

Decarbonising Slovakia

Pathways to climate neutrality in 2050





Dušana Dokupilová
Martina Repíková

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__Decarbonising Slovakia: Pathways to climate neutrality in 2050__ offers an exploration into energy transition by 2050. This monography depicts the potential pathways through which Slovakia could reduce emissions from activities in its industry, energy, transportation, building and agriculture sectors. By applying insights acquired through rigorous research and modelling tools, the publication charts potential options for decarbonisation in a complex manner and reveals how technological innovations, comprehensive policy adjustments, and community engagement are pivotal to this transformation. The publication aims to serve as an example, showing how strategic actions and everyday environmental responsibility could integrate to shape a sustainable future. It aims to explore how initiatives such as renovating buildings, embracing renewable energies, optimizing transportation networks, decarbonising industry, carbon capturing, utilisation and storage of energy, advancing sustainable agriculture, and more, could significantly reduce our carbon footprint and lead to climate neutrality in 2050.

Authors:

RNDr. Dušana Dokupilová, PhD. (The Institute for Forecasting, Centre for Social and Psychological Studies, Slovak Academy of Sciences)

Ing. Martina Repíková (The Institute for Forecasting, Centre for Social and Psychological Studies, Slovak Academy of Sciences)

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Contacts:

dusana.dokupilova@savba.sk

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Authors:

RNDr. Dušana Dokupilová, PhD. (The Institute for Forecasting, Centre for Social and Psychological Studies, Slovak Academy of Sciences)

Ing. Martina Repíková (The Institute for Forecasting, Centre for Social and Psychological Studies, Slovak Academy of Sciences)

Reviewers: Ján Mykhalchyk Hradický

Tomáš Jungwirth Březovský

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Abstract

Decarbonising Slovakia: Pathways to climate neutrality in 2050 presents a potential scenario for Slovakia's ambition towards climate neutrality by 2050, offering actionable strategies across several key sectors: industry, energy, transportation, buildings as well as agriculture, forestry, and land use sector. The study is built upon utilising the "2050 Pathways Explorer" scenario model developed in partnership of Slovak Academy of Sciences with Climact. The model offers a versatile platform for testing various combinations of technological innovations and policy measures, enabling the exploration of their potential impacts on reducing Slovakia's carbon footprint.

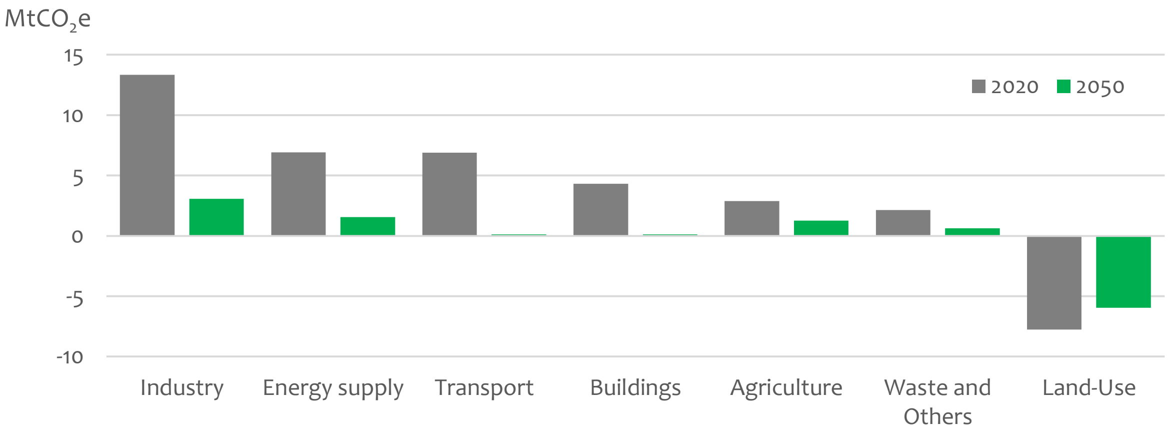
The core of this publication is use of scenario analysis, which facilitates understanding of how different approaches might contribute to achieving emission reduction targets. By integrating behavioural changes with advanced technological solutions, the model provides insights into the effectiveness of energy efficiency improvements, transition to renewable energy, or the adoption of sustainable agricultural and industrial practices. Beyond its academic contributions, this publication also serves as an educational tool, aiming to engage and inform a wide audience about the importance and feasibility of Slovakia's climate ambitions. It aims to foster a deeper public understanding of the policies and technologies needed for a sustainable future, thereby building stronger community support for the necessary transitions. By outlining a possible pathway towards climate neutrality, the publication encourages policymakers, industry leaders and citizens to take the steps to bring Slovakia towards a sustainable, carbon-neutral future.

Executive Summary

This publication outlines a potential decarbonisation pathway for Slovakia, focusing on achieving climate neutrality by 2050 through the integration of various sectoral strategies. Decarbonisation is not viewed as an end goal but a means to ensure a sustainable and improved quality of life for future generations. Through reducing emissions, Slovakia can mitigate the impact of climate change while creating a healthier environment and equitable socio-economic conditions, especially for vulnerable groups.

Key findings from the **2050 Pathways Explorer** model Zero-emission scenario (ZEM) indicate that a combination of policies, technological advancements, and behavioural changes could lead to substantial reductions in greenhouse gas emissions across Slovakia's economy. Significant sectoral transformations could potentially drive total greenhouse gas emissions to net **-0.27 $MtCO_2e$** by 2050. These reductions would involve enhancing energy efficiency, adopting renewable energy sources, and transition of industries, agriculture, transportation, and the energy sector towards low-emission technologies.

Figure 1: Emissions in the Slovak economy in 2020 and 2050 (Scenario ZEM 2024)



Source: Results of modelling in Pathway Explorer

Sectoral contributions

1. **Industrial sector**: The decarbonisation of the industrial sector focuses on energy efficiency improvements, the adoption of **circular economy principles**, and the **transition to low-carbon feedstocks**. Key industries, including steel, play a major role in reducing emissions, further reductions are projected in sectors such as food processing, glass, and wood industries. The industrial sector as a whole could achieve an **81% reduction** in emissions compared to 2021 levels by 2050, reaching level of **2.94 $MtCO_2e$**. This ambitious target would require close collaboration between industries and policymakers to overcome technical barriers and accelerate the adoption of cleaner technologies.

2. **Energy sector**: Energy could remain a key driver of Slovakia's decarbonisation pathway. Greenhouse gas emissions could be reduced to **0.56 $MtCO_2e$**, by **2050** and **51% of Slovakia's final energy consumption** is projected to come from electricity, mainly sourced from renewables such as wind and solar, supplemented by nuclear power. The transition away from fossil fuels, combined with energy efficiency improvements, will reduce emissions significantly across other sectors as well.

3. **Transport sector**: The transport sector, which contributes 18% of emissions, presents one of the biggest challenges due to its reliance on fossil fuels. The primary focus for decarbonisation in this sector should be the **promotion of public transport** and **active mobility** (walking and cycling). Enhancing public transportation systems, improving infrastructure for cyclists and pedestrians, and encouraging lifestyle changes to reduce car dependency are critical. These measures could help decrease emissions while improving urban air quality and public health. The **shift to zero-emission vehicles** could further support this transition, but the priority should remain on reducing overall transport demand and promoting more sustainable, multimodal transport systems. Emissions in the transport sector are projected to reduce to **0.12 $MtCO_2e$** by 2050 under the ZEM 2024 scenario.

4. **Buildings sector**: The building sector is a crucial area for emission reductions. Currently responsible for around 12% of Slovakia's GHG emissions, the implementation of energy-efficient building designs, retrofitting, and improved insulation could potentially lead to significant reductions. By 2050, emissions from this sector could decrease to **0.1 $MtCO_2e$**, primarily through energy efficiency improvements in both residential and non-residential buildings, electrification of heating, and reduced demand for cooling.

5. **Agriculture, forestry, and land use (AFOLU)**: The AFOLU sector, which plays a dual role in emissions and sequestration, could see emission reductions through sustainable agricultural practices, afforestation, and dietary shifts. By 2050, this sector is anticipated to sequester **5.7 $MtCO_2e$**, thanks to forest management practices and carbon capture in soil and biomass.

Policy impact and modelled scenarios

The policies with the most significant impact include:

- **Increased energy efficiency**: Across sectors, Slovakia targets a 38% reduction in energy consumption by 2050 compared to 2021, striving to decouple economic growth from energy use. This could be achieved through improvements in building insulation, industrial processes, and energy-efficient technologies.
- **Support for renewable energy**: By **2030**, **23% of energy consumption** could come from renewables, rising to **51% by 2050**. This transition would be driven by increased investments in wind, solar, and other renewable sources, significantly reducing the reliance on fossil fuels.
- **Technological innovation**: The adoption of **carbon capture, utilization, and storage (CCUS)**, particularly in the energy and industrial sectors, could play a pivotal role in achieving negative emissions by 2050. This technology would help Slovakia reduce emissions from hard-to-abate industries such as steel and cement production and can achieve level of 1.5 $MtCO_2e$ in 2030 and 5 $MtCO_2e$ in 2050.
- **Enhanced regional development policies**: Slovakia's decarbonisation pathway focuses on **balancing regional development**, especially in areas economically dependent on fossil fuels. Investments in sustainable industries and clean energy projects in these regions would ensure an equitable distribution of the benefits from decarbonisation.
- **Support for smart energy systems and grid flexibility**: The integration of **smart grid technologies** would be essential for managing the growing complexity of an energy system dominated by renewables. This could include deploying **energy storage solutions**,

smart metering, and **demand-response systems** to enhance the efficiency and reliability of energy distribution.
- **Decarbonizing heating and cooling systems**: Upgrading **district heating networks** with renewable energy sources such as use of **biomass** and **geothermal** will contribute to the decarbonisation of heating systems. Additionally, promoting **heat pumps** for residential use will help reduce Slovakia's dependence on fossil fuels for heating and cooling.
- **Circular economy and waste reduction**: Integrating **circular economy principles** in the industrial sector will reduce the need for raw materials and lower emissions. This includes adopting the **reuse**, **recycle**, and **recovery** in high-emission industries such as steel, cement, and chemicals, further contributing to Slovakia's decarbonisation goals.

The **ZEM 2024** scenario highlights the combined impact of policy measures and environmentally conscious behaviour in reducing emissions. Behavioural changes are critical, particularly in reducing energy demand and fostering sustainable consumption patterns.

Public awareness and environmental justice

The transition to a low-carbon economy must ensure that the benefits of decarbonisation are distributed equitably. Vulnerable groups, especially in rural and lower-income communities, face disproportionate risks from climate change. While targeted **public education** and awareness campaigns are vital, they are not sufficient on their own to bridge these gaps. A broader range of actions, including policy reforms, incentives for sustainable practices, and infrastructure development, is essential to encourage more sustainable behaviours across all social groups. Involving all stakeholders—from government bodies to individual consumers—in this transition is crucial to achieve not only environmental sustainability but also robust **environmental justice**.

Gaps and further research

Despite the comprehensive nature of the potential pathways outlined, several gaps remain that require further investigation:

- **Economic impacts of decarbonisation**: The transition's impact on Slovakia's labour market, particularly in fossil fuel-reliant industries, remains underexplored. More detailed socio-economic analysis is needed to assess job creation and industrial restructuring.

- **Technological advancements**: While the model assumes technological innovation, the exact trajectory of emerging technologies such as **hydrogen** and **advanced biofuels** requires further exploration, particularly in hard-to-abate sectors.

- **Behavioural change**: The success of decarbonisation depends on public acceptance and behaviour. More research is needed on strategies to engage the population in sustainable practices, such as **dietary shifts** and energy-efficient behaviours.

- **Limits of Pathway Explorer model**: The model does not account for structural changes — economic, social or geopolitical. The economic impact analysis module relies on detailed data on technology costs and is not yet fully developed, lacking evaluations of job creation and industrial transformation. Scenarios are explored without cost optimization, acknowledging that transitioning to a low-carbon economy may entail significant societal costs.

- **Political commitment to climate action:** The current political climate in Slovakia poses challenges to the implementation of ambitious climate policies. A more robust political commitment to climate action is crucial to ensure a smooth and equitable transition.

Conclusion

Decarbonisation is an essential tool for improving the long-term quality of life, not just a goal to reduce emissions. Achieving climate neutrality by 2050 will create a healthier environment, improve living standards, and foster a fairer society. A focus on **environmental justice** and **public education supported by policy reforms, incentives for sustainable practices, and infrastructure development** will ensure that even the most vulnerable populations benefit from these changes, setting the foundation for a sustainable future for all. The pathway to climate neutrality is clear: while substantial challenges remain and coordinated efforts will be required, Slovakia has significant opportunities to progress towards these goals through ambitious policies, technological innovation, and collective action.

List of Abbreviations

AFOLU	Agriculture, Forestry and Land Use
BAT	Best available technologies
BEMS	Building energy management systems
BEV	Battery Electric Vehicle
CAP	Common Agricultural Policy
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon capture and storage
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CZT/DH	District Heating
ECF	European Climate Foundation
EEA	European Environment Agency
EED	Energy efficiency directive
EPBD	Energy performance of buildings directive
ESR	Effort Sharing Regulation
EU	European Union
EU ETS	EU Emissions Trading System
EUCRA	European Climate Risk Assessment
EUR	Euro
FCEV	Fuel-Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWh	Giga Watthours
CHP	Combined Heating Plant
ICE	Vehicle with internal combustion engine
IEP	Institute for Environmental Policy
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
LCS	Low-Carbon Strategy
LTRS	Long-term renovation strategy
LULUCF	Land Use, Land-Use Change and Forestry
MDV SR	Ministry of Transport and Construction of the Slovak Republic
MH SR	Ministry of Economy of the Slovak Republic
$MtCO_2e$	million tons of CO_2 equivalent
MWh	Mega Watthours
MŽP SR	Ministry of Environment of the Slovak Republic
NECP	National Energy and Climate Plan
NZEB	Near-zero energy buildings
PES	Positive energy buildings
PHEV	Plug-in Hybrid Electric Vehicle
RED III	Renewable energy directive
RES	Renewable energy source
SCF	Social Climate Fund
SHMU	Slovak Hydrometeorological Institute
SR	Slovak Republic
TFCE	Total Final Consumption of Energy

TUV	Hot water
TWh	Terra Watthours
USD	US dollars
WAM	Scenario with additional measures
WEM	Scenario with existing measures
ZEB	Zero emission buildings
ZEM	Scenario with zero emission measures

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1. Introduction

Climate neutrality pathway emerges as an essential and unavoidable direction for our society. No action would lead to a future with a very damaged environment and unpredictable weather. The impacts of climate change are spread across the world, significantly impacting both nature as well as human populations. The Intergovernmental Panel on Climate Change (IPCC) increasingly emphasises in their reports the urgent need for starting adaptation strategies alongside mitigation efforts. There is evidence linking the increase in frequency and intensity of extreme weather events to climate change, including more intense heatwaves, hurricanes, floods, and droughts. The rate of sea level rise is accelerating due to the melting of polar ice sheets and glaciers, posing significant risks to coastal communities (IPCC, 2023).

Global temperatures continue to rise and the world is approaching the 1.5°C temperature increase above the pre-industrial average global temperature, a limit set by the Paris Agreement. This threshold has, until recently, been forecast to be exceeded within the next two decades (IPCC, 2022). However, the 1.5°C has been temporarily exceeded in 2024 as the global surface temperature reached 1.5 °C above the 1850-1900 average, for 12 consecutive months in 2024 (C3S, 2024). This increase may become permanent unless substantial emission reductions are implemented immediately.

Slovakia's GHG emissions fell by 49.6% between 1990 and 2022. The energy sector, including transport, accounted for 69% of emissions, with transport alone contributing 21%. Energy emissions have decreased due to fuel switching from coal and oil to natural gas and increased energy efficiency. Biomass in residential heating helped reduce fossil fuel use. The Industrial Processes and Product Use sector, also with 21% share of emissions, has seen slower declines due to the high costs and technical barriers in reducing emissions from mineral, chemical, and metal production. Agriculture, with 5% share, has steadily reduced emissions since 1999 due to declining livestock and fertilizer use. Meanwhile, the waste sector, 5% share, has contributed to rising emissions, particularly methane from landfills have more than doubled since 1990. (SHMU, 2024)

Slovakia has successfully decoupled economic growth from emissions, reducing carbon intensity by 45% from 2007 to 2022, driven by a structural shift toward less energy-intensive industries like automotive and machinery. However, while Slovakia has made significant overall emissions reductions, the rate of emissions reduction per capita has slowed down, particularly in recent years. Despite gains in energy efficiency and industrial restructuring, there was slower progress in sectors such as transport and waste. This stagnation of per capita emissions implies that further reductions will require more targeted efforts in these sectors. (SHMU, 2024)

Every country, no matter its size, has a critical role in addressing climate change. Although Slovakia may not be among the largest emitters of greenhouse gases, its contributions are nonetheless important. Slovakia's efforts to reducing emissions are notable on significant on a per capita basis and align with international agreements like the Paris agreement, but also illustrate that economic progress can be compatible with environmental care. These efforts serve as an example to other nations that adopting sustainable practices might support economic development without compromising ecological health.

EU and Slovak ambition – climate neutrality in 2050

European Union member countries, including the Slovak Republic, are actively engaged in efforts to prevent global warming from surpassing 1.5°C since the industrial revolution. In December 2019, the EU launched the European Green Deal, which set the ambitious target of achieving climate neutrality by 2050 (EC, 2019). This target was formally established in the European Climate Law in July 2021, making it legally binding for all member states (EC, 2021c). To meet this objective, the EU must significantly cut greenhouse gas emissions, with any remaining emissions to be neutralised through carbon capture technologies or natural methods (EC, 2019).

Supporting this long-term goal, the EU has also set an interim target to reduce net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. This is outlined in the "Fit for 55" legislative package, which addresses multiple sectors, including energy, transport, and industry, ensuring all policies align with this reduction target (EC, 2021b).

In the context of the European Green Deal, significant legislative adjustments have been made across key sectors:

- **Building Sector**: The revision of the Energy Performance of Buildings Directive (EPBD) and the Renovation Wave Strategy focus on decarbonizing EU buildings by 2050. These initiatives aim to enhance building energy efficiency and double renovation rates, thereby boosting energy and resource efficiency across the EU.
- **Transport Sector**: The Sustainable and Smart Mobility Strategy continues to prioritise reducing emissions and adoption of sustainable fuel use across all transport modes. This is complemented by revised CO_2 emission standards for new cars and vans as well as the Alternative Fuels Infrastructure Regulation, which ensures the necessary infrastructure for alternative fuels. The ReFuelEU Aviation and FuelEU Maritime initiatives specifically target increases in sustainable fuel usage in aviation and maritime transport.
- **Industrial Sector**: Reforms to the EU Emissions Trading System (EU ETS) aim to reduce emission allowances, with the EU ETS 2 extending coverage to new sectors – buildings, road transport and small industry. The Circular Economy Action Plan emphasizes sustainable resource use. Additionally, the Green Deal Industrial Plan and the Net-Zero Industry Act aim to foster the competitiveness of the EU's net-zero industry by creating favourable conditions for clean technology and green job creation.
- **AFOLU Sector (Agriculture, Forestry, and Other Land Use)**: The Common Agricultural Policy (CAP) 2021-2027, Land Use, Land Use Change and Forestry Regulation (LULUCF) and the EU Biodiversity Strategy for 2030 focus on promoting sustainable practices and protecting natural ecosystems. These policies align with broader legislative initiatives such as EU's new strategy to ensure that agricultural supply chains are deforestation-free.
- **Energy Sector**: The "Clean Energy for All Europeans" package, the EU Hydrogen Strategy, the RepowerEU and the EU Strategy for Energy System Integration facilitate the transition from fossil fuels to cleaner energy sources. The revised Renewable Energy directive raises the EU's renewable energy consumption target to 42.5% by 2030. The revised Energy Efficiency Directive sets a new EU-wide target to reduce energy consumption by 11.7% by 2030 compared to 2020 levels.
- **Carbon Offsets:** The Carbon Border Adjustment Mechanism (CBAM) and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) are critical in addressing carbon emissions associated with international trade and aviation.
- **Other EU regulations:** The Effort Sharing Regulation (ESR) and the Social Climate Fund (SCF) are integral to distributing responsibilities and financial support across Member States, ensuring collective achievement of climate targets, especially focusing on social equity and transitional fairness

To meet the EU's climate and sustainability objectives, it is essential for all member states to harmonise their national policies with these ambitious targets, while taking into account their unique local conditions and capacities. Each country must adopt effective strategies and policies to ensure that these goals can be achieved within the designated time frame.

