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Achieving Climate Neutrality in Hungary by 2050: Application of the Pathways Explorer 2050 Model

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ABSTRACT

This research utilises the Climate 2050 Pathways Explorer (PE) model, which incorporates Hungary's social and economic context, to explore pathways for achieving climate neutrality by 2050. The study integrates historical data, sectoral reports, and strategies outlined by the Hungarian government, employing a freely accessible online simulation model. The PE model provides an economy-wide analysis, examining interactions across nearly one hundred adjustable parameters. Dynamic and static scenarios are compared to assess the extent and nature of emissions reductions across sectors such as energy, transportation, construction, food, agriculture, forestry, industry, and waste management, in response to various policy interventions. The findings indicate that Hungary's current National Energy and Climate Plan (NECP) is insufficient to achieve the 2050 climate neutrality target. Alternative scenarios are proposed, ranging from projections based on historical trends to strategies necessitating transformative changes, innovation, and significant investment. The study underscores the importance of improving energy efficiency, expanding renewable energy sources, reducing dependence on fossil fuels, and decarbonising critical sectors such as transportation and agriculture through technological advancements and policy measures. The analysis highlights the necessity of adopting advanced technologies over an extended timeframe and implementing long-term policies supported by comprehensive investment programmes. These measures are essential for enabling Hungary to align with global efforts to combat climate change and transition to a low-carbon economy.

1. Introduction

The imperative to incorporate supply-side measures across all industries into systems aimed at achieving climate neutrality is increasingly recognised. Decision-makers and scholars alike have progressively acknowledged the critical necessity of such measures [1-5]. The development of sustainable energy systems is crucial in the fight against climate change and for achieving climate

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neutrality. According to the International Renewable Energy Agency (IRENA), investing in a global energy system transformation will require substantial resource inputs to integrate energy storage, grids, and renewable energy sources over the coming decades [6].

Additionally, the International Energy Agency (IEA) highlights the pivotal role of hydrogen technologies in decarbonising not only industrial sectors but also transportation and building heating systems [7]. In the next 30 years, Hungary aims to meet the CO2 reduction targets set by EU policy. Specifically, the EU aims to reduce greenhouse gas emissions by 40% below 1990 levels by 2030, with a potential revision to 55% as part of the forthcoming "Fit for 55" legislative package [8]. Furthermore, the EU has set a target to achieve climate neutrality by 2050 [9]. However, the effectiveness of decarbonisation actions is significantly influenced by Hungary's unique economic and social context. Hungary possesses substantial biomass potential, which could contribute to the diversification of renewable energy sources and enhance energy security [10]. In addition to biomass, Hungary has untapped geothermal energy potential, which could become a vital renewable resource for heating and electricity generation in the future [11]. Despite these advantages, Hungary faces challenges such as limited investments, the absence of advanced technologies, and insufficient public involvement in the transition process.

In Hungary, as across Europe, seven key sectors are responsible for greenhouse gas (GHG) emissions: energy production, transportation, building stock, industrial production, agriculture and land use, and waste management. CO2 monitoring in Hungary commenced in 1981, and numerous initiatives were launched in the 1990s to monitor GHG emissions across various ecosystems [12]. Reductions have been achieved across all sectors, and under the EU-28 timeline, Hungary was required to attain a 10% reduction in GHG emissions from 2005 levels by 2020 [13]. In addition to these efforts, the transition to electric vehicles in the transport sector, alongside the widespread adoption of energy-efficient building technologies, has contributed to Hungary's progress [14;15]. Nevertheless, to meet future climate goals, Hungary must significantly increase investment in renewable energy capacity and grid modernisation, with an estimated €150 billion to €200 billion required by 2050 [16].

Recently, Hungary has established a framework for the energy industry aimed at minimising carbon dioxide emissions across supply and consumption chains, including heat production, the electricity sector, and transportation [17]. The National Energy Strategy for 2030 prioritises renewable energy sources as the second most crucial component of sustainable energy initiatives [18]. Numerous studies have examined Hungary's GHG emissions at both local and national levels, with a particular focus on sectors such as agriculture, energy, and transportation [18-20]. It is essential to emphasise that one effective approach to enhancing domestic carbon dioxide sequestration is through afforestation and improvements in sustainable forest management, which can ensure long-term carbon storage [21]. Additionally, land-use practices in Hungary could be further optimised to increase soil carbon sequestration, a resource that remains underutilised despite its significant potential to contribute to emission reduction targets [9].

The body of research on Hungary's GHG emissions can be expanded to include the work of [22], which emerged from a UNEP-funded project conducted in ten countries aimed at understanding the economic aspects of GHG reduction. This study highlights the challenges associated with implementing various emission-reduction measures. Hungary possesses significant potential for cost-effective carbon dioxide reduction through increased energy efficiency, although realising this potential remains a highly complex task. Green Policy Center [23] has provided a set of sectoral recommendations aimed at helping Hungary meet its 2030 climate goals. As noted by McKinsey & Company [16], Hungary's path to net zero hinges on the effectiveness of actions taken across seven economic sectors. Among these, the industrial sector stands out as particularly critical, accounting for over 11% of Hungary's GHG emissions. Transitioning this sector to low-carbon technologies, particularly through hydrogen-based energy systems, could lead to substantial emission reductions and foster innovation [11].

This study seeks to address a significant gap in the existing literature by proposing a comprehensive approach to Hungary's potential pathways towards climate neutrality. While previous research provides valuable insights into decarbonisation strategies, there is a lack of models specifically tailored to Hungary's economic, technological, and social contexts. The aim is to develop a new scenario that outlines how Hungary can achieve climate neutrality by 2050, considering the challenges in these areas, as well as the roles of energy efficiency and renewable energy sources. Using the Pathways Explorer 2050 program, this scenario will identify measures for key economic sectors, illustrating how the transition to net-zero emissions can enhance economic competitiveness and energy security. Ultimately, it aims to inform policymakers and stakeholders on effective strategies to accelerate Hungary's green transition, contributing to broader economic growth and energy sustainability. The paper is structured as follows: after a comprehensive literature review, where previous research is assessed and gaps identified, the Materials and Methods section outlines the modelling framework and details the methods employed. The Results and Discussion section presents sector-specific findings and their implications. Finally, the Conclusions offer recommendations based on the study's findings, discuss the limitations of the research, and suggest directions for future studies.

2. Literature Review

Climate change mitigation measures encompass structural changes, such as the adoption of renewable energy sources in place of fossil fuels and the transformation of agricultural systems; technological innovations, such as energy-efficient buildings and production processes; and lifestyle changes, including low-carbon diets and altered transportation modes [24;25]. These measures affect both demand and supply, influencing production and consumption levels, as well as economic dependencies, such as trade flows and associated carbon emissions [26]. Furthermore, the potential of digitalisation and big data technologies is increasingly recognised for their role in analysing energy use patterns and optimising energy efficiency interventions [14].

Carbon leakage can occur through various channels, including competitiveness, demand, fossil fuel use, and technological effects [27;28], necessitating international cooperation and efficient policy regulation [29;30]. The European Union's CBAM is an example of cross-border initiatives designed to prevent carbon leakage while maintaining competitiveness in line with climate objectives [31]. Such regulations and international climate cooperation are essential for achieving global climate goals. Carbon dioxide emissions reduction and avoidance models can be classified into four main categories. Sectoral models focus on decarbonisation pathways and technological relationships, excluding market mechanisms or broader economic impacts. "Bottom-up" IAMs are capable of modelling key technologies relevant to climate mitigation, though many are not fully equipped to capture variables important for decision-makers, such as bilateral trade of specific goods [32;33].

Notable among modelling efforts are the E3ME and REMIND models, which facilitate the integrated analysis of economic, energy, and climate processes, including carbon pricing [34;35]. These models are particularly useful for determining sectoral emissions reduction goals and evaluating the technical trade-offs involved in achieving reductions on a sector-by-sector basis [36]. For example, the EUCalc model enables the assessment of decarbonisation opportunities and potentials at global, European, and regional levels, allowing for the exploration of changes in lifestyles, production structures, and technologies [37-42]. Energy storage technologies are critical to Hungary's path to climate neutrality by 2050. Evidence suggests that combining energy storage solutions, such as batteries and thermal storage, could mitigate the intermittency of renewable energy sources like solar and wind power [43]. This approach could help stabilise the power grid and ensure a continuous energy supply during peak demand. However, significant financial and technological challenges remain, particularly in low- and middle-income countries like Hungary, which may hinder large-scale deployment.

