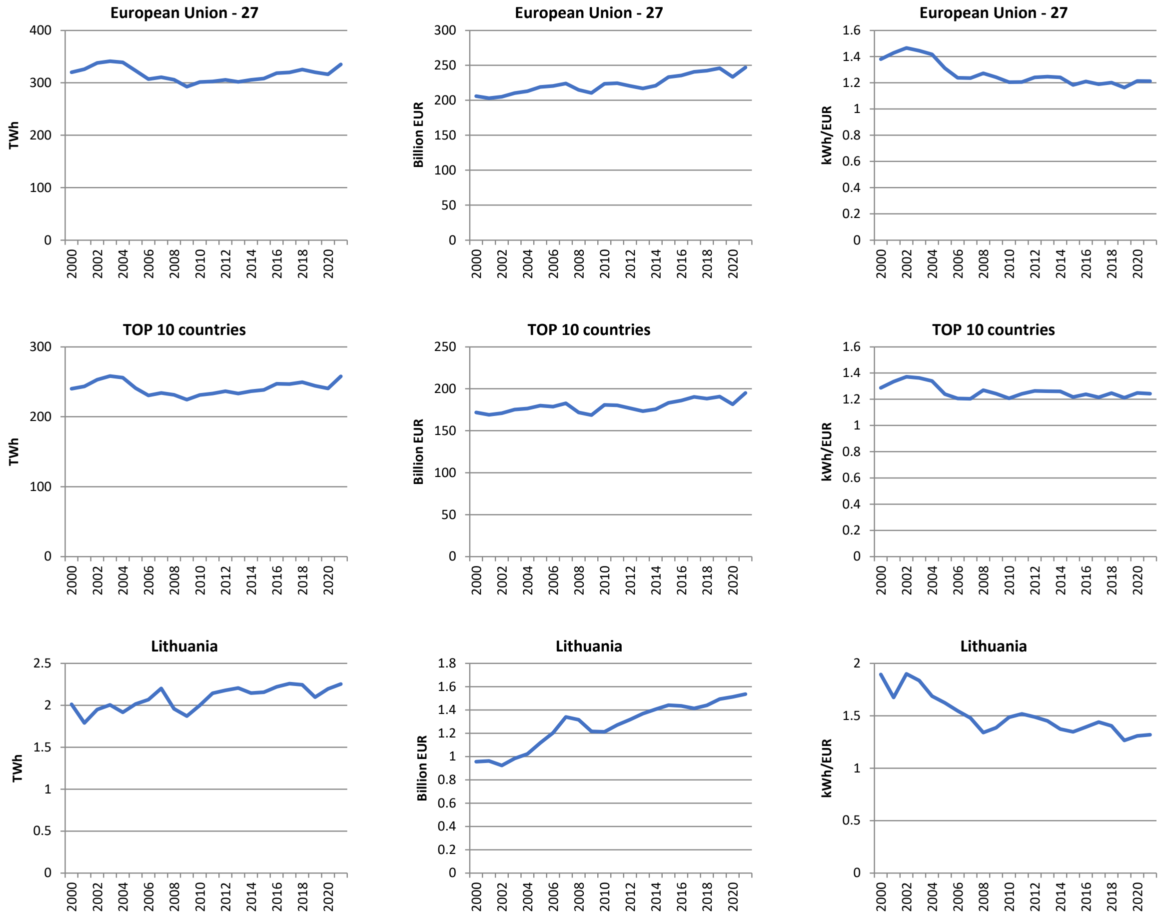


Figure 9. Dynamics of energy intensity in the non-metallic minerals industry of Top10 EU MS and Lithuania from 2000 to 2021, kWh/EUR (figure compiled by authors based on [46,47]).

4.4. Food and Beverage Industry

The food and beverages industry is one of the few economic sectors analysed that has demonstrated a slight increase in final energy consumption at the EU-27 level as well as in Lithuania from 2000 to 2021. Furthermore, value added also identifies an upward trend, particularly in Lithuania, with a 60% increase from 0.96 billion EUR to 1.54 billion EUR (Figure 10). The aforementioned developments have resulted in a relatively constant EU-27 average energy intensity value, while the Lithuanian one has seen a significant reduction.

As illustrated in Figure 11, the intensity values of the food industry are in a declining trend and approaching the weighted average of Top10 EU MS. However, Lithuania's values of this indicator are still in the upper part of the range. In recent years, energy intensity values have exceeded only those of Belgium, the Netherlands, and Finland (from the Top10 EU MS set).



(**a**) (**b**) (**c**)

Figure 10. Dynamics of energy intensity and its constituents in the food, beverages, and tobacco industry in the EU-27, Top10 EU MS, and Lithuania from 2000 to 2021 (figures created by authors based on [48,49]). (**a**) Final energy consumption, TWh; (**b**) value added, chain-linked volumes (2015), billion EUR; (**c**) calculated energy intensity, kWh/EUR.

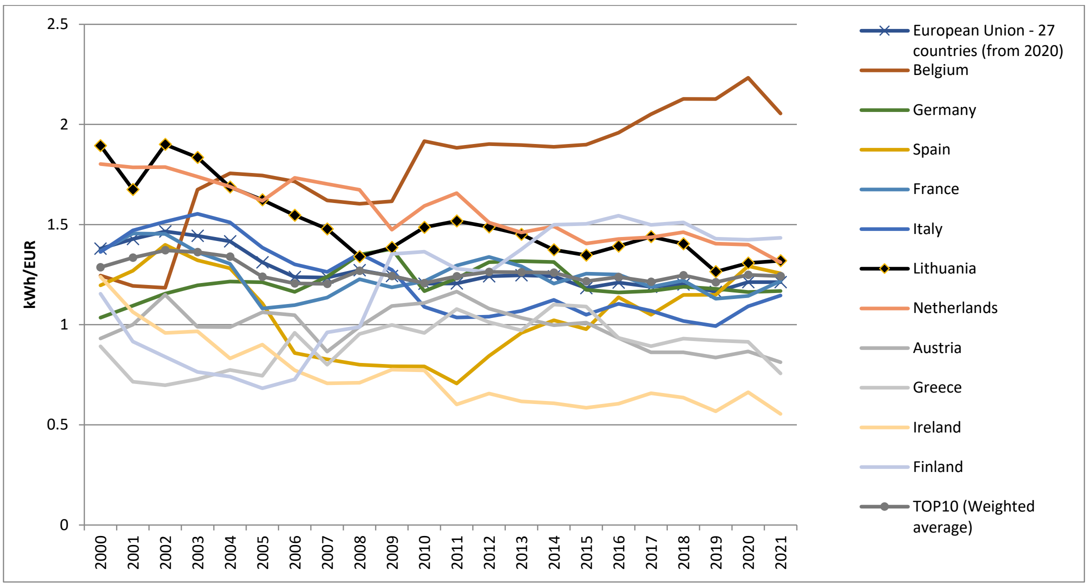


Figure 11. Dynamics of energy intensity in the food, beverages, and tobacco industry of Top10 EU MS and Lithuania from 2000 to 2021, kWh/EUR (figure compiled by authors based on [48,49]).

4.5. Remaining Industries

The remaining industries were aggregated within the framework of the analysis. Concerning Lithuania, it can be noted that the paper, wood, furniture, and textile industries consume the largest share of final energy. It should be noted that depending on the local economic structure, other manufacturing sectors are dominant in individual EU countries. At the EU-27 level, the final energy consumption of the remaining industries shows a downward trend, with a decrease of 13.8% between 2000 and 2021. In the case of Lithuania, fluctuations in fuel demand have been observed, but a growth trend since 2009 is evident. In the EU-27 countries, the value added is relatively constant, with annual fluctuations in the range of 1200 to 1400 billion EUR (Figure 12). In Lithuania, the growth trend is very pronounced, with value added more than quadrupling from 1.3 billion EUR in 2000 to 5.5 billion EUR in 2021. Consequently, Lithuania's energy intensity values have decreased significantly in comparison to those of the EU-27 and Top10 EU MS. However, the stabilisation of intensity values has become evident since 2014, with no further decrease observed, largely due to the rise in final energy consumption in the remaining Lithuanian industries. It should be noted that there is a significant deviation in the energy intensity indicators of Finland and Sweden, which is determined by the energy-intensive paper industry (Figure 13).