In 2019, Slovakia approved the Integrated National Energy and Climate Plan for 2021–2030 (NECP) (Ministry of Economy SR, 2019). This plan outlines the strategy for achieving the country's then-current goals in energy efficiency, renewable energy sources and climate change by 2030. In 2023, an updated NECP was published (Ministry of Economy SR, 2023), reflecting the latest legislative changes within the EU and including revised targets for decarbonisation and greenhouse gas emissions. The updated version places greater emphasis on energy efficiency, energy security, integration of energy markets and technological innovation and competitiveness. It also sets a more ambitious target for reducing greenhouse gas emissions in sectors outside the ETS system in Slovakia, raising the goal to 22.7%, in alignment with the member states' contributions under the Effort Sharing Regulation (EC, 2023d). Additionally, the target share of RES in final energy consumption increased from 19.2% to 23%. After another review, the latest update of NECP is currently under legislative changes. However, at the time of writing, there is limited information available regarding the specific amendments in the updated version. As a result, this study refers to the most recent update publicly available, published in 2023.

Purpose of the publication

The main objective of this publication is to offer both experts and the general public updated insights into the potential development of Slovakia's economy and its individual sectors, assuming the country achieves net-zero greenhouse gas emissions by 2050. The report, along with the freely accessible model on which it is based, seeks to inform and encourage the development of effective policies and strategies in areas such as energy efficiency, renewable energy and climate change mitigation, while facilitating broader discussions on Slovakia's sustainable future.

This publication builds on previous reports released in June 2022 and January 2024 (Dokupilová, Repíková, & Korytárová, 2022; Dokupilová, Repíková, 2024). It aims to enhance the understanding of the interconnections between economic sectors and individual activities and their collective impact on achieving climate neutrality by 2050.

The publication contains the results of modelling the potential pathway for achieving climate neutrality in Slovakia using the "2050 Pathways Explorer" model, which was developed in collaboration between the Slovak Academy of Sciences (SAS) and Climact.

The publication, reports and the model are not intended to replace or compete with the preparation of national-level scenarios and strategies. On the contrary, they are meant to serve as complementary tools to enhance existing knowledge. Notably, because the model is publicly accessible for free, both experts and the general public will have access to an online tool that enables the creation of new potential energy-emission scenarios for the Slovak economy.

2. Climate Change and Decarbonisation

2.1 Impacts of Climate Change

The Intergovernmental Panel on Climate Change (IPCC), the leading international body for the assessment of climate change, has definitively confirmed the undeniable impact of human activities on the climate system. The IPCC's Sixth Assessment Report provides a comprehensive overview of the observed and projected impacts of climate change, emphasising the critical need for immediate and decisive action. (IPCC, 2023)

Global surface temperatures have risen by approximately 1.1°C since the pre-industrial period and the last decade has been the hottest on record. While this increase might seem modest at a first glance, the impacts of climate change are already being felt. Rising temperatures, altered precipitation patterns and an increase in the frequency and intensity of extreme weather events, such as heatwaves, droughts and floods, are evident. Sea levels are rising at an alarming rate, posing significant threats to coastal communities and ecosystems. (IPCC, 2023)

Europe, in particular, is experiencing climate change impacts more intensely than other regions. According to the European Environment Agency (EEA), Europe's climate is warming faster than the global average. The EEA's first European Climate Risk Assessment (EUCRA) highlights that Europe faces significant risks from climate change, including more frequent and intense heatwaves, droughts and flooding events, which could have severe impacts on human health, life quality of individuals, country's agriculture and infrastructure. This accelerated warming amplifies the risks of extreme weather events and requires swift and robust climate action within all Europe (EEA, 2024).

These global trends are mirrored in Slovakia and climate change implications, both observed and expected, require immediate attention. Rising temperatures and heatwaves pose risks to human health, particularly in urban areas. Changes in precipitation patterns threaten to increase the frequency of both droughts and floods, impacting agriculture, water resources and infrastructure (IEA, 2022)

Proof comes also from academic studies highlighting specific impacts of climate change in Slovakia. For instance, in the period 1951-2010, the ratio of liquid to solid precipitation during winters shifted, with liquid precipitation becoming more dominant in lowland areas, especially in western Slovakia. At elevations up to 1000 m, solid precipitation still dominated and the ratio remained balanced. (Madara, 2021) However, Slovak ski resorts, such as those in the High Tatras, are already experiencing challenges related to climate change, including variable snow conditions and increased reliance on artificial snowmaking (with the negative effects of additional water and energy consumption), which have economic and social implications for regions dependent on winter tourism. The resorts adapt to climate change by shifting focus to summer tourism with the development of mountain biking trails and other year-round tourism products. (Gajdošíková, Gajdošík, Maráková, 2018).

Similarly, rising temperatures have altered evaporation, precipitation and moisture levels in agroclimatic zones. Changes in agroclimatic areas from 1961 to 2020 have significantly affected the growing season, with earlier onset and delayed termination of temperatures above 10°C. Southern Slovakia, in particular, has experienced higher temperatures and milder winters (Kišš *et al.*, 2023). The study addressing the issue of rising temperatures and droughts in urban areas emphasizes the need for effective local leadership and community involvement in mitigating the impacts of climate change, particularly in cities where the effects of heat and water scarcity are most pronounced (Ministry of Environment SR, 2021). The impact of climate change will be significant even in social conditions of the households - it is expected the problem of energy poverty will increase due to climate change in Slovakia as the decrease in energy need for heating during winter due to increased average temperature will be significantly outweighed by increased residential cooling requirements in summer causing a significant increase in electricity expenditure (Castaño-Rosa, Barrella et al. 2021, Dokupilová, Stojilovska et al. 2024).

The economic and social costs of climate inaction are substantial. Extreme weather events can disrupt supply chains, damage infrastructure, and lead to significant financial losses. Additionally, climate change can exacerbate social inequalities, particularly affecting vulnerable populations.

The scientific consensus is clear: inaction is not an option. The evidence demonstrates that the effects of climate change are already being felt and they align with the broader scientific understanding of global climate trends. Therefore, addressing climate change must be a top priority to mitigate its worst impacts and ensure a sustainable future for Slovakia.

The impacts of climate change on Slovakia are far-reaching and pose significant risks to human health, economic prosperity, and environmental sustainability. To safeguard our future, immediate and decisive climate action is essential. By investing in sustainable solutions and adopting climate-resilient practices, Slovakia aims to mitigate the worst effects of climate change and build a more resilient and equitable society.

2.2 Global and EU Decarbonisation Goals

The Paris Agreement, adopted in 2015, represents a landmark achievement in international climate diplomacy. Its central aim is to limit global warming to well below 2°Celsius, preferably to 1.5°Celsius, compared to pre-industrial levels. This agreement underscores the global commitment to reduce greenhouse gas emissions and enhance climate resilience (UNFCCC, 2015).

The European Green Deal, introduced by the European Commission in 2019, outlines the EU's strategy to become the first climate-neutral continent by 2050, with an intermediate target of reducing net greenhouse gas emissions by at least 55% below 1990 levels by 2030. The plan includes policies to boost renewable energy, improve energy efficiency and promote sustainable transportation (EC, 2019). To reach this goal, the EU has implemented a comprehensive set of strategies and directives to further support its climate and sustainability goals, such as the Clean Energy for All Europeans Package, the Farm to Fork Strategy, the Biodiversity Strategy for 2030, the European Climate Law, the Circular Economy Action Plan, the EU Building Directive, the Alternative Fuels Infrastructure Directive, the "Fit for 55" package, REPowerEU plan and more. The EU also employs several regulatory mechanisms to meet its climate targets, including the Effort Sharing Regulation and the EU Emissions Trading System. Each of these strategies, directives and mechanisms incorporates various mitigation and adaptation measures, contributing to a holistic approach towards sustainability, innovation and climate resilience.

2.3 Slovakia's Decarbonisation Goals and Strategies

As a member of the European Union, Slovakia is committed to contributing to the EU's ambitious climate targets and several strategic documents have gradually been set in place. The **National Energy and Climate Plan** (NECP), which sets forth targets for renewable energy, energy efficiency and greenhouse gas emissions reduction by 2030. The NECP outlines specific objectives and measures across various sectors to align with the EU's broader climate objectives. The 2019 plan was modified in 2023 to include new goals and objectives. (Ministry of Economy SR, 2019; Ministry of Economy SR, 2023).

The European Commission's 2023 evaluation of the revised NECP highlight the plan's alignment with the EU's climate neutrality goals and the European Green Deal. The assessment calls for stronger integration of renewable energy, namely solar and wind, and more assertive energy saving measures in different sectors. Key areas include reducing greenhouse gas emissions, particularly in sectors not covered by the ETS, decarbonising the transportation sector, improving green investment funding and enhancing public participation in climate action. The Commission also emphasises the need of incorporating REPowerEU components to strengthen energy security and reduce reliance on fossil fuels, with effective monitoring and reporting systems to track progress (EC, 2023g; EC, 2023h).

Figure 2: Overview of EU and Slovak climate and energy policies

EU-wide policies

- European Green Deal
- Fit for 55 Package
- European Climate Law
- Clean Energy for All Europeans
- EU Hydrogen Strategy
- EU Biodiversity Strategy for 2030
- Carbon Border Adjustment MechanismCircular Economy Action Plan
- Forest Strategy for the EU
- Zero Pollution Action Plan
- EU's Strategy on Adaptation to Climate Change
- Carbon Offsetting and Reduction Scheme for International Aviation

Slovak policies

- Integrated National Energy and Climate Plan for 2021–2030 (NECP)
- Low Carbon Development Strategy until 2030 with a View to 2050
- Greener Slovakia – Strategy for the Environmental Policy
- National Air Pollution Control Programme
- Energy Policy

Sector-specific policies

- Building Sector: Energy Performance of Buildings Directive (EPBD), Renovation Wave Strategy
- Transport Sector: Sustainable and Smart Mobility Strategy, CO_2 Emission Standards
- Industry Sector: Net-Zero Industry Act, Energy Efficiency Directive, Industrial Emissions Directive
- Energy Sector: EU Strategy for Energy System Integration, RepowerEU, Energy Efficiency and Renewable Energy Directives
- Agriculture and Forestry: Common Agricultural Policy, LULUCF Regulation, Farm to Fork Strategy

Source: EU and Slovak policy websites

By 2030, Slovakia aims to reduce greenhouse gas emissions in non-ETS sectors by 22,7% relative to 2005 levels, achieve a 23% share of renewable energy in total energy consumption and improve energy efficiency by 30,3%. The energy policy focuses on reducing GHG emissions, securing affordable energy and managing the impact of renewables on electricity prices. Key measures include ensuring a stable supply of low-emission energy, particularly from nuclear power, and promoting energy efficiency to balance present needs with long-term sustainability. Priorities include diversifying sources and infrastructure, reducing emissions, supporting renewable energy sources and expanding nuclear energy. New measures focus on optimisation of smart energy systems, energy storage and waste valorisation. Decarbonising industry processes and transportation through hydrogen and low-carbon technologies as well as promoting energy efficient buildings are also in focus. (Ministry of Economy SR, 2023).

The **Greener Slovakia – Strategy for the Environmental Policy of the Slovak Republic** aims to enhance environmental protection and sustainability via comprehensive objectives. The NECP built on this strategy has since then revised the primary objectives for climate change mitigation and decreasing greenhouse gas emissions. In addition to common themes with NECP, the strategy has the objectives of achieving a 60% recycling rate for municipal waste by 2030, decreasing the amount of waste sent to landfills to 25% by 2035. The objectives include also upgrading sewage systems, preserving biodiversity in forests and meadows, implementing stricter air quality regulations, more responsible water management, eliminating environmental burdens and enhancing monitoring efforts. The plan also aims to achieve eco-design, circular economy and a 70% increase in green public procurement by 2030. Additionally, it seeks to promote sustainability, environmental education and public awareness. (Ministry of Environment SR, 2019).

The **Low Carbon Development Strategy of the Slovak Republic until 2030 with a View to 2050** sets a climate neutrality goal for 2050. The policies to reduce emissions, improve energy efficiency and increase renewable energy usage by 2030 have since then been updated in the NECP. The long-term objective to 2050 is to achieve net-zero greenhouse gas emissions, while also employing strategies for both mitigation and adaptation. Yet, achieving net-zero emissions by 2050 will require further measures and advancements, including enhanced carbon sequestration efforts, that have not yet been fully modelled. By 2050, renewable energy is expected to contribute significantly to meeting the energy demand, its specific contributions will depend on further development and investment. Energy efficiency across all sectors will be crucial in reducing consumption, supporting the transition toward a low-carbon economy. The long-term strategy also encourages the use of low- and zero-emission vehicles, backed by substantial alternative fuel and electric vehicle infrastructure. Carbon capture and storage (CCS) technologies will play a key role in reducing industrial emissions Reforestation, enhancements in land use and the storage of carbon in soil and biomass are also expected to enhance carbon sequestration. Although certain details regarding the exact measures and timeline toward 2050 remain to be fully defined, the strategy sets a clear path toward a low-carbon future, with ongoing adjustments anticipated as technologies and policies evolve. (Ministry of Environment SR, 2020).

3. Scenario analysis and methodology

Exploring future scenarios is fundamental for developing effective climate policies and models play a pivotal role in this process. Through scenario analysis, models allow policymakers to explore various future pathways based on different assumptions about technological advancements, economic growth and societal preferences. This approach helps with identifying potential risks and opportunities associated with different mitigation strategies, providing valuable insights into the long-term implications of various policy decisions.

In addition, models are used to evaluate the potential impacts of specific policy interventions on greenhouse gas emissions, energy consumption and associated economic costs. This evaluation helps policymakers design climate policies that are both cost-effective and socially equitable. Furthermore, models serve as valuable tools for tracking progress toward decarbonisation goals. They allow for the monitoring of reductions in emissions over time, highlighting areas where additional efforts may be necessary to stay on track for achieving climate neutrality.

Despite their utility, it is important to recognize the inherent limitations of models. Since they rely on assumptions about future developments, model outputs are subject to uncertainty. As a result, it is advisable to use multiple models and approaches to obtain a more comprehensive understanding of the challenges and opportunities associated with climate policy. This multi-faceted approach helps mitigate the risks of over-reliance on a single model and provides a more robust foundation for decision-making on the path to climate neutrality. (IPCC, 2014)

The „2050 Pathways Explorer“ model

Determining the volume of greenhouse gas emissions produced within a country as a result of economic activity and natural processes requires a comprehensive approach supported by a robust model. The "2050 Pathways Explorer" is a comprehensive model of energy flows across sectors of the national economy (buildings, industry, transport, energy sector, AFOLU). It integrates the demand for energy, materials, products, land and food, along with the associated greenhouse gas emissions and carbon sequestration.

The model was developed by Climact as part of the Horizon 2020 project "EUCalc" and was inspired by models like EUCalc, GlobalCalc and other computational frameworks (JRC, 2018). Tools such as this model allow for the exploration of a wide range of mitigation options and the testing of various potential measures, both technological and behavioural. However, it is important to note that the model does not automatically include economic analysis. Scenarios are explored without cost optimization, acknowledging that transitioning to a low-carbon economy may entail significant societal costs.

The model is complementary to other macroeconomic models, such as General Equilibrium Models (e.g., PRIMES, TIMES/MARKAL), or sector-specific models. Since strategic documents like the National Energy and Climate Plan for 2021-2030 (Ministry of Economy SR, 2019) and the Low-Carbon Development Strategy of the Slovak Republic until 2030 with a view to 2050 (Ministry of Environment SR, 2020) are based on the Compact Primes Model for Slovakia, the emission trajectories obtained from the "2050 Pathways Explorer" model can be considered complementary to the insights provided in these strategic documents.

The "2050 Pathways Explorer" model draws on data from databases such as Eurostat and IDEES (JRC, 2018), adjusted according to national statistics. An important feature of the model is the use of "levers" that adjust key factors significantly impacting energy consumption and greenhouse gas emissions. These levers are essential for the preparation of scenarios within the model.

The online tool "2050 Pathways Explorer" contained several scenarios as of October 2024:

- **WEM approx:** A scenario reflecting the WEM (with existing measures) model, which serves as the reference scenario with existing measures. It was used in the Integrated National Energy and Climate Plan for Slovakia 2021-2030 and the Low-Carbon Development Strategy of the Slovak Republic until 2030 with a view to 2050.
- **WAM approx**: A scenario reflecting the WAM (with additional measures) model, which includes additional measures and was used in the updated NECP.
- **EST Behaviour**: A behaviour-driven scenario that depicts the trajectory towards climate neutrality driven solely by the conscious actions of citizens based on potential future climate-responsible behaviour.
- **EST Policy**: A policy-driven scenario that illustrates the potential reduction in carbon emissions towards climate neutrality as a result of compliance with government-mandated measures and policies.
- **ZEM 2024**: A scenario that combines environmentally conscious behaviour from the population with government-mandated measures and policies aimed at minimising greenhouse gas emissions. By implementing the proposed measures, Slovakia's economy could achieve climate neutrality by 2050.
- **Ambitious Scenario (AS)**: A scenario designed to achieve climate neutrality by 2040.

Several of these scenarios of possible developments by 2050 were analysed using a comparative method and remain freely accessible on the online platform of "2050 Pathways Explorer".

A key benefit of the model is the ability to choose a vision for Slovakia's development by 2050 and use the levers to create a custom scenario. This allows users to test the impacts of new measures or changes to existing ones, and to assess their interconnections within the entire system. Such system-wide testing can expedite the decision-making process on challenging issues, such as the accelerated phase-out of fossil fuels and the potential implementation of alternative replacements, like heat pumps, solar, or photovoltaic energy, among others. The scenarios are not cost-optimised, which offers the advantage of exploring all possibilities—including those for which the cost trajectory is not yet fully clear.

The model does not account for structural changes that may occur, whether economic, social, or geopolitical in nature. These include military conflicts, such as the conflict in Ukraine, and the associated EU sanctions on energy resources imported from the Russian Federation. Such sanctions impact trade agreements and transportation routes, and may also accelerate technological changes and the transformation of the energy sector. The restriction of trade relations and the significant rise in inflation, which alter the standard behaviour of most economic entities, also affect the entire economic system.

However, these changes in consumer behaviour can be modelled through the adjustment of individual variables—known as "levers"—which allow for the exploration of various possible future scenarios. You can find more information about the model at: https://pathwaysexplorer.climact.com/faq.

The "2050 Pathways Explorer" model is a dynamic tool that continues to evolve. The results and graphs presented in this study reflect the state of the model as of September, 2024. Therefore, they may not perfectly align with the results generated through the online tool available on the website https://pathwaysexplorer.climact.com.

Unless otherwise indicated, all graphs in this document are sourced from the "2050 Pathways Explorer" online tool.