The second key aspect of Hungary's climate strategy focuses on the role of circular economy practices in emissions reduction. Circular economy approaches, including recycling, reusing material waste, and minimising waste generation, are increasingly recognised as effective strategies for reducing resource consumption and GHG emissions [44]. Given that EU legislation has significantly developed Hungary's waste management sector, there remains potential to further improve recycling rates and reduce landfill use in alignment with broader decarbonisation goals. Equally important, yet challenging, is the decarbonisation of Hungary's agricultural sector, which accounts for a significant portion of national GHG emissions, primarily due to methane from livestock and nitrous oxide from fertiliser use. Recent studies suggest that climate-smart agricultural practices, such as precision farming, manure management, and alternative protein production, can substantially reduce emissions while maintaining productivity [45]. These efforts could be complemented by promoting afforestation and sustainable forest management practices, which would enhance carbon dioxide sequestration, supporting emissions reductions across other sectors.

International experience offers valuable insights into the potential benefits and challenges associated with decarbonisation strategies. Denmark's successful transition to a renewable energy system serves as a case study, demonstrating the importance of long-term policy stability and effective public-private cooperation [46]. To inform the design of Hungary's decarbonisation framework, specific lessons are required, particularly in fostering collaboration between government bodies, private investors, and local communities. This will be crucial for the widespread adoption of renewable technologies and energy efficiency measures.

3. Materials and Methods

Exploring the diversity of alternative decarbonisation pathways across Europe represents a proactive approach in addressing the climate change challenge and transitioning towards a sustainable future. Most studies of this nature utilise IAMs, comprehensive tools that integrate various components of the energy system, economy, environment, and climate. These IAMs now enable decision-makers and researchers to develop a range of scenarios, providing insights into the potential impacts of different policy interventions, technological changes, and socio-economic trends on emissions reduction pathways and the energy transition. The core elements of IAMs include:

- Energy System Modelling: Examines energy supply and consumption, including renewables and fossil fuels, and the impact of energy transition.
- Economic Modelling: Assesses economic impacts, costs, investment needs, labour market effects, and growth forecasts.
- Environmental Modelling: Evaluates environmental impacts, such as pollution, resource use, and biodiversity.
- Climate Modelling: Analyses climate effects, such as temperature rise, weather variability, and extreme climate events.

- Policy Analysis: Assesses the impact of political decisions and regulatory frameworks on sustainable development.

IAMs provide insights into the effects of various policy choices and technological options on energy security, environmental quality, and economic development. They help inform policymakers and stakeholders in making decisions about transitioning to a sustainable low-carbon future. By considering social and economic impacts, these models identify the most effective pathways for achieving sustainable development goals. Furthermore, refining modelling tools to capture external effects at the sectoral level is crucial [37].

3.1 EUcalc, GTAP and GTAP-EUCals Models

Examples of IAMs that include energy system, economy, environment, and climate components are EUcalc, GTAP, and GTAP-EUCals. These models have been developed to explore various scenarios and assess the potential impact of emission reductions and energy transitions resulting from policy changes, technological advancements, and socio-economic trends at both regional and global levels. IAMs incorporate energy system modelling, economic, environmental, and climate assessments, and policy analysis, providing policymakers with insights into the interactions between energy, the economy, and the environment to identify pathways for achieving sustainable development. The EUCalc is an integrated tool for EU climate and energy policy decisions, aimed at exploring decarbonisation pathways and assessing the impact of policy interventions within the EU. Customisable for specific sectors such as energy, transport, industry, and buildings, EUCalc offers a holistic view of the impacts. While it supports informed decision-making, it may not fully capture regional diversity within the EU or behavioural factors due to data limitations and simplifications in modelling. Nonetheless, EUCalc is a valuable tool for evaluating decarbonisation pathways and informing policy discussions. A search of the WoS and Scopus databases using the keyword 'IAM' yielded 352 articles over the past 14 years (Figure 1).

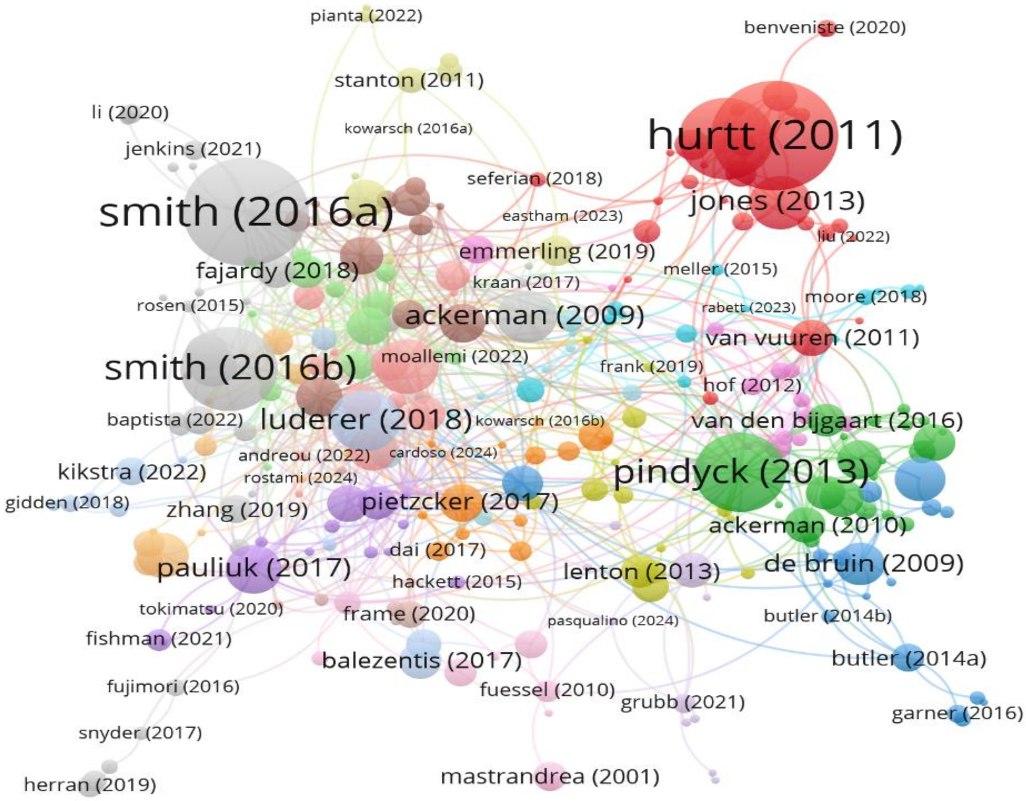
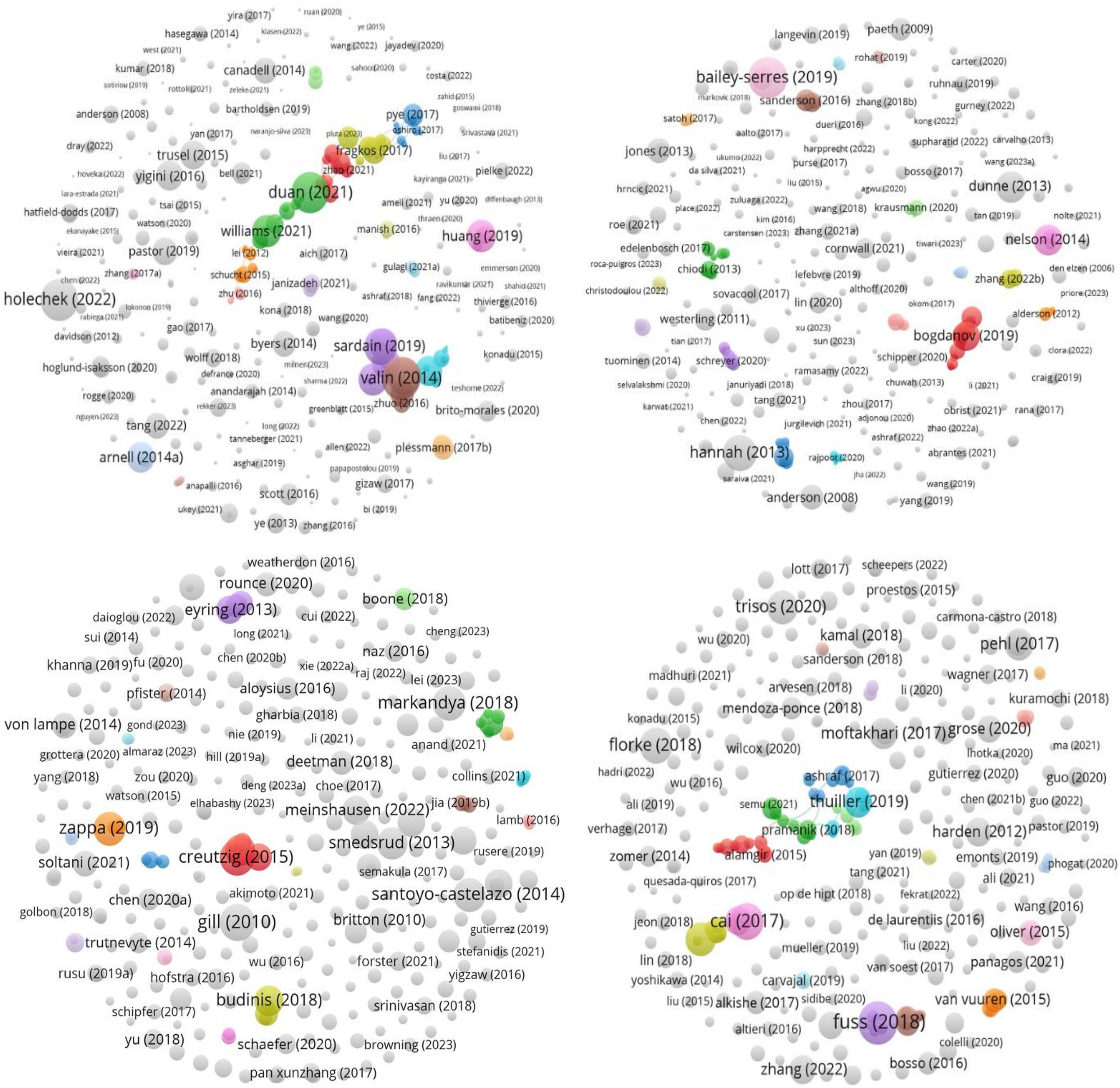


