

**Janusz Zyśk, Maciej Raczyński,
Artur Wyrwa**

Energy System Modelling as a Tool for Assessing Green Transition Policies in Poland

**SERIES: GREEN TRANSFORMATION
POLICY IN POLAND**



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PREFACE

It is widely recognised that Poland's green transformation policy is centred on the shift away from fossil fuels, particularly coal, towards renewable energy sources (RES), with the overarching objective of achieving climate neutrality by 2050. This transition is being pursued through the *Energy Policy of Poland until 2040* (PEP2040), the *National Recovery and Resilience Plan* (NRRP) and European Union regulatory frameworks, including the European Green Deal. These measures encompass the development of renewable energy sources, the modernisation of the energy sector, including the development of nuclear power, improvements in the energy efficiency of buildings, the promotion of low-emission transport and support for innovation. Their implementation requires substantial investment, financed, inter alia, through European Union (EU) funding. Research indicates growing optimism among the Polish public

regarding the potential economic and social benefits of the transition. Nevertheless, the process requires significant levels of investment and entails considerable challenges, particularly for coal-mining regions. It also poses important theoretical, descriptive and practical challenges for the academic community.

The present series of publications, devoted to green transformation policy in Poland, provides an in-depth examination of the issues associated with this field of research. Spanning six volumes, the series enables a multifaceted exploration of the subject matter, integrating theoretical perspectives with practical considerations.

The publication series adopts an interdisciplinary approach, with the aforementioned subject matter providing a common thematic framework for the individual monographs. The authors address issues relating to public policy, management, environmental protection, law and public administration. By bringing these studies together within a single series, the research provides a comprehensive and multidimensional perspective on the issues under consideration.

The first volume in the series reviews the principal approaches employed in contemporary energy system modelling. The analysis confirms that energy system models constitute an important tool for supporting the design, assessment and monitoring of green transition policy.

The examples of their practical application presented in the volume demonstrate the growing importance of such models in the formulation and evaluation of green transition policies. At the same time, the authors emphasise that the development of an integrated modelling framework encompassing the national, regional and local levels could enhance the coherence of energy and climate policy and facilitate the alignment of national transition objectives with the specific characteristics of individual regions and local government units, including their respective potential and constraints.

CHAPTER I

ENERGY SYSTEM MODELLING APPROACHES

Energy modelling currently constitutes one of the fundamental tools supporting decision-making processes in the energy sector. Dynamic changes occurring in the economy, the growing importance of energy security, the necessity to reduce greenhouse gas emissions, and the development of new technologies render the planning of energy system development increasingly complex. The contemporary energy system encompasses not only the electricity sector, but also district heating, transport, industry, the building sector, and agriculture. All these domains remain interconnected, and decisions made in one sector affect the functioning of the others. Under such conditions, the application of mathematical and simulation models enabling the analysis of future development scenarios becomes indispensable. Energy models allow for assessing the impacts of investments, analysing the

influence of climate policy, forecasting energy demand, and identifying the most effective pathways for energy transition. They make it possible to mitigate investment decision-making risks and gain a better understanding of the processes occurring within energy systems.

The development of energy modelling began in the mid-20th century alongside the growing importance of energy for economic development. Initially, simple statistical and econometric models used for forecasting electricity demand predominated. However, the oil crises of the 1970s demonstrated that analysis based solely on historical trends was insufficient. It became necessary to account for technological change, fuel prices, energy policy, and environmental factors.

In the literature, three main groups of energy models are most commonly distinguished: top-down models, bottom-up models, and hybrid models¹. Each of these approaches represents a distinct philosophy for describing

¹ H.-K. Ringkjøb, P.M. Haugan, I.M. Solbrekke, 2018. *A review of modelling tools for energy and electricity systems with large shares of variable renewables*, Renewable and Sustainable Energy Reviews, vol. 96, pp. 440–459; S. Jebaraj, S. Iniyar, 2006. *A review of energy models*, Renewable and Sustainable Energy Reviews, no. 4, vol. 10, pp. 281–311; A. Herbst et al., 2012. *Introduction to Energy Systems Modelling*, Swiss Journal of Economics and Statistics, no. 2, vol. 148, pp. 111–135; D. Connolly et al., 2010. *A review of computer tools for analysing the integration of renewable energy into various energy systems*, Applied Energy, no. 4, vol. 87, pp. 1059–1082.

reality and finds application in different types of analysis. In practice, a combination of various methods is increasingly used to obtain the most reliable possible picture of the future development of the energy sector. The fundamental difference between top-down and bottom-up models stems from the level of analytical detail and the method of representing the operation of the energy system. Top-down models are based on a macroeconomic approach and primarily serve to analyse long-term economic trends and assess the impact of energy policy and climate policy on the economy as a whole. Conversely, bottom-up models focus on a detailed description of energy technologies, energy conversion processes, and opportunities for improving energy efficiency, making them particularly useful in technical analyses and energy infrastructure planning. Top-down models initiate their analysis at the level of the whole economy, employing aggregated economic and social indicators such as gross domestic product, employment levels, or household incomes. These data are subsequently disaggregated to represent individual economic sectors or energy consumer groups. A different logic is applied by bottom-up models, where the starting point consists of data describing specific technologies, devices, enterprises, or households. This information is then aggregated, enabling a comprehensive picture of energy system operations at the regional or national level.

Contemporary energy models must also account for uncertainty regarding future technological developments, fuel prices, climate policy, and the geopolitical situation. For this reason, scenario analyses are gaining increasingly greater importance. Rather than forecasting a single future, several alternative development scenarios are constructed, differing in their level of climate ambition, the pace of technological development, or economic conditions.

The scenario approach allows for better preparation for future challenges and for assessing the resilience of the energy system to various developmental pathways. It currently represents standard practice in analyses conducted by the European Commission, the International Energy Agency, and numerous research institutions. The significance of energy models has grown particularly following the onset of the energy transition associated with the implementation of climate targets. Achieving climate neutrality requires profound changes in the structure of energy production and consumption. Replacing fossil fuels with renewable energy sources, developing energy storage, electrifying transport, and improving energy efficiency are becoming essential. Implementing these measures requires conducting a vast number of technical and economic analyses. Energy models enable the assessment of transition costs, the identification of potential barriers, and the indication of the most effective development pathways. They are utilised at national, regional, and local levels alike.

1.1. Top-Down Energy Models

Top-down models, also referred to as macroeconomic models, began to develop in the 1950s alongside the growing importance of energy demand forecasting². In this approach, the energy sector is analysed as an integral element of the broader economic system, which enables the investigation of interdependencies between energy and other sectors of the economy. These models account for the influence of macroeconomic factors—such as the rate of economic growth, demographic changes, employment levels, or population incomes—on the formation of energy demand. They also allow for evaluating the impacts of energy price fluctuations and the implementation of specific energy and climate policies over a long-term time horizon. Owing to their ability to represent the relationships between economic development, welfare levels, and energy consumption, top-down models serve as a valuable tool for strategic analyses and the assessment of the economic and environmental impacts of various development scenarios. However, their primary limitation lies in a relatively low level of technological detail, which may hinder accounting

² A. Herbst et al., 2012. *Introduction to Energy Systems Modelling*, Swiss Journal of Economics and Statistics, no. 2, vol. 148, pp. 111–135; F. Gherzi, 2015. *Hybrid Bottom-up/Top-down Energy and Economy Outlooks: A Review of IMACLIM-S Experiments*, Frontiers in Environmental Science, vol. 3.

for the impact of innovation and technical progress on the functioning of the energy system. The most prominent representatives of this group include computable general equilibrium (CGE) models, system dynamics (SD) models, econometric models, and Input-Output models.

1.1.1. Computable General Equilibrium Models

One of the most important groups of top-down models comprises computable general equilibrium (CGE) models. They are grounded in market equilibrium theory, according to which all markets tend towards a state of equilibrium between supply and demand. These models enable the analysis of interdependencies between economic sectors and the evaluation of the economic impacts of energy and climate policies by determining a new equilibrium state following the implementation of specific economic or regulatory changes. Consequently, they are frequently utilized by public administration and international organizations to assess the impacts of implementing energy and climate policies. The most widely used computable general equilibrium (CGE) models in energy analyses include, among others, GEM-E3, GTAP-E, ENV-Linkages, PACE, and WorldScan³. The

³ P. Capros et al., GEM-E3 Model Manual, Athens, Greece 2017; J.-M. Burniaux, T.P. Truong, GTAP-E: An Energy-Environmental

GEM-E3 model was developed for the European Commission and is extensively applied to evaluate the impacts of energy, climate, and environmental policies at the level of EU Member States. GTAP-E represents an extension of the global GTAP model to include the energy and environmental sectors, thereby enabling the analysis of the effects of energy price changes and climate policy on international trade and national economies. Meanwhile, ENV-Linkages, developed by the OECD (Organisation for Economic Co-operation and Development), is utilized for analysing long-term economic impacts resulting from the implementation of greenhouse gas emission mitigation strategies.

1.1.2. Econometric Models

Econometric models also play a significant role. They combine economic theory with statistical methods and allow for the identification of relationships between energy consumption and selected socio-economic indicators. Econometric models are particularly useful in short- and medium-term

Version of the GTAP Model. GTAP Technical Paper No. 16, 2002; J. Chateau, R. Dellink, E. Lanzi, An Overview of the OECD ENV-Linkages Model: Version 3. OECD Environment Working Papers No. 65, 2014; A. Herbst et al., 2012. *Introduction to Energy Systems Modelling*, Swiss Journal of Economics and Statistics, no. 2, vol. 148, pp. 111–135.

analyses; however, their effectiveness depends on the quality of available historical data and the stability of economic relationships observed in the past. The development of artificial intelligence methods and neural networks has contributed to enhancing forecast accuracy, especially in the case of short-term electricity demand forecasting. Among the most prominent econometric models utilised in energy analyses are E3ME (Energy-Environment-Economy Model Europe), developed by Cambridge Econometrics, and NEMS (National Energy Modelling System), employed by the US Energy Information Administration (EIA)⁴. The E3ME model enables the analysis of interdependencies between the economy, the environment, and the energy sector, and its results are frequently used in analyses conducted for the European Commission. Meanwhile, NEMS serves to prepare long-term energy projections for the United States, incorporating a detailed representation of end-use energy sectors, fuel markets, and energy technologies.

⁴ E3ME, <https://www.camecon.com/e3me>; Documentation of the National Energy Modeling System (NEMS) modules, <https://www.eia.gov/outlooks/aeo/nems/documentation>.

1.1.3. Input-Output Models

Input-Output models belong to the classic tools utilised for analysing the interdependencies between the energy sector and other branches of the economy. They are grounded in input-output tables, most commonly expressed in monetary units, which describe the mutual linkages between production and consumption sectors. For instance, the construction sector purchases building materials from industry, transport services from the transport sector, and products and services from the energy sector. The Input-Output table thus displays the value of these transactions, representing the scale of economic linkages between individual sectors. Upon supplementing this flow structure with data regarding physical energy consumption or energy intensity coefficients, it becomes possible to determine both direct and indirect energy consumption, as well as to evaluate the impact of changes occurring within a single sector on the functioning of the entire economy⁵. Models of this type find application in, among other areas, energy security analyses, the assessment of climate policy impacts, the determination of the energy and emissions footprints of

⁵ J. Peet, 1993. *Input-output methods of energy analysis*. International Journal of Global Energy Issues, 5(1), pp. 10–18; Ł. Lach, 2020. *Tracing key sectors and important input-output coefficients: Methods and applications*. Kraków.

products, and the study of the economic consequences of energy investments.

Among the most prominent models employing the Input-Output approach are EORA, EXIOBASE, and WIOD (World Input-Output Database)⁶. These tools enable the analysis of energy flows and greenhouse gas emissions at both the national and global levels. Multi-regional Input-Output models (MRIO models) currently hold particular importance, as they allow for accounting for international trade linkages and evaluating the impact of imports and exports on energy consumption and emissions [12]. Furthermore, Input-Output models are increasingly being integrated with bottom-up energy models, enabling the simultaneous analysis of technological and economic aspects of the energy transition⁷.

⁶ M. Lenzen et al., 2013. *Building Eora: A Global Multi-Region Input-Output Database at High Country and Sector Resolution*. Economic Systems Research, 25(1), pp. 20–49; K. Stadler et al., 2018. *EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables*. Journal of Industrial Ecology, 22(3), pp. 502–515; M.P. Timmer et al., 2015. *An Illustrated User Guide to the World Input-Output Database: the Case of Global Automotive Production*. Review of International Economics, 23(3), pp. 575–605.

⁷ Ł. Lach et al., 2025. *Input-output model for forecasting economic and environmental effects of smart meters deployment in Poland*. Energy, 328, art. 136504; Ł. Lach et al., 2026. *On economic and environmental effects of expanding PV deployment in Poland*. Scientific Reports, 16(1), art. 15122.

1.1.4. System Dynamics Models

These models serve to analyse complex systems characterized by the presence of numerous feedback loops, time delays, and cause-and-effect relationships⁸. In contrast to classical economic models, system dynamics models focus on investigating system behavior over time and identifying the mechanisms responsible for observed changes. In these models, the energy system is represented by stocks, flows, and feedback loops that describe the mutual interactions among its elements. Consequently, this enables the analysis of long-term impacts of investment decisions, technological changes, energy policy, or environmental regulations. System dynamics models find wide application in research on the energy transition, energy security, the development of renewable energy sources, and the assessment of climate policy impacts. Models in this group include World3, ENERGY 2020, and EUROGREEN⁹. Intriguing research was conducted using the EUROGREEN

⁸ A. Ford, 2009. *System Dynamics Models of Environment, Energy and Climate Change*, [in:] R.A. Meyers, ed. *Encyclopedia of Complexity and Systems Science*. New York, pp. 9014–9034; L. Schoenenberger et al., 2021. *Structural Analysis of System Dynamics Models*. *Simulation Modelling Practice and Theory*, 110, art. 102333.

⁹ G.O. Barney, 2002. *The Global 2000 Report to the President and the Threshold 21 model: influences of Dana Meadows and system dynamics*. *System Dynamics Review*, 18(2), pp. 123–136; M. Jaccard, 2005. *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy*. Cambridge.

model. Its objective was to address the question of whether achieving climate targets can rely solely on technological progress, energy efficiency gains, and a shift in the energy mix, or whether it also necessitates deeper structural changes in the economy, including demand reduction, altered consumption patterns, or reduced working hours.

1.2. Bottom-Up Energy Models

Bottom-up models represent an alternative to the macroeconomic approach. They are often referred to as engineering models because they focus on a detailed description of energy technologies. The analysis commences at the level of individual devices, installations, or technological processes, and the results are subsequently aggregated to the level of the entire energy system¹⁰.