4. Pathways to climate neutrality

A sectoral approach to decarbonisation should recognize the distinct emissions profiles, technological landscapes and mitigation potentials across different economic sectors. Sectors such as coal and gas power generation, along with fossil fuel production, face greater exposure due to their substantial direct and indirect greenhouse gas emissions (McKinsey, 2022). Furthermore, the pace of decarbonisation varies significantly across sectors, especially between developed and developing countries, influenced by sector-specific technological advancements, economic structures and policy frameworks (Doda, 2016). These differences necessitate tailored strategies to effectively address the unique challenges and opportunities within each sector.

Numerous studies have explored decarbonisation pathways for specific sectors. They proposed frameworks for key industries to align with a 1.5°C pathway, emphasising sector-specific carbon budgets and performance indicators (e.g. Teske et al., 2020). Hard-to-abate sectors such as aviation, shipping, road freight transportation and heavy industry require deep cuts in carbon intensity and demand-side mitigation options (Sharmina et al., 2020).

Decarbonizing diverse economic sectors presents a complex challenge, particularly due to "carbon leakage," where emissions reduction in one region leads to increased emissions elsewhere due to shifting economic activities to countries with laxer emissions constraints due to costs related to climate policies, potentially increasing total emissions. This underscores the need for coordinated global action and policy measures to prevent unintended consequences (EC, 2021a).

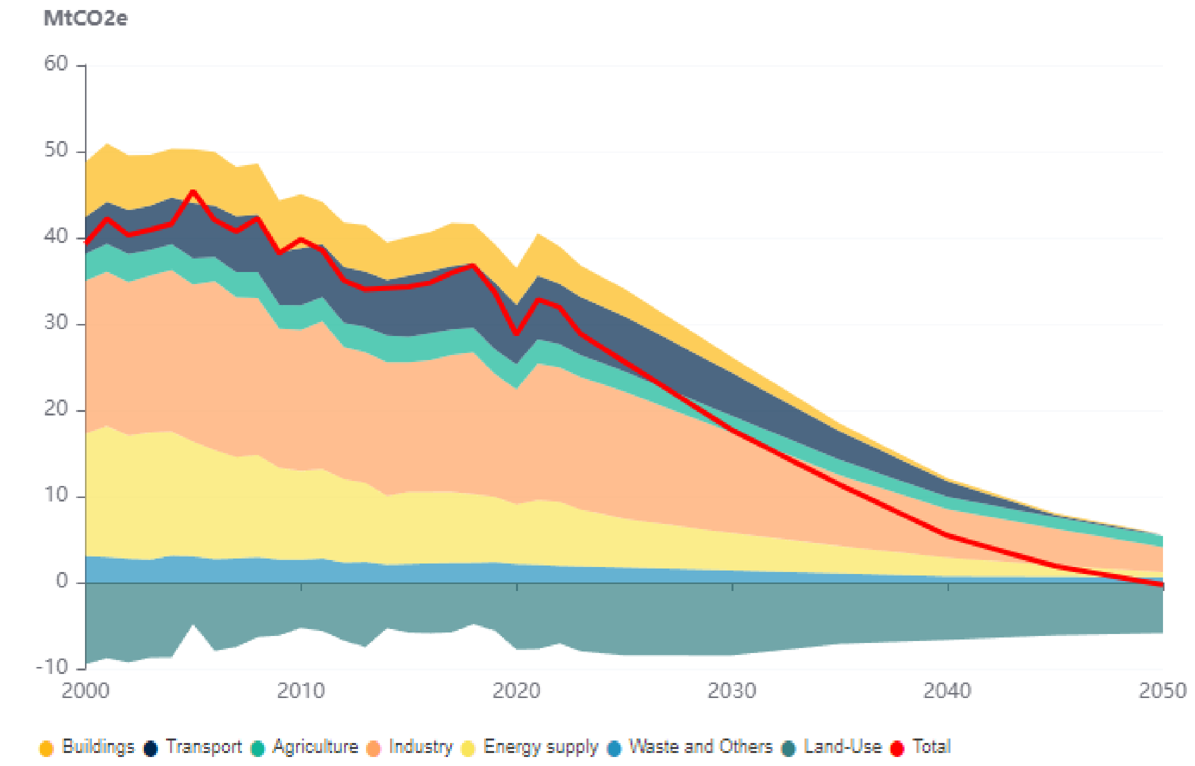
Despite the challenges, significant opportunities exist within each sector. For instance, clean energy investment reached USD 1.4 trillion in 2022 and the global market for key clean energy technologies is projected to be worth around USD 650 billion annually by 2030, more than three times the current level (IEA, 2023a). Recent reports indicate rapid growth in clean energy technologies, such as solar PV, electric vehicles, heat pumps. Nuclear capacity and electrolyser capacity are also expanding, supporting the transition to net-zero emissions. Additionally, improvements in energy efficiency have more than doubled, marking substantial progress (IEA, 2023b). Future research hotspots will include energy structure transformation, energy consumption assessment, carbon dioxide capture technology, biogas resource utilization and urban climate neutrality policy (Wang et al., 2022).

A sectoral analysis of decarbonisation is crucial for developing effective and targeted strategies to achieve global climate goals. By understanding the unique characteristics, challenges and opportunities within each sector, policymakers and stakeholders can work collaboratively to implement tailored solutions that drive a just and equitable transition to a low-carbon future.

Total carbon emissions of Slovak economy (Scenario ZEM 2024)

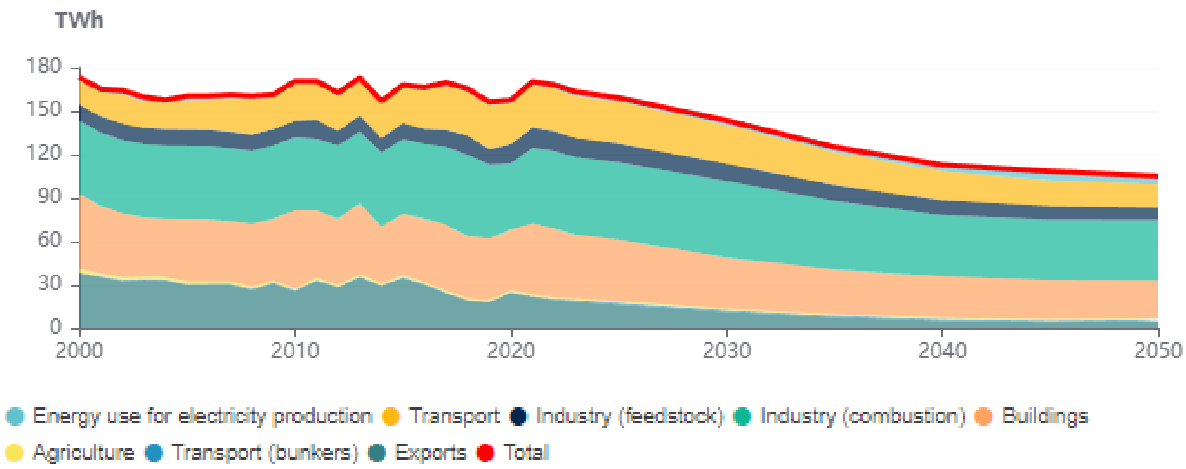
With an appropriate and ambitious combination of policies, measures, and consumer behaviour, the Slovak economy has opportunities to achieve a low-carbon transformation by 2050. Significant changes in public behaviour, alongside meeting the conditions for transforming industry and agriculture, transitioning to sustainable transport, increasing the share of renewable energy sources (RES), and enhancing energy efficiency could reduce greenhouse gas emissions to net -0.27 $MtCO_2e$ by 2050.

Figure 3: Total GHG emissions by sector (Scenario ZEM 2024)



In this scenario, final energy consumption would decrease to 105 TWh by 2050, representing a 34% reduction compared to 2005 and a 38% reduction compared to 2021. The most significant contribution to increased final energy consumption would come from the category of primary energy demand for electricity production, which is projected to rise by 105% compared to 2005.

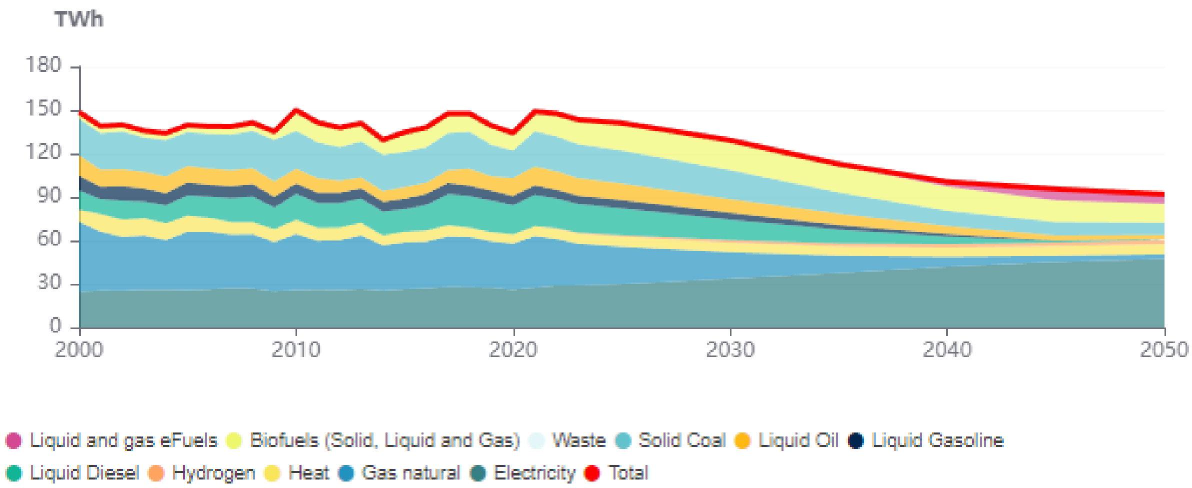
Figure 4: Final energy consumption per sector (Scenario ZEM 2024)



However, this substantial increase in energy consumption might not be accompanied by a rise in greenhouse gas emissions. This could be due to a more efficient and low-carbon energy mix, driven by a higher share of RES, investments in grid flexibility, a shift to nuclear fuel, and energy storage solutions. Other sectors, including industry, agriculture, and buildings, are expected to show a decline in energy consumption. The transport sector is also anticipated see a reduction in energy use, particularly from fossil fuels. The increase will primarily involve in energy use for electricity production incorporating network losses, energy used in refineries and to produce hydrogen and e- fuels.

By 2050, electricity is projected to be the most significant energy carrier, accounting for 51% of Slovakia's final energy consumption. Hydrogen, biofuels, and synthetic fuels are expected to have an increasing, though still modest, share. In contrast, the share of fossil fuels, such as natural gas, petroleum products, and coal, is anticipated to decrease.

Figure 5: Final energy consumption per energy source (Scenario ZEM 2024)



4.1. Industrial processes sector

Slovakia's industry sector presents a significant challenge on the road to climate neutrality by 2050. Heavy industries like steel, cement and chemical production are projected to remain major contributors to these emissions, making industry the sector to be the most GHG emissions intensive sector of Slovak economy with the share of 39% national GHG emissions. Addressing this issue would require for a strategy focusing on innovative technological advancements, systemic alterations in production processes and energy management. Integral to this approach could be the adoption of circular economy principles, the enhancement of energy efficiencies and the deployment of advanced carbon capture and storage technologies. Specific decarbonisation strategies tailored for industries with high emissions are likely necessary to ensure an extensive diminution of industrial emissions across diverse sectors.

4.1.1 Strategic framework

The EU's strategic approach to industrial decarbonisation revolves around achieving a significant reduction in greenhouse gas emissions, targeting a 90% decrease by 2040, compared to 1990 levels, as part of its broader goal of climate neutrality by 2050. Central to this strategy is the adoption of CCUS technologies supported by the Industrial Carbon Management Strategy (EC, 2024b). These are expected to capture about 280 million tons of CO_2 annually by 2040, particularly focusing on high-emission industries such as cement, steel, and chemicals.

Additionally, the Net Zero Industry Act is an initiative building on the Green Deal Industrial Plan and fostering technological independence and clean technologies, aiming for 40% of solar, wind and battery storage technologies to be produced domestically by 2030. This initiative is designed to enhance energy security and reduce reliance on external sources. (EC, 2023c; EC,2023a)

The EU Emissions Trading System is another cornerstone of the EU's regulatory framework, aimed at progressively tightening emission caps beyond 2030. The 2026 review of the EU ETS will determine if industrial carbon removals will be integrated into the existing EU ETS or if a new separate trading mechanism will be established. To attract private sector investment in diverse technologies on a voluntary market, the Carbon Removal Certification Framework will also certify industrial carbon removals from BECCS or DAC, alongside carbon farming or binding carbon in long-lasting products and materials. (EC,2022a) Complementing this is the Carbon Border Adjustment Mechanism, which imposes tariffs on imports from regions with less stringent environmental regulations. This mechanism will move from the initial phase to the definitive phase in 2026. (EC, 2023k)

Slovakia's industrial emissions included in the EU ESR are required not to increase by more than 40% by 2030 (vs. 2005). NECP industrial decarbonisation strategy includes the electrification of the steel sector, substitution of fossil fuels with alternative fuels, energy efficiency improvements in industrial processes, waste heat utilisation and support for clean technology, hydrogen and innovation (Ministry of Economy SR, 2023).

4.1.2 Carbon capture, utilisation and storage

Carbon capture, utilisation and storage (CCUS) technologies are designed to mitigate the environmental impact of carbon dioxide emissions from industrial and power generating facilities. These technologies offer solutions for capturing CO_2, transporting it and either storing it in geological formations or repurposing it for industrial applications. (IEA, 2019b; IEA, 2021d)

- Capture: This stage involves the separation of CO_2 from flue gases, employing technologies such as chemical absorption with amines, physical separation through membranes or cryogenic processes, oxy-fuel combustion in a high-purity oxygen environment and chemical or calcium looping.
- Transport: Once captured, CO_2 is typically compressed into a liquid form and transported via pipelines — considered the most economical for long distances. Alternatively, CO_2 can be transported by ships for offshore storage or by trucks and rail for shorter distances.
- Storage and utilisation: CO_2 can be permanently sequestered in depleted oil and gas reservoirs or saline aquifers. Additionally, it can be utilised in various industrial processes, including enhancing oil recovery, producing chemicals and building materials and synthesising cleaner-burning fuels.

CCUS not only captures emissions but also contributes to carbon removal through (IEA, 2019b; IEA, 2021d):

- Bioenergy with CCUS (BECCS): Combining biomass combustion for power generation with CCUS, where the net removal of CO_2 occurs as biomass absorbs CO2 during its growth cycle and the subsequent emissions are captured and stored.
- Direct air capture and storage (DACS): DACS technology directly removes CO_2 from the atmosphere. Coupled with CCUS, it facilitates the permanent storage of CO_2, offering a route to large-scale negative emissions.

CCUS is crucial for decarbonizing sectors that are challenging to abate, such as cement and steel production, and complements renewable energy solutions in sectors where direct adoption is constrained. Moreover, CCUS facilitates the production of clean hydrogen by capturing CO_2 emissions from hydrogen production processes. Despite its potential, CCUS faces challenges such as high operational costs, the need for extensive infrastructure and ensuring the safe and permanent storage of CO_2 to prevent leakage. Overcoming these challenges requires ongoing technological innovation, supportive policies and substantial investment. (IEA, 2019b; IEA, 2021d)

CCUS represents a vital technology set for mitigating climate change, offering viable solutions for reducing global CO_2 emissions. However, realising its full potential demands enhanced research, development and policy frameworks to address its current limitations and promote broader deployment. (IEA, 2019b; IEA, 2021d)

4.1.3 Material and energy efficiency, circular economy principles and waste reduction

Embracing circular economy principles is essential for mitigating emissions within heavy industries such as steel, cement and chemicals. Through prioritising the reuse, recycling and recovery of materials, these sectors can significantly decrease their dependency on virgin raw materials and the associated energy use and emissions. Enhanced material efficiency strategies — including the adoption of lightweight materials, extending product lifespans and reducing waste through innovative manufacturing processes—are crucial. (Rissman et al., 2020) Such practices not only curtail material costs but also align with global sustainability goals.

4.1.4 Decarbonisation strategies in specific high emissions industries

Metal and steel industry

The steel industry is a major contributor to industrial carbon emissions worldwide and Slovakia is no exception. Traditionally, steelmaking is energy-intensive, relying heavily on carbon-based energy sources which emit large quantities of CO_2. The urgency to mitigate these emissions has prompted a strategic overhaul towards sustainable practices within the sector (IEA, 2020c).

The steel industry is primarily driven by traditional blast furnace-basic oxygen furnace methods. This conventional method involves using coke, a fossil fuel, to reduce iron ore, resulting in substantial CO_2 emissions due to the high temperatures required. Notable trends in decarbonisation efforts include the integration of renewable energy sources, development of carbon capture and storage technologies and increasing the use of electric arc furnace (EAF) techniques alongside or in place of blast furnace methods where applicable, particularly in processes involving recycled steel or Direct Reduced Iron (DRI). In addition, integrating CCS technology can potentially lead to near-zero emissions. (Bataille et al., 2024; Rissman et al., 2020).

Renewable energy sources provide a solid foundation for steel production, particularly through the more sustainable EAF technology, which utilises electricity to melt recycled scrap metal. This significantly cuts energy consumption and emissions compared to traditional BF methods. (Bataille et al., 2024; Diez et al., 2023; Rissman et al., 2020) EAFs also emit less than half the carbon dioxide per ton of steel compared to the Blast Furnace – Basic Oxygen Furnaces (BF-BOFs), making this crucial step in the industry's decarbonisation efforts (World Steel Association, 2023). Additionally, renewable hydrogen, produced using green electricity through electrolysis, is emerging as an alternative to coking coal in the direct reduction of iron processes. (Bataille et al., 2024, Rissman et al., 2020) For DRI processes coupled with EAF, where hydrogen produced via electrolysis powered by renewable energy is used as a reducing agent, integrating CCS technology can potentially lead to near-zero emissions (JRC, 2024a).

CCS technology is essential for mitigating emissions that cannot be entirely eliminated through alternative fuel or efficiency improvements. By capturing CO_2 emissions at their source and storing them underground, CCS effectively prevents its release into the atmosphere and can reduce the environmental impact of existing steel plants. (IEA, 2023b; Tian et al., 2018) Retrofitting existing BF-BOF setups with CCS looks feasible, but requires substantial adjustments in plant operations to accommodate CCS technology (JRC, 2024a).

Chemical and petrochemical industry

The chemical and petrochemical industry have high energy consumption and depend on fossil fuels to meet the high energy demands of chemical reactions and as feedstocks (IEA, 2020a; Rissman et al., 2020). To decarbonise these sectors, strategies must not only account for the carbon stored in synthetic organic products, but also integrate renewables-based solutions, electrification and biomass utilisation (Saygin & Gielen, 2021; Rissman et al., 2020).

Innovations in emerging electrochemical processes are proving to be a promising avenue for reducing the carbon footprint in petrochemical production, nitrogen compounds and metal smelting (Xia et al., 2022). These advancements complement efforts in green chemistry, which focuses on designing processes and products that minimise or eliminate hazardous substances. Additionally, the development of bio-based chemicals, using biomass instead of petroleum, supports the expansion of biorefineries and the transition towards a circular bio-economy (EC, 2018b). On a related note, carbon capture and utilisation technology transforms captured CO_2 into valuable products like fuels, chemicals and building materials (Nesterenko et al., 2023; Rissman et al., 2020).

Cement industry

The cement industry emits GHG emissions from the calcination process and energy consumption during production. Cement is very important in modern infrastructure. It is used extensively in constructing buildings and various types of infrastructure, including renewable energy installations like wind turbines (IEA, 2023a).