Fig.1. Network of Publications on the EUcalc Software Over the Past 10 Years (VOSviewer)

3.2 Climate 2050 Pathways Explorer Model

In the last decade, many experts and professionals have utilised the Climate 2050 Pathways Explorer to study and plan future climate policies. This tool is particularly valuable for achieving climate goals, such as reducing carbon dioxide emissions and mitigating global warming in the coming decades. The Climate 2050 Pathways Explorer Model was designed to support policymakers, researchers, and the public, offering a clearer understanding of different approaches to meeting the long-term targets outlined by the European Commission [9], particularly the goal of achieving net-zero greenhouse gas emissions by 2050. By integrating data and assumptions regarding technology, policies, behaviour, and the economy, the model illustrates various pathways and their impacts on climate, energy, and society. A search in WoS and Scopus using the term "Climate 2050 Pathways" yielded 2,376 articles published in the past eight years (Figure 2).



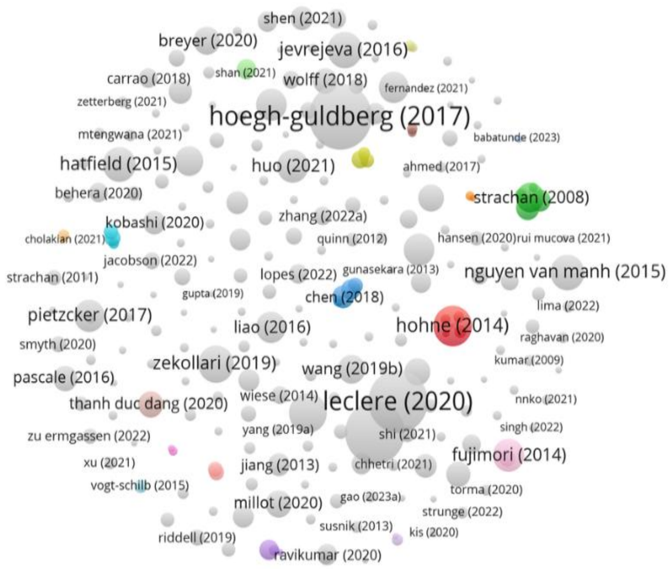


Fig.2. Network of Publications on the Climate 2050 Pathways Over the Past 10 Years (VOSviewer)

This study employs the Climate 2050 Pathways Explorer Model (PE), specifically adapted to the Hungarian economic and social context. The model is an open-source online simulation, with data sourced from historical records, sectoral reports, and governmental strategies provided by Hungarian institutions such as the Green Policy Centre and the Regional Energy Economics Research Centre. It operates at the national level and is not designed for forecasting emissions at the local or company-specific scale. Covering the entire economy, the model enables the investigation of synergies and interlinkages between sectors. The PE model offers nearly 100 parameters that can be adjusted by the user on a four-point scale to explore different measures and scenarios. Rather than performing cost optimisation, the model displays the effects of preselected measures, thus avoiding uncertainties associated with predicting costs for technologies that are not yet developed. While it can estimate costs, the model does not quantify impacts on employment or GDP and currently includes only carbon dioxide, methane, and nitrous oxide among greenhouse gases.

The Climate 2050 Pathways Explorer Model allows for the analysis of sectoral transformations and emissions reductions under different policy scenarios through static and dynamic simulations. Static scenarios provide reference points for calibration, derived from external models and policy documents. The dynamic scenarios, on the other hand, are calculated based on user-defined parameters, offering more flexibility for analysis. Currently, the model incorporates three fixed scenarios from the Hungarian government. These include one based on the National Energy and Climate Plan (NECP), which reflects current measures (WEM from NECP); another based on planned measures (WAM from NECP); and a third representing the "Early Action" scenario of the National Clean Development Strategy. For the purposes of this study, we utilised the dynamic modelling capabilities of the PE to investigate Hungary's potential pathways to climate neutrality in greater detail.

Key parameters and indicators were grouped by sectors for data analysis, covering energy production, transportation, buildings, food, agriculture, forestry and land use, industry, demographics, and waste management. For example, the energy model compares domestic energy demand, renewable energy potential, and fossil fuel reliance while simulating low-carbon pathways. The transport model predicts energy needs and emissions, accounting for travel demand, transport modes, and fuel types. Building models consider energy use for heating, cooling, and cooking, with a range of energy sources. The food, agriculture, and land use sector evaluates emissions based on dietary habits, bioenergy production, and trade balances. The industry sector assesses emissions from energy use and production processes, incorporating material economy, fuel substitution, and carbon capture. The Climate 2050 Pathways Explorer supports scenario analysis, aiding scholars and policymakers in planning measures to achieve long-term climate goals.

4. Results and Discussion

Using the 2050 PE model, this study analysed greenhouse gas (GHG) emissions across Hungary's economic sectors, focusing on scenarios outlined in the National Energy and Climate Plan (NECP). The analysis showed that neither the With Existing Measures (WEM) nor the With Additional Measures (WAM) scenarios will achieve the EU's Fit for 55 targets by 2050. In the WEM scenario, Hungary's total emissions are projected at 35.53 MtCO2e (Figure 3), while the WAM scenario forecasts 18.66 MtCO2e (Figure 4) — both exceeding the required reductions. To explore potential pathways to carbon neutrality, the study proposed four ambition levels (P1–P4) for each sector, ranging from historical trends (P1) to transformative measures requiring significant technological and societal advancements (P4).