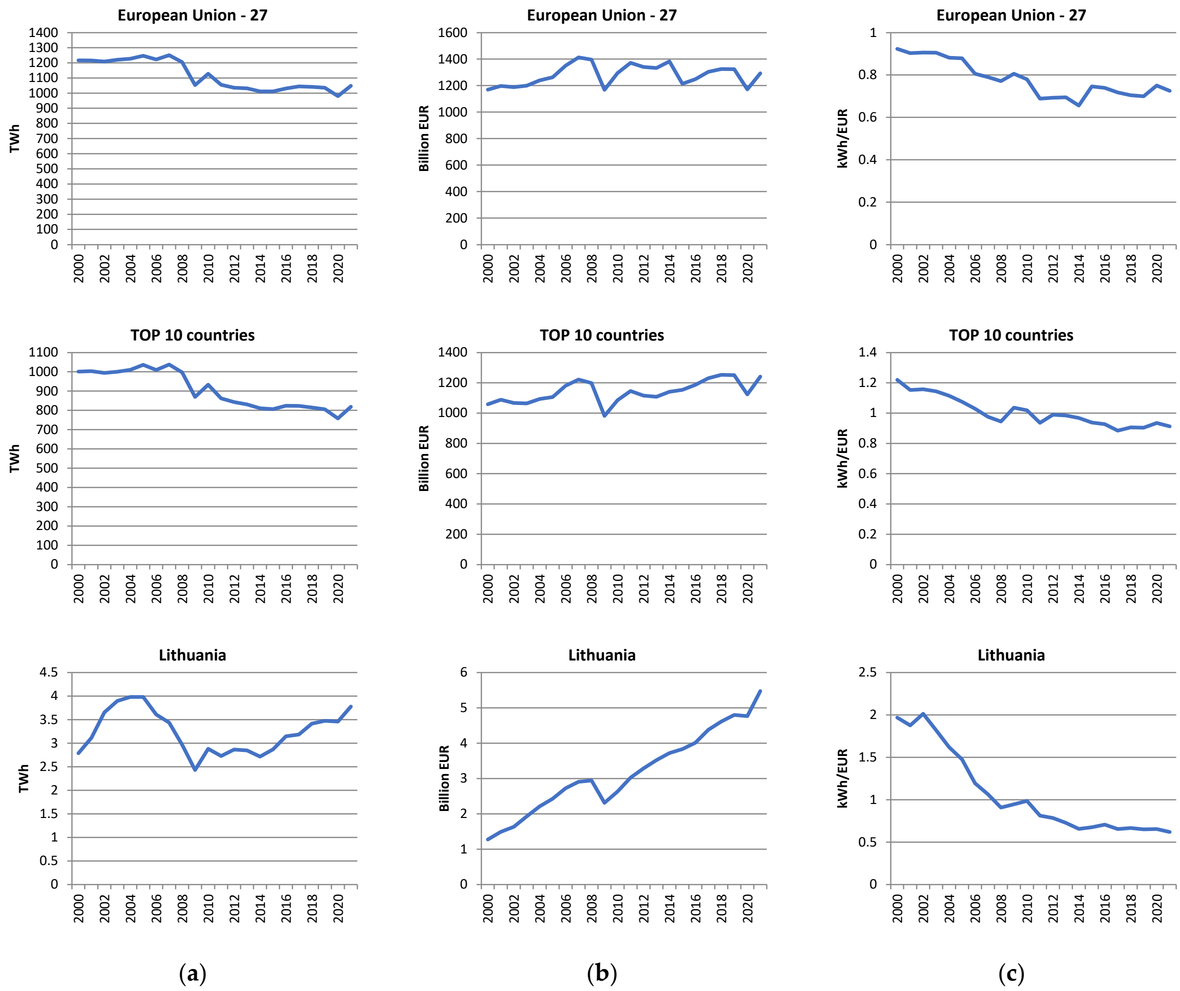


Figure 12. Dynamics of energy intensity and its constituents in the remaining industry in the EU-27, Top10 EU MS, and Lithuania from 2000 to 2021 (figures created by authors based on [50,51]). (**a**) Final energy consumption, TWh; (**b**) value added, chain-linked volumes (2015), billion EUR; (**c**) calculated energy intensity, kWh/EUR.

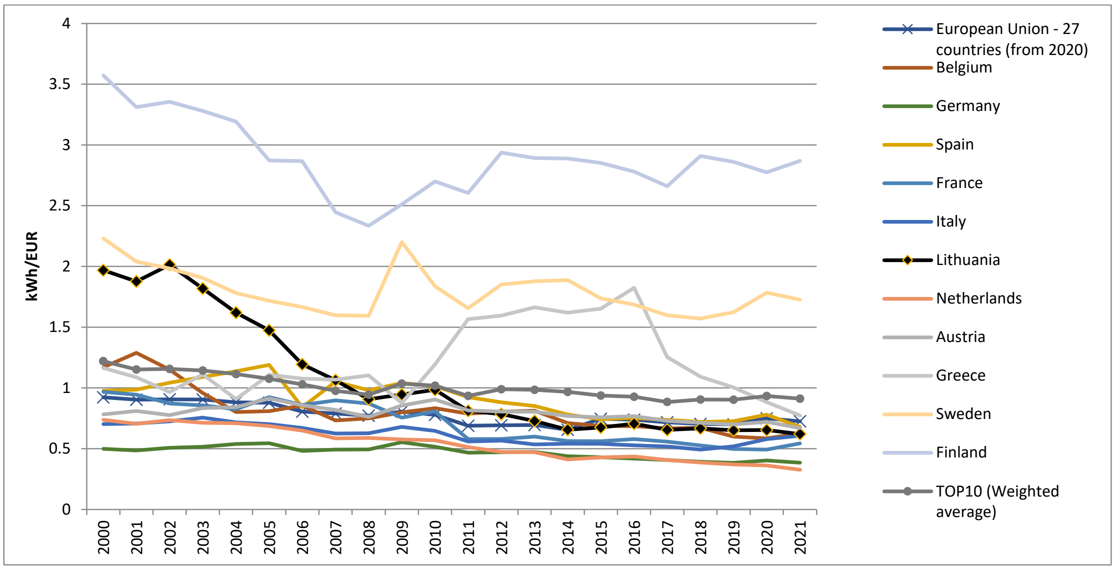


Figure 13. Dynamics of energy intensity in the remaining industries of Top10 EU MS and Lithuania from 2000 to 2021, kWh/EUR (figure compiled by authors based on [50,51]).

4.6. Summary of Historical Data Analysis

The historical analysis of final energy consumption per unit of value added demonstrates a notable decline across most European countries, including Lithuania. As evidenced by the data presented above, the economic crisis of 2008 or the pandemic has caused noticeable short-term fluctuations. However, these events have not influenced the long-term trends in final energy consumption, value added, and energy intensity. As long as external shocks in the economy do not alter the direction for longer periods, they do not impact our forecast and do not require to be specifically reflected in the methodology.

The energy intensity indicator has decreased in all industries considered from 2000 to 2021, both individually in Lithuania and as an aggregated EU-27 or Top10 EU MS indicator. Even so, there is a notable disparity in the rate of energy intensity reduction. The Lithuanian industry is distinguished by a more rapid rate of decrease in energy intensity compared to the most economically developed Top10 EU MS. Over the past two decades, Lithuania has made a major breakthrough among the most advanced countries. The primary factor contributing to the divergence between Lithuania and the top 10 countries in the 2000s was the disparity in their respective levels of economic and technological development. Lithuania's initial position was characterised by a low level of economic activity in comparison to EU countries, coupled with the utilisation of inefficient and outdated technologies inherited from its past.

Currently, the values of energy intensity in certain sectors of Lithuanian industry have reached levels of the most developed European countries. Nevertheless, in the most energy-intensive industries, such as chemicals, Lithuania's energy intensity indicators are still higher than those of the most economically advanced EU countries. In addition, analysing the dynamics of the indicator, a trend emerges indicating that the rate of improvement in energy intensity in Lithuania is decelerating, suggesting that maintaining the current pace of reduction will be increasingly challenging, if not unfeasible. It is also noteworthy that, in contrast to the EU-27 level, Lithuania's cumulative final energy consumption in industry increased over the period from 2000 to 2021. However, value added increased at a more rapid pace, and in some industries, this indicator was a factor a few times higher. Consequently, the results of the data analysis indicate that rapid economic development was the key variable enabling the impressive reductions in intensity. This suggests that there is unexploited potential for increasing the efficiency of energy consumption in Lithuanian industry. Efficiency issues require more attention from both industry representatives and policy makers. The implementation of efficiency measures needs to be accelerated by switching to innovative and less energy-consuming technologies. Such solutions are of vital importance from the perspective of reducing CO_2 emissions if the sector is to intensify its decarbonisation efforts.

4.7. Models and Forecasts of Energy Intensities in Manufacturing Industries

Table 3 presents a summary of the forecasting models, key accuracy estimates, the actual energy intensity value in 2021, and the forecasted value for 2050 in manufacturing industries of the Top10 EU MS.

As illustrated by Table 3, the energy intensity in the total manufacturing industry of Top10 EU MS is projected to decline in the future under cases of linear, logarithmic, and exponential trendlines but slightly increase if the moving average trendline is considered. The established trendlines are deemed reliable and fit the historical energy intensity data well, as indicated by the R^2 values, which range from 0.9446 to 0.9935. Forecasts of energy intensity are accurate, as MAPEs range from 2.2 to 3.0%. The linear and exponential forecasting models provide the most accurate results, with the lowest MAPE value of 2.2%. During the forecast horizon, energy intensity could be halved from 1.20 in 2021 to 0.58 (linear) or 0.78 (exponential) kWh/EUR in 2050, respectively.