Decarbonisation strategies for the cement industry are diverse and can be categorised into four main approaches: efficiency improvements, alternative fuels, material usage adjustments and CCUS (JRC, 2024b; Rissman et al., 2020). Among these, the highest potential for emissions reduction by 2050 was identified through strategies such as clinker replacement, optimising concrete mix designs, leveraging thermal mass in buildings, electrifying production processes and enhancing the design of structural elements (Marsh et al., 2023; Rissman et al., 2020). Further reduction in emissions can be achieved by cement recycling, substituting traditional fossil fuels with biomass, industrial wastes and recycled materials, carbon utilisation, as well as transport and infrastructure optimisation to reduce indirect emissions (IEA, 2023a; IEAa, 2020, ECRA, 2022).

Addressing the cement industry's environmental impact requires a multifaceted approach, focusing on reducing emissions while ensuring operational efficiency and economic viability (IEA, 2023a).

Automotive industry

The automotive sector is undergoing a profound transformation, as it shifts from internal combustion engine vehicles to electric vehicles and hybrid technologies, as battery electric vehicles are now considered the primary means of decarbonizing passenger cars. Additionally, for more demanding applications such as heavy-duty and long-haul transportation, hydrogen fuel cell electric vehicles are being increasingly considered.

The European Union has set forth ambitious targets to decrease CO_2 emissions from new cars and plans to ban the sale of new fossil fuel vehicles from 2035 (EC, 2023i). In addition, wider adoption of alternative fuels and expansion of charging infrastructure can assist in overcoming barriers such as the high cost of infrastructure, limited vehicle range and inadequate charging facilities (EC, 2023b). The hydrogen production from low-carbon methods utilising renewable energy sources such as hydropower is considered particularly significant for Slovakia (IEA, 2019a; IEA, 2023c; Ďurčanský et al., 2022).

The automotive sector is embracing decarbonisation through the adoption of Industry 4.0 technologies. These include automation, artificial intelligence (AI) and the Internet of Things (IoT), which significantly enhance energy efficiency by enabling continuous monitoring and optimization of energy consumption (JRC, 2020; JRC, 2024c). The Slovak automotive sector is making substantial progress by investing in advanced robotics and energy management systems. These investments not only optimise production processes but also align with EU regulatory standards, thereby reducing both operational costs and emissions (Nagy & Lăzăroiu, 2022; Valášková et al., 2022; Smolka & Papulová, 2022). In addition, the sector is increasingly incorporating lightweight materials such as high-strength steel, aluminium, carbon fibre and advanced composites into vehicle designs. This integration not only improves fuel efficiency and performance but also tackles the challenges associated with the cost and complexity of production techniques (Jenny & Kabecha, 2023; Mohammadi et al., 2022).

Food processing industry

The food processing industry faces issues spanning energy usage, waste management, renewable energy adoption and supply chain emissions. Innovations in energy-efficient technologies, notably, the adoption of advanced refrigeration systems employing low global warming potential refrigerants like ammonia and CO_2, are on the rise, alongside smart energy management systems that optimise real-time energy use to reduce energy consumption (IEA, 2018).

Emerging electrified technologies play a pivotal role in processes such as drying, evaporation, thawing, tempering and baking, where they enable faster and more efficient heat transfer (Atuonwu & Tassou, 2020). In parallel, the implementation of waste reduction and recycling measures, including the conversion of food waste into biogas through anaerobic digestion, not only mitigate waste but also produce renewable energy (Kulla et al., 2022).

Transitioning to renewable energy sources further exemplifies the industry's commitment to decarbonisation. The integration of solar PV systems, biomass, geothermal energy and wind turbines into food processing facilities are becoming increasingly common. This transition is complemented by the adoption of energy-efficient technologies such as heat recovery systems and insulated steam pipelines, which enhance energy performance (IRENA and FAO, 2021).

The adoption of electric vehicles for transportation, the use of sustainable packaging materials (such as lightweight and biodegradable materials) and the optimisation logistics are further options to minimise carbon footprints in the food processing supply chain (Sovacool et al., 2021; Plastics Europe, 2022).

Machinery and equipment manufacturing

The decarbonisation of machinery and equipment manufacturing industry is advancing through material and energy efficiency improvements. It involves optimising the use of raw materials and energy to reduce waste and emissions, as well as embracing circular economy principles to enhance product lifespans and recycling (IEA, 2020b; Bjoern, Jæger & Upadhyay, 2019). Choosing the right raw materials is essential for boosting both productivity and sustainability. Leveraging the potential of Industry 4.0 technologies, including IoT, big data analytics and AI, to achieve real-time monitoring and optimization of production processes, can further boost energy efficiency and reduce costs (Butt, 2020; Valášková et al., 2022).

Pulp and paper industry

The pulp and paper industry is known for its high water and energy consumption. Efforts to lower carbon emissions include enhancing water and energy efficiency. This involves investing in advanced technologies and processes that minimise water usage and improve energy management. The use of sustainable raw materials such as certified wood and the incorporation of recycled fibres help in reducing the overall environmental impact. In terms of energy consumption, the integration of biomass energy provides a renewable energy source that can significantly cut down carbon emissions. (Lipiäinen et al., 2023; Nurdiawati & Urban, 2021)

In addition to material and energy efficiency improvements, sectoral decarbonisation strategies and CCUS, a holistic approach to industry decarbonisation involves also:

- **Innovative R&D**: Amplifying investment in R&D is vital for pioneering clean technologies, including advanced biofuels and next-gen carbon capture.
- **Economic incentives via carbon pricing**: Implementing mechanisms like carbon taxes or emission trading schemes motivates emissions reduction by increasing the cost of carbon.

- **Infrastructure for low-carbon transition**: Developing infrastructure essential for renewables, CCS and EVs paves the way for a sustainable industrial base.

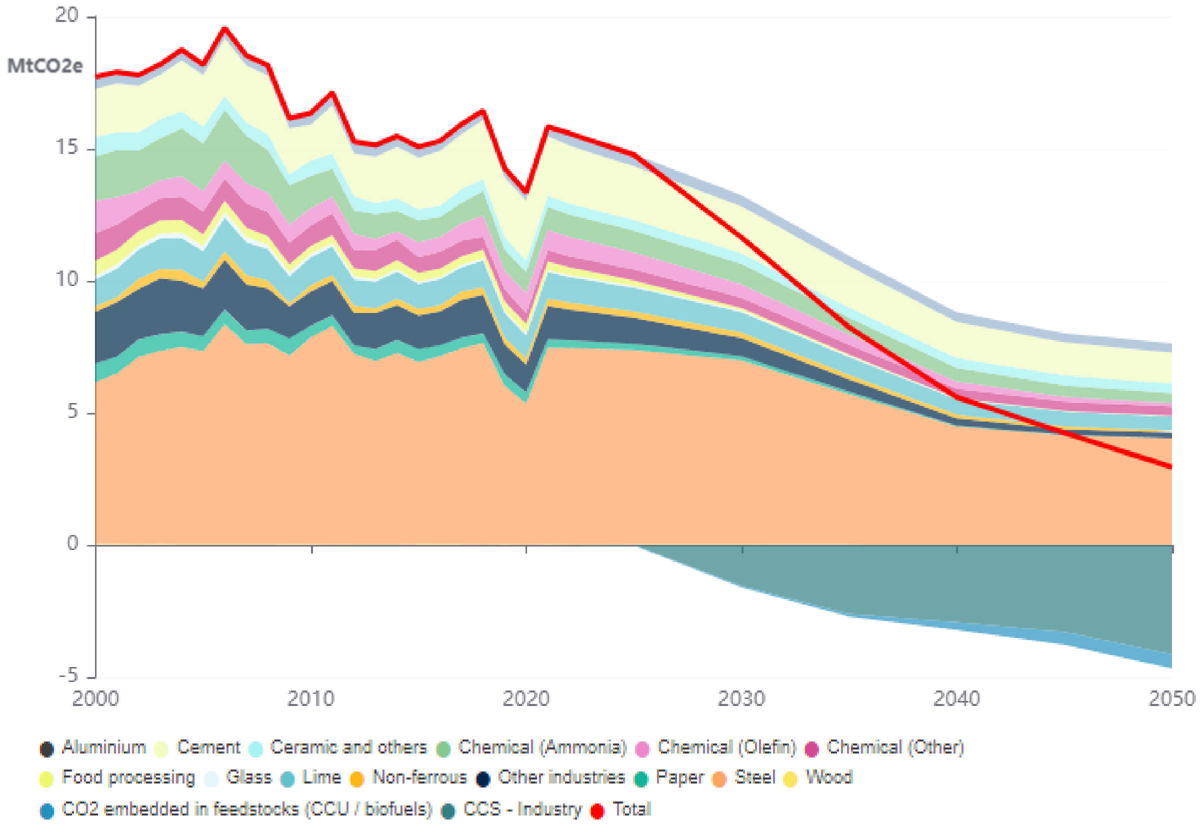
These strategies collectively advance the decarbonisation of the industry sector, steering it towards meeting stringent global climate targets. (Rissman et al., 2020)

According to the Slovak marginal abatement cost curve (MACC), the most substantial reductions in greenhouse gas emissions are achievable through the electrification and efficiency improvements of the steel industry, which alone can abate up to 6.2 million tonnes of CO_2 equivalent annually by 2030. (Ministry of Finance SR, 2022) Similarly, the automotive sector must accelerate its transition to electric vehicles, in alignment with EU regulations phasing out internal combustion engines by 2035. Moreover, efficiency improvements across the metal, machinery and equipment manufacturing sectors are crucial, leveraging advancements in cleaner technologies and optimised manufacturing processes. Additionally, the adoption of circular economy principles in sectors like pulp and paper and the gradual transition to low-carbon feedstocks in the chemical sector are vital. These strategies not only align with environmental targets but also support sustainable industrial practices. Collaboration between industry stakeholders, research institutions and policymakers is essential to share best practices, overcome technological barriers and ensure a coordinated approach to decarbonisation.

Industry sector decarbonisation pathway (Scenario ZEM 2024)

By implementing the proposed measures, it would be possible to reduce greenhouse gas emissions from the industry sector to 2.94 $MtCO_2e$, representing an 81% decrease compared to 2021 levels. Despite anticipated reductions, the steel, cement and chemical production are projected to remain major contributors to these emissions. The most significant percentage reductions could be achieved in the food processing, glass, wood processing, and paper industries.

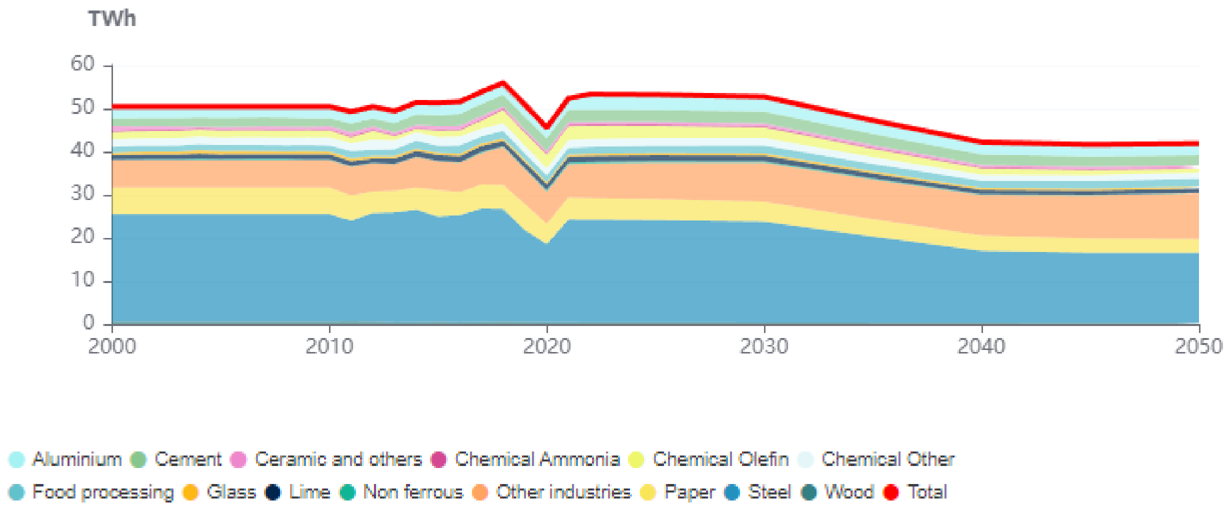
Figure 6: GHG emissions in industry sector (Scenario ZEM 2024)



In this transition, the role of CCS would prove essential, facilitating significant reductions particularly within high-emission sectors such as steel and cement. By 2050, it is anticipated that CCS technologies will be capable of capturing and sequestering approximately 2.6 $MtCO_2e$ annually in the industry sector. The deployment of CCS would benefit from technological advancements and increased financial backing, ensuring a substantial contribution to the targeted reduction of emissions in the designated industries.

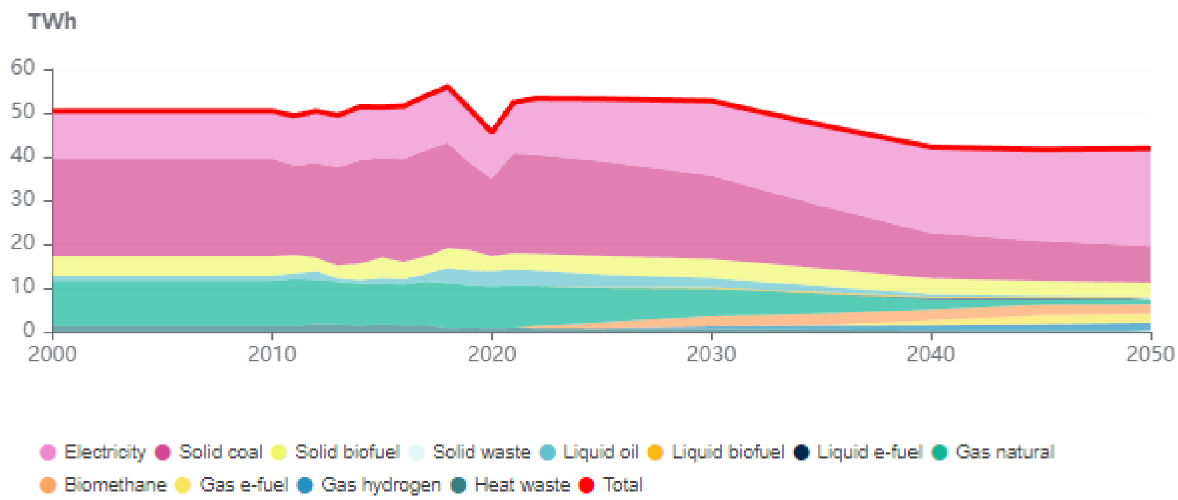
However, energy demand in the combustion part of industry sector is expected to decrease by only 20% compared to 2021, reaching a level of 36 TWh. Of this, 39% of the energy would be used in the steel industry.

Figure 7: Energy demand in industry sector - Energy use (Scenario ZEM 2024)



The most significant energy carrier in the industry sector by 2050 is expected be electricity, which would cover 65% of the demand. During this period, the share of biofuels, biomethane, and synthetic fuels would also increase. In contrast, the use of fossil fuels such as natural gas, coal, and other conventional fuels would decline.

Figure 8: Energy demand by vector in industry sector - Energy use (Scenario ZEM 2024)



Measures in the industry sector that would contribute to achieving climate neutrality by 2050:

- Maintain steel and aluminium production at current (2022) levels.
- In secondary steel production increase the use of EAF to at least 66% by 2050.
- In steel production increase energy efficiency of primary steel Blast Oxygen Furnaces by 5% (in TWh/t of manufactured material) by 2050.
- Increase the share of recycled materials in metals production (at least 30% in aluminium and 35% in steel production), in glass to 60%, by 2050.
- Maintain or slightly reduce production of cement, lime, ammonia, and paper.
- In glass production increase energy efficiency by 13% (in TWh/t of manufactured material), in aluminium production by 18% by 2050.
- In food production increase energy efficiency by 26% by 2050.
- In wood production increase energy efficiency by 7% (in TWh/t of manufactured material) till 2050, in paper production by 18% by 2050.
- Reduce demand for textile industry products by 40%.
- Reduce demand for furniture products by 17%.
- Support energy-efficient and emission-friendly technologies (tax reductions).
- Utilise waste heat from industrial processes (legislation/regulations, financial support).
- Reduce waste in the food industry.
- Encourage the rational use of agricultural products.
- Reduce packaging and promote the use of eco-friendly materials for packaging goods (through legislation/regulations)—aim for at least a 50% reduction in packaging use.
- Promote eco-friendly technologies (funding for development and implementation).
- Extend the lifespan of products—promote longer use of the items we own, combined with potential repairs.

4.2. Energy sector

To achieve net-zero emissions by 2050, Slovakia's energy sector should address transition to sustainable energy systems. The share of greenhouse gas emission in the energy sector is around 19 % in 2023, with Slovakia benefitting from nuclear power production. The diverse energy mix presents both challenges and opportunities in the pursuit of decarbonisation.

Slovakia's energy landscape is a mix of nuclear power, fossil fuels and a growing share of renewable energy sources. The country can leverage its nuclear energy to drive electrification across industries like transportation and steel. With the closure of coal-fired plants and the commissioning of a new nuclear reactor in Mochovce, the emissions from the power sector decreased (Ministry of Finance SR, 2022). Further comprehensive transformation measures for the energy system leverage advancements in renewable energy, decarbonisation of district heating and cooling networks, energy storage, smart grid technology and carbon capture and storage.

4.2.1 Renewable energy Integration

Slovakia has made progress in increasing the adoption of renewable energy sources in recent years, driven by the implementation of key EU policies like the Clean Energy for All Europeans package and the European Green Deal. However, the country still has one of the lowest renewable energy penetration rates in the EU, with only minimal wind energy capacity installed.

Slovakia’s renewable energy mix is currently dominated by solar power and, despite its potential, the country has one of the lowest installed capacities for wind power in Europe. (Sabovčík et al., 2024) The installed capacity of solar PV systems stood at 500 MW in 2023, but households and businesses sought to reduce electricity costs and ensure energy self-sufficiency during the energy crises with new installations expanding rapidly. This substantial growth in solar electricity production is expected to continue, expanding further through energy communities. The current installed wind energy capacity is relatively low, at 3 MW in 2023. More ambitious projects, such as the wind farms Drahovce, Skalica West, Skalica East, Tvrdošín, Galanta 1 and 2, Sziget, Rúbaň, and others, are currently undergoing environmental impact assessments. (Enviroportal, 2024)

However, wind park projects face opposition from the locals from various reasons in the Environmental Impact Assessment (EIA) process, potentially delaying or even halting projects. In spite these challenges, the European Union's REPowerEU initiative introduced a program, managed by the European Commission's Energy and Industry Geography Lab, to strategically identify specific 'go-to areas' for renewable energy development, focusing on wind and solar power (EC, 2022c). By leveraging detailed geographical and environmental data, this systematic approach ensures the areas align with both national and broader EU energy and climate strategies, effecting a more structured and efficient rollout of renewable energy projects across Slovakia

The advantages of renewables such as solar and wind include abundant resource availability and absence of greenhouse gas emissions from operation. However, renewable energy sources such as solar and wind face intermittency problems due to weather conditions and time-of-day effects (solar energy during the day, wind energy typically higher at night). (IEA, 2021a; Sabovčík et al., 2024) In order to reduce intermittency in electricity production, wind and solar energy can complement each other. The wind tends to produce electricity when solar energy is low, especially at night. A study analysing four specific locations in Slovakia for wind energy potential, finds complementary development of both solar and wind resources should be promoted, with the ideal solar-to-wind capacity ratio to be approximately 2.2–2.3:1 (Sabovčík et al., 2024). Other challenges include high initial costs, especially for wind parks, regulatory barriers and complex permitting processes. In addition, the environmental impacts of manufacturing solar panels and wind turbines must be considered (IEA, 2021a, Sabovčík et al., 2024). Policy measures should include feed-in tariffs, net metering schemes and investment grants played a crucial role in promoting the installations of both utility-scale and distributed solar PV deployment throughout the country (IRENA, 2019).

