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Circular Economy and Electromobility: Technologies, Materials and Sustainable Solutions for Industry

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Abstract

The book focuses on innovative approaches to sustainable industrial production, innovative solutions in waste recovery and recycling, energy recovery from waste, and efficient energy production with minimal environmental impact. Furthermore, it also addresses the use of renewable energy sources, the circular economy, and the reduction of the carbon footprint.
The publication consists of eight interrelated and logically organized chapters.
Innovative solutions related to waste material recovery are discussed in Chapters 1, 2. The first chapter presents a patented technology for the recovery of multilayer materials. The second chapter focuses on the development of an original technology for the conversion of waste polyurethane foam into shaped thermal insulation elements.
Chapters 3 and 4 discuss issues related to health protection. Chapter 3 presents research into the reduction of transport noise through the application of noise barriers. Based on measurement results, it highlights the benefits of their use from both the health and economic costs perspectives. Chapter 4 focuses on energy recovery from waste textiles.
The fifth chapter describes an innovative approach to the recovery of rubber waste from the automotive industry through its incorporation into wood-cement boards.
Smart waste economy is discussed in Chapter 6. It relates to the application of industrial building ventilation systems using IoT and Smart Industry.
Chapters 7 and 8 provide economic and statistical analyses. Chapter 7 deals with the analysis of the amount and structure of waste from the automotive industry. It provides analytical inputs for discussions related to the development of processing capacities and more efficient industrial waste management in Slovakia. Chapter 8 focuses on scenarios of electric vehicle sales in EU countries, as well as the effectiveness of fiscal incentives in the transition towards electromobility.

Keywords

automotive, electromobility, sustainable industrial production, innovative solutions, reduction of transport noise, waste recovery, polyurethane foam, multilayer materials, rubber, energy recovery waste textiles, circular economy, reduction of the carbon footprint, statistical analyses.

Circular Economy and Electromobility: Technologies, Materials and Sustainable Solutions for Industry

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Bratislava, 2026

UNIVNET – University and Industrial Research and Education Platform
of the Recycling Society

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Foreword

Dear members of the professional community, readers, and friends,

we are pleased to present this publication of the National Association UNIVNET – a university, industrial, and research-educational platform. The main objective of the association is to carry out forecasting and research and development activities focused on the search for new technologies and techniques for efficient smart waste recovery with the aim to minimize negative environmental impacts on conserving primary energy and raw material resources.

The UNIVNET platform was established through an agreement signed between the Ministry of Education, Research, Development and Youth of the Slovak Republic (MŠVVaM) and the Slovak University of Technology in Bratislava (STU), which serves as the lead partner of the consortium. In addition to STU in Bratislava, the consortium includes The University of Economics in Bratislava, the Technical University of Košice, the University of Žilina, the Technical University in Zvolen, and the Automotive Industry Association of the Slovak Republic as partner organizations.

The publication you have just started browsing is a continuation of the previous five publications presenting the achievements of the association over the past six years. This publication builds on the objectives of the Research and Innovation Strategy for Smart Specialisation of the Slovak Republic (SK RIS3 2021+). The strategy outlines the innovation policy framework conception, aiming to support innovation at the national, regional, and international levels and thereby contribute to the national economic growth and prosperity.

The book focuses on innovative approaches to sustainable industrial production, innovative solutions in waste recovery and recycling, energy recovery from waste, and efficient energy production with minimal environmental impact. Furthermore, it also addresses the use of renewable energy sources, the circular economy, and the reduction of the carbon footprint.

The topics addressed will facilitate the transfer of scientific findings into practical innovations, supporting solutions for a sustainable and competitive economy in Slovakia. By providing relevant information, the publication brings together academics, entrepreneurs, and public administration representatives, fostering dialogue and creating synergistic processes that support the effective implementation of innovative solutions. New information, their transparent sharing, experiences, know-how, and innovative solutions enable the faster implementation of the latest trends in environmental protection and contribute to the achievement of the strategic objectives of smart specialisation in the field of the circular economy.

The publication consists of eight interrelated and logically organized chapters.

Innovative solutions related to waste material recovery are discussed in Chapters 1, 2, and 5. The first chapter presents a patented technology for the recovery of multilayer materials. The second chapter focuses on the development of an original technology for the conversion of waste polyurethane foam into shaped thermal insulation elements. The fifth chapter describes an innovative approach to the recovery of rubber waste from the automotive industry through its incorporation into wood-cement boards.

Chapters 3 and 4 discuss issues related to health protection. Chapter 3 presents research into the reduction of transport noise through the application of noise barriers. Based on measurement results, it highlights the benefits of their use from both the health and economic costs perspectives. Chapter 4 focuses on energy recovery from waste textiles.

Smart waste economy is discussed in Chapter 6. It relates to the application of industrial building ventilation systems using IoT and Smart Industry. It examines the impact of their application from the perspectives of air quality protection, energy savings, and investment costs during the building operation.

Chapters 7 and 8 provide economic and statistical analyses. Chapter 7 deals with the analysis of the amount and structure of waste from the automotive industry. It provides analytical inputs for discussions related to the development of processing capacities and more efficient industrial waste management in Slovakia. Chapter 8 focuses on scenarios of electric vehicle sales in EU countries, as well as the effectiveness of fiscal incentives in the transition towards electromobility. It also examines the impact of this transformation on the national economy of Slovakia. The chapter's findings show that the restoring the competitiveness of the Slovak processing industry should be considered one of the key economic policy priorities.

We wish you pleasant reading and believe that the publication will provide you with the necessary information on the current state and challenges of waste management in the automotive industry.