Table 3. Forecasting models, their key accuracy estimates, actual energy intensity value in 2021, and forecast in 2050 in manufacturing industries of Top10 EU MS (own estimations).

Forecasting Model	R^2	MAPE, %	Energy Intensity Values, kWh/EUR	
			2021	2050
Total manufacturing industry				
$\bar{I}_{MI;p10;Y} = -0.0196 \times Y + 1.5798$	0.9934	2.2	1.20	0.58
$\bar{I}_{MI;Top10;Y} = -0.149 \times ln(Y) + 1.6827$	0.9446	2.9	1.20	1.10
$\bar{I}_{MI;p10;Y} = 1.5839 \times e^{-0.014Y}$	0.9935	2.2	1.20	0.78
Moving average Top10 EU MS	–	3.0	1.20	1.20
Chemical and petrochemical industry				
$\bar{I}_{MI;p10;Y} = -0.0431 \times Y + 5.0132$	0.9608	3.4	3.98	2.82
$\bar{I}_{MI;p10;Y} = -0.305 \times ln(Y) + 5.1898$	0.7598	4.2	3.98	3.99
$\bar{I}_{MI;p10;Y} = 5.0538 \times e^{-0.01Y}$	0.9641	3.4	3.98	3.03
Moving average Top10 EU MS	–	3.6	3.98	3.98
Non-metallic minerals industry				
$\bar{I}_{MI;p10;Y} = -0.0606 \times Y + 6.4737$	0.9865	2.4	4.85	3.38
$\bar{I}_{MI;p10;Y} = -0.418l \times ln(Y) + 6.6978$	0.8388	3.3	4.85	5.05
$\bar{I}_{MI;p10;Y} = 6.5384 \times e^{-0.011Y}$	0.9867	2.4	4.85	3.71
Moving average Top10 EU MS	–	3.0	5.46 (2020)	5.10
Food, beverages, and tobacco industry				
$\bar{I}_{MI;p10;Y} = -0.0055 \times Y + 1.3252$	0.9196	2.3	1.20	1.05
$\bar{I}_{MI;p10;Y} = -0.044 \times ln(Y) + 1.359$	0.7267	2.3	1.20	1.19
$\bar{I}_{MI;p10;Y} = 1.3203 \times e^{-0.004Y}$	0.9053	4.1	1.20	1.08
Moving average Top10 EU MS	–	2.7	1.20	1.22
Remaining manufacturing industries				
$\bar{I}_{MI;p10;Y} = -0.0069 \times Y + 1.0544$	0.8156	5.8	1.07	0.70
$\bar{I}_{MI;p10;Y} = -0.072 \times ln(Y) + 1.1336$	0.7015	4.5	1.07	0.85
$\bar{I}_{MI;p10;Y} = 1.0528 \times e^{-0.007Y}$	0.8179	5.6	1.07	0.74
Moving average Top10 EU MS	–	5.6	1.07	1.05

Moving on to sector-specific data, forecasting models indicate that the energy intensity of the chemical industry in Top10 EU MS will decrease. The largest decreases resulted from the linear and exponential forecasting models, with a reduction from 3.98 kWh/EUR in 2021 to 2.82 or 3.03 kWh/EUR in 2050, respectively. Their reliabilities are high (R^2 = 0.9608–0.9641), and the forecasts are highly accurate (MAPE = 3.4%). The logarithmic and moving average models also demonstrate accurate forecasts (MAPE = 3.6–4.2%). The latter models assume that energy intensity in the chemical industry will remain relatively stable and, in 2050, will be approximately equal to the level observed in 2021 (4.00 kWh/EUR).

The forecasting models, except for the moving average model, indicate that energy intensity will decline in the non-metallic mineral industries of the Top10 EU MS. Again, the linear and exponential models expect the highest improvements in energy intensity, while the logarithmic model expects the lowest ones in 2050. Nonetheless, all the models provide highly accurate forecasts of energy intensity (MAPE = 2.4–3.3%). Following the moving average model, energy intensity in the non-metallic mineral industry is projected to reduce by 7% from 5.46 kWh/EUR in 2020 to 5.10 kWh/EUR until 2028, and, later on, it will remain stable.

The highest intensity reductions for the food, beverages, and tobacco industries are forecasted by linear and exponential models from 1.20 kWh/EUR to 1.05 and 1.08 kWh/EUR in 2050, respectively. The latter models fit the data, as R^2 equals 0.9053–0.9196, and forecasts are very accurate as MAPEs are around 2.3–4.1%. The energy intensity forecasts based on the logarithmic and moving average models show no reduction in energy intensity value in the forecasting horizon (approximately 1.20 kWh/EUR).

Finally, it is anticipated that the aggregate remaining manufacturing industries will exhibit the lowest energy intensity—about 0.70–1.05 kWh/EUR in 2050. The linear, exponential, and logarithmic forecasting models are highly accurate, as their R^2 = 0.7015–0.8179 and the MAPEs = 4.5–5.8% fall within the limits of great accuracy. The latter models demonstrate decreases in energy intensity of 20–35% in 2050 in comparison to 2021. The moving average model assumes no relevant improvements in energy intensity in Top10 EU MS.

Despite the observed variation in R^2 and MAPE values, the energy intensity forecasting models discussed are reliable and produce accurate forecasts of energy intensity in 2050. We assume that Lithuanian manufacturing industries will aim to achieve similar energy intensities as the Top10 EU MS by 2050 (forecasts provided above illustrate assumed target values for Lithuanian manufacturing industries, Table 3). Initially, all energy intensity forecasts are considered to be linearly achievable by corresponding manufacturing industries in Lithuania, as Equation (8) proposes. Further analysis is conducted to determine the accuracy of energy intensity forecasts for the Lithuanian manufacturing industries in comparison to the target values of the Top10 EU MS (Table 3). For this purpose, we apply the MAPE concept (Equation (7)) and consider that $I_{A;Y}$ is target values of energy intensity for the manufacturing industry in Top10 EU MS in year Y and $I_{F;Y}$ is energy intensity forecasts for respective Lithuanian manufacturing industries in year Y. The accuracy of energy intensity forecasts for Lithuanian manufacturing industries was evaluated according to each forecasting model of the Top10 EU MS (Table 3), resulting in 20 assessments of forecast accuracy for Lithuania (Figure 14).

As previously discussed, our research hypothesis was that manufacturing industries in Lithuania would reach the energy intensities projected for the Top10 EU MS. In this case, the calculated MAPE values of these forecasts are expected to fluctuate between 4.0% and 19.6%, depending on the industry sector (Figure 14). The logarithmic or the moving average forecasting model of Top10 EU MS should be applied to forecast energy intensity in the total Lithuanian manufacturing industry (MAPE = 4.0%); for the chemicals—the exponential model (MAPE = 8.7%); for the non-metallic minerals industry—the logarithmic (MAPE = 3.5%); for the food, beverages, and tobacco—the logarithmic (MAPE = 4.1%) or the moving average model (MAPE = 4.0%). MAPEs of the energy intensity forecasts for the remaining aggregate industries are relatively high (MAPE = 15.3–19.6%), indicating that none of the forecasting models should be selected. The linear, exponential, and logarithmic trend lines are illogical, as they predict an increase in energy intensity. There are no data on the possible development of energy-intensive industries or other factors that could justify the results of the increasing trend. Consequently, for the case of remaining industries, the assumption of a "catching up" economy is rejected. An alternative approach is adopted, according to which the energy intensity of the remaining industries will change following the trendline selected for the historical data (Figure 15g).