Bottom-up models allow for the inclusion of technical parameters of technologies, such as efficiency, operational lifespan, capital and operating costs, or fuel consumption. Consequently, this enables a detailed evaluation of the impact of individual technologies on the functioning of the energy system. This approach is particularly useful in

¹⁰ M.G. Prina et al., 2020. *Classification and challenges of bottom-up energy system models - A review*. Renewable and Sustainable Energy Reviews, 129, art. 109917.

analyses of the energy transition and in planning investments in new generating capacity.

1.2.1. Optimisation Models

One of the most important groups of bottom-up models comprises optimisation models. Their primary objective is to determine the most cost-effective configuration of the energy system under specified technical, economic, and environmental constraints. Most commonly, the objective function aims to minimise the total costs of the energy system over the entire period under analysis. Among the best-known optimisation models is MARKAL¹¹. This model was developed within the framework of the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA) and served for many years as a fundamental tool for energy analyses. MARKAL represents the energy system as a network of technologies interconnected by energy flows, thereby enabling the evaluation of energy investments and the assessment of various energy policy options. The successor to MARKAL is TIMES, which currently stands as one of the most widely used energy modelling tools globally.

¹¹ R. Loulou, G. Goldstein, K. Noble, Documentation for the MARKAL Family of Models, 2004.

TIMES retains the core assumptions of MARKAL while offering significantly greater flexibility and a more realistic representation of investment processes. The model allows for the simultaneous analysis of the electricity, heating, transport, industry, buildings, and agriculture sectors¹². The MESSAGE model, developed by the International Institute for Applied Systems Analysis (IIASA), has also gained substantial popularity¹³. This tool is extensively utilised in global analyses and climate scenarios prepared for international organisations. Owing to its detailed representation of energy technologies, it enables the evaluation of diverse decarbonisation pathways for the economy.

1.2.2. Simulation Models

In contrast to optimisation models, which seek a solution that minimises costs or maximises a specified objective function, simulation models focus on analysing the impacts

¹² S. Allena-Ozolina et al., *Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling*, [in:] 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia 2020, pp. 1–7.

¹³ N. Nakicenovic and K. Riahi, 2003. *Model Runs with MESSAGE in the Context of the Further Development of the Kyoto-Protocol*. Laxenburg: International Institute for Applied Systems Analysis (IIASA).

of adopted assumptions and development scenarios¹⁴. Consequently, they enable the evaluation of the effects of technological, economic, social, or regulatory changes on the functioning of the energy system. Simulation models make it possible to analyse complex processes occurring within the energy sector, such as shifts in energy consumption patterns, the deployment of low-emission technologies, consumer responses to changes in energy carrier prices, or the outcomes of implementing energy and climate policy instruments. In these models, the user defines scenarios for system development, and the consequences of the adopted assumptions are subsequently evaluated over successive periods. This approach allows for accounting for market imperfections, bounded information availability, and the behaviour of various stakeholder groups, which are frequently omitted in classical optimisation models.

Among the most popular simulation models applied in energy planning are the Long-range Energy Alternatives Planning System (LEAP) and the Model for Analysis of Energy Demand (MAED)¹⁵. These tools enable the analysis

¹⁴ S.C. Bhattacharyya, G.R. Timilsina, 2010. *A review of energy system models*, International Journal of Energy Sector Management, no. 4, vol. 4, pp. 494–518.

¹⁵ S. Battulga and S. Dhakal, 2023. *Energy Demand Modeling for the Transition of a Coal-Dependent City to a Low-Carbon City: The Case of Ulaanbaatar City*. Energies, 16(17), art. 6291; AEA, 2006. *Model for Analysis of Energy Demand (MAED-2)*. Vienna: International

of long-term energy sector development scenarios, energy demand forecasting, and the assessment of the impacts of implementing diverse energy and climate strategies. The LEAP model has gained particularly widespread application, being utilised by governmental bodies, international organisations, and research institutions for energy transition analyses at local, regional, and national levels.

An advantage of simulation models is their relatively high flexibility and their capacity to represent complex interdependencies occurring across economic sectors. They facilitate the analysis of numerous alternative development scenarios with relatively low input data requirements compared to advanced optimisation models. At the same time, the results obtained using simulation models are highly dependent on data quality and the validity of the underlying assumptions. Furthermore, these models do not identify an optimal solution; rather, they merely illustrate the consequences of specific decisions and development pathways. For this reason, they are frequently employed as decision-support tools in energy planning and public policy evaluation, complementing the insights gained from optimisation and economic models.

Atomic Energy Agency; C. Heaps, 2022. *LEAP: Low Emissions Analysis Platform*. Stockholm Environment Institute (SEI), <https://www.sei.org/tools/leap-low-emissions-analysis-platform/>.

1.2.3. Partial Equilibrium Models

These models focus on the analysis of a single market or a selected sector of the economy, under the assumption that other sectors do not undergo significant changes or that their impact on the area under analysis is negligible. Consequently, this enables a detailed representation of the processes occurring within a specific sector, such as electricity generation, district heating, transport, or the fuel market¹⁶.

In partial equilibrium models, prices as well as production and consumption volumes are determined based on the equilibrium between supply and demand within the sector under analysis. These models make it possible to evaluate the effects of fuel price fluctuations, the deployment of new technologies, environmental regulations, or energy and climate policy instruments. Unlike general equilibrium models, they do not account for all interlinkages across the economy, rendering them less demanding in terms of data requirements and computational power.

Partial equilibrium models are particularly widely used in energy sector analyses, where they facilitate a granular representation of energy generation, conversion, and

¹⁶ L. Suganthi and A.A. Samuel, 2012. *Energy models for demand forecasting—A review*. Renewable and Sustainable Energy Reviews, 16(2), pp. 1223–1240.

end-use technologies. Among the most prominent tools in this category are the PRIMES and POLES (Prospective Outlook on Long-term Energy Systems) models¹⁷.

1.2.4. Agent-Based Models

Agent-Based Models (ABM) represent a group of simulation models used for the analysis of complex systems composed of multiple autonomous entities, referred to as agents¹⁸. This concept originates from research on artificial intelligence, complex systems theory, and behavioural economics. In agent-based models, each agent represents a specific entity, such as a household, an enterprise, an energy system operator, an investor, or a public institution. Agents make decisions in accordance with established behavioural rules, responding both to environmental changes and to the actions of other system participants.

¹⁷ European Commission, 2023. *PRIMES Energy System Model. Joint Research Centre Policy Model Inventory*, <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-primess>; P. Criqui and S. Mima, 2012. *European climate—energy security nexus: A model based scenario analysis*. *Energy Policy*, 41, pp. 827–842.

¹⁸ C.M. Macal and M.J. North, 2010. *Tutorial on agent-based modelling and simulation*. *Journal of Simulation*, 4(3), pp. 151–162; P. Ringler, D. Keles and W. Fichtner, 2016. *Agent-based modelling and simulation of smart electricity grids and markets – A literature review*. *Renewable and Sustainable Energy Reviews*, 57, pp. 205–215.

The primary advantage of agent-based models is their ability to represent decision-making processes occurring at the level of individual entities and to analyse the impacts of their mutual interactions. Consequently, these models enable the study of phenomena that are difficult to capture using classical optimisation or economic models, such as the adoption of new technologies, consumer behaviour, investment processes, or the functioning of energy markets. In contrast to equilibrium models, agent-based models do not assume the existence of a market equilibrium state; rather, they allow for analysing the process of reaching equilibrium or the occurrence of disequilibrium states.

In the energy sector, ABM tools find application in, among other areas, analysing the development of distributed generation, the integration of renewable energy sources, the operation of local energy communities, demand-side management, and the simulation of electricity markets. Examples of such models include PowerACE (Power Market Model), EMLab-Generation, and MASCEM (Multi-Agent Simulator of Competitive Electricity Markets)¹⁹.

¹⁹ F. Sensfuß, M. Ragwitz and M. Genoese, 2008. *The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany*. Energy Policy, 36(8), pp. 3086–3094; M. Dahl, A. Brun and G.B. Andresen, 2017. *Using ensemble weather predictions in district heating operation and load forecasting*. Applied Energy, 193, pp. 455–465; J.-M. Lin and S.-J. Huang, 2003. *A novel algorithm for power system prediction-*

A limitation of this approach is the high complexity of the models and the necessity of acquiring large amounts of data describing the behaviour of individual agents. Furthermore, simulation results are frequently sensitive to the adopted assumptions regarding decision rules and behavioural parameters, which can complicate their validation and interpretation.

1.3. Hybrid Energy Models

Hybrid models represent an attempt to combine the advantages of various approaches utilised in energy system modelling, in particular top-down and bottom-up models²⁰. They were developed in response to the limitations inherent in both model categories. Top-down models enable the analysis of energy and climate policy impacts across the entire economy, accounting for macroeconomic interdependencies, trade, and the behaviour of market

based state estimation., [in:] 2003 IEEE Power Engineering Society General Meeting. Toronto, ON, Canada, 13–17 July 2003., pp. 747–751.

²⁰ J.-C. Hourcade et al., 2006. *Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of The Energy Journal*. The Energy Journal, 27(2_suppl), pp. 1–11; R. Gaugl, K. Walenta and S. Wogrin, 2025. *A comparative analysis of energy system modeling frameworks*. e+i Elektrotechnik und Informationstechnik, 142(7–8), pp. 508–526.

participants; however, they are characterised by limited technological granularity. Conversely, bottom-up models provide a highly detailed representation of energy technologies and processes occurring within the energy sector, yet they frequently omit broader economic impacts. Hybrid models integrate both approaches, allowing for the simultaneous consideration of technological detail and economic mechanisms.

A hybrid energy model typically comprises a macro-economic model—usually based on general equilibrium theory or econometrics—and one or more sector-specific bottom-up models. This approach enables the analysis of interactions between the economy and the energy sector, taking into account both the responses of economic entities to price and regulatory changes and the feasibility of deploying new energy technologies. An effective hybrid model should ensure technological detail, microeconomic realism, and macroeconomic consistency.

The integration of models can occur in several ways. In the case of soft linking, the outputs of one model are utilised as inputs for another model, with information exchange taking place outside the computational environment. Although relatively simple, this solution can lead to data inconsistencies. A more advanced approach is hard linking, which involves automated information exchange between models during the computational process. This allows for greater consistency of results and a superior

representation of feedback loops between the energy sector and the wider economy.

Among the most prominent hybrid models are ADAM, the National Energy Modeling System (NEMS), MARKAL-MACRO, MESSAGE-MACRO, PRIMES, IMACLIM-R, and systems integrating TIMES energy models with computable general equilibrium (CGE) models²¹. These tools are widely utilised for analysing energy transitions, assessing climate policy impacts, planning energy investments, and forecasting long-term energy system development.

The principal advantage of hybrid models is their capacity to simultaneously account for technological, economic, and environmental aspects. Consequently, they allow for a more realistic assessment of the impacts of deploying new technologies, climate policy instruments, or energy price shifts. Their main drawbacks, however, include high complexity, substantial input data requirements, and the challenges associated with integrating models built on differing theoretical assumptions. Despite these limitations, hybrid models are currently considered among the most promising tools supporting strategic energy and climate planning.

²¹ A.S. Manne and C.O. Wene, 1992. *MARKAL-MACRO: A linked model for energy-economy analysis*. Brookhaven National Laboratory (BNL), <http://www.osti.gov/servlets/purl/10131857-CK3y6E/> [access: 24.06.2026]; M. Chang et al., 2021. *Trends in tools and approaches for modelling the energy transition*. *Applied Energy*, 290, art. 116731.

1.4. AI-Based Energy Models

The dynamic development of artificial intelligence (AI) and machine learning (ML) has led to an increasing interest in their application to energy system modelling²². AI-based models utilise algorithms capable of automatically detecting patterns within large datasets, without requiring a detailed explicit representation of all physical and economic processes occurring within the system under analysis. Consequently, this enables the identification of patterns and the forecasting of highly complex and volatile phenomena. In the energy sector, artificial intelligence models are predominantly applied in forecasting electricity and heat demand, predicting generation from renewable energy sources, managing energy storage systems, optimising power grid operations, and supporting decision-making processes.

Unlike traditional energy models (such as TIMES), AI-based models do not require a detailed representation of the system's technological structure. Instead, they learn the relationships between variables based on historical data. The primary advantages of artificial intelligence

²² A. Mosavi et al., 2019. *State of the Art of Machine Learning Models in Energy Systems, a Systematic Review*. *Energies*, 12(7), art. 1301; G. Kyriakarakos, 2025. *Artificial Intelligence and the Energy Transition*. *Sustainability*, 17(3), art. 1140.

models include their ability to process exceptionally large datasets, their capacity to identify non-linear relationships, and their high forecasting performance.

However, limitations include a strong dependence on the quality of training data and the constrained interpretability of certain algorithms, frequently referred to as the "black box" problem. Furthermore, AI models may exhibit limited capability in analysing long-term scenarios for which relevant historical data do not exist. For these reasons, artificial intelligence is currently regarded primarily as a tool that complements classic energy models rather than a complete substitute for them.

CHAPTER II

THE TIMES ENERGY SYSTEM MODEL

TIMES (The Integrated MARKAL-EFOM System) is one of the most prominent bottom-up tools applied in long-term energy system modelling. It is a 4E (Energy – Economy – Environment – Engineering) model generator developed by the International Energy Agency (IEA) under the Energy Technology Systems Analysis Program (ETSAP)²³. TIMES is therefore not a model describing a single specific country, but a platform enabling users to construct local, national, and multi-regional energy system models.

Models built using TIMES function as partial equilibrium models, as their boundaries primarily encompass the fuel and energy system. They determine the equilibrium between the supply of and demand for energy carriers,

²³ R. Loulou and M. Labriet, 2008. *ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure*. Computational Management Science, 5(1), pp. 7–40.

materials, and energy services, which in economic terms corresponds to the maximisation of total producer and consumer surplus. Conversely, when the user assumes inelastic demand, the optimisation objective reduces to minimising the discounted total system cost of meeting energy service demand. From a mathematical perspective, the baseline version of the TIMES model takes the form of a linear programming problem²⁴. When specific extensions are applied, the model adopts a mixed-integer linear programming (MILP) formulation. In addition to the defined objective function, the mathematical structure of the model encompasses a series of balance equations and constraints that provide a detailed representation of the fuel-and-energy chain, ranging from primary energy extraction, processing, transmission, and distribution, to end-use energy consumption across economic sectors.

In every TIMES model, the energy system is represented as a Reference Energy System (RES), which includes technologies, energy carriers, raw materials, and other commodities such as materials, products, emissions, etc. In this context, the concept of technology is understood more broadly than individual devices; it can denote specific generation assets, installations, and end-use energy

²⁴ R. Loulou and M. Labriet, 2008. *ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure*. Computational Management Science, 5(1), pp. 7–40.

technologies, as well as processes involving extraction, import, conversion, transmission, storage, or energy use.