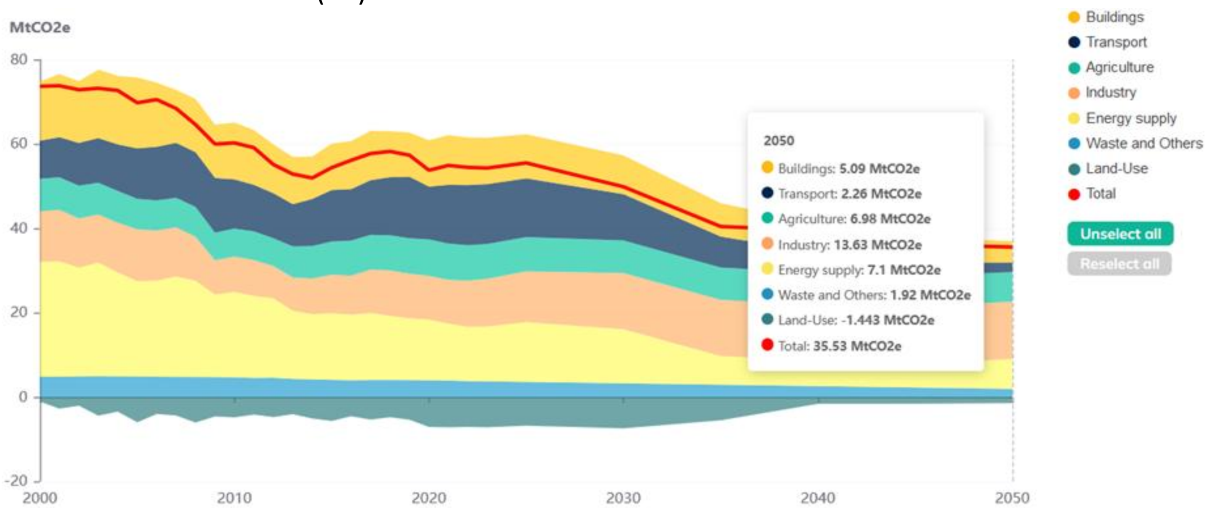


Fig.3. Greenhouse Gas Emissions in Hungary by 2050, According to WEM (From NECP)

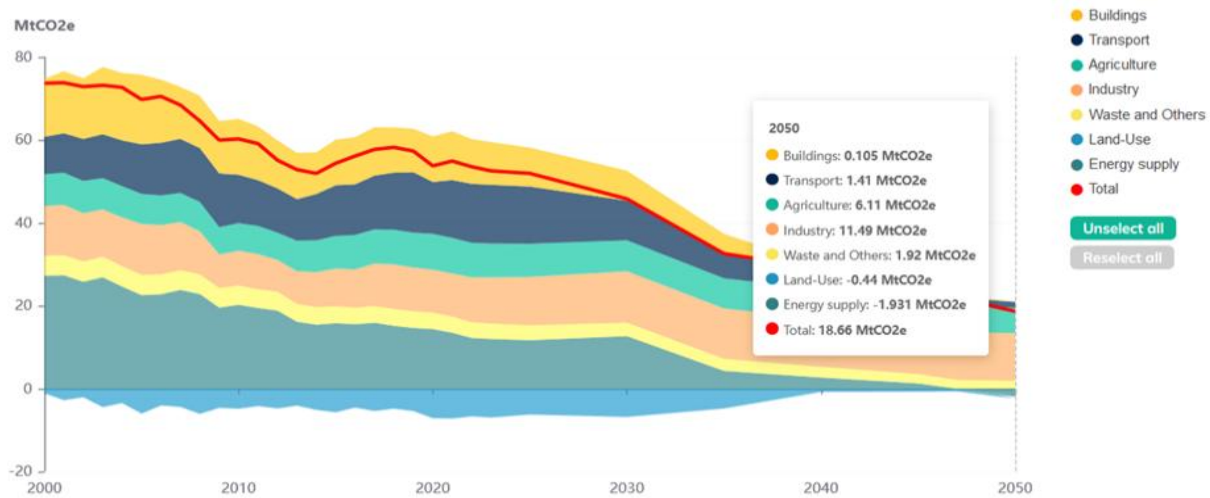


Fig.4. Hungary's Greenhouse Gas Emissions by 2050, According to WAM (From NECP)

Our research is based on the PE Hungary WAM scenario from the NECP, which serves as the reference scenario. This reference scenario forms the foundation for the development of new scenarios. We analysed four different scenarios for each sector—P1 to P4—aiming for minimum greenhouse gas emissions by 2050. The four scenario levels, P1 to P4, represent the following:

- P1: Projections of historical trends.
- P2: Intermediate, more ambitious than a projection based on historical trends but not reaching the full technical potential of available solutions.
- P3: Very Ambitious level, considering current technology evolutions and best practices observed in some geographical areas.
- P4: Transformational but requires profound breaks or efforts, that may include dramatic cost decrease of some technologies, rapid and/or diffuse deployment infrastructure, major technology advancements, and drastic social change.

4.1 Energy Production Sector

Decarbonising electricity generation is critical for Hungary to achieve carbon neutrality by 2050, yet it presents a significant challenge. Energy producers must reduce their reliance on fossil fuels and expand renewable capacity to meet the rising electricity demand without disruptions. In Hungary, over one-third of generation capacity comes from the Paks I nuclear power plant. While gas-fired plants are prevalent, coal plants contribute only 8% to total generation. To reduce emissions further, Hungary must close high-emission plants such as the Matra coal station and either equip gas plants with carbon capture technology or transition them to hydrogen fuel.

However, the greatest challenge will be meeting the anticipated increase in electricity demand over the next three decades. [23] estimates that, due to the decarbonisation of sectors such as transport (with the rise of battery electric vehicles), industrial electricity consumption, green hydrogen use, and electric heating, electricity demand will increase by an additional 180%. By 2050, Hungary will need 2.8 times more electricity than it does today, making energy sector decarbonisation a key element in achieving climate neutrality. Figure 3 illustrates GHG emissions from energy production in Hungary from 2000 to 2050. According to the WEM scenario, GHG emissions are expected to decrease from 13.01 MtCO2e in 2023 to 7.1 MtCO2e by 2050. However, the Fit for 55 targets will not be met under this reference scenario. Using the PE model, we analysed emissions from energy production sub-sectors by 2050, as depicted in Figure 5.

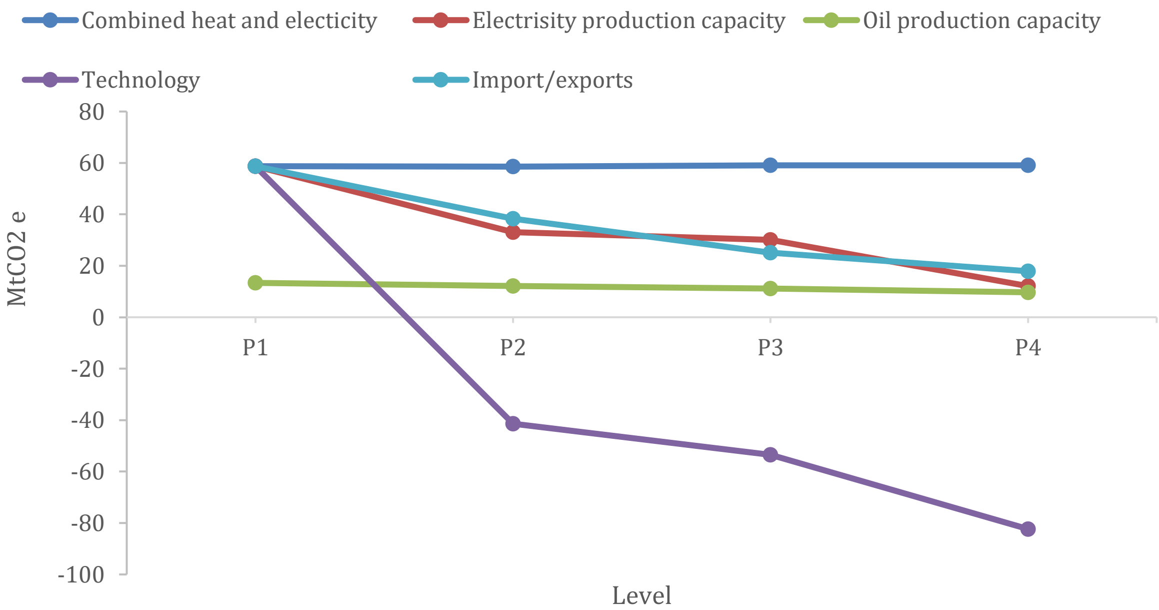


Fig 5. Change of GHG Emissions in Difference Ambition Level in Sector Energy Production in Year 2050

The largest emission reduction occurs in the Technology-Energy sub-sector, even at the P2 level. Figure 6 presents a scenario, where setting the Technology-Energy sub-sector to P2 could achieve GHG neutrality by 2038. This would require a series of measures, including switching energy carriers in combined heat and electricity production, transitioning from natural gas to biogas and bio-liquids, and replacing fossil fuels in refineries with e-gas and biogas.