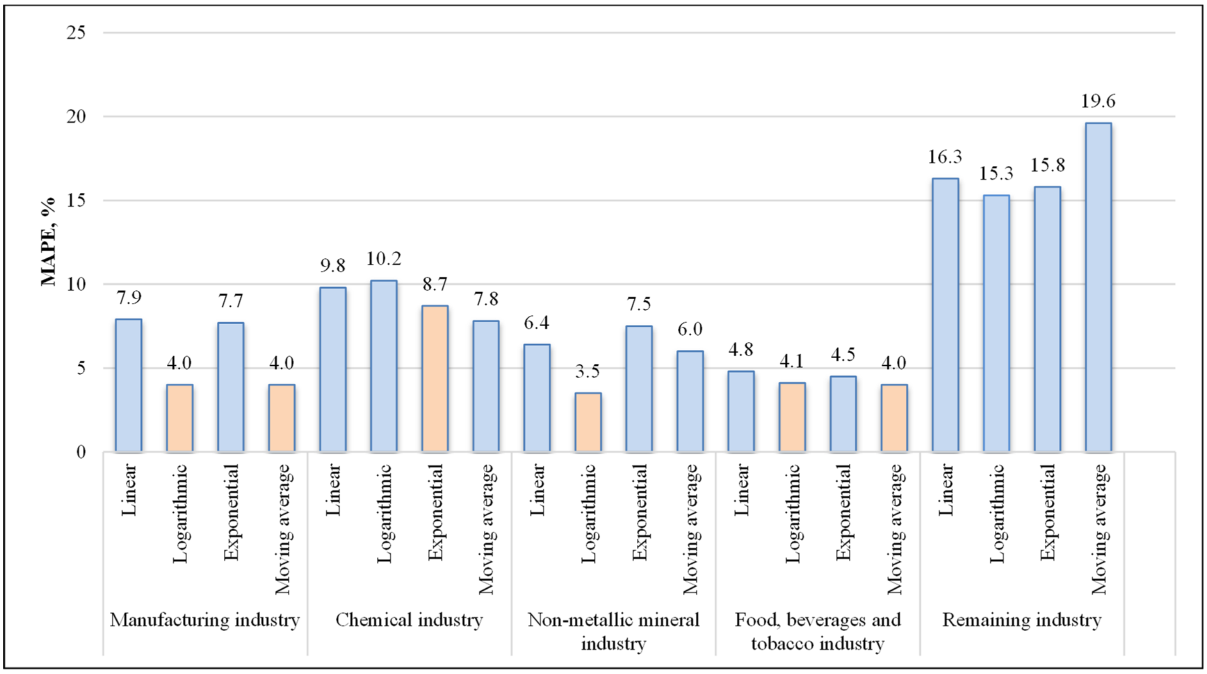
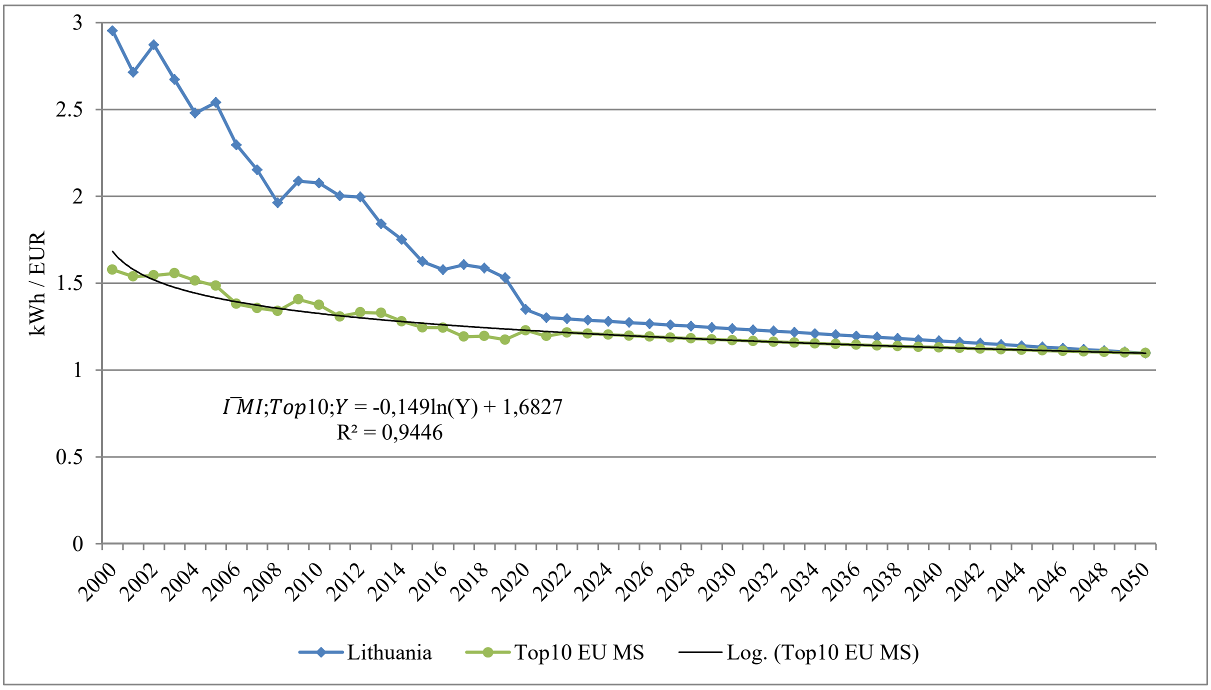


Figure 14. MAPEs of energy intensity forecasts for Lithuanian manufacturing industries (own estimations).

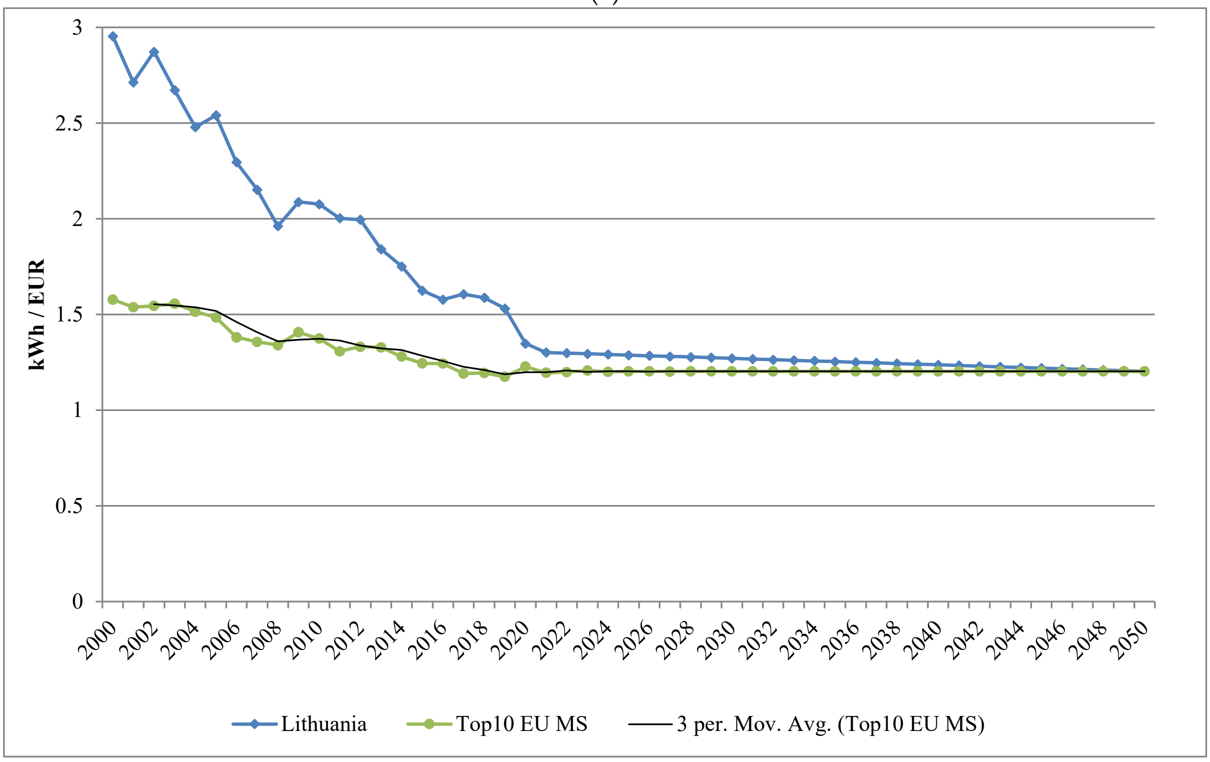
A comparison of the most reliable forecasting models of the Top10 EU MS (Table 3) and Lithuania (Figure 14) reveals that in some cases, the most reliable forecasting models for Lithuania do not correspond to those for the Top10 EU MS. Given the reliability of all the models of the Top10 EU MS, an expert judgement was made as to whether Lithuania could achieve such intensities in the context of its climate and energy policy, its industry efforts and progress. In most cases, the most reliable energy intensity forecasting models for the Top10 EU MS anticipate larger declines in energy intensities over the long-term period than other constructed models. With regard to Lithuania, the objective of more than halving energy intensities over the coming decades may appear to be overly ambitious. This is in line with the findings of the most reliable forecasting models, which suggest that moderate declines in energy intensities should be "catching up". These models were therefore prioritised for further analysis.

Given the diverse historical developments in energy intensities in Lithuanian manufacturing industries, different statistical functions were selected for separate manufacturing industries, with particular attention paid to the relevance of time as a forecasting factor in each of them. This indicated that future improvements in energy intensities will occur in manufacturing industries in different ways. The selection of statistical functions has evaluated the fact that the forecasts of energy intensities ensure that projected energy demands by industry are consistent with the energy demand in the total manufacturing industry.

Figure 15 shows historical developments and forecasts of energy intensity in the manufacturing industries of Top10 EU MS and Lithuania based on the most accurate forecasting models identified above (Figure 14).