In the TIMES model, the primary driving factor is the demand for energy services specified by the user within a chosen development scenario. Furthermore, the user parameterises the existing fuel-and-energy infrastructure, resource potentials and extraction costs, techno-economic characteristics of new technologies, imported fuel prices, and constraints arising from energy and climate policies. Based on these inputs, the model determines the optimal structure of technologies, investments, and energy flows required to satisfy the specified energy demands while adhering to technical, economic, and environmental constraints.

A typical application of this class of models is scenario analysis, in which the sectoral, economic, and environmental impacts of alternative energy system transition pathways are evaluated.

In Polish energy system development studies, the TIMES-PL model—developed by the ESMLab team at the Faculty of Energy and Fuels, AGH University of Krakow—is of particular significance. This model represents a national implementation of the TIMES platform tailored to the operational conditions of the Polish energy system. Its main purpose is to support medium- and long-term development analyses, including the determination of the optimal

technological structure and energy investment program under scenario-defined assumptions²⁵. TIMES-PL maps the country's entire fuel-and-energy chain, encompassing energy supply, the transformation sector, and end-use sectors. The model specifically accounts for fuel sectors, power generation, district heating, refineries, and demand sectors including industry, households, transport, services, and agriculture. This scope enables the analysis not only of individual technology deployment, but also of its impacts on the energy balance, total system costs, emissions, and investment requirements²⁶.

From a practical perspective, TIMES-PL is used to develop national energy transition scenarios up to 2050, assess the costs and impacts of various energy and climate policy options, and support investment and regulatory decision-making²⁷. Within the research of the ESMLab team, the TIMES-PL model is developed alongside other system modelling tools, enabling the integration of long-term investment planning with the operational analysis of the National Power System (KSE). This includes evaluating the integration of renewable energy sources (RES), flexibility requirements, energy storage, hydrogen, district heating,

²⁵ Ibidem.

²⁶ Ibidem.

²⁷ A. Wyrwa, 2015. *An optimization platform for Poland's power sector considering air pollution and health effects*. Environmental Modelling & Software, 74, pp. 227–237.

and demand-side flexibility²⁸. ESMLab AGH also develops TIMES-PL-based models applied in sub-national spatial analyses at the regional and local levels. At these scales, local energy resources, network infrastructure, district heating and residential heating, transport, and local RES integration capabilities become particularly vital.

²⁸ A. Wyrwa et al., 2022. *A new approach for coupling the short- and long-term planning models to design a pathway to carbon neutrality in a coal-based power system*. Energy, 239, art. 122438.

CHAPTER III

REGIONAL AND LOCAL APPLICATIONS: CASE STUDIES

In recent years, regional and local modelling has gained increasing significance²⁹. This is attributable to the fact that numerous initiatives related to the energy transition are implemented by regional and local authorities. Regional energy models enable the analysis of local renewable energy resources, the evaluation of energy storage potential, and the planning of energy infrastructure development³⁰.

²⁹ F. Kachirayil et al., 2022. *Reviewing local and integrated energy system models: insights into flexibility and robustness challenges*. Applied Energy, 324, art. 119666; M. Yazdanie and K. Orehounig, 2023. *A Review and Analysis of Energy Systems Planning Models and Tools for Renewable Energy Integration in Cities*. Journal of Physics: Conference Series, 2600(4), art. 042007.

³⁰ J. Zyśk et al., 2025. *Regional-Scale Energy Modelling for Developing Strategies to Achieve Climate Neutrality*. Energies, 18(7), art. 1787.

A particularly notable direction of development is the integration of energy models with Geographic Information Systems (GIS). This integration allows for the explicit inclusion of the spatial location of buildings, energy infrastructure, renewable energy sources, and transmission networks. Consequently, it enables analyses to be conducted at the level of individual buildings, neighbourhoods, municipalities, or regions³¹.

3.1. Climate Neutrality: Policy Context

Climate neutrality denotes a state in which human-induced greenhouse gas emissions are balanced by their absorption or removal from the atmosphere, leading to net-zero emissions³². In practice, this requires a significant reduction in greenhouse gas emissions across all economic sectors, particularly in energy, building, transport, industry, and agriculture.

The importance of climate neutrality stems from observed climate changes associated with increasing atmospheric

³¹ A. Massimo et al., 2014. *Development of a Geographical Information System (GIS) for the Integration of Solar Energy in the Energy Planning of a Wide Area*. Sustainability, 6(9), pp. 5730–5744.

³² United Nations, Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Decisions adopted by the Conference of the Parties, 2016.

concentrations of greenhouse gases. The impacts include rising average air temperatures, an increased frequency of extreme weather events, ecosystem degradation, and growing threats to energy, economic, and social security. Mitigating these negative impacts requires coordinated action at international, national, regional, and local levels.

The foundational document setting global directions for climate action is the Paris Agreement, adopted at the COP21 conference in 2015³³. Its primary objective is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. Achieving these targets requires the progressive decarbonisation of the global economy and reaching climate neutrality in the second half of the 21st century.

Within the European Union, the flagship strategic policy framework guiding this transition is the European Green Deal³⁴. It aims to transform the European economy into a climate-neutral one by 2050 while maintaining economic

³³ UNFCCC, 2016. *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015. Decisions adopted by the Conference of the Parties*. FCCC/CP/2015/10/Add.1. Bonn: United Nations Framework Convention on Climate Change.

³⁴ European Commission, n.d. *The European Green Deal: Striving to be the first climate-neutral continent*, https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

competitiveness and high living standards. This strategy encompasses the expansion of renewable energy sources, energy efficiency improvements, the electrification of the economy, the development of a circular economy, and the deployment of innovative low-emission technologies³⁵. A key component in implementing the European Green Deal is the “Fit for 55” legislative package, which targets a reduction in greenhouse gas emissions of at least 55% by 2030 compared to 1990 levels³⁶. The package includes, among other measures, the reform of the EU Emissions Trading System (EU ETS), higher renewable energy targets, stricter energy efficiency requirements, and measures supporting the deployment of electromobility and low-emission transport.

The objectives of EU climate policy have been integrated into the National Energy and Climate Plan (NECP)³⁷. This document outlines the pathway for transforming the Polish

³⁵ European Commission, n.d. *Policy scenarios for delivering the European Green Deal*, https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en.

³⁶ European Commission, 2021. *‘Fit for 55’: delivering the EU’s 2030 Climate Target on the way to climate neutrality*. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2021) 550 final. Brussels: European Commission.

³⁷ Ministry of Climate and Environment, 2025. *National Energy and Climate Plan for 2030 (Update of the 2019 National Energy*

energy sector, including the development of renewable energy sources, energy efficiency improvements, greenhouse gas emission reductions, and the phased reduction of fossil fuel use. The updated NECP incorporates the heightened targets resulting from the Fit for 55 package and the long-term objective of achieving climate neutrality.

At the regional level, climate-related action is defined in the Regional Climate and Energy Action Plan for the Lesser Poland Voivodeship³⁸. Both the original document adopted in 2020 and its subsequent update emphasize the necessity to reduce greenhouse gas emissions, increase the share of renewable energy sources, and improve energy efficiency. These documents establish a framework for the region's energy transition in line with national and European policy targets.

and Climate Plan – NECP). Warsaw: Ministry of Climate and Environment.

³⁸ Marshal's Office of the Małopolska Region, 2020. *Regional Action Plan for Climate and Energy [Regionalny Plan Działań dla Klimatu i Energii]*. Annex No. 1 to Resolution No. 228/20 of the Board of the Małopolska Region of 18 February 2020. Kraków: Marshal's Office of the Małopolska Region; Marshal's Office of the Małopolska Region, 2026. *Regional Action Plan for Climate and Energy up to 2030 with a Perspective to 2050 – Update [Regionalny Plan Działań dla Klimatu i Energii do roku 2030 z perspektywą do 2050 – aktualizacja]*. Annex No. 1 to Resolution No. 286/26 of the Board of the Małopolska Region of 10 February 2026. Kraków: Marshal's Office of the Małopolska Region.

Achieving climate neutrality yields not only environmental but also economic and social benefits. Phasing down fossil fuel consumption improves air quality, reduces reliance on imported energy commodities, and enhances energy security. Simultaneously, the deployment of renewable energy sources, energy storage systems, and advanced energy technologies creates new opportunities for economic development and strengthens economic resilience against energy price volatility and geopolitical shifts. Consequently, climate neutrality represents one of the most critical development vectors for contemporary economies and energy systems.

3.2. Aim and Scope of the Regional Study

The primary objective of this study was to conduct scenario analyses regarding the development of the energy system of the Lesser Poland Voivodeship over the period 2020–2052, and to identify optimal energy investment pathways under varying socio-economic and climate development assumptions. Particular attention was paid to evaluating the impact of different ambition levels regarding greenhouse gas emission reductions and the pursuit of climate neutrality for the region. As part of the research, four development scenarios were formulated: Stagnation, National, Małopolska (Regional), and Optimistic.

The model encompassed the entire energy system of the Lesser Poland Voivodeship, accounting for energy supply and processing sectors, electricity and district heating generation, as well as the building sector, transport, industry, services, agriculture, and other energy transformation processes. The analysis also incorporated the capacity of forest ecosystems to sequester carbon dioxide. The detailed scope of the modelling and the structure of the analysed sectors are presented in Table 4.1.

Table 4.1. Sectors covered by the modelling system

Sector	Activities / Sub-sectors
Energy	Emissions from fossil fuel consumption for electricity and heat generation.
Buildings	Emissions from fuel consumption in public (municipal) buildings, non-public (non-municipal) buildings, and residential buildings (single-family, multi-family, and associated non-residential structures, e.g. garages).
Transport	Emissions from fuel consumption in public transport (including rail and municipal transit) and private transport (including infrastructure).
Economy / Industry & Waste	Waste management and emissions from landfilling; water and wastewater management and emissions from wastewater treatment; industry, process emissions from industrial production, and emissions from fuel combustion across the commercial/industrial sector.
Agriculture	Emissions from crop production (including synthetic fertilisers), emissions from livestock farming (including manure management), and emissions from fuel consumption.
Forestry & Land Use (LULUCF)	Emissions from fuel consumption and sequestration by forests.

Source: authors' own elaboration based on the data and modelling described in the text.

3.2.1. Sectoral Representation in TIMES-MAŁOPOLSKA

The TIMES-MAŁOPOLSKA model was developed as a decision-support tool for planning and analysing the development of the energy system of the Lesser Poland Voivodeship. Its structure is built upon the TIMES (The Integrated MARKAL-EFOM System) model generator, developed under the auspices of the International Energy Agency (IEA) and widely applied for energy system modelling at local, regional, national, and international scales³⁹.

The model enables medium- and long-term scenario analyses aimed at identifying optimal energy transition pathways for the region. Specifically, it determines the most cost-effective technological structure and investment roadmap under given socio-economic and environmental development conditions. The core objective of the model is to ensure adequate generation capacity to meet projected

³⁹ S. Allena-Ozolina et al., *Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling*, [in:] 2020 IEEE 61th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia 2020, pp. 1–7; F. Amorim et al., 2014. *Electricity decarbonisation pathways for 2050 in Portugal: A TIMES (The Integrated MARKAL-EFOM System) based approach in closed versus open systems modelling*, *Energy*, vol. 69, pp. 104–112; A. Wyrwa et al., 2021. *A new approach for coupling the short- and long-term planning models to design a pathway to carbon neutrality in a coal-based power system*, *Energy*, vol. 122438.

energy demand while minimising total system operating and capital costs.

During the optimization process, the model determines the type, capacity, and timing of new energy investments across the supply, transformation, and end-use demand sectors. The objective function minimises the sum of discounted total energy system costs across the entire planning horizon. The model structure incorporates qualitative data describing the energy system layout, available technologies, and energy carriers, alongside quantitative data encompassing techno-economic performance parameters, fuel prices, and emission factors. Energy producers are represented by discrete technological modules, whereas end-users are aggregated into energy service demand categories.

A fundamental assumption of the model is that the market operates under conditions of perfect competition and perfect foresight regarding future system parameters, such as fuel prices, technology cost trajectories, and environmental constraints. Nevertheless, additional real-world policy constraints can be introduced, including greenhouse gas emission ceilings, renewable energy targets, or energy efficiency mandates.

In the power and heat sector, the model explicitly depicts existing generation units down to individual power plants, combined heat and power (CHP) plants, and district heating plants with an installed thermal capacity exceeding 10 MW. Within the region, this encompasses one thermal

power plant, four CHP plants, and 22 utility and industrial heating plants. The model also accounts for the region's sole operational pumped-storage hydropower plant at Niedzica (with a turbine capacity of 92 MWe and a pumping capacity of 89 MWe).

A suite of candidate future energy technologies is defined using key techno-economic parameters: specific capital expenditure (CAPEX), fixed and variable operation and maintenance costs (OPEX), thermal/electrical efficiency, CO₂ emission factors, and technical lifetimes. Variable OPEX excludes fuel costs, as fuel procurement is modelled as a separate cost stream. The candidate technology portfolio aligns closely with the options outlined in the National Energy and Climate Plan (NECP)⁴⁰. Reflecting rapid technological maturity, specific CAPEX for renewable energy technologies is assumed to decrease gradually through 2050, with the steepest cost reductions assigned to solar photovoltaics (PV). To accommodate growing shares of variable renewables, the model allows investment in utility-scale electricity storage assets. Alongside the existing pumped-storage capacity, the set of new technologies in the TIMES-MAŁOPOLSKA model also includes cutting-edge

⁴⁰ Ministry of Climate and Environment, 2025. *National Energy and Climate Plan for 2030 (Update of the 2019 National Energy and Climate Plan – NECP)*. Warsaw: Ministry of Climate and Environment.

energy storage solutions. The power grid is discretised into three voltage levels: high voltage (HV), medium voltage (MV), and low voltage (LV). Electricity generation can feed into any level, while transmission and transformation processes model power flows from higher to lower voltage levels, accounting for line and transformer losses. Households and agriculture are restricted to the LV network; energy imports occur exclusively at the HV level, whereas transport and service sectors do not draw directly from the HV grid. End-user electricity pricing incorporates transmission and distribution tariffs estimated from published schedules of PSE S.A. and TAURON Dystrybucja S.A.⁴¹. Fuel import and wholesale supply costs through 2050 are sourced from authoritative projections⁴². Carbon price

⁴¹ Energy Regulatory Office, 2019. *Tariff of Polskie Sieci Elektroenergetyczne S.A. [Taryfa Polskich Sieci Elektroenergetycznych S.A.]. Decision of the President of the Energy Regulatory Office No. DRE.WPR.4211.4.16.2019.BTS/JSz of 17 December 2019.* Warsaw: Energy Regulatory Office, <https://bip.ure.gov.pl/download/3/11787/PSE.pdf> [access: 12.09.2022]; Energy Regulatory Office, 2024. *Tariff for Electricity Distribution Services of TAURON Dystrybucja S.A. for 2025 [Taryfa dla usług dystrybucji energii elektrycznej TAURON Dystrybucja S.A. na rok 2025]. Decision of the President of the Energy Regulatory Office No. DRE.WRE.4211.47.9.2024. ASa1 of 16 December 2024.* Warsaw: Energy Regulatory Office, <https://bip.ure.gov.pl/bip/taryfy-i-inne-decyzje-b/energia-elektryczna/4570,Taryfy-opublikowane-w-2024-r.html> [access: 18.08.2025].