Geothermal energy can be used either directly for heating and cooling purposes, alternatively for energy storage and power production (Farghali et al., 2023). Geothermal heat pumps are a common technology for this direct use, where the temperature difference between the ground and the surface is leveraged to provide efficient heating and cooling (Galgaro et. Al, 2017). The growth in solar panel installations in households and small industrial enterprises has increased demand for heat pumps. Additionally, geothermal energy can be used for thermal energy storage, increasing the flexibility and reliability of the energy system. In addition to heat, geothermal power plants can be built to provide baseload renewable electricity that is not dependent on weather conditions, enhancing the stability of the energy supply (IRENA and IGA, 2023). Realising the full potential of Slovakia's geothermal resources will require targeted policy support, investment in research and development and the implementation of enabling regulatory frameworks to facilitate the widespread deployment of geothermal energy technologies across the country.

Bioenergy, derived from organic materials such as wood, agricultural residues and energy crops, can be used for heat and electricity generation or for producing biofuels like ethanol and biodiesel (IRENA 2020). Biomass is considered a renewable energy source because the carbon dioxide released during its combustion can be reabsorbed by growing plants, resulting in a closed carbon cycle. The sustainable utilisation of biomass resources can therefore play a key role in reducing greenhouse gas emissions and transitioning to a low-carbon energy system (Farghali et al., 2023).

Advances in energy storage technologies, such as batteries and hydrogen storage, will be key to integrating higher shares of variable renewable energy sources and ensuring the stability and reliability of the grid (IRENA, 2020). Battery storage can help manage the short-term variability of solar and wind power, while hydrogen storage can provide long-term seasonal storage to address energy demand fluctuations. (IRENA, 2020; IRENA, 2024)

4.2.2 Energy efficiency and electrification

Boosting energy efficiency will require a shift towards electrifying industrial processes and heating/cooling systems in buildings (IEA, 2021a). This will involve replacing fossil fuel-powered equipment and appliances with more efficient, electric-powered alternatives (IRENA, IEA and REN21, 2020). Further substantial emissions reductions in industrial processes can yield measures such as energy audits, process optimization and waste heat recovery (IEA, 2021b).

Hydrogen technologies, including hydrogen-powered industrial processes and heating systems, complement electrification efforts and address hard-to-abate emissions. Hydrogen can be produced from renewable energy sources through electrolysis, providing a clean and versatile energy carrier that can be used in various applications (IEA, 2019, IRENA 2024).

4.2.3 Decarbonisation of Heating and Cooling systems

Heating and cooling systems play a critical role in Slovakia's energy transition and decarbonisation efforts. Comprehensive policies, investment programs and regional planning efforts will be necessary to facilitate the widespread deployment of this decarbonized district heating infrastructure across Slovakia.

In Slovakia, district heating networks can be upgraded to use renewable energy sources such as biomass, geothermal and waste heat recovery. This transition towards decarbonized district heating, powered by sustainable and circular sources of heat, can provide a more efficient and environmentally friendly alternative to individual building-level heating solutions (IRENA, IEA and REN21, 2020). In addition, green hydrogen is also a potential source to replace natural gas for heating in district heating networks (Šrámka et al., 2022). Individual family homes can transition to solar thermal, electric heat pumps and other low-carbon heating solutions. The revised EU Directive on the Energy Performance of Buildings calls for a phase out the use of fossil fuel boilers for heating in buildings by 2040 (EC, 2024a).

The importance of smaller, localised solutions, such as energy communities and the installation of small-scale energy sources for energy self-sufficiency, will also grow. This includes the installation of photovoltaic panels on roofs and walls of private and public buildings, as well as on unused built-up areas, such as the roofs of industrial buildings and parking lots of logistics centres and warehouses. (Ďurčanský, 2024)

4.2.4 Carbon capture, utilisation and storage (CCUS)

The development and integration of CCUS, BECCS and DAC technologies in Slovakia's energy system could provide a valuable complement to the country's transition. These carbon capture and removal technologies could help address emissions from hard-to-abate sectors and potentially even achieve net negative emissions, further supporting the net-zero emissions by 2050.

4.2.5 Digitalization and cybersecurity

Smart grid technologies, such as advanced metering infrastructure, energy management systems and demand response programs, enhance energy distribution efficiency and grid reliability. These technologies enable real-time monitoring and control of energy flows, optimise the integration of renewable energy sources and improve load balancing (IEA, 2017).

Smart meters and advanced distribution management systems provide detailed insights into energy consumption patterns, allowing grid operators and their energy management systems, leveraging AI and machine learning algorithms, to better match supply and demand and consumers to manage their energy use more effectively (JRC, 2022d).

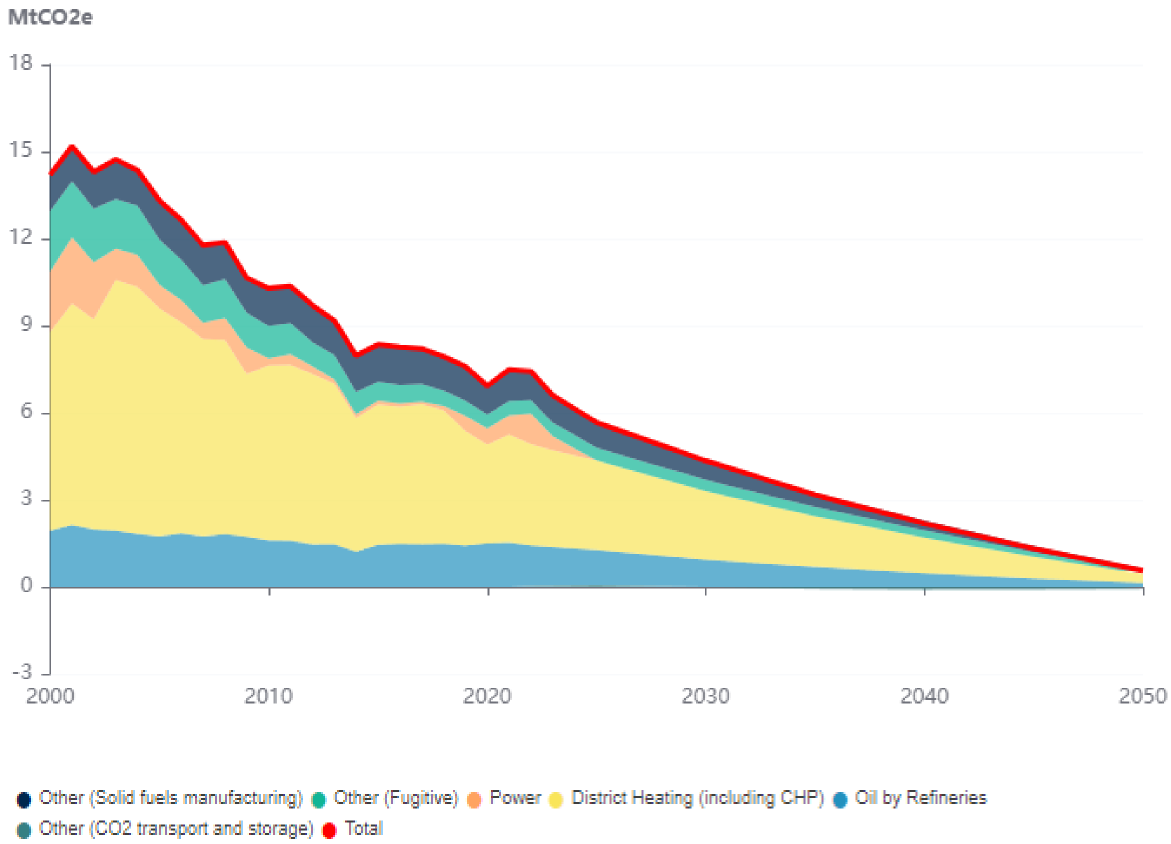
Digitalization of the energy system, including the deployment of smart meters and the implementation of smart grid technologies, can enhance the efficiency and flexibility of energy distribution and demand-side management. As energy systems become increasingly digitised, they become more vulnerable to cyber-attacks that could disrupt energy supply, compromise data integrity and damage infrastructure (Kaster & Sen, 2014; Pandey & Misra, 2016; Acharya et al., 2020; Mohammadpourfard et al., 2021;). The increasing penetration of connected devices, such as smart and electric vehicle charging stations, has expanded the attack surface and created new entry points for potential adversaries (Ramotsoela et al., 2023).

Implementing comprehensive cybersecurity strategies, including threat detection, risk assessment, and incident response, is crucial for maintaining the security and resilience of digitalized energy systems.

Energy sector decarbonisation pathway (Scenario ZEM 2024)

The energy sector could achieve climate neutrality by 2050. Through implementation of carbon capture and storage (CCS), greenhouse gas emissions could be reduced to 0.556 $MtCO_2e$. The captured and stored carbon could then be utilised in industry through innovative technologies, such as in the production of plastics, chemicals, and other materials, as well as in the creation of synthetic fuels, including synthetic aviation fuel, which is currently difficult to replace with a low-carbon alternative.

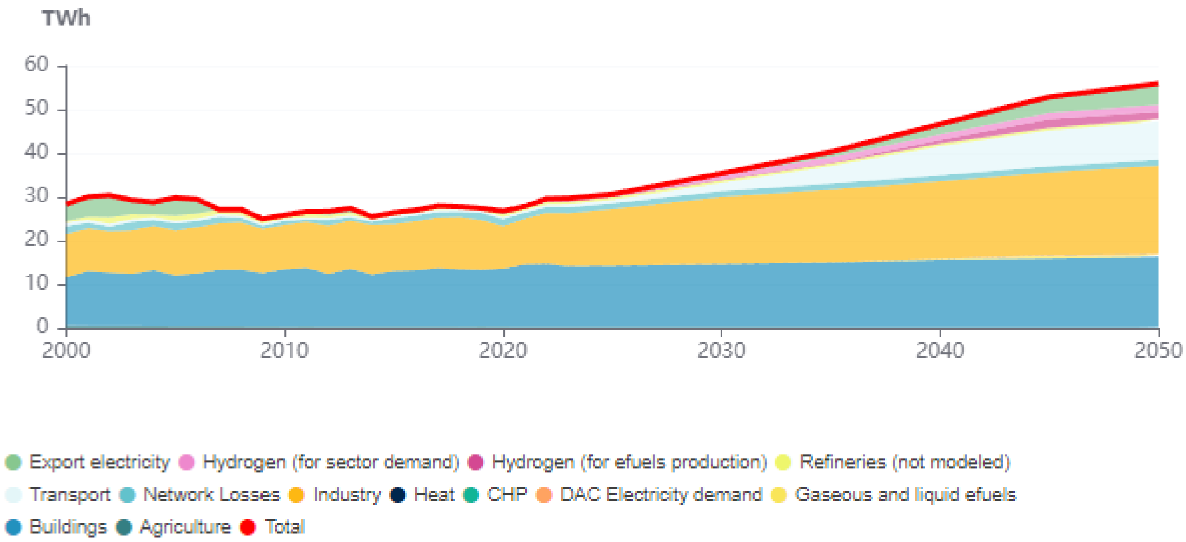
Figure 9: GHG Emissions by energy production technologies (Scenario ZEM 2024)



In this scenario, the electricity demand is projected to increase by nearly 83% between 2021 and 2050, reaching 50 TWh. Slovakia will likely become a net exporter of the electricity, following the commissioning of the third and the fourth unit of the Mochovce nuclear power plant. Nuclear energy is expected to remain a stable energy source with a capacity of 3 GW, potentially supplemented by small modular reactors, if needed. Electricity generated from low-carbon sources (nuclear and renewables) would become the primary energy source in Slovakia.

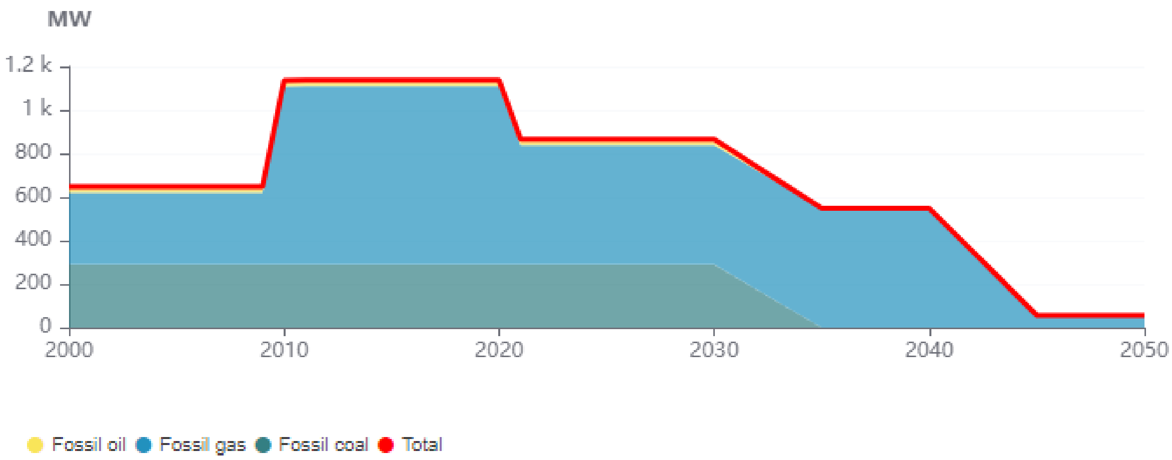
The most significant increase in electricity demand is expected in the transportation sector. The industry sector is anticipated to be the most energy-demanding, consuming 40% of the electricity, followed by buildings with a 32% share. Nearly 17% of electricity would be needed in the transportation sector. This energy mix would require high-capacity energy storage and increased flexibility in the transmission and distribution grid.

Figure 10: Electricity demand per sector (Scenario ZEM 2024)

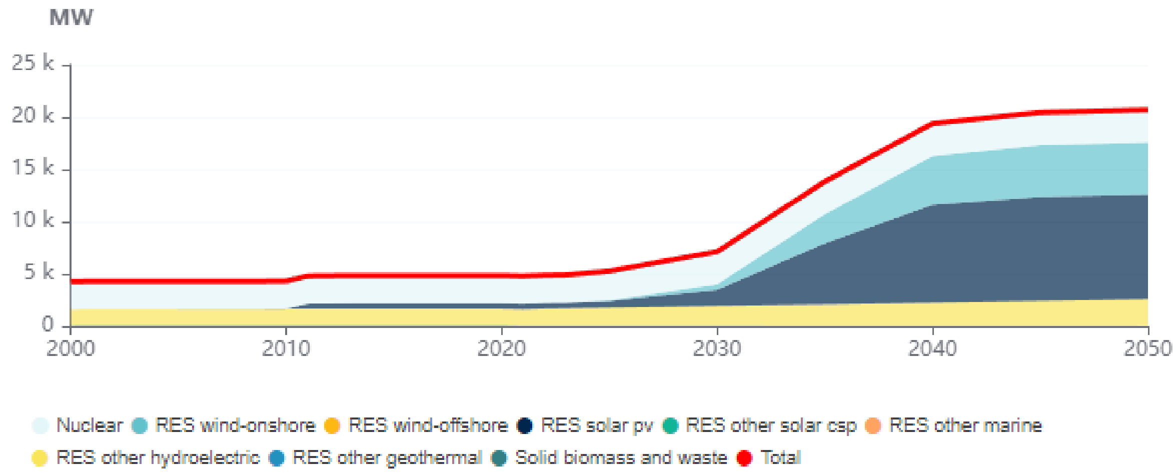


In response to rising energy prices due to geopolitical shifts, particularly the military intervention in Ukraine and the EU sanctions against the Russian Federation on the import of energy resources into EU member states, a slight change in Slovakia's energy mix and shifts in the suppliers of key energy resources have been observed.

Figure 11: Total capacities of electricity production from fossil fuels, nuclear and RES (Scenario ZEM 2024)



* Coal production capacity has essentially been phased out by 2023 in Slovakia, except for small-scale heating plants with significantly lower capacities, not exceeding 300 MW in total.



Modelled measures in the energy sector that could contribute to achieving climate neutrality by 2050:

- Expand solar power capacity from 550 MW to 10 GW.
- Increase wind power capacity from 3 MW to 5 GW.
- Expand nuclear power plant capacity from 2.6 GW to 3 GW.
- Expand hydropower capacity from 2.5 GW to 2.6 GW.
- Increase biomass and waste-to-energy plant capacity from 200 MW to 1 GW.
- Enhance carbon capture from refinery processes to 50%.
- Increase the use of geothermal energy from 0 GW to at least 0.12 GW.
- Decommission coal power plants in line with the Action Plan for the Transformation of the Upper Nitra Region (by 2023) (MIRRI, 2021).

4.3. Transport sector

The transport sector is a significant contributor to greenhouse gas emissions in the European Union, accounting for roughly 18 % of the total emissions in Slovakia in 2022. The transport sector is one of the most challenging areas to decarbonise due to its dependency on fossil fuels and the decentralised nature of its emissions. To achieve net zero, a significant shift towards a multimodal transport system that prioritises public transport and active mobility, coupled with zero-emission vehicles and transport need and demand management, is essential.

4.3.1 Strategic framework

The EU's Sustainable and Smart Mobility Strategy provides a framework for the transition to Zero-Emission Vehicles (ZEVs) (EC, 2020d):

- **New vehicle emissions rules:** In 2022, the EU set tighter rules for new vehicles to help cut down on pollution. By 2030, the goal is to reduce CO_2 emissions from new cars by 55% and from new vans by 50%, compared to 2021. By 2035, these emissions should be cut down by 100%, although there are some exceptions for vehicles using synthetic fuels. (EC, 2023i) Different countries in the EU have set their own specific goals. For example, Italy and France have plans to stop selling new conventional cars by 2035 and 2030, respectively. Similarly, Ireland and Great Britain are pushing for more electric vehicles (EVs) with ambitious targets for 2030 and 2035. (IEA, 2024)
- Expansion of the **charging infrastructure** for electric vehicles via the Alternative Fuels Infrastructure Regulation, adopted in 2021, setting targets for the deployment of charging stations for both cars and heavy-duty vehicles (EC, 2023a). This addresses a key concern for potential EV buyers, commonly referred to as "range anxiety" – the fear of running out of power before reaching a charging station. For long-distance travel and heavy-duty vehicles, hydrogen fuel cell technology presents a more promising solution than electric power. (Rose, Neumann, 2020; UN, 2021; Rinaldi et al., 2023). The EU is also supporting the development and deployment of hydrogen refuelling infrastructure through initiatives like the Fuel Cells and Hydrogen Joint Undertaking.
- **Financial incentives**, such as purchase subsidies and tax breaks, can significantly reduce the upfront cost of ZEVs and encourage consumer adoption. (EC, 2020d; IEA, 2024) Additionally, some cities offer benefits like free parking or access to bus lanes for ZEVs (c40, 2021). The effectiveness of these incentives is being studied and refined to maximize their impact (Wangsness et al., 2020).