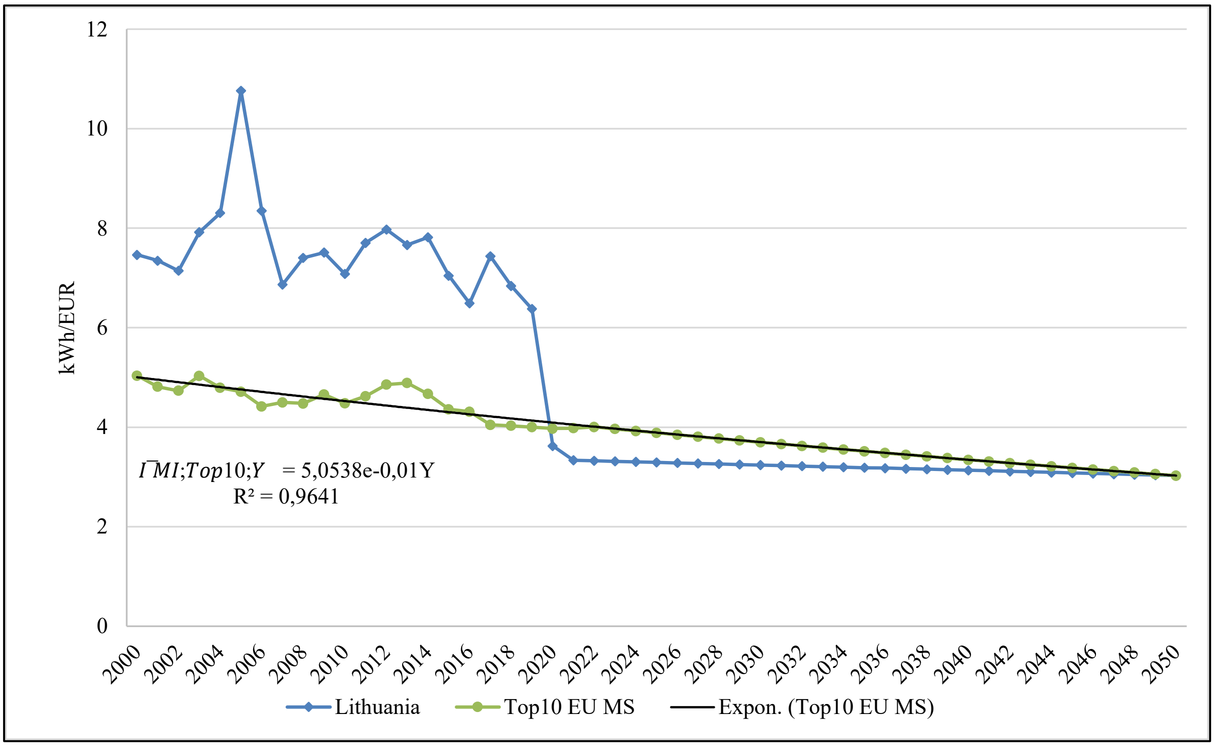


(**a**)



(**b**)

Figure 15. *Cont.*



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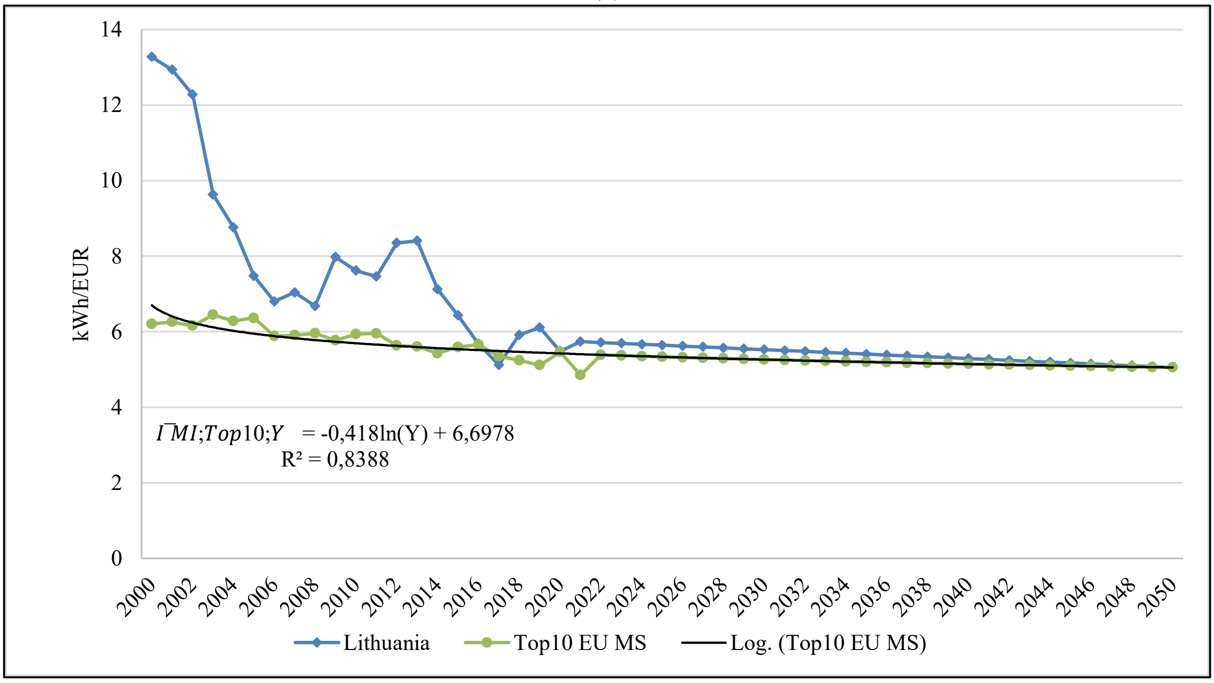
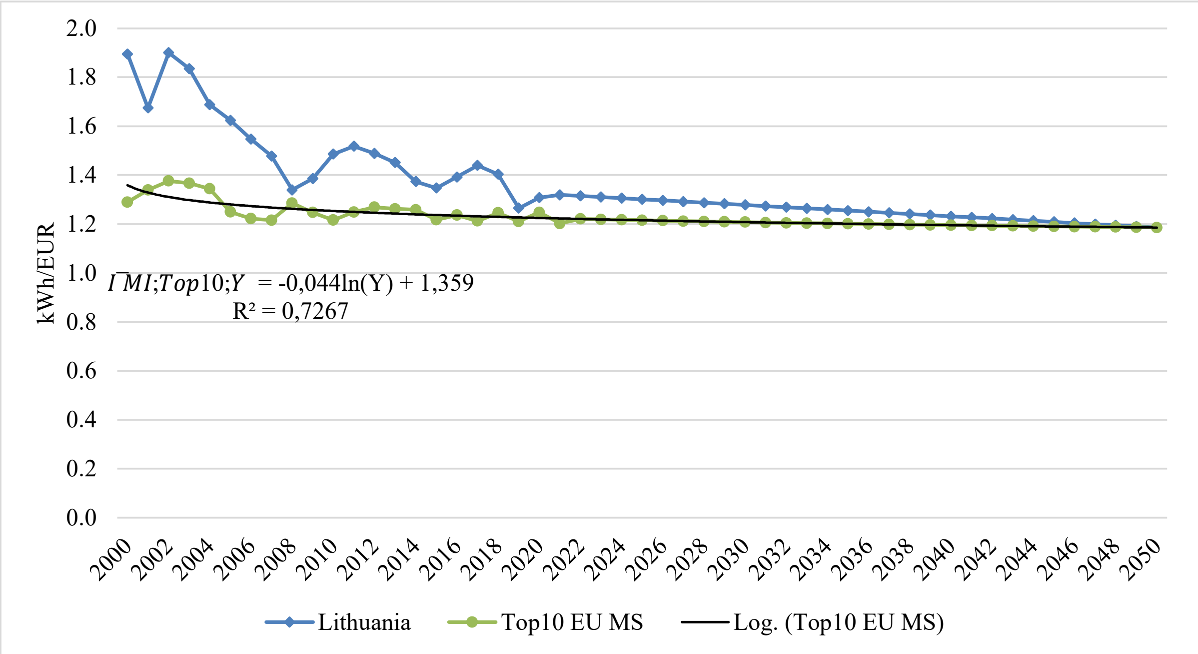


(**d**)

Figure 15. *Cont.*



(e)