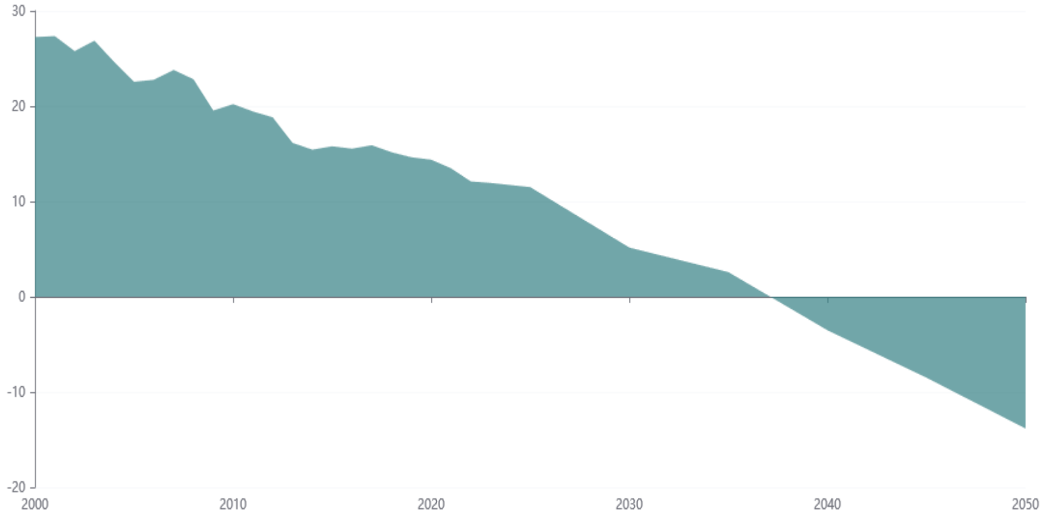


Fig.6. GHG Emissions by Sector Energy Production in Ambition Level P2

Expectations regarding the future evolution of energy carrier prices can be approached either exogenously or endogenously, with the program’s cost estimations still under refinement. The projected quadrupling of the economy by 2050 will increase demands for energy carriers and raw materials. Under current trends, fossil fuels are expected to account for 85% of energy carriers by 2050, with BRICS nations, including Indonesia, likely to consume a significant portion of this [47]. However, these trends exacerbate the degradation of natural environmental capital, threatening the growth in living standards over the coming decades. [48] suggests we are entering a new era, akin to the industrial revolution, where energy will become cheaper and more accessible, particularly in low-income countries. Geopolitics will shift as nations reduce their reliance on expensive coal, oil, and gas imports. Clean renewable energy sources will combat climate change and reduce pollution. According to [49], 2023 marked the first year in which renewable energy production surpassed fossil fuels and nuclear power, with renewables contributing 44.7% of total energy production, a 12.4% increase from the previous year. Meanwhile, fossil-fuel-generated power fell by 19.7%, accounting for 32.5% of total electricity, while nuclear power remained stable, contributing 22.8% to the EU’s electricity supply.

4.2 Transportation Sector

In 2023, Hungary's transportation sector was a major contributor to carbon dioxide emissions, producing 14.19 $MtCO_2e$, or 26.14% of total emissions, primarily from road transport. Figure 3 illustrates emission trends from 2000 to 2050 under the WEM scenario. By 2050, emissions are projected to decline to 2.26 $MtCO_2e$, with reductions accelerating after 2030. However, Hungary is not expected to meet the Fit for 55 targets under the reference scenario. Using the PE model, sub-sectors were analysed across ambition levels from P1 to P4, including Transport, Freight, Passenger, and Technology and Fuels. Figure 7 highlights that, by 2050, substantial emission reduction opportunities exist within the Technology and Fuels sub-sector.

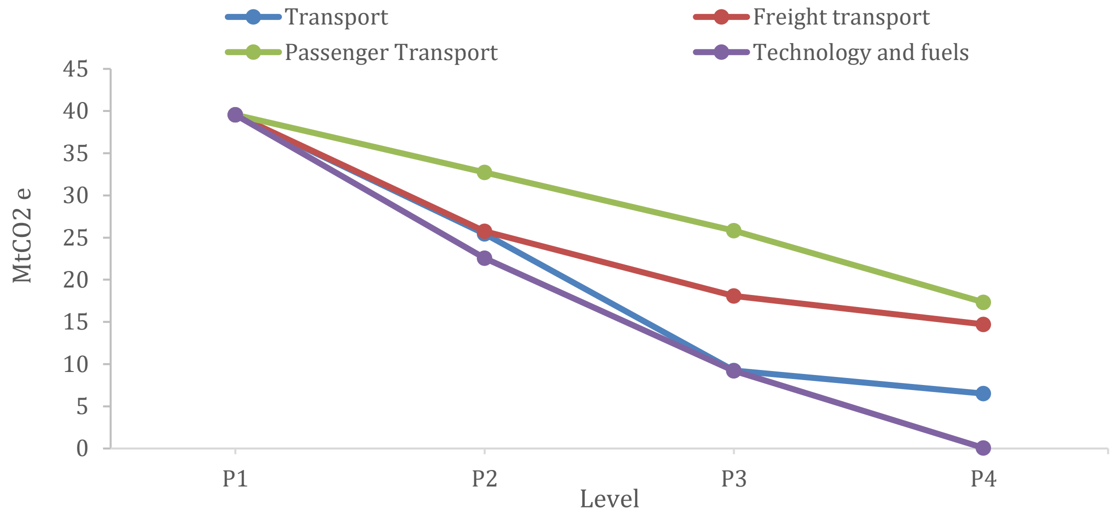


Fig.7. Change of GHG Emissions in Difference Ambition Level in Sector Transports in Year 2050

A new scenario (Figure 8) introduces more ambitious measures, suggesting that the transport sector could achieve GHG neutrality by 2040. The proposed measures include:

- Electric Drive Trains: Increasing adoption by 30% for ships and 10% for aircraft by 2040 compared to 2021.
- Biofuels: Transitioning to 100% biofuel usage by 2040.
- Electric Fuels: Achieving 100% adoption of electric fuels by 2040.

These measures present a clear pathway for decarbonising the transport sector in Hungary, ultimately contributing to climate neutrality.

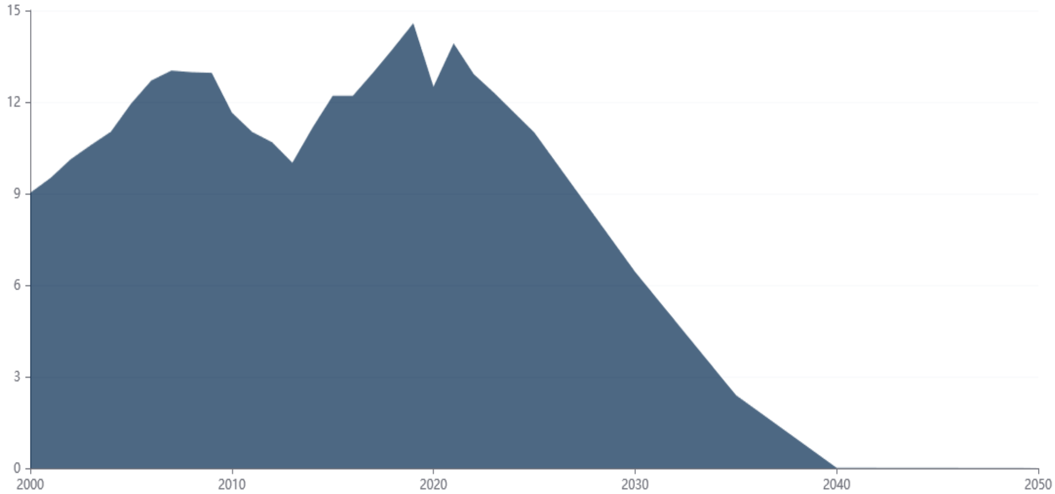


Fig.8. GHG Emissions by Sector Transport in Ambition Level P4

4.3 Building Sector

In 2023, Hungary's GHG emissions from the building sector were approximately 10.99 $MtCO_2e$, contributing 20.2% of national emissions, primarily from heating, hot water production, and cooking. According to the WEM scenario, these emissions are projected to reduce to 5.09 $MtCO_2e$ by 2050. Our analysis of the sector, covering the sub-sectors of Building, Residential, Services, and Residential Services, was conducted across four pathways (P1–P4) for 2050. Figure 9 illustrates the potential emission reductions at varying ambition levels across these sectors. The Residential Services sector exhibits the largest deviation. To achieve P4, the following steps are proposed:

- Technological Efficiency Improvements:

○ Heating: Increase the use of direct electricity to 100% from 74.1% in 2021, and heat pumps to 300% from 249.7% in 2021.