The Slovak NECP sets clear and measurable targets for reducing greenhouse gas (GHG) emissions in the transport sector. By 2030, the road transport sector emissions should limit the increase to 29% compared to 2005 levels. The renewable energy in the transport sector should reach 14% by 2030, primarily through the increased use of advanced biofuels and renewable fuels of non-biological origin, as well electricity. A key component of this strategy is to increase the share of public transport, including rail transport for both passengers and freight and implementation of smart transport systems. (Ministry of Economy SR, 2023)

4.3.2 Role of public transport and active mobility

Public transport and active mobility (such as cycling and walking) will remain crucial components of a sustainable transport system. These modes of transport offer significantly lower carbon footprints compared to private vehicles. Encouraging pedestrian passage, cycling and walking can help reduce traffic congestion in urban areas, leading to improved air quality, shorter travel times and a more efficient use of road space. Moreover, promoting cycling and walking supports physical activity, fostering healthier lifestyles for city residents. (EEA, 2020; ITF, 2021; ITF, 2023)

A key aspect of sustainable urban mobility is shifting away from private vehicle use towards public transport. To make public transit a more appealing option for daily commuters, it is essential to improve its availability, reliability and efficiency. This includes increasing bus frequency, extending transit routes to underserved areas and implementing integrated ticketing systems that facilitate seamless transfers between different transport modes. The deployment of real-time information systems to display arrival times and route disruptions can also enhance user experience. Another vital factor is building an inclusive public transport system ensuring accessibility for people with disabilities, coverage of rural or hard-to-reach areas and affordable housing. Additionally, investments in infrastructure such as bus rapid transit systems and efficient intercity networks can help decrease urban traffic volumes and reduce emissions. (EEA, 2023; JRC, 2022a; JRC, 2022b; ITF, 2023, UN 2021)

Encouraging active mobility requires the development of extensive infrastructure that supports cycling and walking. This includes building dedicated bike lanes, separated cycling paths and pedestrian zones to promote zero-emission travel. Creating a safer and more inviting environment for pedestrians and cyclists can be achieved by implementing traffic-calming measures, reducing vehicle speeds and establishing car-free zones in city centres. Secure bike parking facilities are also crucial for encouraging cycling. (EEA, 2020; UN, 2021, ITF, 2023)

Public awareness and education play a significant role in promoting the benefits of active mobility. Campaigns and educational programs can encourage more people to choose cycling and walking for short trips. The development of cycling infrastructure, including dedicated lanes and paths, is essential for making cycling a safe and convenient mode of transport. Additionally, micro mobility solutions, such as shared bike and e-scooter programs, offer convenient last-mile connectivity, reducing reliance on private cars for short-distance trips. (EEA, 2020; UN,2021)

4.3.3 Transport demand and traffic management

Transport demand management strategies aim to optimise the use and efficiency of transport networks to minimise unnecessary trips and reduce emissions (UN, 2021, Transport & Environment, 2022).

Reducing the demand for transport relies on strategic urban planning that shortens travel distances, promotes sustainable transportation options and helps alleviate congestion. Smart urban design is central to this effort, with cities increasingly embracing mixed-use developments where residential, commercial and recreational spaces are located near each other, minimising the need for lengthy commutes. Many cities are adopting compact city models, encouraging walking and cycling as practical alternatives to driving by making essential services easily accessible. (EEA, 2020; UN, 2021; ITF, 2021; ITF, 2023)

In freight logistics, enhancing efficiency can be achieved by shifting freight transport from road to rail, which offers lower emissions per ton-kilometre. Other methods include platooning to reduce aerodynamic drag, increasing truck capacity and implementing advanced coordination systems (UN, 2021; EEA, 2022; ITF, 2023).

Traffic flow can be improved by optimising traffic light operations and introducing intelligent transportation systems, which enhance route planning and real-time traffic management. These measures reduce idle time, smooth traffic speeds, and minimise stops, leading to lower fuel consumption and emissions. (UN, 2021; EEA, 2023)

Additionally, smarter parking solutions, such as real-time parking information systems and pricing strategies, help decrease the time vehicles spend idling while searching for parking, further reducing emissions. (EEA, 2023; ITF 2023)

Overall, the use of technology to optimise routes, reduce idling, and enhance transport efficiency is critical. Smart systems can integrate real-time data to improve operational efficiency across public transport networks and freight logistics. (EEA, 2023; ITF 2023)

Enhancing intermodality in freight transport focuses on streamlining the transfer of goods across multiple transport modes, such as shifting from ship to rail to truck. This strategy optimises logistics by selecting the most efficient mode for each leg of the journey, leading to reduced transportation costs and a lower environmental footprint. Additionally, the growing emphasis on transitioning to a circular economy drives interest in localised production-consumption models, shorter supply chains, reuse practices, and digital manufacturing. If these trends expand on a large scale, they could significantly alter freight transport volumes and reshape logistics networks. (EEA, 2022; ITF, 2019)

4.3.4 Transition to zero-emission vehicles and improving energy efficiency

Zero-emission vehicles, including battery, plug-in and fuel cell electric vehicles, represent the next advancement in reducing automotive emissions. As countries adopt renewable and low-emission electricity generation, ZEVs offer a dual benefit: mitigating climate change and cutting fossil fuel use. (IEA, 2020a) The shift away from fossil fuels in the transport sector involves adopting various alternative fuel types suitable for different modes of transport, alongside the expansion of necessary infrastructure.

1. Electric vehicles (EVs): EVs are most suitable for passenger cars and light commercial vehicles. The widespread adoption of EVs necessitates a robust infrastructure of charging points. Urban areas require fast-charging stations to accommodate daily commuters, while highways need charging points at regular intervals to facilitate long-distance travel (Skaloumpakas et al., 2022; Rinaldi et al., 2023).
2. Hydrogen fuel cells: Hydrogen is particularly effective for freight and long-distance transport, including buses and trucks. Hydrogen fuel cells offer a high gravimetric energy density, making them ideal for routes requiring heavy payloads and longer ranges. Developing a network of hydrogen refuelling stations is crucial for adoption of hydrogen fuelled vehicles, with strategic placement along major freight corridors and in industrial hubs (UN, 2021; Rose, Neumann, 2020; Rinaldi at al., 2023).
3. Biofuels: Suitable for both passenger vehicles and freight transport, biofuels like biodiesel and bioethanol are compatible with existing combustion engine technologies, making them a transitional fuel option. For aviation, biojet fuels derived from organic materials can significantly reduce the carbon footprint of air travel (UN, 2021; IEA, 2023b; IRENA 2021).
4. Synthetic Fuels: Synthetic carbon-neutral gasoline and diesel, produced through carbon capture and green hydrogen processes, serve as alternatives that can be used without modifying current engine designs and use of existing infrastructure. They are especially promising for aviation and maritime transport, where electrification is challenging.

However, it's more expensive as its production is more energy intensive. And the production of carbon-neutral kerosene for aviation will likely be prioritised over gasoline, as there is no other suitable solution for aviation, yet (IEA, 2023b; IEA, 2023d, Transport & Environment, 2023).

Implementing stricter fuel efficiency standards for new vehicles can reduce the fuel consumption of traditional and hybrid vehicles during the transition phase to fully decarbonised alternatives (Transport & Environment, 2023). Strong fleet electrification can significantly reduce tank to wheel CO_2 emissions. Yet, complementary policies are needed to mitigate the upstream CO_2 emission for battery production, grid to emission losses, etc. (Krause et al., 2020) Meanwhile, the swift increase in EV sales strains battery supply chains and critical metal resources, notably lithium, anticipated to be scarce until 2030. To mitigate these bottlenecks, options include battery innovation to diversify designs to reduce reliance on critical minerals or finding alternatives. (IEA, 2023b)

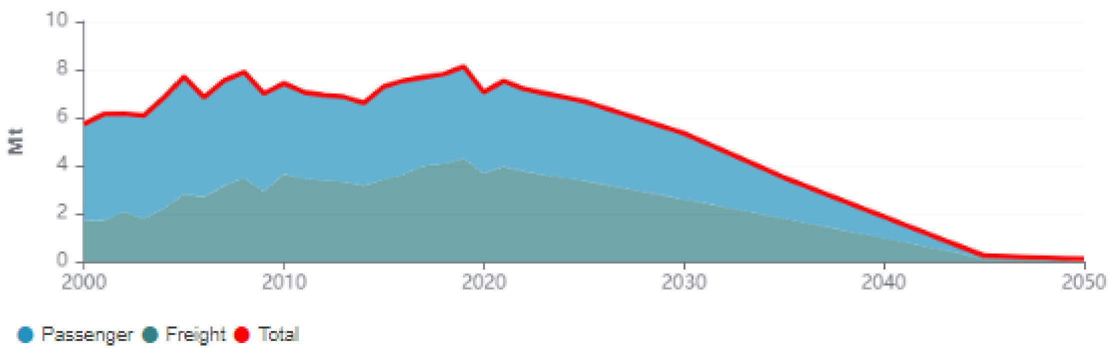
Reducing fossil fuel use and CO_2 emissions in heavy-duty trucking, maritime shipping and aviation is challenging due to their high energy and power density requirements. Currently, alternative fuel technologies for these modes are underdeveloped and likely to be initially more expensive than fossil fuel-based fuels. However, operational and technical innovations can improve energy efficiency in the short to medium term, while switching to low-carbon fuels and electric powertrains will drive long-term emissions reductions (IEA, 2020a; ICCT, 2021).

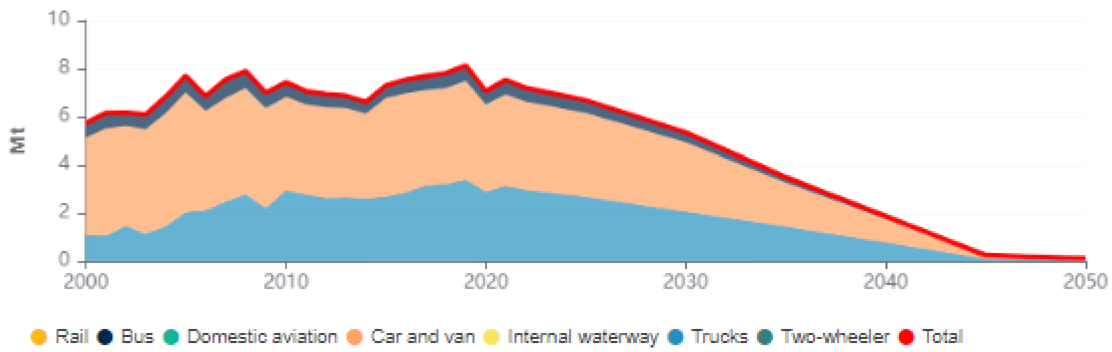
Improving the efficiency of internal combustion engine (ICE) vehicles has significantly reduced oil consumption and CO_2 emissions in passenger transport, supported by widespread fuel economy standards and hybrid powertrains. (IEA, ETP, 2023) In the realm of electric and hybrid vehicles, technological advancements are equally impactful. Improved battery technologies, such as the development of solid-state batteries, offer greater energy density and faster charging capabilities. Additionally, enhancements in electric motor efficiency and power electronics integration contribute substantially to the overall vehicle efficiency, ensuring better performance and longer range (IEA, 2024).

Transport sector decarbonisation pathway (Scenario ZEM 2024)

Carbon emissions in the transport sector are expected to decrease to 0.12 $MtCO_2e$ in 2050. This reduction would primarily result from the transition to zero-emission vehicles powered by alternative fuels, including electricity, biofuels, and synthetic fuels, increased use of active transportation (such as walking and cycling), and greater reliance on public transport.

Figure 12: GHG Emissions per subsector and per end-use in transport sector (Scenario ZEM 2024)





In this sector, energy demand would potentially decrease to 16 TWh. Of this, 60% of the energy demand could be met by electricity, while 20% will be supplied by biofuels.

Figure 13: Shifting energy consumption in transport towards clean fuels (Scenario ZEM 2024)

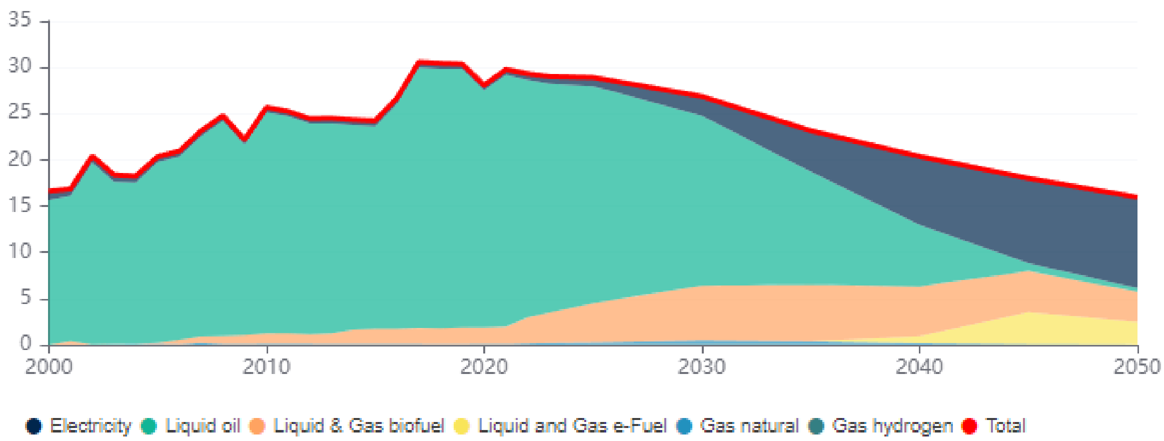
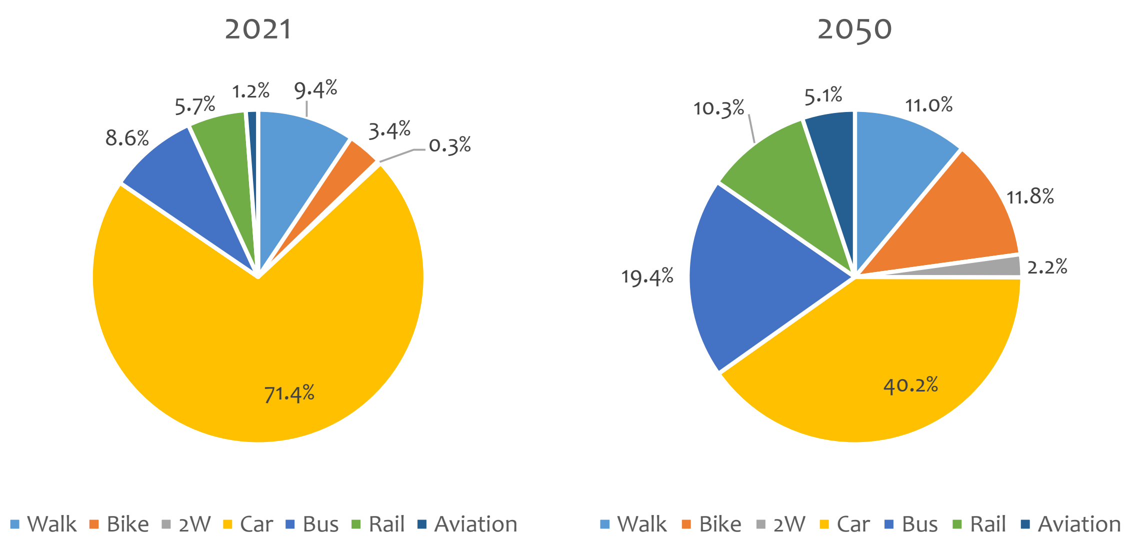


Figure 14: Decline in the share of individual car transport in passenger transportation (Scenario ZEM 2024)



This scenario assumes that by 2050, cars would remain the most commonly used mode of transport, accounting for 40% of all transportation, but its importance might decrease from 2021. Bus transport would also hold a significant share, making up 19% of transport in 2050. The use of buses, measured in passenger kilometres, is projected to increase significantly by 167% compared to 2021. Important 40% and 300% increase aims to be in active transport (walk and bike).

The modelled measures in the transport sector that are expected to contribute to achieving climate neutrality by 2050 include:

- **Reduced use of personal cars in non-urban areas**: the use of personal cars in non-urban areas is projected to decrease by 27 percentage points, which would reduce particulate matter emissions and the number of cars on the roads.
- **Increased use of public transport in non-urban areas**: the utilisation of buses for public transport in non-urban areas is expected to increase by 13 percentage points.
- **Decreased use of personal cars in urban areas**: in urban areas, the use of personal vehicles is projected to decline by 27 percentage points, improving air quality in urban zones and contributing to a reduction in mortality related to emissions.
- **Increased use of public transport in urban areas**: public transport usage in cities is projected to rise by 11 percentage points.
- **Support for public transport expansion**: expanding bus and rail services to enhance public transportation options.
- **Adoption of ZEV**: by 2030, it is anticipated that at least 25% of newly purchased vehicles will be ZEV and 25% low-emission (LEV), with a goal of achieving 100% ZEV by 2040.
- **Use of biofuels and synthetic fuels**: by 2050, biofuels and synthetic fuels are expected to account for 50% of fuel use.
- **Incentives for new heavy-duty vehicle sales**: financial incentives or tax breaks to encourage the purchase of new heavy-duty vehicles.
- **Higher vehicle occupancy**: encouraging carpooling with at least two passengers per vehicle could lead to more efficient use of personal cars.
- **Support for car sharing**: promoting car-sharing initiatives could reduce the need for car ownership, especially in densely populated urban areas, and decrease demand for parking
- **Increased active transport**: by 2050, active transport—such as cycling, and walking—is expected to rise by 300% and 40% compared to 2021.
- **Increased cycling in cities**: cycling is expected to increase by 9 percentage points in urban areas.
- **Increased parking fees and urban access restrictions**: implementing higher parking fees and restrictions on high-emission vehicles entering cities.
- **Development of cycling infrastructure**: building more bike lanes and pedestrian pathways to support urban and suburban mobility.
- **Stricter emission limits for new vehicles**: tightening emission standards for new cars in line with the EU's "Fit for 55" package, which aims to phase out the sale of new internal combustion engine cars and vans by 2035.

4.4. Buildings sector

The building sector is pivotal in the transition towards a low-carbon economy, contributing significantly to global energy consumption and greenhouse gas emissions. Buildings account for nearly 40% of energy consumption and 36% of CO_2 emissions in the European Union in 2022 (Ministry of Transport and Construction SR, 2020). In Slovakia buildings account for 12 %of GHG emissions – much less than in the EU what is caused by GHG intensive industries in Slovakia.

4.4.1 Current policy framework for the building sector

The building sector in Slovakia, comprising residential, commercial, industrial and public buildings, faces distinct challenges and opportunities for energy efficiency improvements and emissions reductions. Key decarbonisation strategies include retrofitting existing buildings, enhancing insulation and adopting near-zero energy building (NZEB) and zero-emission buildings (ZEB) standards.

The European Union has implemented several directives to drive energy efficiency in the building sector, such as the Energy Performance of Buildings Directive, the Energy Efficiency Directive and the Renewable Energy Directive. These directives are critical in shaping Slovakia's legislative framework for building sector decarbonisation.

1. The Energy Performance of Buildings Directive (EPBD) focuses on improving building energy efficiency. It includes measures such as issuing regular energy performance certificates, setting minimum energy performance standards, and requiring new and renovated buildings to be Nearly Zero-Energy Buildings (NZEB) until 2030 and to become zero-emission buildings (ZEB) from 2030 onwards. Existing buildings are expected to become ZEB by 2050. (EC, 2018a; EC, 2024a)
2. The Energy Efficiency Directive (EED) aims to enhance energy efficiency across all sectors, including buildings. It introduces mandatory measures to help the EU meet its efficiency targets. Recently, the target for improving energy efficiency by 2030 has been increased from 32.5% to 55%, relative to 1990 levels. The requirement for public buildings to undergo renovations at a rate of 3% annually now covers all branches of public administration (EC, 2012; EC, 2023j).
3. The Renewable Energy Directive (RED III) promotes the use of energy from renewable sources, encouraging the integration of renewable technologies like photovoltaic panels and solar thermal systems in buildings (EC, 2023f).

Slovakia's national legislative framework for building sector decarbonisation is influenced by these EU directives, along with national strategies and policies aimed at improving energy efficiency and reducing greenhouse gas emissions. Low-Carbon Development Strategy (LCS) sets a long-term vision for reducing greenhouse gas emissions by 2050 also in the building sector, emphasising energy-efficient technologies and renewable energy sources (Ministry of Environment SR, 2020).