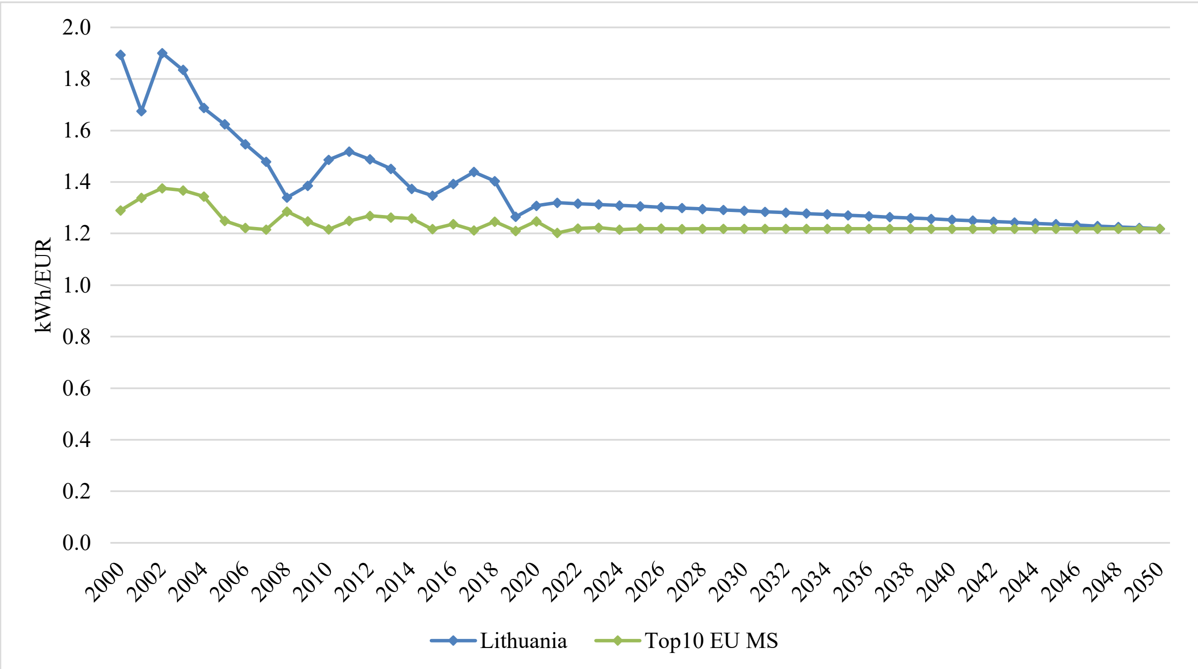


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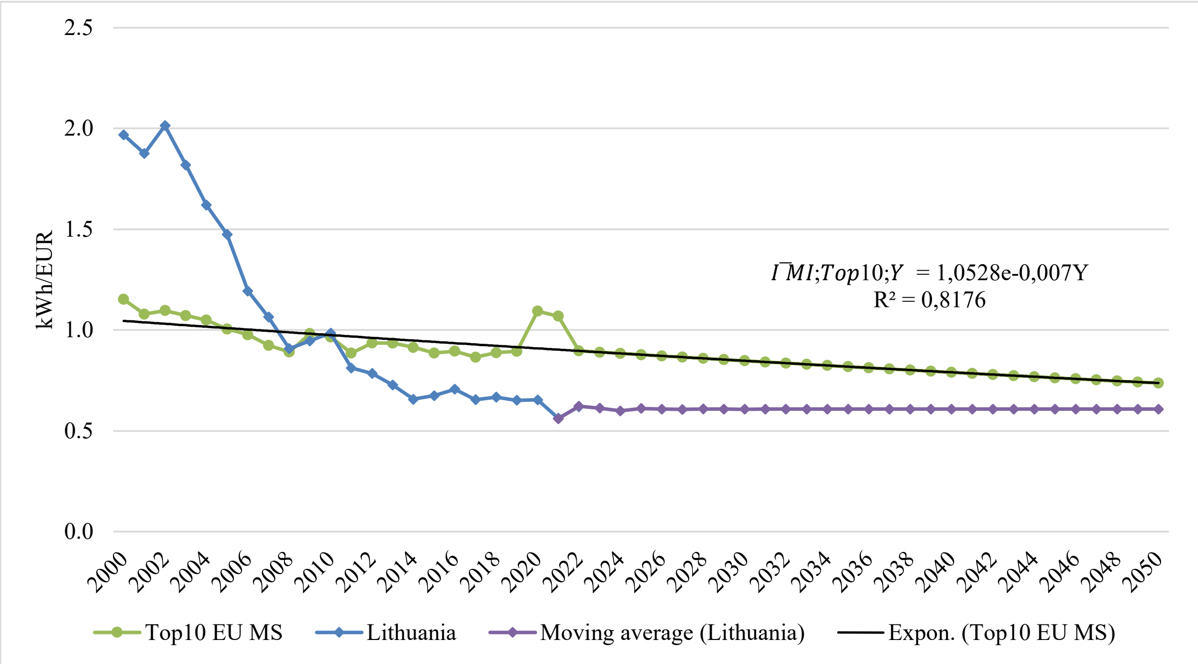
Figure 15. *Cont*.



(**g**)

Figure 15. Historical developments and forecasts of energy intensity in manufacturing industries of Top10 EU MS and Lithuania (own estimations). (**a**) Total manufacturing industry (logarithmic trendline); (**b**) total manufacturing industry (moving average trendline); (**c**) chemical and petrochemical industry (exponential trendline); (**d**) non-metallic mineral industry (logarithmic trendline); (**e**) food, beverages, and tobacco (logarithmic trendline); (**f**) food, beverages, and tobacco (moving average trendline); (**g**) remaining industry (moving average trendline for Lithuanian historical data).

Our forecasts resulted in energy intensity improvement in Lithuanian manufacturing industries following the trend of Top10 EU MS. (Figure 15). It is expected to reduce the energy intensity of the total manufacturing industry in Lithuania by 8% (Figure 15b) to 16% (Figure 15a) in 2050, thereby reaching a value of 1.10–1.20 kWh/EUR. The largest improvements are projected in the non-metallic minerals industry, with a decline of 12% in 2050 (Figure 15d), followed by the food, beverages, and tobacco industry with an anticipated 10% reduction (Figure 15e), and the chemical industry anticipates reduction by 9% (Figure 15c). The highest energy intensity will remain in the non-metallic mineral industry, with a value of 5.05 kWh/EUR in 2050 (Figure 15d). Energy intensity in the chemical industry is expected to be 3.03 kWh/EUR (Figure 15c), and in the food industry, 1.19–1.22 kWh/EUR (Figure 15e,f). As shown in Figure 15g, energy intensity for the remaining Lithuanian industries will develop according to the moving average trendline, i.e., it will remain stable (MAPE = 14.5%) and will be lower compared to Top10 EU MS.

5. Discussion and Implications

The results of our research contribute to the literature that applies time series forecasting techniques to construct energy intensity forecasting models. They justify the relevance of the linear, logarithmic, exponential, and moving average trendlines to accurately forecast energy intensity in manufacturing industries of "catching up" economies, like Lithuania, which strive to achieve at least average EU development levels. While the majority of previous research [28,29] agreed on the application of the linear or exponential [31] regression methods to forecast energy intensities, our study supports various time series forecasting techniques and identifies the most reliable ones for the crucial manufacturing industries in the country. Previous research focused on Pakistan or China cases, which have different policy, economic, and fuel consumption structures in manufacturing industries or selects developed countries but use old historical data. Our research includes the latest available comprehensive data (at the moment of study, 2021 data include all necessary details for specific industry sectors). It also proposes the sequential methodological steps on how to implement the long-term energy intensity forecasting task, especially in the MAED. In Table 4, our research results were compared to results achieved by [28–31].

As Table 4 demonstrates, our work differs significantly from previous research in terms of geographical coverage, the length of the primary data analysis period, the latest data, the forecasting horizon, the industry disaggregation, the variety of statistical functions applied, and the disclosure of model form, its qualitative parameters, and forecast accuracy evaluations. A commonality between the studies is the regression of energy intensities against time, which was identified as an informative forecasting factor in the models. Despite the fact that Eder et al. [31] studied the economy as a whole and we studied manufacturing industries, the results of our research support the conclusion of the Eder et al. [31] study—the energy intensities of developing countries will catch up with the energy intensities of developed countries in the long run. It is widely accepted among scientists that, over time, the energy intensity of economic sectors will decline at varying rates, depending on the region or economic sector. In detail, our forecast indicated that the energy intensity of manufacturing industries would decrease at a slower rate than previously assumed by Sánchez-Durán et al. [28] and Chen et al. [30]. The latter assumed that after the implementation of energy efficiency measures, energy intensity could be reduced by 6.5% a year in high-energy-intensive industries and by 5.0% a year in other industries. However, the methodology used to determine the rates of change in energy intensity due to the adaptation of energy efficiency remained unclear. The advantage of the research carried out by Chen et al. [30] is that it considers various energy intensities by type of fuel, device, and economic sector in different scenarios. Our research has derived energy intensities at the level of the manufacturing industry, which is a limitation. While following the historical average growth rate, under the business-as-usual and the active government control scenarios, energy intensity will increase by 2.25% a year in the high-energy-intensive industries. In contrast, it will significantly decrease under the incentive energy-saving scenario. The latter scenario demonstrated that energy efficiency measures are beneficial in transforming the structure of energy demand.

Following [28–31], to discuss and assess the implications of prepared energy intensity projections in practice, we have calculated the final energy demand for the manufacturing sector up to 2050. It is not possible to make comparisons between the results of this study and other official sources due to a lack of official data in the country regarding developments in energy intensity within the manufacturing industry. The National Energy and Climate Plan 2030 (NECP2030) [52] and the Lithuanian Energy Independence Strategy 2050 [6] (NEIS2050) are key documents of energy sector development in the country and crucial information sources when developing energy scenarios. The NEIS2050 assumed that energy intensity will almost halve in the country until 2050. This is equivalent to a reduction from 170 kgoe/1000 EUR in 2020 to 80 kgoe/1000 EUR in 2050, representing a 2.4% annual reduction. However, these data are not disaggregated by energy-consuming economy sectors. It is not realistic to expect that such energy efficiency gains can be universally achieved across all sectors of the economy. For instance, the new National Energy Independence Strategy (2024) indicates that industrial electricity demand alone should reach 12.6 TWh in 2050, representing a fourfold increase from 4 TWh in 2021 [53]. The energy intensity and its forecast do not identify the specific energy resources that will be utilised to meet the demand; rather, they provide grounds for an estimate of the total future final energy demand. It is evident that the anticipated economic growth will also necessitate the utilisation of energy resources. Considering the expected growth in value added to the total Lithuanian manufacturing industry, three scenarios of final energy consumption were analysed (Figure 16).