○ Cooling: Increase efficiency to 350%, up from 287.16% in 2021.

○ Gas Heating: Increase efficiency to 94.5%, from 64.89% in 2021.

- Fuel Transition to Green Energy Sources:

○ Shift to biogas, hydrogen, and e-gas: Achieve a share of e-gas that meets 60% of demand by 2050, up from 0% in 2021.

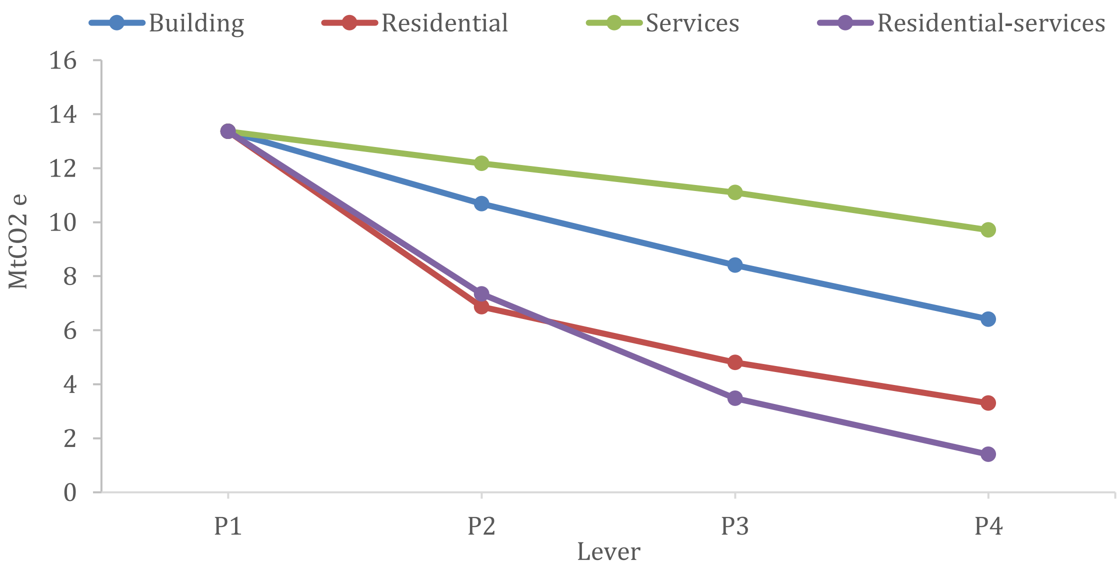


Fig.9. Change of GHG Emissions in Difference Ambition Level in Sector Buildings in Year 2050

Figure 10 presents a new scenario where Residential Services are on track to meet the P4 target based on the aforementioned progress. Achieving near-zero emissions in the building sector will necessitate:

- Energy efficiency measures in heating, cooling, and lighting systems.
- Adoption of sustainable construction materials and designs.
- Deployment of geothermal and solar energy technologies.
- Integration of intelligent public transport systems to enable sustainable urban growth.

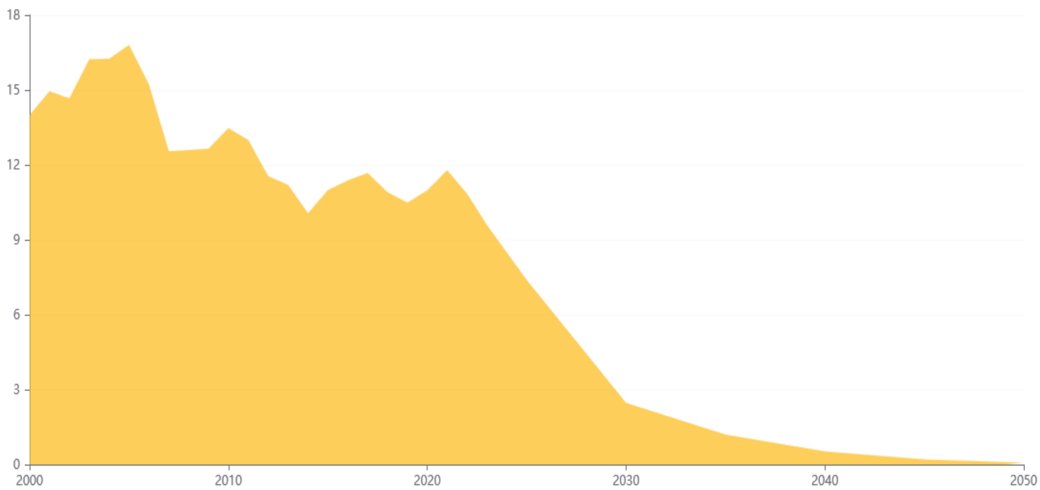


Fig.10. GHG Emissions by Sector Building in Ambition Level P4

[23] proposes the establishment of a long-term building energy programme until 2050, emphasising deep renovations tailored to the needs and income levels of various households. Upper-income groups could access interest-subsidised loans, while the middle class would be offered a mix of non-refundable grants and interest-subsidised loans. For low-income households, nearly full non-refundable subsidies, along with free consulting, should be provided. The support intensity would range from 30-40% of eligible costs, in line with energy efficiency and emission reduction goals. A state credit guarantee fund could assist the lower-middle class, and financing through ESCO companies is also a potential option. Additionally, applying a reduced VAT rate on renovation materials and green labour costs is recommended.

4.4 Food, Agriculture, Forestry and Land Use Sector

Agriculture is one of the most challenging sectors to decarbonise, primarily due to the early stage of development of many necessary technologies and the widespread nature of agricultural activities. In our analysis, we consider factors such as food consumption habits, agricultural practices, land use, bioenergy production, and energy consumption. Figure 3 illustrates GHG emission trends in the Food, Agriculture, Forestry, and Land Use sector in Hungary from 2000 to 2050. Under the WEM scenario, FAFLU emissions are projected to reach 5.67 $MtCO_2e$ by 2050, with agriculture alone accounting for 6.98 $MtCO_2e$, a reduction from 8.25 $MtCO_2e$ in 2023. Using the Pathways Explorer model, we find that the greatest emission reductions in this sector can be achieved in the Diet, Waste, and Others sub-sectors, as depicted in Figure 11.

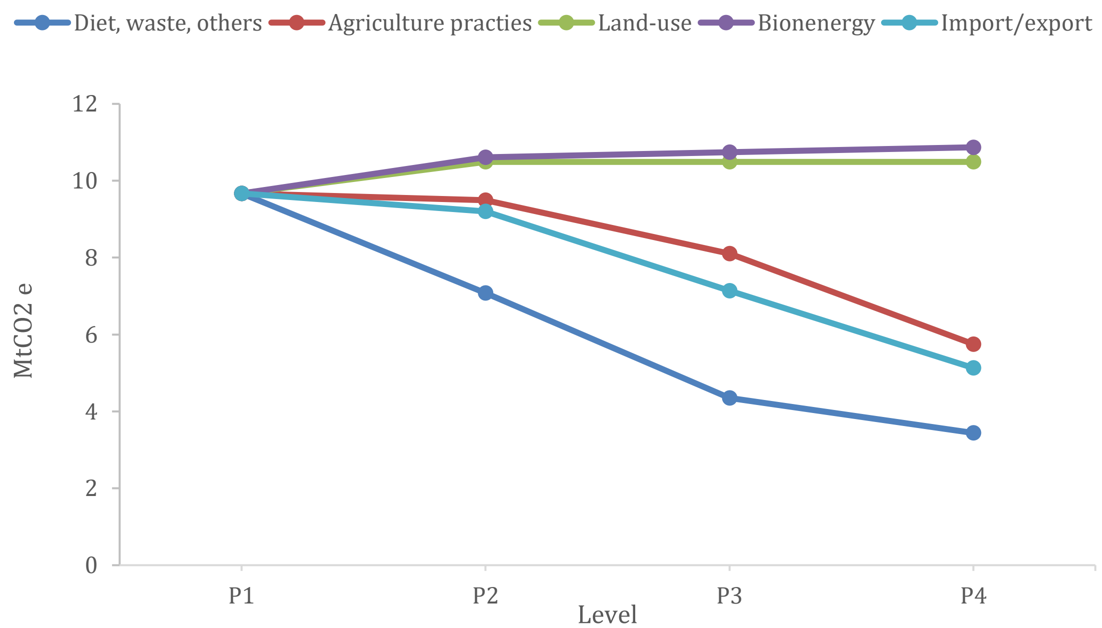


Fig.11. Change of GHG Emissions in Difference Ambition Level in Sector Food, Agriculture, Forestry and Land Use in Year 2050

Even under the ambitious P4 scenario, achieving zero GHG emissions by 2050 in the agriculture and land use sectors is not feasible, though substantial reductions are possible. Agriculture could reduce emissions to 1.45 $MtCO_2e$, while land use could achieve a reduction of -11.175 $MtCO_2e$, as shown in Figure 12.