⁴² Ministry of Climate and Environment, 2021. *Conclusions from Forecast Analyses for the Energy Sector [Wnioski z analiz*

trajectories under the EU Emissions Trading System (EU ETS and ETS II) align with NECP assumptions⁴³.

Renewable energy technologies encompass both centralized and distributed utility-scale installations. Investment decisions regarding new capacity are driven by demand projections, retirement schedules of legacy assets, resource availability, technology cost learning curves, and carbon allowance prices.

The transport sector covers passenger and freight movements across road and rail modes. Passenger transport encompasses passenger cars, buses, trams, motorcycles, and passenger rail, while freight is handled via heavy goods road transport and rail freight. Emergency and utility

prognostycznych dla sektora energetycznego]. Warsaw: Ministry of Climate and Environment; Główny Instytut Górnictwa, 2013. *Coal for the Polish Power Sector in the Perspective of 2050 – Scenario Analyses [Węgiel dla polskiej energetyki w perspektywie 2050 roku – analizy scenariuszowe]*. Katowice: Główny Instytut Górnictwa; IEA, 2020. *Levelised Cost of Electricity Calculator: Interactive table of LCOE estimates from Projected Costs of Generating Electricity 2020*. Paris: International Energy Agency, <https://www.iea.org/articles/levelised-cost-of-electricity-calculator> [access: 26.07.2021]; Ministry of Climate and Environment, 2025. *National Energy and Climate Plan for 2030 (Update of the 2019 National Energy and Climate Plan – NECP)*. Warsaw: Ministry of Climate and Environment.

⁴³ Ministry of Climate and Environment, 2025. *National Energy and Climate Plan for 2030 (Update of the 2019 National Energy and Climate Plan – NECP)*. Warsaw: Ministry of Climate and Environment.

vehicles (fire engines, ambulances, etc.) are also represented. Transport technologies are differentiated by fuel type, including liquid fossil fuels, liquefied petroleum gas (LPG), and electricity. Gasoline and diesel blends account for mandated biofuel blending ratios. Demand for transport services, expressed in passenger-kilometres (pkm) and tonne-kilometres (tkm), is specified exogenously over the model horizon; baseline 2020 values stood at 25,761 million pkm and 33,170 million tkm, respectively. Vehicle annual mileages and specific fuel consumptions are disaggregated by vehicle class and drivetrain⁴⁴. Occupancy rates, payload factors, and road-class distributions are derived from empirical mobility surveys⁴⁵. Vehicle purchase cost trajectories

⁴⁴ J. Waśkiewicz and P. Pawlak, 2017. *Expert Forecasts of Changes in Road Transport Sector Activity* [Proгноzy eksperckie zmian aktywności sektora transportu drogowego]. Warsaw: KOBiZE / IOŚ-PIB.

⁴⁵ Eurostat, 2022. *Passenger road transport on national territory, by type of vehicles registered in the reporting country*. Luxembourg: Eurostat, https://ec.europa.eu/eurostat/databrowser/view/ROAD_PA_MOV/default/table?lang=en [access: 05.06.2022]; Eurostat, 2022. *Railway transport measurement – passengers*. Luxembourg: Eurostat, https://ec.europa.eu/eurostat/databrowser/view/rail_pa_quartal/default/table?lang=en [access: 01.09.2022]; Eurostat, 2022. *Goods transported by type of transport*. Luxembourg: Eurostat, https://ec.europa.eu/eurostat/databrowser/view/RAIL_GO_TYPEPAS__custom_3599985/default/table?lang=en [access: 05.06.2022]; Kraków City Hall, 2021. *Report on the State of the City of Kraków 2020* [Raport o stanie Miasta 2020]. Kraków: Kraków City Hall (UMK); European Commission, n.d. *TREMOVE: an EU-wide transport model*. Brussels: European Commission, <https://>

up to 2050 assume cost reductions for electric and hydrogen fuel cell vehicles, whereas internal combustion engine vehicle costs remain flat⁴⁶. Energy carrier prices reflect imported crude/refined products as well as domestically

ec.europa.eu/environment/archives/air/models/tremove.htm; Eurostat, 2022. *Road traffic by type of vehicle (million Vkm). Luxembourg: Eurostat*, <http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do> [access: 05.02.2022]; J. Zieliński et al., 2021. *Synthesis of the Results of General Traffic Measurement (GPR) 2020/21 on the Non-urban National Road Network [Synteza wyników GPR 2020/21 na zamiejskiej sieci dróg krajowych]*. Warsaw: General Directorate for National Roads and Motorways (GDDKiA); J. Zieliński et al., 2021. *Synthesis of the Results of General Traffic Measurement (GPR) 2020/21 on the Non-urban Regional Road Network [Synteza wyników GPR 2020/21 na zamiejskiej sieci dróg wojewódzkich]*. Warsaw: General Directorate for National Roads and Motorways (GDDKiA); Tarnów City Hall, 2021. *Report on the State of the City of Tarnów 2020 [Raport o stanie miasta 2020]*. Tarnów: Tarnów City Hall; Office of Rail Transport, 2019. *Railways in Voivodeships – Utilisation and Transport Policy [Kolej w województwach – wykorzystanie i polityka transportowa]*. Warsaw: Office of Rail Transport (UTK); Office of Rail Transport, 2021. *Summary 2021: Passenger and Freight Transport [Podsumowanie 2021: Przewozy pasażerskie i towarowe]*. Warsaw: Office of Rail Transport (UTK); Office of Rail Transport, 2021. *Passenger Railways in Voivodeships – Dynamics of Changes in 2010–2020 [Koleje pasażerskie w województwach – dynamika zmian w latach 2010–2020]*. Warsaw: Office of Rail Transport (UTK); NewRail, 2023. *D-RAIL Project*. Newcastle: NewRail – Centre for Railway Research, Newcastle University.

⁴⁶ European Commission Joint Research Centre, 2023. *PRIMES-TREMOVE Transport Model*. Ispra: Joint Research Centre (JRC), <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-primess-tremove>.

produced or converted carriers (e.g. electricity). A public charging infrastructure ratio of 1 charger per 10 battery electric vehicles is assumed. Passenger car service life is set at 25 years to reflect the observed fleet dynamics in Poland (where the average operational vehicle age is 16–17 years); other vehicle categories are assigned operational lifetimes ranging from 12 to 20 years.

The residential sector is disaggregated into three dwelling archetypes: single-family houses, terraced houses, and multi-family apartment buildings. Each building type is represented by a simplified physical model capturing dwelling count, floor heights, window-to-wall ratios, and envelope surface areas. Thermal energy demand for space heating, domestic hot water, and appliance electricity consumption is calculated based on building age cohorts and thermal envelope performance standards. Thermal retrofit options and associated capital costs are explicitly modelled⁴⁷.

⁴⁷ Statistics Poland, 2021. *Energy Consumption in Households – Estimates for 2019* [Zużycie energii w gospodarstwach domowych – szacunki danych za rok 2019]. Warsaw: Statistics Poland (GUS); Statistics Poland, 2021. *Energy Consumption in Households – Estimates for 2020* [Zużycie energii w gospodarstwach domowych – szacunki danych za rok 2020]. Warsaw: Statistics Poland (GUS), <https://dane.gov.pl/pl/dataset/2061,szacunki-danych-o-zuzyciu-energii-w-gospodarstwach/resource/38941/table> [access: 01.10.2022]; Statistics Poland, 2021. *Housing Economy and Municipal Infrastructure in 2020* [Gospodarka mieszkaniowa i infrastruktura

The commercial and public services sector is structured analogously to the residential sector, with floor area serving as the primary driver of space heating and cooling demand.

The industrial sector explicitly models individual CHP and heating plants with thermal/electrical capacities exceeding 10 MW, while smaller facilities are aggregated. Industrial facilities emitting over 100 tonnes of CO₂ annually are grouped into seven primary sub-sectors (with their 2020 share of industrial CO₂ emissions, excluding industrial energy plants, shown in parentheses): food processing (19.5%), chemicals (13.6%), paper and wood products (1.2%), metallurgy (44.5%), non-metallic mineral products excluding cement (9.5%), cement manufacturing alone (0.7%), machinery (3.8%), and other minor industrial facilities emitting under 100 tonnes of CO₂/year (7.1%). Due to heterogeneous process characteristics, industrial decarbonisation is modelled using marginal abatement cost curves expressed per tonne of CO₂ avoided⁴⁸.

komunalna w 2020 r.]. Warsaw: Statistics Poland (GUS); M. Potyra, 2016. *Household Projection for the Years 2016–2050 [Prognoza gospodarstw domowych na lata 2016–2050]*. Warsaw: Statistics Poland (GUS); IWU, 2022. *Residential Building Typology: Poland. Darmstadt: Institut Wohnen und Umwelt GmbH*, <https://episcopus.eu/building-typology/country/pl/> [access: 03.06.2022]; A. Chiodi et al., 2017. *JRC-EU-TIMES 2017 Upgrade – Buildings and Heating and Cooling Technologies*. Petten: European Commission Joint Research Centre.

⁴⁸ J. Zyśk et al., 2023. *Małopolska Towards Climate Neutrality – Modelling Studies [Małopolska ku neutralności klimatycznej – badania modelowe]*. Kraków: AGH University of Krakow;

The region's single operational cement plant as of 2023 is explicitly parameterised as a standalone entity.

The agricultural sector captures major greenhouse gas sources, including enteric fermentation, livestock manure management, agricultural soil management, residue decomposition/burning, and fuel consumption in machinery. Given the high uncertainty surrounding livestock population trends and the absence of explicit policy targets at the national or EU level, livestock populations are held constant at 2020 baseline levels. In 2020, the regional agricultural fleet comprised 8,552 combine harvesters and 106,391 tractors. Fleet turnover is modelled through the progressive replacement of conventional internal combustion machinery with biodiesel and battery-electric power units⁴⁹.

Forestry and Land Use (LULUCF) are categorized into three pools: existing mature forests, regenerated forests, and afforestation on former non-forest land. This enables the accounting of forest management on net regional carbon balances. In 2020, forest cover in the Lesser Poland Voivodeship stood at 434,482 ha (28.75% of regional land

J. Zyśk et al., 2025. *Regional-Scale Energy Modelling for Developing Strategies to Achieve Climate Neutrality*. *Energies*, 18(7), art. 1787.

⁴⁹ Statistics Poland, n.d. *Local Data Bank [Bank Danych Lokalnych]*. Warsaw: Statistics Poland (GUS), <https://bdl.stat.gov.pl/bdl/dane/podgrup/temat>.

area)⁵⁰. Historical annual afforestation rates for 2018–2020 were 19.32 ha, 54.53 ha, and 27.54 ha, respectively, alongside approximately 1,300 ha/year of natural/assisted forest regeneration following harvests. Age-dependent net CO_2 sequestration rates are assigned: 2.224 t CO_2 /ha/year for stands older than 5 years, and 3.916 t CO_2 /ha/year for stands aged 5 years or younger⁵¹. Afforestation establishment costs are set at 20,000 PLN/ha⁵².

The baseline 2020 regional greenhouse gas inventory incorporates carbon dioxide CO_2 , methane CH_4 , and nitrous oxide N_2O . Carbon dioxide dominates total emissions at 16,391 kt. Methane emissions totaled 54.53 kt, and nitrous oxide emissions reached 1.76 kt originating predominantly from agriculture and waste management.

⁵⁰ Statistics Poland, n.d. *Local Data Bank [Bank Danych Lokalnych]*. Warsaw: Statistics Poland (GUS). <https://bdl.stat.gov.pl/bdl/dane/podgrup/temat>.

⁵¹ KOBiZE, 2024. *National Inventory Report 2024: Common Reporting Format (CRF) Tables for 1988–2022*. Submitted to EU EIONET on 15 March 2024. Warsaw: National Centre for Emissions Management (KOBiZE / IOŚ-PIB).

⁵² Ministry of Climate and Environment, 2023. *National Programme for Augmentation of Forest Cover [Krajowy Program Zwiększania Lesistości]*. Warsaw: Ministry of Climate and Environment; K. Kurowska and H. Kryszk, 2017. *Profitability of afforestation of agricultural land under the Rural Development Programme [Opłacalność zalesień gruntów rolnych w ramach Programu Rozwoju Obszarów Wiejskich]*. Sylwan, 161(12), pp. 1035–1045.

The 2020 regional energy balance constructed for model calibration indicates a gross primary energy supply of 278,758 TJ. Primary energy sources comprise hard coal (95,334 TJ), crude oil and refined petroleum products (78,681 TJ), natural gas and gaseous fuels (54,165 TJ), renewable sources and biofuels (22,723 TJ), and net imported electricity (27,855 TJ). Indigenous extraction is dominated by hard coal (67,956 TJ) and renewables (22,723 TJ), whereas refined oil products (78,425 TJ), natural gas (50,119 TJ), and net power imports (27,855 TJ) are supplied via inter-regional inflows. Primary energy consumption in transformation processes (power and district heat generation) totaled 61,528 TJ, dominated by hard coal (48,500 TJ), yielding 17,882 TJ of district heat and 17,411 TJ of electricity. Own use by energy plants consumed 744 TJ of heat and 1,508 TJ of power, with distribution losses amounting to 2,032 TJ for heat and 636 TJ for electricity.

Total final energy consumption (TFEC) reached 251,173 TJ. The largest consumption block comprises the combined buildings and commercial sectors (113,064 TJ), with residential buildings alone accounting for 101,301 TJ, supplied by natural gas (24,821 TJ), hard coal (21,354 TJ), renewables (15,120 TJ), district heat (12,641 TJ), and electricity (23,385 TJ). Industrial energy consumption totaled 72,806 TJ, led by natural gas (24,292 TJ), hard coal (24,280 TJ), and electricity (18,353 TJ). The transport sector remains

heavily dependent on petroleum fuels (60,921 TJ out of 65,303 TJ TFEC), with minor shares of renewables (2,658 TJ), natural gas (862 TJ), and electricity (862 TJ). Agriculture and forestry consumed 11,763 TJ, predominantly refined petroleum products (9,638 TJ) for mobile machinery.

Sectoral emissions in 2020 show that the power and heat sector was the single largest contributor to CO₂ emissions (5,101 kt, followed by transport (3,933 kt CO₂, industry (3,872 kt CO₂, and residential/commercial buildings (3,584 kt CO₂. Agriculture emitted 867 kt CO₂, though its climate impact is dominated by methane (17.85 kt CH₄ and nitrous oxide (1.37 kt N₂O. Methane emissions were led by waste/industrial processes (30.14 kt CH₄ and livestock enteric/manure sources. Nitrous oxide emissions stemmed mainly from synthetic nitrogen fertilizer application and soil management, with a minor contribution from industrial waste (0.39 kt N₂O. Forest ecosystems sequestered approximately 966 kt CO₂, partially offsetting gross emissions.