Several decrees and regulations enhance the energy performance of buildings in Slovakia, focusing on setting minimum energy performance requirements, regular inspections and energy performance certificates to ensure compliance. Key measures and targets for improving energy efficiency and reducing greenhouse gas emissions in the building sector are then outlined within the NECP (Ministry of Economy SR, 2019), the Long-term renovation strategy (LTRS) (Ministry of Transport and Construction SR, 2020), energy savings obligation, financial mechanisms, building codes and regulations for enhancing energy performance and renewable energy integration.

4.4.2 Energy efficiency improvements

Energy efficiency improvements in the building sector are essential for reducing energy consumption and greenhouse gas emissions. Slovakia has implemented various strategies to enhance energy efficiency, focusing on retrofitting existing buildings and designing energy-efficient new constructions.

Retrofitting existing buildings

The existing buildings in Slovakia use approximately 29% of final energy consumption and 12% of GHG emissions. Buildings lose energy efficiency over time. Therefore, in order to lower energy consumption and to comply with the latest energy performance standards older buildings require comprehensive retrofits.

In Slovakia, nearly 75% of apartment buildings and 55 % family homes were renovated during the past 20-25 years, but the majority of them have to be renovated again (Euractiv, 2024). The remaining are energy inefficient, needing urgent and extensive renovation efforts. On the contrary, non-residential building renovation is very slow. (Ministry of Transport and Construction SR, 2020) The renovation rate for public buildings in Slovakia averaged 1.9% annually between 2020 and 2023 (Budovy pre budúcnosť, 2024). The Energy Efficiency Directive mandates a 3% annual renovation rate for public buildings through 2030 (EC, 2024c). The building renovations in public sector, commercial and industrial sectors are usually relying on European funding, while the energy performance contracting has not gained popularity yet. (Ministry of Transport and Construction SR , 2020) Implementing comprehensive energy-efficient measures up to the NZEB (and ZEB beyond 2030) will be required by the recast EPBD. This can lead to substantial reductions in both energy consumption and greenhouse gas emissions in the building sector, however, more funding and technical support is needed.

These targets can be achieved by strategic retrofitting that addresses building resilience, resource conservation and energy supply reliability (Williams-Eynon, 2022). It can involve, for instance:

- Upgrading wall, roof and floor insulation to help reduce heat loss, improving thermal comfort and reducing energy consumption for heating and cooling (Ministry of Transport and Construction SR, 2020; OECD, 2022).
- Using high-performance insulation materials, such as aerogels and vacuum insulation panels, for better performance (JRC, 2022c).
- Installing double or triple-glazed windows with low-emissivity coatings to minimise heat transfer. Modern window technologies can also incorporate gas fills like argon or krypton to enhance thermal performance (JRC, 2022c).
- Reducing solar heat gain through new technologies such as smart adaptive windows that use thermochromic, photochromic or electrochromic glazing, or photovoltaic glazing (JRC, 2022c).
- Switching to energy-saving LED lighting, upgrading heating, ventilation and air conditioning (Williams-Eynon, A., 2022).
- Implementing smart thermostats that enable better control over heating and cooling systems by learning user preferences and optimising energy use accordingly. They can reduce energy consumption by adjusting the temperature based on occupancy and weather conditions (Ministry of Transport and Construction SR, 2020).
- Minimising resource use by incorporating water conservation efforts, including the use of low-flow fixtures and rainwater harvesting systems. These kinds of improvements can help reduce energy intensity and operational costs (Williams-Eynon, A., 2022).

- Enhancing energy supply reliability with installation of on-site renewable energy systems, such as solar panels, paired with energy storage solutions or heat pumps. They can be seen as reliable ways to maintain energy supply during disruptions (Williams-Eynon, A., 2022).
- Connecting buildings to district heating and cooling networks that rely on renewable energy sources (Williams-Eynon, A., 2022).

These approaches, when applied together, are widely viewed as essential for reducing energy consumption, cutting emissions and providing long-term sustainability.

Retrofitting can result in substantial energy savings and GHG emission reductions. Comprehensive retrofitting can reduce energy consumption in residential buildings by up to 50-70%. This translates to significant reductions in carbon emissions, contributing to national and EU climate goals (EC, 2020b; Ministry of Transport and Construction SR, 2020). Retrofitting offers economic advantages such as decreased energy expenses for both building proprietors and inhabitants. Moreover, reducing energy costs can alleviate energy poverty, increasing disposable incomes for households (Ministry of Transport and Construction SR, 2020). In addition, retrofitting can improve interior comfort and health by enhancing air quality and minimising exposure to severe temperatures (Williams-Eynon, A., 2022). From a social perspective, the extensive implementation of retrofitting can generate employment opportunities in the building and energy industries, hence promoting economic growth (IEA, 2019c).

Financial support mechanisms play a crucial role in enabling energy-efficient renovations. Building owners are encouraged to make necessary improvements through offers of grants and subsidies. Low-interest loans for renovation projects can also ease the cost burden. Additionally, fostering public-private partnerships can attract private investment, amplifying the scale and impact of energy efficiency projects. Together, these strategies are key to removing the financial barriers and driving building renovations (Ministry of Transport and Construction SR, 2020).

Designing energy-efficient new buildings and neighbourhoods

The building sector is going through an innovative transformation in order to improve energy efficiency and reduce greenhouse gas emissions. These advancements include smart building technologies, advanced heat pumps, building automation systems, energy-efficient windows and the integration of digitalization and data analytics.

Constructing new buildings with high energy performance standards involves adopting design principles that prioritise energy efficiency. Passive house standards, nearly zero-energy buildings, positive energy buildings and zero-emission buildings are key frameworks. Integrating innovative technologies is essential for achieving optimal energy performance in newly constructed buildings.

Additionally, there is a growing emphasis on the use of sustainable materials and the circular economy in construction, aiming to reduce the overall environmental impact of buildings (Pomponi and Moncaster, 2017). Similarly, it is very important to assess the environmental impact of the materials, the cradle-to-gate embodied carbon, based on the equivalent embodied CO_2 emissions produced e.g. during manufacturing, transport and/or installation, up to the entire life-cycle of construction materials or components (JRC, 2022c).

Smart technologies, energy-efficient appliances and eco-design

The integration of efficiency standards, the Ecodesign Directive, technological advancements, smart building technologies and consumer awareness forms a comprehensive strategy to enhance energy efficiency.

Efficiency standards for appliances are essential for reducing energy consumption in buildings. (IEA/4E TCP, 2021). Meanwhile, the new European Ecodesign Directive sets mandatory ecological requirements for sustainable, energy-using and energy-related products sold in the EU and aims to improve the environmental performance of products throughout their lifecycle, from design to disposal (EC, 2023e).

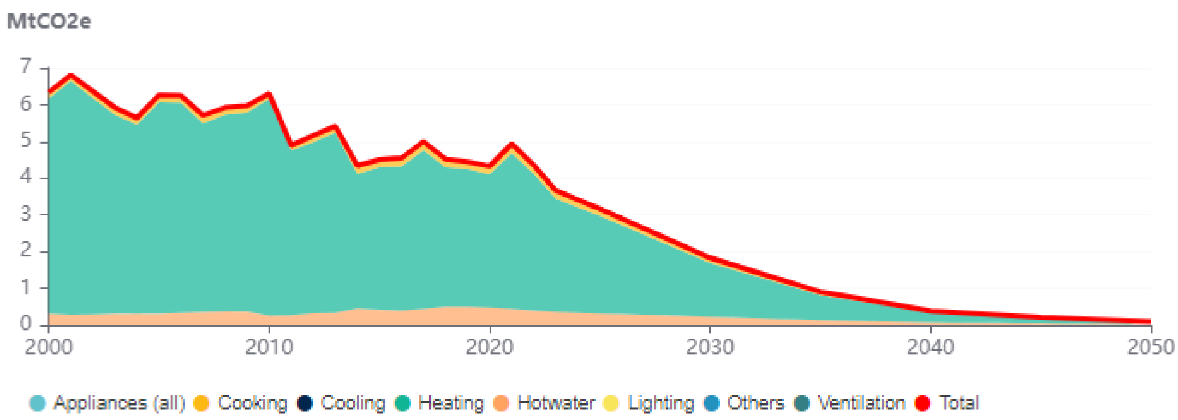
Smart building technologies provide intelligent control over heating, cooling and ventilation, optimising energy consumption based on real-time conditions and occupancy patterns. These technologies include smart thermostats, building energy management systems (BEMS) and Internet of Things (IoT) devices. BEMS integrates various building systems, such as heating, ventilation and air conditioning, lighting and security, for centralised control and optimization. By monitoring energy consumption and automatically adjusting settings based on occupancy and weather conditions, BEMS can significantly improve building energy efficiency. Meanwhile, IoT devices enable real-time monitoring and control of building systems, providing granular data on energy use. This data can be used to identify inefficiencies and optimise building operations, but caution should be executed in terms of cyber security of the devices (Mischos, Dalagdi, and Vrakas, 2023).

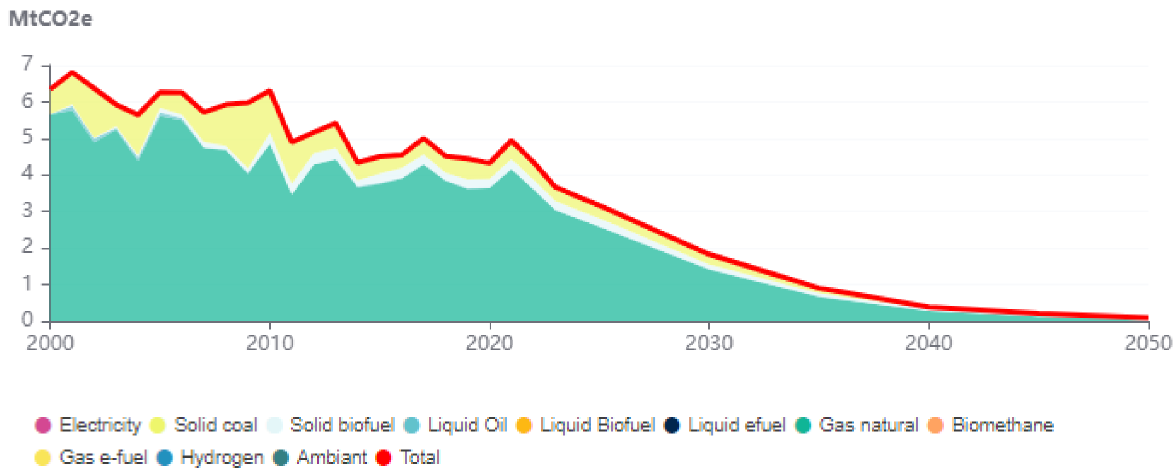
Raising consumer awareness about the benefits of energy-efficient appliances is vital for encouraging their adoption. Information campaigns and energy labels help consumers make informed choices, leading to increased market penetration of energy-efficient products. (IEA/4E TCP, 2021).

Buildings sector decarbonisation pathway (Scenario ZEM 2024)

By 2050, emissions in the building sector are expected to decrease to 0.1 $MtCO_2e$. The majority of emissions in this sector currently stem from heating (85%) and the production of hot water (10%). Insulating and renovating both residential and administrative buildings is expected to reduce the demand for heating and other energy needs. District heating (DH) systems could become more efficient by transitioning to high-efficiency central heating systems with a substantial share of heat generated from renewable energy sources (RES), in line with EU legislation, particularly the Renewable Energy Directive (RED III). Moving away from the use of natural gas and solid fossil fuels as heating sources in individual heating systems, smaller boiler houses, and residential homes could potentially reduce emissions in the building sector to nearly zero.

Figure 15: GHG Emissions per end-use and per vector in buildings sector (Scenario ZEM 2024)



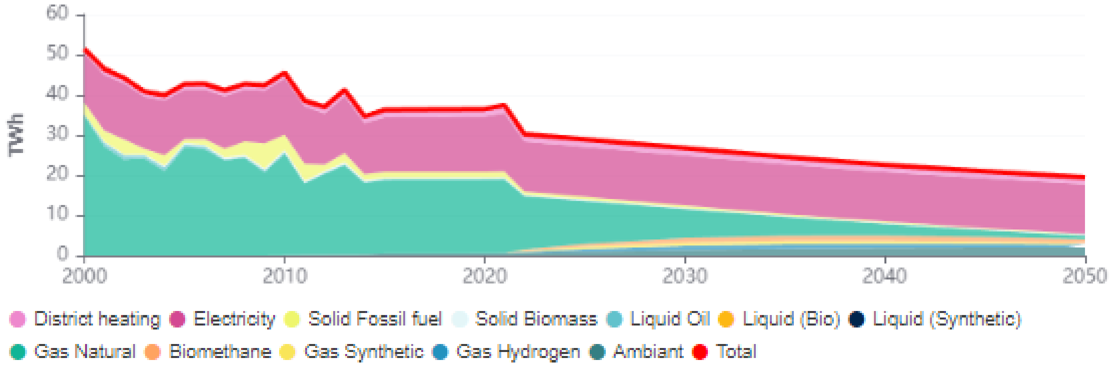


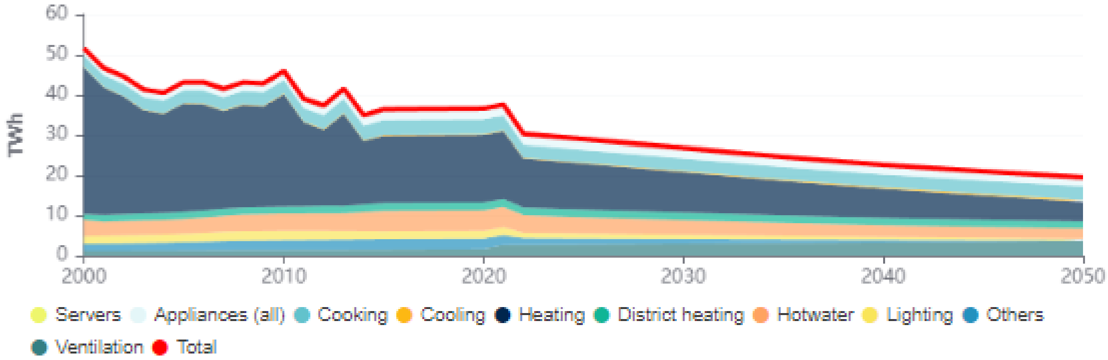
Energy demand is projected to decrease to 26.4 TWh by 2050, representing a 40% reduction compared to 2005 and a 47% reduction compared to 2021. Significant reductions in energy demand are expected in heating, with an 73% decrease, and in lighting, with a 23% decrease compared to 2005.

Key changes by 2050 compared to 2021 include:

- **99% reduction in natural gas use outside of district heating systems**: This decline could be attributed to the increased use of renewable energy sources (electricity) and improved energy efficiency. In line with global efforts to reduce greenhouse gas emissions and achieve the goals of the Paris Agreement, demand for natural gas — a less emissive but still fossil-based energy source — is expected to decrease and almost disappear. This trend could be further supported by technological advancements in renewable energy and the growing demand for green technologies.
- **73% reduction in energy needed for heating**: This significant decrease is anticipated due to building renovations, improved insulation, and the development of more efficient heating systems. The introduction of new materials and technologies, such as smart thermostats and heat pumps, could contribute to higher energy efficiency in heating systems. Additionally, the share of renewable energy in heating would increase.
- **46% reduction in energy needed for hot water preparation**: This decrease is linked to advances in hot water preparation technologies and the broader adoption of energy-efficient water heaters and solar water heaters. Better-insulated piping systems and increased awareness of energy-saving opportunities could also contribute to lower energy consumption for hot water preparation.
- **90% reduction in the use of solid fossil fuels**: This decline would result from a combination of factors, including the increased adoption of renewable energy sources, the widespread deployment of energy storage technologies, and investments in green infrastructure and innovations.

Figure 16: Energy demand per vector and per end-use in the buildings sector





In our scenario, we model the implementation of the following measures in the building sector, which we anticipate would contribute to achieving climate neutrality by 2050:

- **Improving Building Energy Efficiency:** Mandatory renovation of buildings with low energy ratings, including energy efficiency standards and support for low-income households and public buildings.
- **Elimination of Least Efficient Buildings**: Renovation or demolition of buildings with the lowest energy efficiency.
- **Support for District Heating:** Increase in the proportion of residential and non-residential spaces connected to district heating systems by 7% and 3%, respectively, for more efficient use of heat production systems.
- **Electrification of Heating:** By 2050, 58% of residential and 70% of non-residential spaces will use heat pumps for space heating.
- **Enhancing Device Energy Efficiency:** Implementation of energy efficiency standards and financial support for low-income households to improve the efficiency of appliances.
- **Energy-Responsible Behaviour:** Residents are anticipated to adopt environmentally responsible behaviours in both summer and winter—such as sensible ventilation, heating, and using natural cooling methods—to reduce the need for air conditioning and overall energy consumption.
- **Reduced Energy Demand for Hot Water:** Energy demand for hot water preparation in residential spaces is expected to decrease by 3% by 2050 compared to 2021, thanks to more efficient use of hot water, and energy-efficient water heating devices (heat pumps and solar instead of coal, gas or direct electricity).
- **Significant Reductions in Non-Residential Hot Water Demand:** A reduction in energy demand for hot water in non-residential spaces by 60–90% by 2050 compared to 2021, with a 83% reduction in schools and a 95% reduction in private office spaces.

- **Limited Use of Air Conditioning**: By 2050, only 30% of households and up to 60% of non-residential spaces would use air conditioning. Other spaces would rely on alternative cooling methods, such as external shading systems, to maintain optimal indoor temperatures.
- **Stable Indoor Temperature**: Maintaining stable temperatures in heated or cooled spaces will prevent unnecessary energy waste, with no change in heating/cooling temperatures in residential spaces.
- **Transition to Electric Cooking**: Gradual replacement of gas stoves with electric alternatives, leading to the complete phase-out of gas appliances in households by 2050 due to the electrification of cooking.
- **Energy-Efficient Appliances**: Households are expected to prioritise purchasing highly energy-efficient appliances and only buy what they need. This approach would assist in maintaining a stable number of electrical appliances in homes, despite an expected increase in the purchase of certain devices—such as a 50% rise in the number of computers per household between 2021 and 2050.
- Stabilised **Energy Consumption for Appliances**: Maintaining current daily usage levels of appliances such as televisions, washing machines, dryers, and dishwashers are expected to help control overall energy consumption in households, with daily usage in 2050 remaining unchanged compared to 2021.
- **Efficient Housing Choices**: Individuals are expected to make economical housing choices by not expanding their living spaces unless necessary due to an increase in household members.
- **Subsidies and Support for Electrification**: Financial and informational support for the electrification of heating and hot water preparation.
- **Support for Solar Panels**: Subsidies for solar panels, particularly for low-income households, or tax incentives for businesses to install solar panels.

4.5. Agriculture, Forestry, and Other Land Use (AFOLU) sector

The Agriculture, Forestry, and Other Land Use (AFOLU) sector plays a crucial role in climate change mitigation. It is responsible for 7% of greenhouse gas emissions, but it also offers substantial opportunities for carbon sequestration and emissions reduction. As part of the transition towards a low-carbon economy by 2050, it is crucial to adopt sustainable agricultural practices that reduce GHG emissions.

The EU's Green Deal and its associated Farm to Fork and Biodiversity strategies together with the Common Agricultural Policy set ambitious targets for sustainable agriculture and forestry. These strategies emphasise the role of climate friendly agricultural practices and nature-based solutions, including carbon farming, in achieving climate neutrality (EC, 2019; EC, 2022b; EC, 2020c; EC, 2020a).