Table 4. Comparison of research results (own work).

Author	Country	Year of Analysis	Time Horizon	Industry	Method	Forecasting Factor	Models	Reliability of Models	Accuracy of Forecasts	Energy Intensity at the End of Forecasting Horizon	Expected Energy Intensity Changes during Forecasting Horizon
Our estimations	Lithuania	2000–2021	Until 2050	Total manufacturing, chemical and petrochemical, non-metallic mineral, food, beverages, and tobacco, and remaining industry	Logarithmic, exponential, and moving average trendlines	Time	Figure 15	Figure 15	MAPE, Figure 14	1.1–1.2 kWh/EUR, 3.03 kWh/EUR, 5.05 kWh/EUR, 1.19–1.22 kWh/EUR, 0.61 kWh/EUR, respectively	Decline by 0.3–0.5%, 0.3%, 0.4%, 0.3% a year and increase by 0.9% a year, respectively
Sánchez-Durán et al. (2019) [28]	Spain	1990–2015	Until 2030	Total industry	Linear regression	Time	NA	NA	RMSE	59.8 toe/million EUR	Decline by 2.4% a year
Chen et al. [30]	Hunan province, China	2005–2012	Until 2030	High-energy-intensive industry, other industry	Average growth rate	Time	NA	NA	NA	NA	Under business-as-usual scenario, increase by 2.25% a year in energy-intensive industry, but decline by 3.36% a year in other industries. Under EE scenario, decline by 6.5% and 5.0%, respectively
Eder et al. [31]	Europe, America, China, Africa	1980–2015	Until 2040	Economy-wide	Exponential	Time	NA	R2, Fisher criterion	Mean approximation error (MAE)	Level of energy intensity of developing economies will gradually converge to catch up with the level of energy intensity of the developed economies	

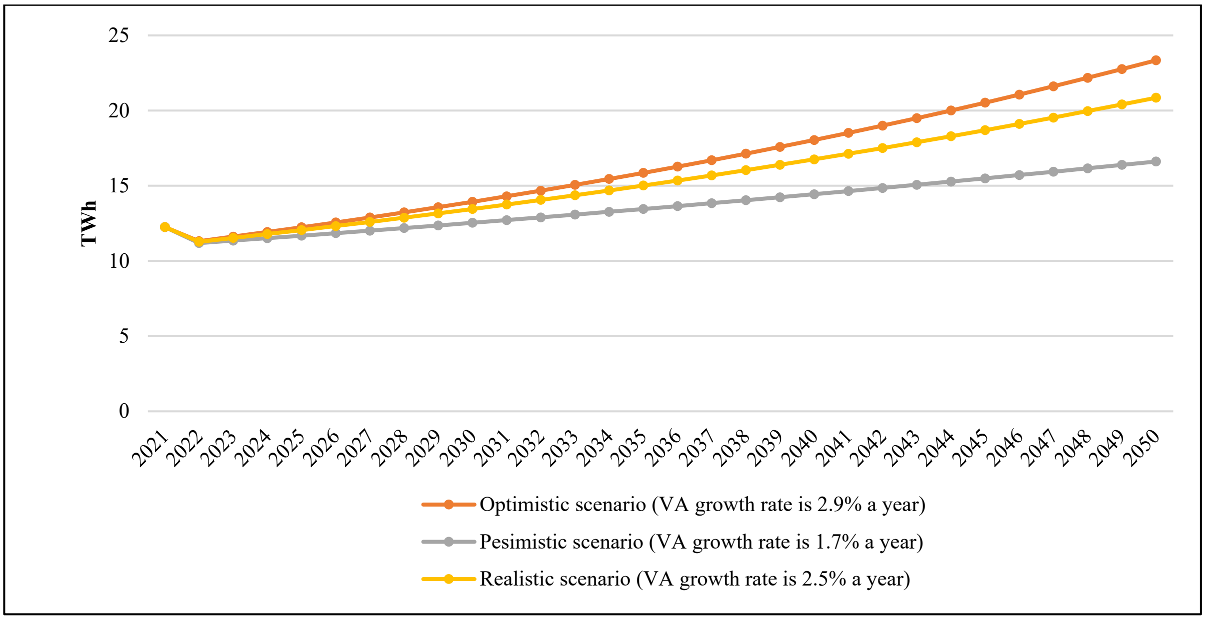


Figure 16. Forecasts of final energy consumption in the Lithuanian manufacturing industry from 2022 to 2050 subject to different value-added growth scenarios, TWh (own estimations).

As shown in Figure 16, the consumption of final energy in the Lithuanian manufacturing industry is expected to increase in the future. The optimistic scenario defines that it will grow at a rate of 2.2% a year from 12.25 TWh in 2021 to 23.35 TWh in 2050. The pessimistic scenario considers moderate growth of the final energy consumption at a rate of 1.0% to 16.62 TWh in 2050, while the realistic scenario foresees an increase of 1.8% a year to 20.86 TWh in 2050. Based on this, the expected growth in final energy consumption by the Lithuanian manufacturing industries is presented in Figure 17.

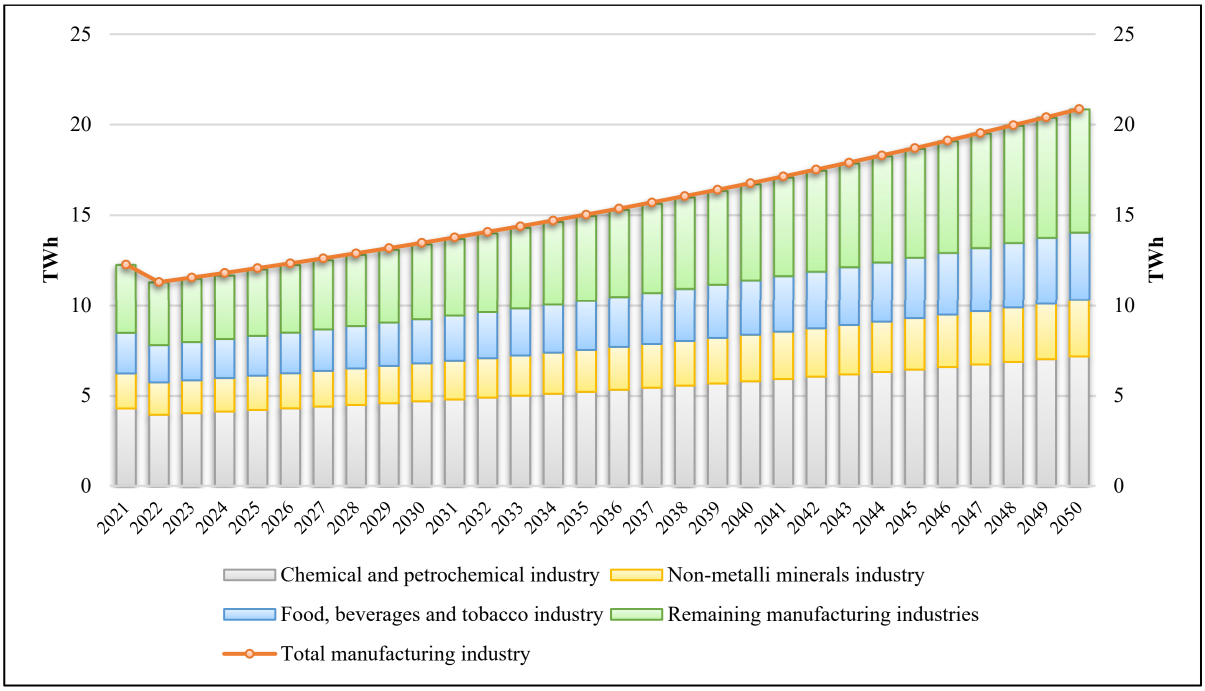


Figure 17. Forecasts of final energy consumption in the specified Lithuanian manufacturing industries (realistic scenario), TWh (own estimations).

Final energy consumption in the non-metallic mineral industry will grow by 1.6% a year to 3.15 TWh in 2050, in the chemical and food, beverages, and tobacco by 2.1% a year to 7.16 TWh and 3.73 TWh, respectively, and in the remaining industries by 2.0% a year to 6.81 TWh in 2050. The effect of energy intensity on the increase in final energy consumption in the manufacturing industry is revealed through the decomposition analysis (Figure 18).