Regional renewable energy potentials were parameterised as follows: geothermal heat potential is estimated at 5,160 TJ/year, mine water heat recovery at 475 TJ/year, solar thermal collectors at 3,019 TJ/year, and heat pumps at 48,416 TJ/year⁵³. For renewable power, solar PV exhibits the largest technical potential (30,918 TJ/year), followed by

⁵³ A. Sowizdżał et al., 2022. *Assessment of Renewable Energy Potential in the Małopolska Voivodeship [Ocena potencjału OZE w województwie małopolskim]*. Kraków: AGH University of Krakow

onshore wind (5,643 TJ/year) and small hydro (540 TJ/year). Biomass and biogas potentials contribute up to 16,871 TJ/year and 3,616 TJ/year, respectively.

3.2.2. Scenario Design

To evaluate potential transition pathways for the energy system of the Lesser Poland Voivodeship, four scenarios were formulated, differing in their level of climate and energy ambitions: Stagnation, Małopolska, National, and Optimistic.

The Stagnation scenario serves as a baseline counterfactual, assuming limited intervention regarding energy transition and climate mitigation. No additional greenhouse gas emission reduction targets are enforced. Final energy consumption remains close to 2020 baseline levels, with the share of renewable energy sources capped at a maximum of 20% of gross final energy consumption. This scenario reflects a trajectory in which energy system development relies primarily on historical trends and minimal modernisation efforts.

The Małopolska scenario is aligned with the regional targets set out in the Regional Action Plan for Climate and

Energy for the Małopolska Region (RACPE)⁵⁴. It stipulates a reduction in greenhouse gas emissions of at least 40% by 2030 compared to 1990 levels, and the achievement of climate neutrality by 2050. Furthermore, it mandates an increase in the renewable energy share to a minimum of 32% of gross final energy consumption, alongside an 8.81% reduction in final energy demand relative to the PRIMES 2020 reference projections⁵⁵. This scenario mirrors the implementation of regional climate and energy policies.

The National scenario is derived from the assumptions and projections articulated in the National Energy and Climate Plan (NECP)⁵⁶. This variant assumes a greenhouse gas emission reduction of 50.4% by 2030 and 70% by 2040 relative to 1990 levels. It also projects an increase in the share of renewable energy sources to 32.6% by 2030 and 58.4% by 2040. In terms of energy efficiency, it fore-

⁵⁴ Marshal's Office of the Małopolska Region, 2020. *Regional Action Plan for Climate and Energy [Regionalny Plan Działań dla Klimatu i Energii]*. Annex No. 1 to Resolution No. 228/20 of the Board of the Małopolska Region of 18 February 2020. Kraków: Marshal's Office of the Małopolska Region.

⁵⁵ European Commission Joint Research Centre, n.d. *PRIMES Energy System Model*. *Ispra: Joint Research Centre (JRC)*, <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-prim.es>.

⁵⁶ Ministry of Climate and Environment, 2025. *National Energy and Climate Plan for 2030 (Update of the 2019 National Energy and Climate Plan – NECP)*. Warsaw: Ministry of Climate and Environment.

sees a decrease in final energy consumption of 12.8% and primary energy consumption of 14.4% compared to the PRIMES 2020 reference baseline. This scenario illustrates a decarbonisation trajectory consistent with national energy policy directives.

The Optimistic scenario represents the most ambitious transformation pathway and is built upon the European Union climate targets established under the "Fit for 55" legislative package⁵⁷. It assumes a minimum net greenhouse gas emission reduction of 55% by 2030 compared to 1990 levels, and the attainment of full climate neutrality by 2050. Concurrently, it projects an increase in the share of renewables to at least 42.5% of gross final energy consumption and an 11.7% reduction in final energy demand relative to the PRIMES 2020 reference scenario. This trajectory reflects an accelerated deployment of advanced low-carbon energy technologies and deep decarbonisation across all economic sectors.

⁵⁷ European Commission, 2021. "Fit for 55" delivering the EU's 2030 Climate Target on the way to climate neutrality. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2021) 550 final. Brussels: European Commission.

3.2.3. Regional Modelling Results

Figure 4.1 illustrates the projected trajectories of CO₂ emissions in the Lesser Poland Voivodeship over the period 2020–2050 across the four analysed scenarios: Stagnation, National, Małopolska, and Optimistic.

The smallest emission reductions occur in the Stagnation scenario, in which total annual emissions plateau at approximately 11 Mt CO₂ by 2050. Nevertheless, even under this baseline variant, a substantial contraction in power sector emissions is observed despite the absence of explicit decarbonisation mandates. This drop stems from a structural reduction in coal consumption, driven not by policy constraints but by economic mechanisms: local hard coal-fired power generation loses cost-competitiveness relative to electricity imports from outside the voivodeship (Fig. 4.2). The levelised cost of coal-fired electricity remains elevated due to baseline fuel procurement costs combined with the financial burden of compliance under the EU Emissions Trading System (EU ETS). Consequently, transport, industry/economy, and the building sector remain the dominant sources of residual emissions in the Stagnation scenario, underscoring the limited breadth of voluntary market-driven transition.

Substantially deeper decarbonisation is achieved in the National scenario, where total emissions drop

to approximately 6 Mt CO₂ by 2050. These reductions are primarily driven by the transformation of the power sector and building heating systems, resulting from widespread energy efficiency improvements, accelerated electrification, and a higher penetration of renewable energy sources (RES).

The most decisive trajectories are demonstrated by the Małopolska and Optimistic scenarios, where total regional emissions decline from approximately 17 Mt CO₂ in 2020 to near-zero levels by 2050. Sharp abatement is recorded across the building, energy supply, and industrial sectors, leaving the transport sector as the primary source of hard-to-abate residual emissions. Across all four scenarios, the Land Use, Land-Use Change and Forestry (LULUCF) sector maintains a negative net emissions balance, acting as a persistent carbon sink that partially offsets residual gross emissions from other economic sectors.

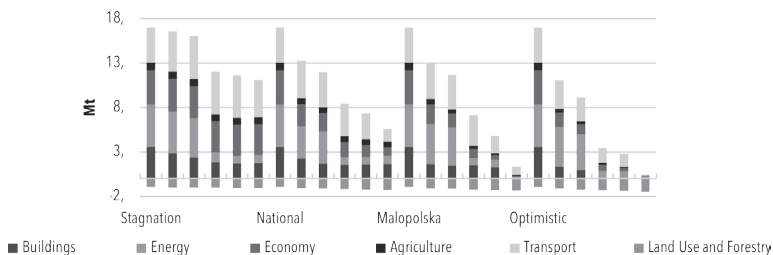


Fig. 4.1. CO₂ emissions across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

The reduction of greenhouse gas emissions, the phase-out of fossil fuels, and the structural transformation of individual sectors also contribute to a significant mitigation of other air pollutants (SO₂, NO_x, and particulate matter), including fine particulate matter PM_{2.5} – suspended particles with an aerodynamic diameter of up to 2.5 µm), which ranks among the most harmful air pollutants due to its detrimental impact on human health. Across all analysed scenarios, a substantial decline in PM_{2.5} emissions is recorded over the period 2020–2050 (Fig. 4.2).

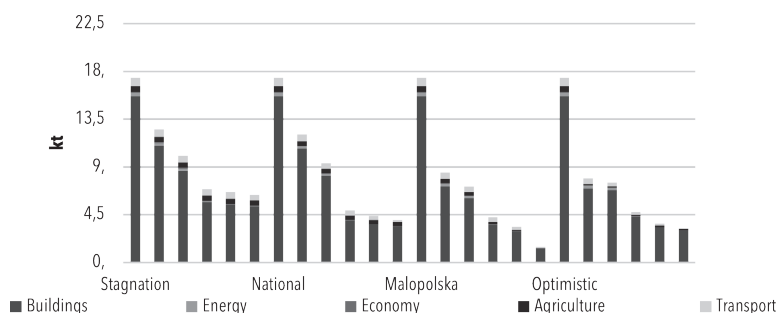


Fig. 4.2. PM_{2.5} emissions across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

However, the magnitude of this reduction depends directly on the level of ambition embedded in the energy transition pathway. The smallest emission drop is achieved in the Stagnation scenario, where PM_{2.5} emissions

decreased by 63% relative to the base year. Substantially deeper reductions are obtained in the National and Optimistic scenarios, whereas the most pronounced abatement was observed in the Małopolska scenario, where PM_{2.5} emissions dropped by 91%.

The installed electrical capacities are presented in Fig. 4.2., while electricity production and imports are shown in Fig. 4.2. In the Stagnation scenario, despite the absence of additional climate and energy targets, significant development of photovoltaics and natural gas-based sources is observed. A slight increase also applies to installations based on biogas, biomass, and wind energy. By 2045, coal-fired capacity completely disappears. Even in the absence of emission constraints, the model eliminates these units due to their high operational costs. The elevated generation costs in coal-fired power plants and combined heat and power (CHP) plants, resulting primarily from the cost of purchasing CO₂ emission allowances, make electricity imports more cost-effective than domestic generation from coal sources.

In the Małopolska scenario, dynamic growth of photovoltaics is projected, with its installed capacity reaching approximately 6 GW by 2050. Concurrently, the capacity of gas-fired units increases significantly, exceeding 2 GW by the end of the analysed period. By 2035, the first Small Modular Reactor (SMR) also appears in the voivodeship. Owing

to the limited potential of local renewable energy sources, internal electricity generation is insufficient to cover the region's demand fully, which necessitates maintaining electricity imports. Substantial electricity imports also occur in the National and Optimistic scenarios. In the Małopolska scenario, electricity imports reach approximately 50 PJ, whereas domestic production accounts for around 45 PJ. Photovoltaic installations (around 21 PJ) and SMRs (around 8 PJ) account for the largest shares of regional power generation. Across all analysed scenarios, the complete phase-out of coal-fired power generation occurs around 2040. Simultaneously, a progressive process of electrification across end-use sectors is observed. Consequently, electricity demand in the voivodeship increases from approximately 43 PJ in 2020 to 75 PJ, 96 PJ, 76 PJ, and 82 PJ by 2050 under the Stagnation, Małopolska, National, and Optimistic scenarios, respectively.

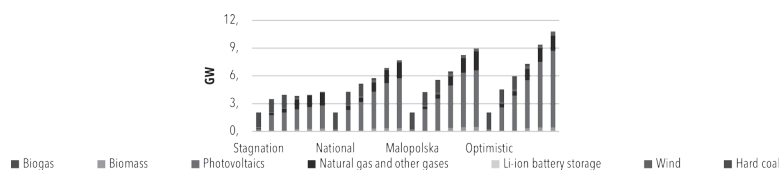


Fig. 4.3. Installed electrical capacities across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

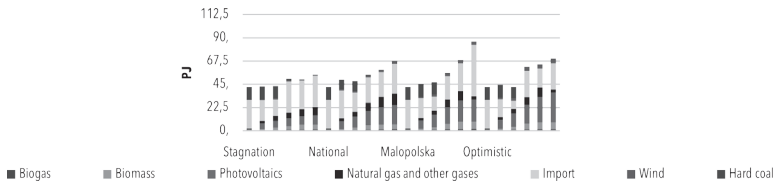


Fig. 4.4. Electricity generation and imports across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

The building sector encompasses both residential buildings, referred to hereinafter as the household sector (disaggregated in the model into multi-family buildings, terraced single-family houses, and detached single-family houses), and commercial and public service buildings. Households account for a substantial share of final energy consumption, directly influencing residents' quality of life, space heating costs, and ambient air quality. It is precisely within this sector that a significant portion of measures aimed at alleviating energy poverty, enhancing energy efficiency, and reducing air pollutant emissions from individual heating sources is concentrated.

In 2020, the dominant energy carriers in households were biomass, hard coal, natural gas, district heat, and electricity (Fig. 4.3.). In the Stagnation scenario, hard coal utilization is assumed to persist until approximately 2035, after which it is gradually substituted by electricity, biomass, natural gas, and district heat. By 2050, compared

to 2020 baseline levels, the consumption of electricity, biomass, natural gas, and district heat increases by 36%, 28%, 28%, and 31%, respectively, whereas total final energy consumption decreases by approximately 10%.

Substantially deeper structural shifts are foreseen in the Małopolska scenario. Between 2020 and 2050, overall energy consumption in households drops by 42%, reaching a level of approximately 44 PJ in 2050. Near-complete phase-out of fossil fuels occurs, with electricity and district heat emerging as the dominant energy carriers. Hard coal is phased out from households well before 2030. In the National scenario, household energy consumption likewise decreases to approximately 44 PJ by 2050, accompanied by a rising share of electricity, district heat, and natural gas.

The most pronounced transformations take place under the updated Optimistic scenario. Household energy consumption declines from 54 PJ in 2030 to 42 PJ in 2050. Electricity becomes the primary energy carrier, its share reaching 43%, followed by district heat (31%) and biomass (22%). A pivotal element of this residential transformation is the deployment of heat pumps. The installed electrical capacity of these devices expands between 2020 and 2050 by 365%, 488%, 394%, and 610% under the Stagnation, Małopolska, National, and Optimistic scenarios, respectively. These results demonstrate that heating electrification alongside building envelope energy efficiency improvements will

constitute key drivers for attaining the voivodeship's climate targets.

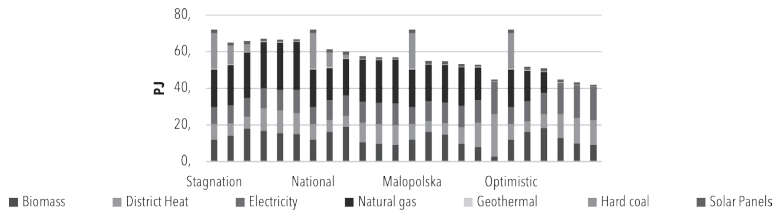


Fig. 4.5. Heat generation sources in the household sector across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

Investment costs are presented in Fig. 4.4. They encompass capital expenditures associated with the transformation of individual sectors of the economy. In the transport sector, the costs account for the purchase of new vehicles and the expansion of charging infrastructure. In agriculture, investment costs include the procurement of new machinery and the implementation of new technologies. In the building sector, the costs cover the acquisition of new energy equipment as well as thermal modernization expenditures, whereas in the energy sector, investments comprise new generation sources and energy storage systems. In forestry, afforestation costs are included, while in the industrial/economy sector, costs relate to greenhouse gas emission reductions, disaggregated by industry branch and depth

of modernization (shallow, medium, and deep). Potential costs associated with the expansion of power transmission and distribution grids were not included in the analysis.