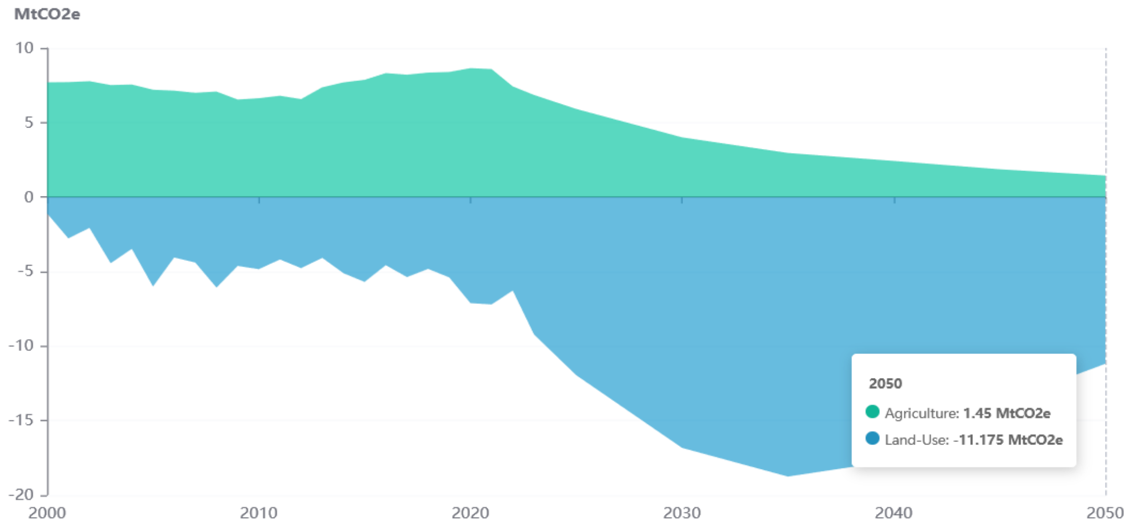


Fig.12. GHG Emissions by Sector Food, Agriculture, Forestry and Land Use in Ambition Level P4

Key actions to achieve these reductions include reducing aquatic calorie consumption to 67% of 2015 levels, reducing crop product calorie consumption to 67% of 2015 levels, and cutting meat (both white and red) calorie consumption to 25% of 2015 levels by 2050. Additionally, a shift from red meat to white meat and from meat to vegetable proteins (such as pulses) will be implemented, reaching 100% by 2050. Furthermore, food waste will be reduced by 75%, bringing it down to 25% of 2015 levels by 2050.

4.5 Industry Sector

In 2023, Hungary's industrial sector contributed 11.14% of total CO_2 emissions, presenting significant decarbonisation challenges due to costly or unavailable technologies, especially until the completion of the Paks II nuclear plant. Improving energy efficiency in heavy industry could reduce emissions by up to 30% by 2030, while carbon capture, utilisation, and storage (CCUS) could address harder-to-abate emissions. Figure 3 illustrates industrial emission trends from 2000 to 2050. Under the WEM scenario, emissions are projected to stabilise at 13.63 $MtCO_2e$ by 2050, but Hungary's domestic goals will not be met. The PE model identifies key subsectors for significant reductions, including Link Material, Fuel Switch, Technology, Import/Export, and Key Consumption Behaviours (Figure 13).

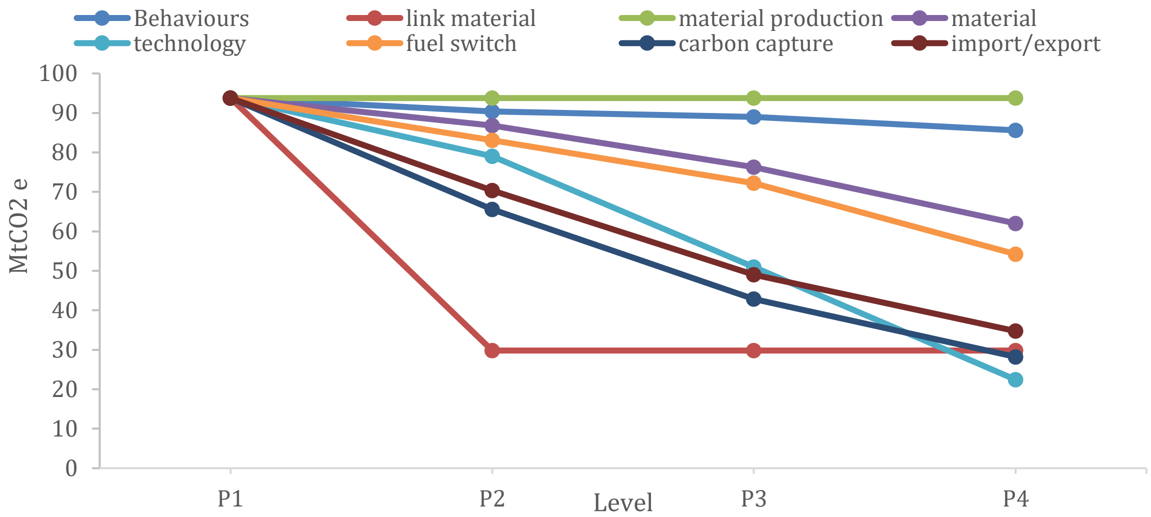


Fig 13. GHG Emissions by Sector Industry in Ambition Levels

A new scenario, as depicted in Figure 14, suggests that at the P4 ambition level for the Fuel Switch sub-sector, Hungary's emissions could potentially be reduced by 2.94 $MtCO_2e$. This reduction would require extensive measures, including electrification, gasification, the adoption of hydrogen, biofuels, e-fuels, and green ammonia. Energy efficiency improvements, enhanced equipment performance, carbon capture technologies, and demand management optimisation will also serve as complementary measures alongside alternative fuels in reducing industrial emissions.