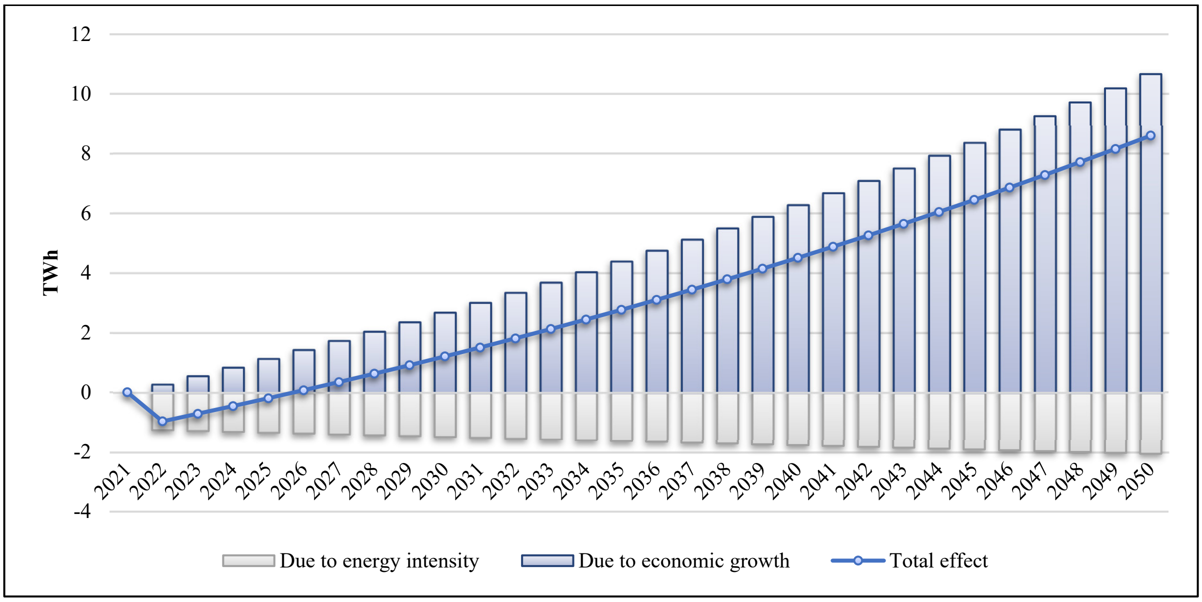


Figure 18. Decomposition of final energy consumption increase in the manufacturing industry (realistic scenario), TWh (own estimations).

The effects of energy intensity and economic growth result in an increase in final energy consumption by 8.61 TWh in 2050. While due to economic growth at a rate of 2.5% per year final energy consumption in the manufacturing industry will significantly increase by 10.67 TWh, the decrease in energy intensity at a rate of 0.26% a year will reduce final energy consumption by 2.06 TWh. Thus, the results demonstrate that economic growth is a key underlying factor influencing final energy consumption in the Lithuanian manufacturing industry, but the decreasing energy intensity allows for balancing future energy consumption.

6. Conclusions

The objective of this research was to identify energy intensity forecasting models and prepare forecasts for key manufacturing industries, with a particular focus on "catching-up" European economies. Future energy intensity values are a basis for energy demand projections. The case of Lithuania, which has been identified as an example of a "catching-up" economy, was analysed in the context of its efforts to strengthen economic development while simultaneously improving energy efficiency and achieving gradual decarbonisation. Our study justified the application of econometric functions to construct energy intensity forecasting models for manufacturing industries and prepare highly accurate forecasts. The methodology employed and similar research could be applied to other EU Member States that comply with the definition of "catching up" economies.

A historical analysis of calculated energy intensity and its two main components (value added and final energy consumption) in the EU manufacturing industries was conducted (2000 to 2021). The statistical data examined served as the foundation for energy intensity forecasts until 2050. Analysis demonstrates a notable decline in energy intensity indicators across most European countries, including Lithuania. Over the past two decades, Lithuania has made a breakthrough towards the most advanced countries in terms of energy intensity. Nevertheless, in the most energy-intensive industries, such as chemicals, Lithuania's energy intensity indicators are still higher than those of the most economically advanced EU countries.

The Lithuanian industry is distinguished by a more rapid rate of decrease in energy intensity compared to the most economically developed EU countries (Top10 EU MS). Consequently, the values observed in individual Lithuanian manufacturing industries have already reached levels comparable to Top10 EU MS. The significant increase in value added was a key factor in the impressive reduction in energy intensity. Energy-efficient technologies also played a role. However, the dynamics of the indicator show that the energy intensity improvement rate in Lithuania is slowing down. This indicates that maintaining the observed reduction pace will be challenging, especially given the ongoing rise in Lithuania's cumulative final energy consumption in the industry. To remain competitive in the current energy efficiency landscape, industry stakeholders are advised to invest in digitisation, modernisation, optimisation, and automation systems for manufacturing equipment and systems and to employ energy technologies utilising RES and alternative fuels.

An analysis was conducted of energy intensity forecasting models for manufacturing industries in Top10 EU MS. This revealed that linear, logarithmic, exponential, and moving average trendlines could be applied to construct energy intensity forecasting models. The trendline-based energy intensity forecasting models were found to be reliable due to their R^2 values close to 1 (R^2 = 0.7015–0.9935). Furthermore, the prepared forecasts are highly accurate, with estimated mean absolute percentage error (MAPE) values falling within a range below 10%. Based on the forecasting results, it can be concluded that the energy intensity in the manufacturing industry of the Top10 EU MS will decrease, except for the moving average trendline, which in most cases is constant or shows minor increases. The largest projected decreases in energy intensity are forecasted by linear and exponential forecasting models prepared for the chemical, non-metallic mineral, and remaining industries, which reach 24–35%.

In consideration of the R^2 and MAPE indicators of the forecasting model, it is appropriate to use the linear trendline to forecast energy intensity of the total manufacturing (R^2 = 0.9934, MAPE = 2.2%), the chemicals (R^2 = 0.9196, MAPE = 2.3%), the non-metallic mineral products (R^2 = 0.9865, MAPE = 2.4%) and the food, beverages, and tobacco (R^2 = 0.9415, MAPE = 3.7%). The exponential trendline is suitable for forecasting energy intensity for the total manufacturing (R^2 = 0.9935, MAPE = 2.2%), the chemicals (R^2 = 0.9641, MAPE = 3.4%), and the non-metallic mineral products (R^2 = 0.9867, MAPE = 3.4%). The logarithmic trendline for the food, beverages, and tobacco (R^2 = 0.7267, MAPE = 2.3%) and the remaining aggregate industries (R^2 = 0.7015, MAPE = 4.5%). The most reliable models indicate that energy intensity will decrease to 3.38–3.71 kWh/EUR in the non-metallic mineral industry, 2.82–3.03 kWh/EUR in the chemical industry, 1.05–1.19 kWh/EUR in the food, beverages, and tobacco industry, and 0.85 kWh/EUR in the remaining aggregate manufacturing industries of the Top10 EU MS in 2050.

The long-term objective of Lithuanian manufacturing industries was set to achieve projected Top10 EU MS energy intensities by 2050. The analysis has demonstrated that established models for the Top10 EU MS are also applicable for forecasting energy intensities in Lithuania. For higher forecast accuracy, the application of logarithmic or moving average trendlines instead of the linear trendline in the total manufacturing industry could result in a reduction in MAPE from 7.9% to 4.0%. A reduction from 9.8% to 8.7% could be achieved if the exponential trendline is selected instead of the linear trendline in the chemical industry. Similarly, a reduction from 6.4% to 3.5% could be attained if the logarithmic trendline is chosen instead of the linear trendline in the non-metallic mineral industry. In the food, beverages, and tobacco industries, the logarithmic or moving average trendlines could improve MAPE from 4.8% to 4.0%. The latter forecasting models indicate that energy intensity could decline by up to 16% to 1.10 kWh/EUR in Lithuania's manufacturing industry by 2050. In particular, the intensity could decrease by 9% to 3.03 kWh/EUR in the chemical industry, by up to 10% to 1.19 kWh/EUR in the food, beverages, and tobacco industry, by 12% to 5.05 kWh/EUR in the non-metallic mineral industry, and by 8% to 0.61 kWh/EUR in all remaining industries.

The forecasted energy intensity of Lithuanian manufacturing industries has a significant impact on projections of final energy consumption. Our estimations indicate that, as a result of improvements in energy intensity, final energy consumption in Lithuanian manufacturing industries will decrease by 2.06 TWh in 2050. Nevertheless, the expected average economic growth of 2.5% per annum will result in an increase in final energy consumption by 10.7 TWh in 2050. Consequently, further investigation of this phenomenon is recommended. Energy efficiency still has unexploited potential in the Lithuanian industry and requires immediate attention from industry, research, and policy makers.

The implementation of efficiency measures and the adoption of innovative or less energy-consuming technologies could impact the energy intensity. The two major industry sectors in Lithuania—chemicals and non-metallic minerals—could potentially decarbonise in different pathways. These include the utilisation of green hydrogen in the manufacturing of ammonia and the electrification or carbon capture and storage in cement manufacturing. Consequently, further research is required, particularly in the context of emerging technologies and their potential impact on energy intensity.

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