Cumulative investment costs over the 2023–2052 period amount to €117 billion (2020 prices) in the Stagnation scenario. In the Małopolska scenario, total capital expenditures likewise reach €117 billion (2020 prices). The breakdown by sector is as follows: buildings – 16%, energy – 11.0%, industry/economy – 0.9%, forestry – 0.3%, agriculture – 4.4%, and transport – 67.5%. The National scenario projects total investment costs at 108 billion PLN. The lowest total investment costs are obtained in the updated Optimistic scenario, where they amount to €94 billion (2020 prices).

It should be emphasized that transport sector costs also include vehicle purchases that would occur independently of implemented climate, energy, or transport policies. Investment costs in transport amount to €92, €74, €79, and €53 billion (2020 prices) under the Stagnation, Małopolska, National, and Optimistic scenarios, respectively. The results indicate that replacing internal combustion engine vehicles with low-emission vehicles can lead to a reduction in overall investment costs, primarily due to the anticipated decrease in the cost of electric technologies in subsequent decades. In the Optimistic scenario, the total vehicle fleet size also decreases, as trips are increasingly undertaken via public transport.

Regarding the industrial/economy sector, only estimated greenhouse gas emission reduction costs were included. It should be borne in mind that enterprises, irrespective of climate policy, incur expenditures related to business development, technology modernization, energy efficiency improvements, and operational cost reductions. Furthermore, investments in industrial heating plants and combined heat and power (CHP) plants were allocated to the energy sector.

Average annual investment costs per capita in the Lesser Poland Voivodeship amount to €1,187 (2020 prices) in the Stagnation scenario, €1,189 (2020 prices) in the Małopolska scenario, €1,096 (2020 prices) in the National scenario, and €952 (2020 prices) in the updated Optimistic scenario. Excluding the transport sector, these annual per capita values stand at €255, €386, €340, and €412 (2020 prices), respectively.

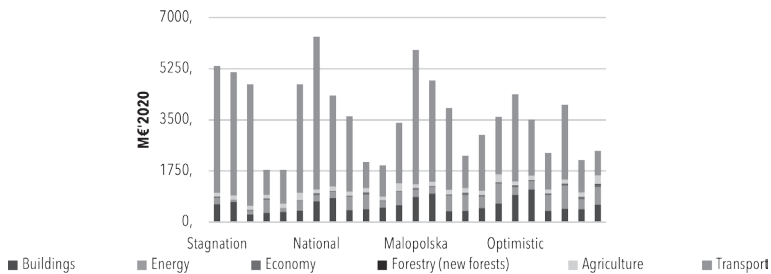


Fig. 4.6. Investment costs across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

Figure 4.7 presents average electricity generation costs across individual scenarios. It should be emphasised that the Lesser Poland Voivodeship does not operate a separate electricity market, as purchase and sale prices are determined by the national wholesale market. Nevertheless, generation costs play a critical role in the competitiveness of the regional economy, particularly for commercial enterprises operating self-generation capacity or entering into long-term power purchase agreements (PPAs). These costs also dictate the level of regional energy self-sufficiency, given that locally generated power must compete cost-effectively against electricity imported from outside the voivodeship.

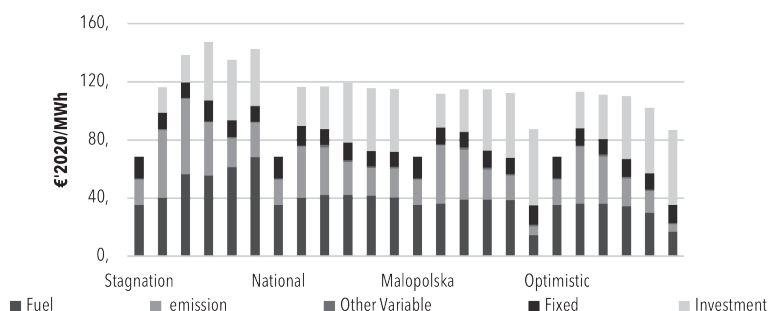


Fig. 4.7. Electricity costs across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

The highest electricity generation costs under the Stagnation scenario occur in 2040, reaching approximately €148/

MWh (2020 prices). In the Małopolska scenario, the peak cost occurs in 2035 at around €115/MWh (2020 prices). For the National scenario, the highest cost was recorded in 2040 at approximately €119/MWh (2020 prices), whereas under the Optimistic scenario, the peak cost appears earliest, in 2030, reaching around €113/MWh (2020 prices). By 2050, electricity generation costs amount to €143/MWh, €87/MWh, €115/MWh, and €87/MWh (2020 prices) under the Stagnation, Małopolska, National, and Optimistic scenarios, respectively. Notably, under the Małopolska and Optimistic scenarios, 2050 electricity generation costs (excluding capital expenditures, consistent with the 2020 baseline methodology) are lower than in the base year.

An analysis of the cost structure reveals that under the Stagnation scenario in 2040, fuel costs account for the largest share (38%), followed by capital expenditures (27%), CO₂ emission allowance costs (25%), and fixed operation and maintenance (O&M) costs (10%). In the Małopolska scenario in 2035, the breakdown of cost components stands at 34% for fuel, 30% for CO₂ emission allowances, 26% for capital expenditures, and 10% for other O&M costs. Under the National scenario in 2040, fuel costs constitute 36% of total generation costs, capital expenditures represent 34%, CO₂ emission allowance costs account for 19%, and remaining costs make up 11%. For the Optimistic scenario, these respective shares stand at 32%, 22%, 35%, and 11%.

As the energy transition progresses, the structure of generation costs shifts fundamentally. By 2050, fuel costs dominate the Stagnation scenario (48%), alongside capital expenditures at 27%, CO₂ emission costs at 17%, and other costs at 8%. In the Małopolska scenario, capital expenditures become the primary cost component (60%), while the shares of fuel costs and CO₂ emission allowances fall to 17% and 7%, respectively. A similar trajectory is observed in the Optimistic scenario, where capital expenditures account for 59% of total electricity generation costs, with fuel costs representing 19% and CO₂ emission costs dropping to just 6%. In the National scenario, the capital expenditure share reaches 38%, fuel costs represent 35%, CO₂ emission costs account for 17%, and remaining costs stand at 10%. These results indicate that as the penetration of renewable energy sources and low-emission technologies increases, the weight of fuel and CO₂ allowance costs diminishes, whereas capital expenditures associated with constructing new generation capacity and energy infrastructure play an increasingly dominant role.

District heat is an energy carrier produced and consumed locally; therefore, its cost directly impacts the economic well-being of residents and the functioning of the regional economy. Unlike electricity, district heat cannot be imported from outside the region, and its prices are predominantly shaped by local technical, fuel, and

regulatory conditions. The cost of district heat influences levels of energy poverty, the competitiveness of the local economy, and the investment attractiveness of individual municipalities. Concurrently, the development of efficient district heating systems contributes to mitigating emissions from individual heating sources while improving user comfort and energy security.

Figure 4.8 presents the average generation costs of district heat over the period 2020–2050 across the individual scenarios. In the Stagnation scenario, heat generation costs rise almost continuously throughout the analyzed period, reaching approximately €35.5/GJ (2020 prices) by 2050. This represents a nearly threefold increase compared to 2020 baseline levels. Simultaneously, the share of fuel costs increases from 56% of total generation costs in 2020 to 67% in 2050.

In the Małopolska scenario, the highest generation costs for district heat occur around 2030, peaking at €28.2/GJ (2020 prices). In subsequent years, costs systematically decline, falling below base-year levels by 2050. This drop results from the widespread deployment of low-emission technologies and the reduced consumption of fossil fuels. By 2050, capital expenditures dominate the cost structure, accounting for approximately 58% of the total.

A similar trend is observed in the National scenario. Peak heat generation costs appear around 2030, followed by a pronounced decline through 2040, before experiencing

a slight resurgence in the subsequent decade. The significant cost reduction between 2035 and 2040 stems primarily from the phase-out of fossil-fuelled units burdened by CO₂ emission allowance costs.

In the Optimistic scenario, a substantial drop in heat generation costs is likewise evident between 2030 and 2040. This decline is driven by the rapid implementation of zero-emission technologies and the near-total elimination of carbon costs. Consequently, following an initial phase of capital-intensive investments, the district heating system becomes less dependent on fuel prices and climate policy costs, yielding long-term cost stabilization.

These results indicate that scenarios assuming deep energy transition incur temporary cost increases during the initial investment phase. Over the long term, however, they yield lower and more stable heat generation costs than a pathway relying on continued fossil fuel dependence.

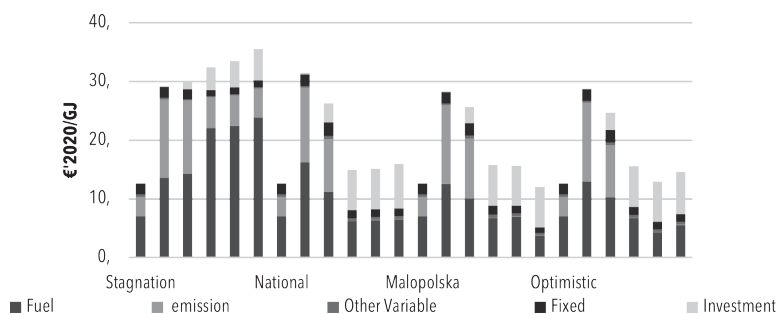


Fig. 4.8. District heat costs across the considered scenarios

Source: authors' own elaboration based on the data and modelling described in the text.

3.2.4. Key Findings from the Regional Analysis

In this study, an analysis of the energy and climate transition of the Lesser Poland Voivodeship was conducted. Four development variants were evaluated: Stagnation, National, Małopolska, and Optimistic. The performed analyses confirm that regardless of the adopted transition pathway, the voivodeship will undergo profound structural changes in its energy sector.

Even under the Stagnation scenario, a gradual phase-out of coal-fired power generation takes place. This stems primarily from the escalating operational costs of coal-based units, including the costs of purchasing CO₂ emission allowances. Consequently, even without additional climate targets, electricity imports become more cost-effective than domestic generation from coal sources. Across all analysed scenarios, a significant expansion of installed photovoltaic capacity and a growth in natural gas-based generation are observed. In the more ambitious scenarios, Small Modular Reactors (SMRs) also emerge.

Concurrently, the potential of renewable energy sources available within the voivodeship proves insufficient to meet future electricity demand fully. This implies the necessity of maintaining substantial electricity imports through to 2050.

The energy transition leads to a substantial reduction in greenhouse gas emissions and a marked improvement in ambient air quality. Alongside the decline in CO₂ emissions,

a decrease in fine particulate matter PM_{2.5} emissions—which rank among the most harmful air pollutants—is also recorded. The largest emission abatements were achieved under the Małopolska and Optimistic scenarios, whereas the smallest were recorded under the Stagnation scenario. This demonstrates that implementing more ambitious climate targets yields not only global climate mitigation co-benefits, but also directly enhances the health and well-being of the region's inhabitants.

In the building sector, an increasing role for electricity, district heat, and modern heating technologies is observed across all scenarios. Heat pumps play a particularly vital role, experiencing dynamic expansion alongside accelerating electrification. These shifts contribute to reducing fossil fuel consumption and enhancing the overall energy efficiency of the building stock.

The economic analyses indicate that more ambitious scenarios require higher capital expenditures associated with modernising energy infrastructure, expanding renewable energy capacity, electrifying transport, and deep building retrofits. However, these larger investment outlays translate into superior operational parameters for the energy system over the long term. This is particularly evident in electricity and district heat generation costs.

The highest electricity generation costs were recorded under the Stagnation scenario, whereas the lowest were

achieved under the Małopolska and Optimistic scenarios. The results indicate that expanding low-emission energy sources and reducing fossil fuel reliance mitigate the exposure of final energy costs to volatile fuel prices and CO₂ allowance costs. Over the long term, this yields a stabilisation of power generation costs.

Similar dynamics were observed in the district heating sector. Under the Stagnation scenario, heat generation costs rise continuously throughout the analysed period, whereas in the remaining scenarios, an initial investment-driven cost surge is followed by stabilisation or decline. This indicates that modernising district heating networks and deploying low-emission technologies can reduce heat delivery costs in the long run.

The findings demonstrate that achieving the climate targets of the Lesser Poland Voivodeship is technically feasible using existing and emerging energy technologies. However, the transition necessitates substantial capital investments, continued energy efficiency improvements, and consistent support for low-emission deployment. Crucially, these actions deliver tangible environmental, health, and economic benefits, enhancing the quality of life for residents and bolstering the long-term competitiveness of the region.

3.3. Modelling Energy Self-Sufficiency in the Municipality of Ochotnica Dolna

3.3.1. Local Energy Self-Sufficiency: Concept and Context

Contemporary challenges related to energy security, climate change, and rising energy costs underscore the growing significance of local energy self-sufficiency. It denotes the capacity of a designated area (e.g. a municipality) to cover its own energy demand using locally available resources and technologies. This approach enhances security of supply, reduces dependence on external suppliers, and strengthens resilience against fuel and energy price volatility.

The development of local energy sources, particularly renewables, also yields tangible economic and social co-benefits. It fosters local job creation, stimulates regional investment, and retains a larger share of financial capital within the municipal economy. Concurrently, it enhances residents' quality of life by improving energy cost stability and mitigating the adverse environmental impacts of the energy sector.

A compelling rationale for advancing energy self-sufficiency is the imperative to abate greenhouse gas emissions and improve ambient air quality. Harnessing local renewable energy sources—such as solar energy, biomass, or biogas—allows for substantial reductions in CO₂ emissions

and atmospheric pollutants, directly supporting the climate objectives of Poland and the European Union.

This concept is particularly vital for municipalities characterized by dispersed settlement patterns and limited access to centralized energy infrastructure. In such areas, local energy generation enhances supply reliability, reduces transmission losses, and improves the overall operational efficiency of the energy system.

Pursuing energy self-sufficiency aligns directly with the objectives of the European Green Deal, Poland's Energy Policy until 2040 (PEP2040), the National Energy and Climate Plan (NECP), and the Regional Climate and Energy Action Plan for the Lesser Poland Voivodeship⁵⁸. These strategic documents emphasize the expansion of renewable energy sources, energy efficiency improvements, and the active participation of local authorities in the energy transition.

⁵⁸ Ministry of Climate and Environment (2021) *Polityka Energetyczna Polski do 2040 r.* [Energy Policy of Poland until 2040]. <https://www.gov.pl/web/klimat/polityka-energetyczna-polski>; Ministry of Climate and Environment (2025) *Krajowy Plan w dziedzinie Energii i Klimatu do 2030 r. (aktualizacja KPEiK z 2019 r.)* [National Energy and Climate Plan until 2030 (update of the 2019 NECP)]. Warsaw: Ministry of Climate and Environment; Marshal's Office of the Małopolska Region (2026) *Regionalny Plan Działań dla Klimatu i Energii do roku 2030 z perspektywą do 2050 – aktualizacja* [Regional Climate and Energy Action Plan until 2030 with a perspective to 2050 – Update]. Annex No. 1 to Resolution No. 286/26 of the Board of the Małopolska Region of 10 February 2026. Kraków: Marshal's Office of the Małopolska Region.