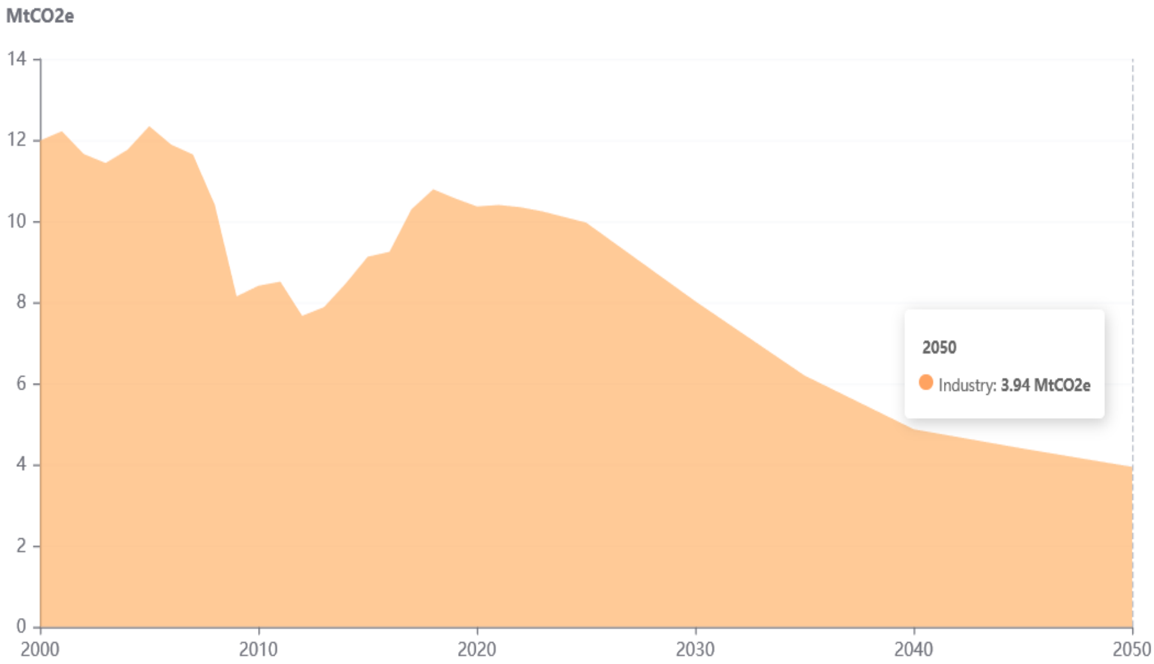


Fig.14. GHG Emissions by Sector Industry in Ambition Level P4

4.6. Demographic and Long-Term Waste Management Sector

This category outlines significant changes in population dynamics, household distribution (urban and rural), household sizes, waste management, and greenhouse gas emissions. Given that climate change is currently ranked as the greatest environmental and health threat of this century [3], there is an urgent need for action, particularly regarding its socio-economic impacts in Hungary. By 2050, climate change may increase heatwave alert days in Hungary by 20 to 70%, highlighting the need for improved adaptation strategies. Forecasting the socio-economic impacts of climate change is challenging, as changes in demographics or economic conditions do not always align with climate factors. According to two variants, Hungary's population is expected to range between 8 and 9 million by 2051, with a low variant predicting 7.5 million. Both models estimate a population of 8.3 to 8.5 million. Since Hungary's EU accession, waste management capacity has evolved, aligning with the transition to a circular economy. The 2021-2027 National Waste Management Plan aims to make Hungary's waste sector a model for circular economy practices, ensuring waste is economically reusable. Our ambitious P4 waste management plan for 2050 targets a 95% reduction in N2O emissions to 0.0 Mt, CO2 emissions to 0.01 Mt, and a similar reduction in CH4 emissions. For global warming, we anticipate a P3 scenario, which predicts a global temperature rise of 2°C to 3°C by 2100. If Hungary successfully implements these waste management strategies, emissions could be reduced from 1.98 $MtCO_2e$ (Figure 3) to 0.204 $MtCO_2e$ by 2050 (Figure 15).

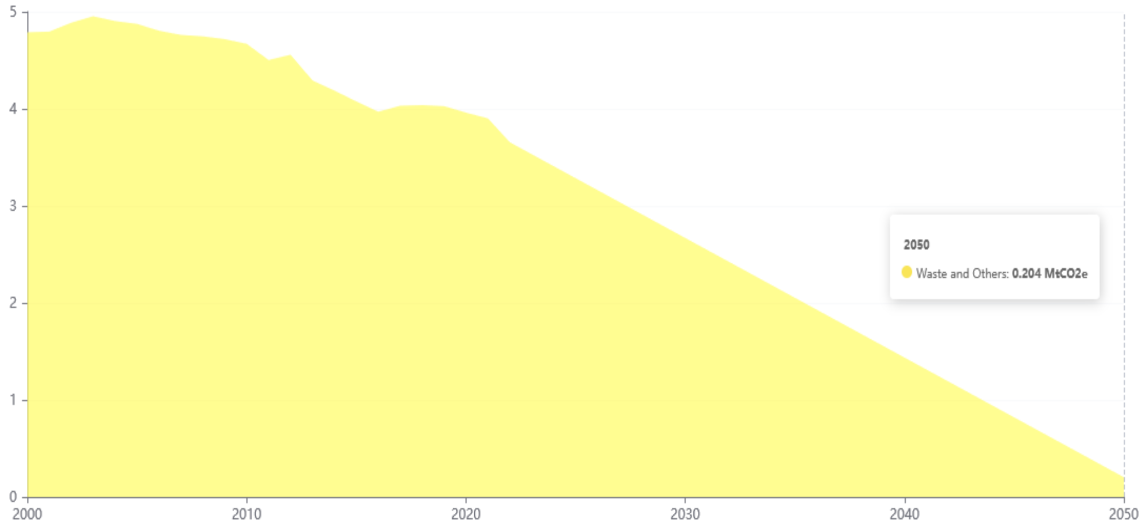


Fig.15. GHG Emissions by Sector Demographic and Long-Term Waste Management

5. Conclusion

Achieving climate neutrality by 2050 in Hungary requires significant investments, estimated at 24,709 billion HUF across all sectors. While these costs are considerable, the long-term benefits, including decarbonisation of the economy, will outweigh them. Investments will support the transition to low-GHG technologies and infrastructure, contributing to broader goals such as environmental sustainability, energy security, and public health. Hungary is on track to meet its 2030 GHG target (a 40% reduction from 1990 levels) through EU co-financed investments and market interventions, but this will fall short of the 2050 climate neutrality goal. Thus, meeting the 2030 target does not guarantee the achievement of the long-term 2050 target. Transitioning to climate neutrality is a critical national priority, offering both climate policy benefits and protection against the severe impacts of climate change. However, ongoing monitoring and responsive policy-making will be essential for achieving this goal. This research focuses on key indicators relevant to achieving climate neutrality in Hungary by 2050:

- Energy Efficiency: Improving energy efficiency across buildings, industries, and transport can significantly reduce energy consumption and emissions. The adoption of energy-efficient technologies and increased renovation rates in residential and service buildings are essential. New building energy regulations, though a step forward, require stricter standards for energy efficiency and renewable integration.
- Renewable Energy: Expanding solar, wind, biomass, and geothermal energy, alongside developing energy storage, is crucial for decarbonising Hungary's energy mix. Diversifying energy sources and modernising the grid will optimise renewable energy use, especially in district heating and residential sectors.
- Reducing Fossil Fuels: Gradual phasing out of oil, gas, and coal, particularly through the closure of high-emission plants like Matra, and the completion of the Paks II nuclear plant, are vital for reducing emissions. Nuclear power, alongside renewable sources, can decarbonise electricity generation, but careful planning for integration with energy storage is necessary.
- Transportation Decarbonisation: Promoting electric vehicles, enhancing charging infrastructure, and encouraging public transport, walking, and cycling are priorities. Hungary leads the region in electric vehicle adoption but needs to expand charging infrastructure.
- Sustainable Agriculture and Forestry: Climate-smart practices, such as afforestation,

sustainable forestry, and bioenergy production, will sequester carbon and support ecosystem services. Transitioning towards circular economies and reducing food waste are also crucial.

- Innovation and Technology: Advancements in low-carbon technologies, industrial digitalisation, and carbon capture technologies will be essential for reducing industrial emissions. Hydrogen's potential in energy storage, transportation, and industrial processes is growing, with significant contributions to decarbonisation strategies.

These actions, supported by technological innovation and effective policy, are fundamental for Hungary to achieve its 2050 climate neutrality goal. These milestones will ensure Hungary achieves its climate neutrality targets by 2050, while enhancing energy independence and economic competitiveness. However, these measures will only succeed with sustained long-term state support and the establishment of legal and regulatory frameworks that incentivise investments in energy efficiency and renewable energy. Additionally, awareness-raising initiatives are crucial in promoting sustainable lifestyles and consumption patterns. In the next phase of our research, we will compare the climate neutrality goals and the strategies implemented to achieve these targets in the V4 countries. The focus will be on energy efficiency programmes, strategies to increase the share of renewable energy, and measures to decarbonise the industrial and transport sectors. Particular attention will be given to regulatory frameworks, social acceptance, and economic incentives that underpin the feasibility of such goals. Simultaneously, we will highlight recommendations for Hungary to adopt best practices from the region.

Author Contributions

All authors contributed to the study conception and design, to the material preparation, data collection and analysis, to the writing of the first draft and of the final version of the manuscript. All authors read and approved the final manuscript.

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Data Availability Statement

The datasets are generated or analyzed during this study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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