Within the framework of the EU Effort Sharing Regulation, the agricultural sector in Slovakia aims to reduce emissions by 10% by 2030 compared to 2005 levels. Measures to achieve this target include the optimization of organic fertiliser management, such as proper storage practices, and the reduction of N2O and ammonia emissions. To enhance carbon sequestration in the LULUCF sector, afforestation of 23,000 hectares of permanent grassland and the conversion of 50,000 hectares of arable land to grassland by 2040 will be needed, in addition to restoring and protecting wetlands and peatlands, supporting agroforestry systems and developing green infrastructure. Meanwhile, Slovakia's Low-carbon strategy identifies a gap of 7 $MtCO_2e$ equivalent necessary to achieve climate neutrality by 2050, which is expected to be offset by the LULUCF sector. Further research is planned to achieve it (Ministry of Economy SR, 2023; Ministry of Environment SR, 2020).

4.5.1 Sustainable practices and carbon sequestration

The Intergovernmental Panel on Climate Change identifies the AFOLU sector as having significant potential for emissions reduction and carbon sequestration (IPCC, 2023). Sustainable agricultural practices, forest management techniques and dedicated carbon sequestration methods are crucial for achieving these reductions. There are various mitigation options in EU agriculture taking into account regional circumstances and cost effectiveness (Fellmann, T. et al., 2021).

Sustainable climate smart agricultural practices

Sustainable climate smart agricultural practices, such as improved nutrient management, conservation tillage, cover cropping, precision farming and agroforestry, can contribute to greenhouse gas emissions reductions and increased carbon storage in soils and biomass (IPCC, 2022). It is crucial to focus on lowering nitrous oxide emissions from the agriculture sector, as it is a very potent greenhouse gas linked to agricultural operations. Its global warming potential is approximately 300 times greater than that of carbon dioxide (IPCC, 2022).

Forest management techniques

Similarly, sustainable forest management techniques, such as afforestation, reforestation and improved forest protection, can play a crucial role in enhancing carbon sequestration in the AFOLU sector. Forest management techniques are crucial in mitigating climate change by enhancing carbon sequestration and reducing emissions. Afforestation and reforestation are recognized for their ability to sequester carbon dioxide effectively. Improved Forest Management practices optimise forest health and productivity while minimising carbon emissions. Techniques such as controlled burns and selective logging aim at enhancing ecosystem resilience and reducing emissions from wildfires (IPCC, 2007; IPCC, 2019). Forest conservation efforts, aimed at protecting existing forest ecosystems from deforestation and degradation, are also essential for maintaining carbon stocks. (Griscom et al., 2017). Together, these forest management strategies underscore the multifaceted role of forests in climate change mitigation, offering scalable solutions to enhance carbon sequestration and reduce emissions across diverse landscapes.

4.5.2 Dietary Changes and Their Impact

Shifting dietary patterns, particularly reducing meat consumption and increasing plant-based food intake, is increasingly recognized as crucial for mitigating climate change and improving environmental sustainability.

Reducing meat consumption and transitioning towards plant-based diets represent pivotal strategies in mitigating GHG emissions associated with food production. For instance, producing 1 kg of beef emits approximately 60 kg CO_2-equivalent, whereas producing 1 kg of legumes emits only around 0.9 kg CO_2-equivalent (Poore & Nemecek, 2018). This stark contrast underscores the substantial emission savings achievable through dietary shifts. Furthermore, diversifying protein sources to include legumes and nuts not only lowers emissions but also enhances land use efficiency, as these crops typically require less land and water compared to livestock farming. Transitioning to plant-based diets can reduce dietary GHG emissions by up to 70% compared to high-meat diets (Aleksandrowicz et al., 2016).

However, while the environmental benefits are evident, socio-economic considerations must also be addressed. Challenges such as cultural preferences, economic impacts on livestock-dependent communities and nutritional adequacy of plant-based diets necessitate comprehensive policy frameworks and consumer education initiatives to facilitate a smooth transition towards sustainable dietary patterns (Aleksandrowicz et al., 2016).

4.5.3 Food Waste Reduction Strategies

Food waste in the EU is a major contributor to greenhouse gas emissions, accounting for 8-10% of global GHG emissions. In the EU, 53% of all food is wasted annually. Food waste in Slovakia is approximately 65 kg per year per capita (UNEP, 2024). This indicates a significant opportunity to reduce food waste. Strategies include improved food planning and shopping, proper food storage and consumer education and awareness campaigns. These measures can help minimise food loss and ensure more food reaches those who need it (FAO, 2019).

Reducing food waste includes creating grocery lists and meal plans to avoid overbuying, learning proper food storage techniques to extend shelf life and raising awareness about the environmental impact of food waste. Effective policy interventions and technological innovations, such as smart packaging and sensor-based monitoring systems, also hold promise in further reducing food waste by enhancing shelf life and optimising supply chain efficiency (Hebrok & Boks, 2017).

Redirecting surplus food to food banks is also an important option to consider. In 2022, the European food banks recovered and redistributed over 876 316 tonnes of food, assisting 12.4 million people in need. This can prevent food from ending up in landfills where it would decompose anaerobically, producing methane, which is a potent greenhouse gas (European Food Banks Federation, 2022). Composting organic waste can reduce methane emissions by up to 80%

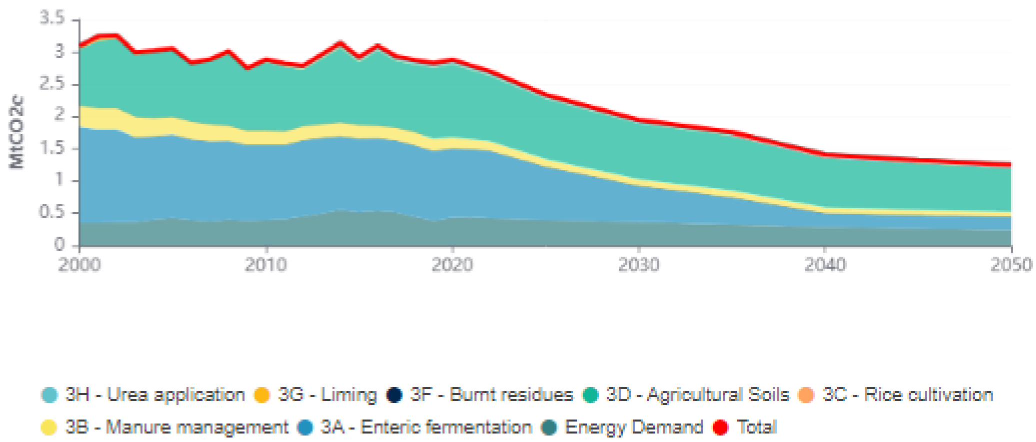
per ton of waste processed, contributing to renewable energy production through anaerobic digestion (Catorza et al., 2021).

In conclusion, the AFOLU sector presents both challenges and opportunities for climate change mitigation. Implementing sustainable agricultural practices, managing forests responsibly and making informed dietary choices can significantly reduce greenhouse gas emissions. Balancing environmental benefits with socio-economic considerations, including equitable food redistribution and economic incentives for waste reduction, remains crucial for achieving sustainable food systems and food security.

AFOLU sector decarbonisation pathway (Scenario ZEM 2024)

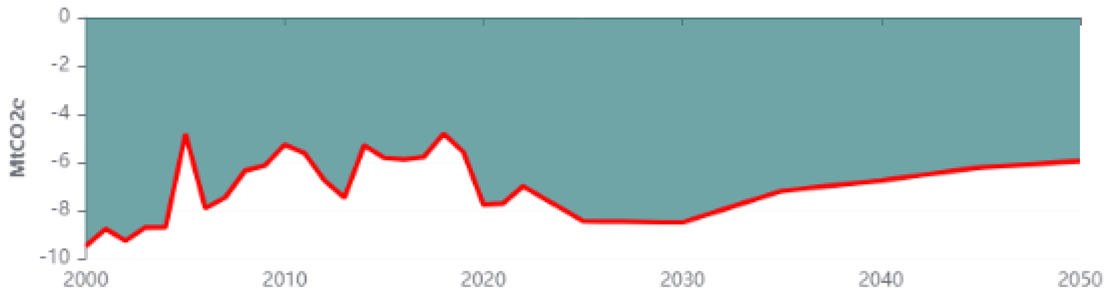
Achieving climate neutrality requires changes in behaviour not only among the general population but also among farmers and foresters in various areas. The IPCC emphasised the importance of the AFOLU sector in its Special Report on Climate Change and Land. (IPCC, 2022). In Slovakia, the agriculture sector accounts for approximately 7% of total net anthropogenic greenhouse gas emissions. The Forestry and Land Use sector makes a significant contribution to reducing GHG emissions. It captures 4 times the GHG emissions generated in agriculture making the AFOLU to be the net absorber of emissions. With the proposed measures, emissions from the agriculture sector in Slovakia could be reduced to 1.28 $MtCO_2e$.

Figure 17: GHG emissions in agriculture sector (Scenario ZEM 2024)



Carbon capture in the AFOLU sector is a critical element in the fight against climate change. This sector has a unique potential for carbon sequestration, which is the process of capturing and storing atmospheric carbon dioxide. Activities that support carbon sequestration in the AFOLU sector include afforestation and reforestation, agroforestry, soil carbon sequestration, wetland and peatland restoration, grassland management, biochar production, and biomass energy with carbon capture and storage (BECCS). It would be crucial to implement these strategies in a manner that is both environmentally sustainable and socially equitable. By 2050, carbon capture from this sector could reach up to 5.7 $MtCO_2e$. The stagnation of sequestration is a result of the age structure of forests. In case of following existing measures in the sectors, the LULUCF sequestration could decrease to 2.34 $MtCO_2e$ (UNFCCC).

Figure 18: Emissions from forestry and land-use (Scenario ZEM 2024)



Measures selected for the AFOLU sector that, according to our scenario, could potentially contribute to achieving climate neutrality by 2050:

- Increase energy efficiency in agriculture and transition to biofuels, with the goal of achieving 25% biofuel use in the agricultural sector.
- Optimise manure storage with a focus on minimising methane emissions.
- Reduce meat consumption to 75% of its current caloric value, which can lower emissions associated with livestock farming and meat production.
- Replace 30% of red meat consumed with white meat to reduce methane and other greenhouse gas emissions, as poultry farming is less emission-intensive than cattle farming.
- Substitute 30% of meat protein with plant-based proteins from legumes, which have a lower carbon footprint and are a more sustainable alternative to animal proteins.
- Reduce food waste by 50% from current levels, significantly decreasing emissions associated with food production, distribution, and storage.
- Change dietary habits by reducing egg consumption by 26% and starchy foods by 18%, which will decrease demand for intensive agricultural products.
- Promote less intensive agriculture by reducing pesticide and fertiliser use by 20% compared to 2021 levels by 2050.
- Replace the missing caloric intake with increased fruit consumption—an 18% increase in fruit consumption is projected.
- Preserve agricultural land and natural ecosystems by avoiding the expansion of built-up areas with permanent structures.
- Substitute 3% of animal feed with alternative protein sources, such as algae and insects, which do not come from traditional agricultural products.
- Utilise bioenergy derived from traditional agricultural crops.
- Reduce subsidies and support for red meat production and limit its import.
- Support sustainable land management practices, including crop rotation and organic farming, and increase the use of pastures for cattle grazing.
- Afforest and plant trees on at least 33% of released land, and maintain healthy forests by limiting the negative impacts of climate change on them.
- Preserve and protect old-growth and natural forests.
- Protect and restore peatlands and wetlands in watersheds, as these ecosystems are crucial for carbon sequestration and also play an important role in biodiversity and water regulation.

- Promote measures within sustainable forest management aimed at increasing carbon sequestration.
- Apply close-to-nature forest management practices in areas with the third level of protection and higher, which supports biodiversity and the preservation of natural ecosystems, particularly in forests.
- Implement measures to significantly reduce the share of incidental logging in Slovak forests.
- Increase the share of long-lasting wood products, including those used for construction.
- Maintain and restore grasslands.

5. Socio-economic implications

Achieving climate neutrality by 2050 in Slovakia presents a complex mix of challenges and opportunities, particularly in terms of its economic, employment and investment needs. It is important to acknowledge that this analysis has not fully addressed the socio-economic implications of decarbonisation, such as its impact on employment, income distribution and the cost burden of decarbonisation on different sectors of the economy and society.

Transitioning to a low-carbon economy will necessitate substantial investment in renewable energy, energy efficiency and clean technologies. While these investments have the potential to drive economic growth and create jobs, it is critical to ensure the transition is fair for all. Moving labour from fossil fuel-based sectors to emerging green industries will require extensive reskilling programs. Regions heavily reliant on traditional industries will need targeted support to avoid economic decline.

The industrial sector in Slovakia, particularly those dependent on fossil fuels, will face challenges in reducing emissions and adopting cleaner energy sources. However, this also presents opportunities for advancements in clean technology and sustainable manufacturing, particularly in the automotive and battery production sectors. Innovation in energy-efficient technologies and renewable energy use will be important to maintaining industrial competitiveness.

The regional impacts of decarbonisation must also be addressed. Industrial regions that rely on fossil fuels may face economic difficulties unless policies encourage diversification and investment in sustainable industries. In contrast, regions with clean energy projects can expect to benefit from their completion. Balancing regional development through targeted investments in infrastructure and education is essential for ensuring an equitable transition.

Investing in renewable energy, clean technology and infrastructure offers significant economic opportunities. The extent to which Slovakia can attract public and private investment will determine its success in transitioning to a low-carbon economy. A stable policy framework that fosters innovation and encourages green finance will be crucial in leveraging these opportunities.

Ensuring the benefits of decarbonisation are equitably distributed is paramount. Vulnerable groups, including lower-income households and regions dependent on fossil fuels, may face disproportionate impacts such as job losses or rising costs. Addressing energy and transport poverty and implementing inclusive transition strategies are essential for public acceptance and the overall success of decarbonisation. Policymakers must ensure social support mechanisms, affordable energy access and equal opportunities in new green job markets. Engaging Slovakia’s younger generation in environmental initiatives and green technology can further drive policy innovation.

Accurately estimating the investment cost of decarbonization by 2050 poses significant challenges, which is why these estimates are not included in this study. The "2050 Pathways Explorer" model contains well developed modules for mapping emissions paths, technology adoption, and policy impacts but the cost estimate module is not yet fully developed, lacking economic cost forecasts and its impacts. The model is currently set up primarily on environmental outcomes and does not account for changing structural, market and technology conditions over time.

Data limitations and uncertainty also make cost estimates difficult. Reliable estimates need detailed data on future technology prices, energy market trends, and global economic conditions—factors that are hard to predict over several decades. For instance, the costs of emerging technologies like carbon capture and advanced renewables are uncertain and depend on technological and economic shifts.

The policy landscape adds further complexity. Investment needs are closely tied to future policies at both national and EU levels, including subsidies, carbon pricing, and financial incentives. Changes in these areas could significantly affect investment requirements, making long-term estimates unreliable.

Economic variables such as inflation and currency fluctuations also complicate projections, as they can vary widely over time. Predicting these trends accurately for the next 25 years is challenging and adds another layer of uncertainty to cost estimates.

Decarbonization efforts also vary across sectors such as industry, transport, and energy, each with its own challenges and timelines. This sectoral variability makes it difficult to create a single, comprehensive cost estimate for the entire economy's transition to climate neutrality.

The scope of this study is to outline possible pathways to achieve climate neutrality and assess their impact on emissions reduction, focusing on technology, policy, and behaviour rather than detailed cost analysis. Providing speculative cost estimates could mislead stakeholders.

While reports from other countries can offer some insight into potential costs, these figures often differ due to local conditions and cannot be directly applied to Slovakia. Differences in energy sources, industrial structures, and socioeconomic contexts require context-specific cost modelling, which is beyond this study’s scope.

The current political climate in Slovakia also presents challenges for ambitious climate policies. Stronger political support will be needed to ensure an equitable transition. With investments in sustainable solutions, support for vulnerable communities, and international cooperation, Slovakia could make meaningful progress towards a sustainable future.

6. Conclusion

The latest findings from the IPCC and advances in climate modelling underscore the urgent need for immediate and ambitious actions to mitigate climate change and adapt to its impacts. These findings provide a scientifically reliable foundation for policymakers, businesses and communities to make informed decisions on climate action. Both the EU and the Slovak Republic are progressing towards climate neutrality as part of their climate initiatives. We believe that this publication can contribute to a broader understanding and enhance the quality of discussions on potential pathways to achieving climate neutrality in Slovakia by 2050.

In the pursuit of climate neutrality by 2050, Slovakia would need to embrace a multifaceted strategy across various sectors. Through the combination of selected measures, total greenhouse gas emissions in Slovakia could be reduced to net -0.27 $MtCO_2e$ by 2050. We anticipate a reduction in final energy consumption by 34% by 2050 compared to 2005 and by 38% compared to 2021. This projection also accounts for the expected increase in electricity consumption due to intensified electrification. Here are the streamlined recommendations for each key area:

- **Industrial Sector** (2.94 $MtCO_2e$): Implement advanced carbon capture, utilisation, and storage technologies. Focus on improving material and energy efficiency in the industry, particularly in sectors with high emission rates. The most significant reductions could be achieved in steel and chemical industries and the highest percentage reductions could stem from the food processing, glass, wood processing, and paper industries.
- **Energy Sector** (0.556 $MtCO_2e$): Increase the adoption of renewable energy sources, incorporate it safely into the national grid and further electrify the energy system. Enhance energy efficiency across all platforms. This should include a major shift towards digitalization and cybersecurity to support these changes.
- **Transportation Sector** (0.12 $MtCO_2e$ by 2050): Emphasise an increase in public and active transport utilisation complemented by the rapid transition to zero-emission vehicles. It's essential to foster a cultural shift and lifestyle changes towards minimising reliance on personal vehicles.
- **Building Sector** (0.1 $MtCO_2e$ by 2050): Achieve significant reductions in emissions by improving energy efficiency in heating and hot water systems. Enhance comprehensive retrofitting, insulating and renovating of both residential and administrative buildings to reduce energy consumption and emissions effectively.
- **Agriculture, Forestry, and Land Use Sector** (net absorber, carbon capture of LULUCF 5.7 $MtCO_2e$, while agriculture 1.28 $MtCO_2e$): Adopt sustainable agricultural practices and increase efforts in carbon sequestration. Promote dietary shifts towards less meat consumption.

In this analysis, we did not place significant emphasis on describing technological innovations or adaptation strategies. We assume the expansion of available innovative technologies, alongside technological advancements in various sectors, particularly in industry and energy, as well as the implementation of measures for climate change adaptation along with mitigation efforts.

For a comprehensive assessment of the transition to a low-carbon economy, it would be necessary to conduct a socio-economic analysis of the impacts of this transition, including an examination of factors such as labour market changes and the specific effects of industrial decarbonisation on Slovakia's economy. The 2050 Pathways Explorer model already includes a component that allows for the analysis of the economic impact of individual measures. However, this module heavily depends on high-quality, detailed data regarding the costs of various technological innovations, as well as accurate quantification of the mentioned measures. As a result, we have not yet carried out a detailed analysis of the economic impacts of these ambitious goals, including job creation, industrial transformation, and social consequences.

Therefore, in this publication, we assume that the costs associated with transitioning to a low-carbon economy will be substantial, but unavoidable. Achieving the ambitious goal of climate neutrality would require significantly increased efforts and the involvement of all stakeholders—whether it be the government, which sets policies, standards, and the overall direction of the economy, or businesses and households, which have the ability to significantly influence energy and resource consumption.

Additionally, the current political landscape in Slovakia presents challenges for ambitious climate action and the scenarios presented in this publication. A stronger political commitment to climate action is essential to address the complex interplay between economic, social and environmental factors.

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