3.3.2. Aim and Scope of the Municipal Study

The objective of this study was to formulate an energy transition strategy for the Ochotnica Dolna municipality, aimed at achieving energy self-sufficiency and climate neutrality by 2050. The analysis accounted for local spatial, environmental, and socio-economic conditions, alongside the deployment potential of renewable energy sources and energy efficiency measures.

In the initial stage, an assessment of the municipality's baseline energy system was conducted, encompassing final energy consumption, energy infrastructure, renewable energy utilization, and greenhouse gas emission sources. Geographic Information System (GIS) tools were employed to identify developmental potential and spatial constraints.

Subsequently, energy transition pathways were developed, incorporating the expansion of renewable energy generation, energy retrofits of buildings and heating systems, and the deployment of distributed energy resources. The costs and co-benefits of the proposed measures were evaluated, including their impacts on emission levels, ambient air quality, and energy costs.

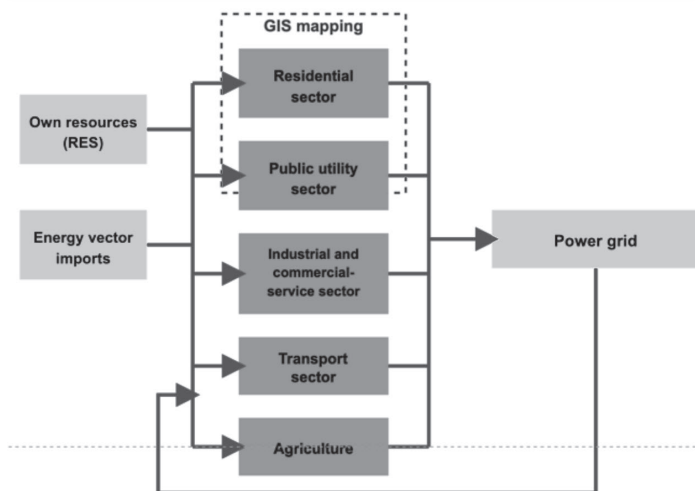


Fig. 4.9. General topology of the model utilized for local-level modelling

Source: author's own elaboration.

The core deliverable of this research was the construction of a localized 4E (Energy – Economy – Environment – Engineering) model, facilitating the analysis of complex interdependencies among energy systems, economic factors, technological parameters, and environmental impacts to support strategic decision-making for municipal development.

The analytical scope covered all key operational sectors of the municipality, including residential buildings, public buildings, industrial and commercial activities, transport, agriculture, and forestry (Fig. 4.9). The year 2023 was

established as the reference baseline, with the modeling horizon extending to 2050.

The analytical results were rendered in five-year intervals, where values assigned to a given year represent the five-year moving average encompassing the two preceding years, the target year, and the two subsequent years. This approach mitigates the influence of short-term interannual fluctuations, providing a clearer representation of long-term transition trajectories.

For the purpose of this research, a bespoke local energy-climate model was constructed using the TIMES model generator⁵⁹. The model was integrated with a spatial GIS database containing granular information on individual buildings located within the municipality. Energy self-sufficiency was evaluated on an annual balancing basis. Under this accounting framework, temporary real-time power deficits may be offset by imports from the external grid, provided that on an annual cumulative basis, total imported energy does not exceed the volume of locally generated surplus energy exported to the grid.

⁵⁹ S. Allena-Ozolins, A. Gravelsins, A. Blumberga and D. Blumberga, 2020. 'Integrated MARKAL-EFOM System (TIMES) Model for Energy Sector Modelling', in 2020 IEEE 61st International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON). Riga, Latvia, 5–7 November 2020, pp. 1–7.

3.4.3. Municipal Data and Model Inputs

The Ochotnica Dolna municipality is a rural administrative district (*gmina*) located in the southern part of the Lesser Poland Voivodeship, within the Nowy Targ County. It comprises four settlement units: Ochotnica Dolna, serving as the seat of the municipal authorities, Ochotnica Górna, Tylmanowa, and the hamlet of Młynne, which administratively belongs to Ochotnica Dolna. The total land area of the municipality is approximately 141 km². The land-use structure consists predominantly of forests, covering nearly 60% of the area, and agricultural land, accounting for approximately 40%. The municipality is characterized by exceptional natural values; its territory encompasses portions of the Gorce National Park and the Poprad Landscape Park, which shape both the landscape attractiveness of the region and its future development potential.

The population of the municipality has been steadily increasing. In 1995, the population stood at 7,299, growing to 8,238 in 2010 and 8,433 in 2020. In 2023 and 2024, the recorded population reached 8,489 and 8,505 residents, respectively.

In 2023, total final energy consumption in the Ochotnica Dolna municipality amounted to 371.9 TJ. The largest energy consumer was the residential sector, consuming 259.0 TJ, which represents nearly 70% of the

municipality's total energy demand. The energy carrier structure was dominated by biomass (151.0 TJ) and hard coal (118.5 TJ), which together accounted for approximately 73% of total energy consumption. The transport sector also held a significant share in the energy balance, with energy consumption totaling 52.8 TJ, derived almost entirely from liquid fuels. Electricity consumption reached 24.9 TJ, with the primary end-users being households, the industrial and commercial-service sector, and agriculture. The detailed energy balance is presented in Table 4.2. Total annual CO₂ emissions in the municipality amount to 15,756 tonnes, with the residential sector constituting the largest emission source, accounting for approximately 58% (Table 4.3).

Table 4.2. Energy balance of the Ochotnica Dolna municipality in 2023 [TJ]

Sector/Source	Electricity	Natural gas	Heating oil	Diesel, motor gasoline and LPG	Hard coal	Biomass	Total
Residential	14,0	4,19	0,0	0,0	104,7	136,1	259,0
Public utility buildings	2,4	0,0	3,5	0,0	7,4	8,2	21,5
Industrial and commercial-service	3,5	0,8	2,2	0,0	3,2	3,5	13,2
Transport (local traffic)	0,0	0,0	0,0	18,3	0,0	0,0	18,3
Transport (transit traffic)	0,0	0,0	0,0	34,5	0,0	0,0	34,5

Sector/Source	Electricity	Natural gas	Heating oil	Diesel, motor gasoline and LPG	Hard coal	Biomass	Total
Municipal public lighting	1,6	0,0	0,0	0,0	0,0	0,0	1,6
Agriculture	3,4	0,0	0,0	13,7	3,2	3,2	23,5
Forestry	0,0	0,0	0,3	0,0	0,0	0,0	0,3
Total	24,9	5,0	6,0	66,5	118,5	151,0	371,9

Source: authors' own elaboration based on the data and modelling described in the text.

Table 4.3. CO₂ emissions from the Ochotnica Dolna municipality

	Emission [t]
Residential	9100
Public utility buildings	983
Industrial and commercial-service	524
Transport (local traffic)	1309
Transport (transit traffic)	2467
Agriculture	1349
Forestry	23
Total	15756

Source: authors' own elaboration based on the data and modelling described in the text.

The photovoltaic (PV) potential was estimated at 288 TJ, and that of biomass at 157 TJ. The biogas potential was estimated at 4.102 million m³ from crop residues, 0.32 million m³ from manure, and 0.13 m³ from municipal organic waste.

Due to the fact that the majority of energy carriers are consumed in the residential sector, each residential building and each public utility building was modeled individually in both the residential and public utility sector models. According to the Topographic Objects Database BDOT10k (GIS), the number of residential buildings was 3,024, while in 2025, the number of public utility buildings (health centres, public and private educational institutions, churches, rural cultural centres, voluntary fire departments, etc.) stood at 43⁶⁰.

Each building in the model was described using the following parameters:

- 1) Usable energy demand: based on floor area and unit consumption.
- 2) Thermal characteristics of walls, windows, and roofs: based on field observations, each building was assigned to one of 8 combinations determining whether the windows, walls, and roof were in good or poor condition. The largest group, comprising 801 buildings, had walls, windows, and roofs in poor condition, whereas in 544 buildings, the condition of all three elements

⁶⁰ Head Office of Geodesy and Cartography, 2025. Topographic Objects Database (BDOT10k). <https://www.geoportal.gov.pl/pl/dane/baza-danych-obiektow-topograficznych-bdot10k>; B. Kłojzy-Karczmarczyk et al., 2023. Low-Emission Economy Plan for the Ochotnica Dolna Municipality with PONE Elements. Ochotnica Dolna.

was assessed as good. Unit usable energy consumption in the buildings ranged from 60 to 200 kWh/m². Out of 3,024 residential buildings, 7 had a usable energy demand of 60–70 kWh/m², 569 fell into the 120–130 kWh/m² range, and the highest consumption (190–200 kWh/m²) was recorded for 4 buildings.

- 3) Heating system parameters: based on the Central Register of Building Emissions (CEEB) database⁶¹; technologies include boilers and stoves for lump biomass, wood pellets, hard coal, natural gas, heating oil, as well as heat pumps and electric heaters.
- 4) Utilization of renewable energy sources (RES) and energy storage systems: the municipality features approximately 50 solar thermal water heating systems, 1,100 individual photovoltaic installations with a total capacity of 2,673 kWp, and 12 PV installations belonging to local government units (JST) with a combined capacity of 383.46 kWp.
- 5) Building thermal modernization potential: determined on the basis of historical consumption, the current degree of thermal insulation, window, wall, and roof surface areas, also taking into account the capital expenditure (CAPEX) required.

⁶¹ General Inspectorate of Building Supervision, 2022. Central Register of Building Emissions. <https://www.gunb.gov.pl/podmenu/1713> [access: 8 June 2022].

- 6) RES utilization potential: based on roof surface areas and current heating sources (in the case of biomass consumption).

The service sector includes, among others, restaurants, guesthouses, retail shops, window sales and installation companies, construction and municipal enterprises, and entities providing geological services. The industrial sector is primarily represented by a sawmill operating within the municipality.

Road transport within the municipality includes both local and transit traffic. Transit traffic comprises vehicles travelling along a 4.884 km section of Voivodeship Road DW 969 (Krościenko nad Dunajcem – Zabrzeż) passing through the municipality. On average, 8.5 thousand vehicles travel along this road daily, of which over 7.3 thousand are passenger cars⁶². For local traffic, the vehicle fleet was estimated at 4,911 vehicles⁶³. In accordance with the municipality's development strategy, it is planned to deploy a local public transport system powered by electricity generated from PV installations. The application of Vehicle-to-Grid (V2G) technology is also assumed. The project foresees the acquisition of one 9-seater minibus and two 20-seater

⁶² General Directorate for National Roads and Motorways, 2021. General Traffic Measurement 2020/2021. <https://www.gov.pl/web/gddkia/generalny-pomiar-ruchu-20202021>.

⁶³ Statistics Poland, 2026. Local Data Bank. <https://bdl.stat.gov.pl/bdl/dane/podgrup/temat>.

minibuses. Additionally, the construction of two charging stations is planned, including one equipped with two 11 kW charging points integrated with a battery energy storage system (BESS-50/125) with a power rating of 50 kW and a capacity of 125 kWh⁶⁴.

It was assumed that approximately 0.7% of the total forest land area undergoes reforestation annually. The unit energy demand associated with reforestation activities was estimated at 6,000 MJ/ha. In the agricultural sector, energy consumption was determined based on the area of agricultural land located within the municipality. Average diesel fuel consumption for operating agricultural machinery (such as tractors and combine harvesters) was set at 85 litres per hectare of arable land. The consumption of other energy carriers was estimated using energy balance data for the Małopolskie Voivodeship, taking into account the local land-use structure and the limited penetration of natural gas in the municipality. This enabled the adjustment of energy intensity indicators to local conditions and the specificity of the analyzed region⁶⁵.

⁶⁴ B. Kłojzy-Karczmarczyk et al., 2023. Low-Emission Economy Plan for the Ochotnica Dolna Municipality with PONE Elements. Ochotnica Dolna.

⁶⁵ J. Zyśk et al., 2023. *Energy and emission balance of the Małopolskie Voivodeship in 2020*. Mining – Informatics, Automation and Electrical Engineering, 1(1), pp. 7–12; J. Zyśk et al., 2023. *Małopolska Towards Climate Neutrality – Model Studies*; J. Zyśk

There are no power or heat generation plants in the municipality that could be classified under the energy transformation sector. However, the municipality features three relatively large electrical energy storage systems with capacities of 134 kWh, 125 kWh, and 180 kWh. The first two have a power rating of 50 kW, while the largest-capacity system operates at 100 kW.

3.3.4. Municipal Modelling Results

In 2023, the structure of energy consumption within the municipality was dominated by hard coal and biomass (Fig. 4.8). In subsequent years, a gradual phase-out of coal usage is projected, leading to its complete elimination from the local energy balance after 2040. Biomass consumption is expected to remain relatively stable throughout the entire period under analysis, reaching approximately 157 TJ in 2050, which corresponds to the estimated potential of this resource within the municipal territory. The utilization of natural gas will remain at a modest level until 2030, after which it will be systematically curtailed.

Concurrently, the reliance on electricity generated by local photovoltaic (PV) installations will increase steadily.

et al., 2025. Energy and Climate Scenarios for the Małopolskie Voivodeship. Kraków.

From 2035 onwards, biodiesel will also enter the energy balance to power agricultural machinery and vehicles. In the final phase of the energy transition, around 2045, the use of biogas is anticipated; however, its share in total energy consumption will remain relatively minor.

The reduction in the consumption of fossil fuels—namely hard coal, natural gas, and petroleum-based fuels (petrol and diesel)—leads to a substantial decline in CO₂ emissions (Fig. 4.9). The most pronounced decrease in emissions is observed in the residential sector, attributable to extensive thermal building modernization and the replacement of coal-fired boilers with modern heat sources powered by biomass and electricity (Fig. 4.10 and Fig. 4.11). This sector also experiences an expansion in electricity demand driven by the widespread adoption of heat pumps.

A significant proportion of the electricity consumed by households will be generated locally as a result of the dynamic expansion of photovoltaic capacity. The total installed PV capacity is projected to reach approximately 12 MW by 2050 (Fig. 4.12). Increasing self-generation and the concomitant reduction in grid electricity purchases contribute to lowering the average cost of electricity for households. It is estimated that the price of electricity will drop from approximately €235'2020/MWh in 2023 to €136'2020/MWh in 2050 (Fig. 4.15).

Average annual capital expenditure (CAPEX) associated with the energy transition amounts to approximately €1,100'2020 per capita (Fig. 4.13 and Fig. 4.14). The largest share of expenditure is attributable to the transport sector, where average annual capital outlay reaches approximately €860'2020 per capita. It should be emphasized, however, that even in the absence of an energy transition, substantial capital expenditure would still be required for the routine replacement of vehicles reaching the end of their operational lifespan. In the residential sector, average annual capital expenditure stands at approximately €220'2020 per capita, whereas in the public tertiary sector (TER), it accounts for roughly €20'2020 per capita.

Peak capital expenditure in the transport sector is projected for the period 2048–2052, when total investments will reach approximately €75 million'2020 (Fig. 4.14). In the remaining sectors, the highest capital outlays will occur between 2033 and 2042, totaling approximately €30 million'2020 (Fig. 4.13).

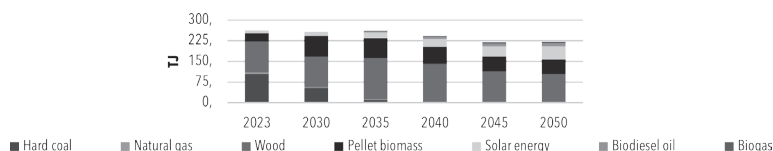


Fig. 4.10. Primary energy carrier consumption in the municipality

Source: authors' own elaboration based on the data and modelling described in the text.

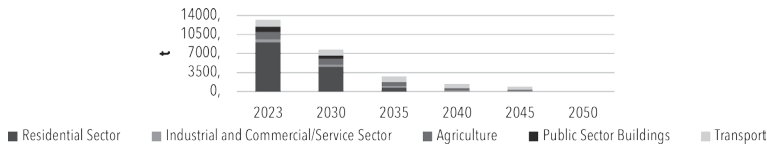


Fig. 4.11. Emission from fuels covered by ETS2 within the municipality

Source: authors' own elaboration based on the data and modelling described in the text.

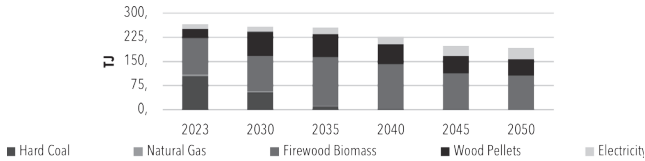


Fig. 4.12. Consumption of purchased energy carriers in the residential sector (excluding self-consumption of PV electricity)

Source: authors' own elaboration based on the data and modelling described in the text.

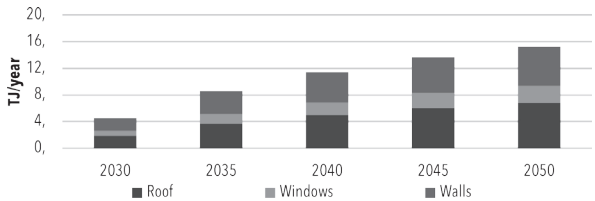


Fig. 4.13. Thermal modernization investments expressed as cumulative final energy savings

Source: authors' own elaboration based on the data and modelling described in the text.

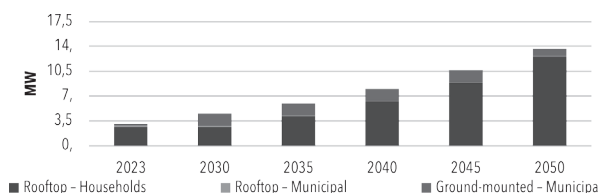


Fig. 4.14. Installed PV capacity in the municipality

Source: authors' own elaboration based on the data and modelling described in the text.

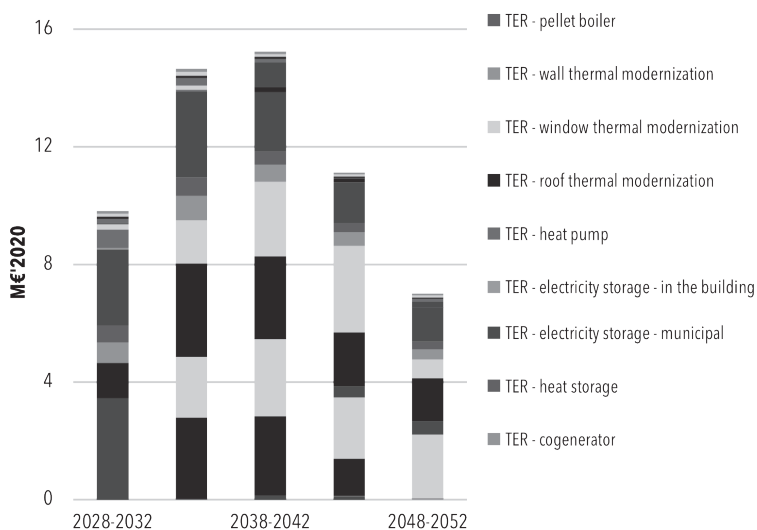


Fig. 4.15. Capital expenditures in individual years excluding the transport sector. TER denotes the public service sector, RSD denotes the residential sector, IND denotes the industrial and commercial/services sector, and AGR denotes the agricultural sector

Source: authors' own elaboration based on the data and modelling described in the text.

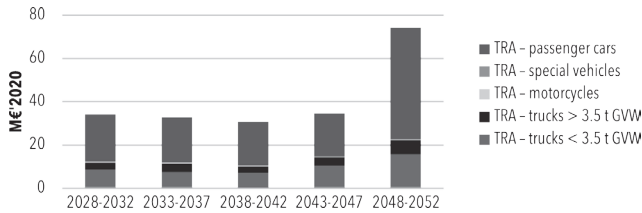


Fig. 4.16. Capital expenditures in individual years for the transport sector

Source: authors' own elaboration based on the data and modelling described in the text.

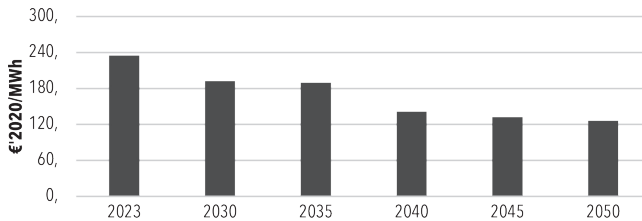


Fig. 4.17. Average electricity price for households, taking into account investment installments for new generation capacities, self-generation, grid purchases, as well as transmission fees and taxes

Source: authors' own elaboration based on the data and modelling described in the text.

3.3.5. Key Findings from the Municipal Analysis

The analysis carried out demonstrates that achieving energy self-sufficiency and climate neutrality for the municipality of Ochotnica Dolna by 2050 is feasible, provided that actions encompassing all sectors of the local economy are

implemented consistently. A pivotal element of the energy transition is the progressive phase-out of fossil fuels—principally hard coal—and their substitution with renewable energy sources, primarily biomass, solar energy, and biogas. The residential sector exerts the most significant influence on energy consumption and greenhouse gas emissions, accounting for approximately 70% of energy consumption and 58% of CO₂ emissions in 2023. Deep thermal building modernization, the upgrading of heating systems, and the electrification of energy consumption enable a substantial reduction in energy demand and the near-total elimination of emissions in this sector by 2050. Photovoltaic installations constitute the primary source of electricity in the analyzed scenario, with total installed capacity expanding to 13.7 MW by 2050. On an annual basis, power generation exceeds local demand while maintaining grid interaction with the national power system. Furthermore, the deployment of energy storage systems plays a vital role in enhancing system flexibility and operational security.

The transition also encompasses the remaining sectors of the economy. The transport sector undergoes gradual vehicle electrification, whereas the industrial, service, agricultural, and public tertiary sectors exhibit a substitution of fossil fuels with electricity, biomass, biogas, and biodiesel. From 2035 onwards, the production and utilization of biogas, alongside the application of hydrogen

and biodiesel, emerge within the municipality. Hard coal is completely eliminated from the energy balance prior to 2050. The economic analysis indicates that while the transition necessitates substantial capital expenditure (CAPEX), a major portion of these outlays is intrinsically linked to routine asset replacement, such as the renewal of vehicles and energy equipment. Concurrently, the transition yields a reduction in fossil fuel procurement costs, lowers expenditure associated with the ETS2 regime, and decreases energy costs over the long term.

The findings of this research indicate that the developed modeling approach holds broader applicability beyond the municipality of Ochotnica Dolna, offering relevance to other local government units characterized by diverse spatial and economic conditions. A particularly compelling territory for the implementation of similar concepts is Eastern Wielkopolska, which is currently undergoing a structural transition away from lignite-based power generation. The insights gained during the development of this local energy and climate model can provide strategic support in planning measures aimed at increasing the share of renewable energy sources, improving energy efficiency, and attaining climate neutrality alongside greater energy self-sufficiency across that region as well.

CONCLUSIONS

The conducted review of modelling methods and the presented examples of their practical application confirm the growing importance of energy systems models in the design and evaluation of green transition policy. The scale of changes resulting from the necessity to reduce greenhouse gas emissions and achieve climate neutrality means that the energy transition cannot be analyzed solely from the perspective of the power sector's development. It encompasses simultaneous transformations in the generation, conversion, storage, and consumption of energy, as well as the deep modernization of the building stock, transport, industry, district heating, and agriculture. Consequently, it becomes essential to utilize tools that enable the analysis of the entire energy system and the interdependencies among its constituent components.

The diversity of methods applied in energy modelling stems from the complexity of the analyzed processes and the varying needs of model users. Top-down models enable the assessment of climate and energy policy impacts on the broader economy, output levels, employment, trade, and household incomes. Conversely, bottom-up models supply detailed information regarding energy technologies, infrastructure, capital expenditure costs, and emission mitigation potentials. Simulation, system dynamics, and agent-based models allow for the analysis of market participant behaviors, technology adoption processes, and the effects of dynamic feedback loops and temporal lags. However, no single approach can fully capture all technological, economic, environmental, and social dimensions of the energy transition.

For this reason, one of the most critical avenues in the advancement of energy modelling is the integration of diverse analytical methodologies. Hybrid models allow for the combination of a detailed technology-explicit representation with macroeconomic process analysis, while developments in artificial intelligence and machine learning create opportunities to leverage increasingly large datasets for forecasting and optimizing energy system performance. In the future, combining optimization, economic, geospatial, and AI methods within integrated decision support systems could prove particularly vital. Such an approach

will enable a superior representation of the energy transition's complexity and reduce the uncertainties associated with projecting long-term system development.

The TIMES model generator presented in this study exemplifies a tool that enables comprehensive energy systems analysis. Its primary advantage lies in its capacity to provide a detailed mapping of the entire fuel-to-power supply chain and to evaluate long-term investment decisions. Models constructed using TIMES make it possible to identify technological and investment pathways that fulfill specified climate and energy targets while minimizing cumulative system costs. Concurrently, the structural architecture of the generator facilitates model construction across multiple spatial scales, allowing a consistent analytical framework to be applied to transition planning at national, regional, and municipal levels.

The practical experience gained through the development of the TIMES-PL, TIMES-MAŁOPOLSKA, and local Ochotnica Dolna municipal models demonstrates that energy systems modelling can support climate and energy policy across different governance tiers. The national model enables the analysis of overall transition pathways for the energy system and evaluates the impacts of meeting national and European climate targets. The regional model accounts for the specific economic structure, energy resource availability, existing infrastructure, and emission

reduction potential characteristic of a given voivodeship. Meanwhile, local-level modelling facilitates a transition to the resolution of individual buildings, local energy installations, and specific investments executed by municipal authorities, local enterprises, and residents.

Analyses conducted for the Małopolskie Voivodeship indicate that attaining climate neutrality requires profound and coordinated structural transformations across all sectors of the economy. No single technology or intervention suffices to achieve long-term climate objectives. A simultaneous expansion of renewable energy sources, energy storage systems, grid infrastructure reinforcement, energy efficiency improvements, deep building retrofits, transport electrification, and the adoption of low-carbon industrial technologies is required. Furthermore, mitigating agricultural emissions and maintaining or enhancing carbon sequestration by forests and other ecosystems remain critically important.

Regional modelling results also confirm that the pace of transition and the scope of required capital investments depend heavily on the ambition level of climate policy. Scenarios assuming accelerated emission reductions necessitate earlier capital deployment into low-carbon technologies, grid expansion, and higher outlays for energy efficiency. Simultaneously, initiating the transition earlier mitigates the risk of requiring abrupt, high-cost

technological overhauls in the final years of the planning horizon. Scenario modelling thus enables not only the evaluation of the energy system's target state but also the formulation of action roadmaps and the identification of key investment decision nodes.

The example of local modelling highlights the substantial potential of applying energy models within local government units. Integrating energy models with Geographic Information Systems (GIS) enables the identification of local energy resources, the assessment of renewable energy installation potentials, the analysis of building retrofit requirements, and the strategic planning of energy storage and transport infrastructure. Consequently, it becomes possible to bridge overarching strategic goals with actionable, site-specific investments implemented at the municipal level. Developing such analytical tools can significantly enhance the capacity of local authorities to draft municipal climate and energy plans and to successfully secure capital funding for project implementation.

A paramount challenge remains ensuring alignment between national, regional, and municipal modelling efforts. Targets established in national strategic documents must be directly actionable across individual regions and municipalities. Concurrently, regional and local analytical findings ought to inform national decision-makers regarding actual emission reduction potentials, renewable

resource availability, infrastructural constraints, and capital investment requirements. Establishing a bidirectional data and results exchange across modelling tiers would substantially enhance the quality of energy transition planning in Poland.

Another essential direction for future development involves improving the quality, accessibility, and standardization of model input data. Building granular regional and local models requires the aggregation of information from multiple data streams, including public statistics, energy utilities, municipal authorities, geospatial systems, and sector-specific data on buildings, transport, and economic activity. Developing national and regional energy databases along with standardized data-exchange protocols could considerably reduce model development costs and enhance the comparability of analytical outputs.

Energy systems models should not be treated as tools for making deterministic predictions about the future. Their fundamental purpose is to serve as decision-support systems by evaluating alternative scenarios, identifying structural interdependencies among system components, and assessing the consequences of various climate and energy policy options. Because modelling outputs depend directly on input data quality, core assumptions, and the fidelity of system representation, they must be interpreted alongside rigorous uncertainty analysis and expert judgement.

Future developments in energy systems modelling in Poland should aim to establish a coherent, multi-level analytical system supporting energy and climate policy execution. Integrating national, regional, and municipal models, employing geospatial data, advancing hybrid methods, and applying artificial intelligence can significantly expand capabilities for evaluating energy transition impacts. Ensuring process continuity, regular data and scenario updating, and the wider adoption of modelling insights by public administrations and municipal authorities will be of decisive importance.

Ultimately, the successful execution of the green transition demands decision-making grounded in robust empirical data, scenario-based analyses, and comprehensive evaluations of technological, economic, environmental, and social impacts. Energy systems modelling can serve as a unified analytical platform connecting European and national policy objectives with real-world execution capacity at the regional and municipal levels. The ongoing development and systematic application of these tools will increase policy efficacy, optimize transition expenditure, and strengthen Poland's energy security amidst dynamic technological, economic, and geopolitical shifts.

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