Bratislava, 15.07. 2026

Martin Lábaj
Ľubomír Šooš

1. Innovative Technologies for the Recovery of Multi-Layer Materials

1.1. Introduction

As a result of changing requirements and increasing demands on products, the use of multi-layer laminated materials is growing. We can find them in cars as windscreen material, in construction in the form of various railings or transparent floors, or in the energy sector in photovoltaic panels (Fig. 1.1). A requirement for such glass is sufficient resistance to mechanical damage and adverse weather conditions. Recycling such materials is challenging but is of great importance in terms of the environment, energy and technology, as the individual materials can serve as important secondary raw materials. This work focuses on the analysis of multi-layer laminated materials (MLM), existing methods for their processing and our innovative processing method.

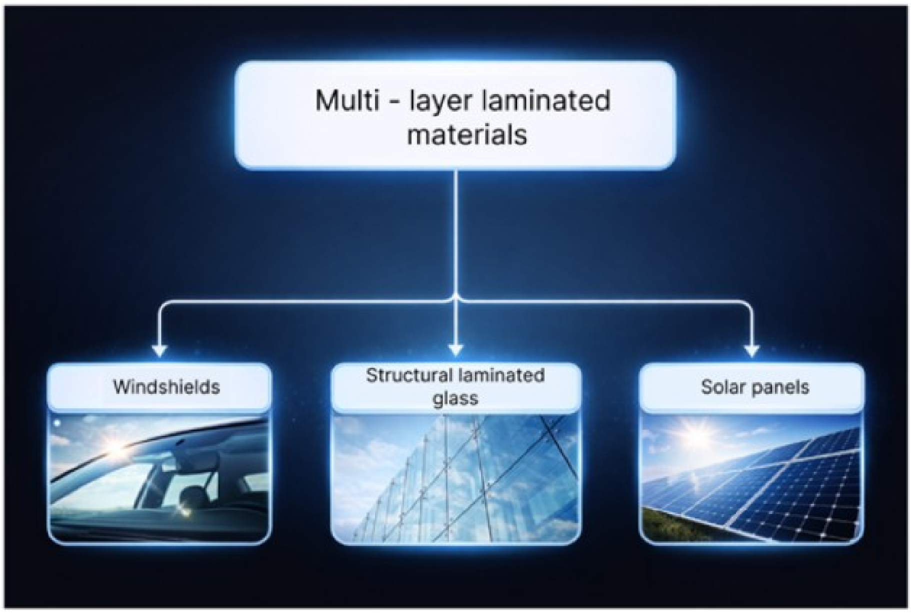


Fig. 1.1 Classification of laminated materials

1.2. Characterisation of multi-layer laminated materials

In order for the glass to meet the above requirements, the production of laminated MLM glass is relatively difficult and requires both high-quality raw materials and reliable technology. The basis of these materials is glass. Tempering glass increases its strength and flexibility, but because it has internal stress, when it breaks, it shatters into small fragments without sharp edges, so they do not cause injury. Double- or triple-layer glass is bonded together with a film.

The basic principle involves layering two or more sheets and bonding them together using an adhesive, elastic interlayer (Fig. 1.2). This ensures the glass behaves safely after breaking or increases its resistance to forced entry..

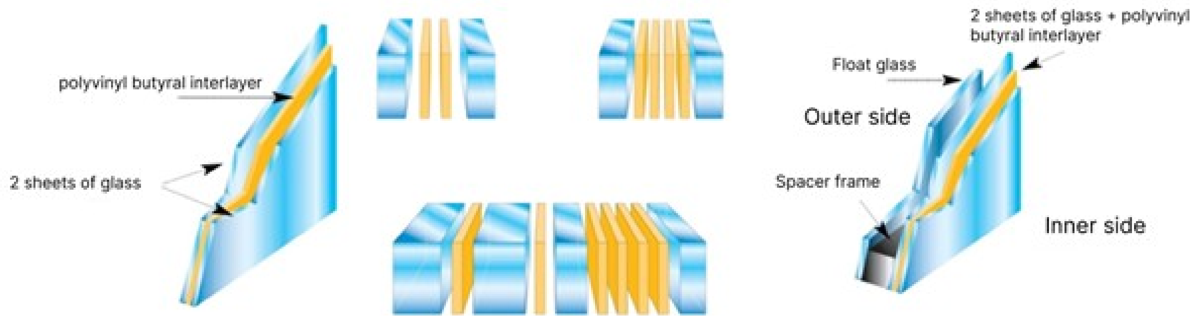


Fig. 1.2 Examples of laminated flat glass

For MLM, float glass, patterned cast glass or products derived from these basic types of glass are used, which can be further modified, e.g. thermally toughened (tempered) glass. During the technological lamination process, an elastic material with good adhesion to glass is inserted between the glass sheets. Commonly used materials are polyvinyl butyral (PVB) with a standard thickness of 0.38 mm, ethyl vinyl acetate (EVA) or SentryGlassPlus (SGP) ionoplast. It is possible to produce flat and bent laminated glass, whose final properties are mainly influenced by the thickness and number of glass sheets and the thickness and properties of the film used. One advantage of laminated glass is that the sheet retains some structural integrity even after breaking, as the glass fragments remain adhered to the interlayer [10].

The actual production technology of MLM depends on the type of interlayer used. Laminated glass with PVB film is usually produced using an autoclave under high pressure and temperature. During production, cleaned glass sheets are stacked on top of one another in a specific order with an interlayer in between and are then preheated to approximately 70 °C and pressed between rollers, expelling any excess air. The MLM is then pressed in an autoclave at a temperature of approximately 140 °C under a pressure of 0.8 MPa (Fig. 1.3 Diagram of the laminated glass production process) [11]. After the pressing process is complete, the glass cools naturally inside the autoclave using water coolers as the pressure is reduced. The use of an EVA (ethylene vinyl acetate) interlayer makes it possible to insert various materials into the interlayer. Examples of materials inserted between layers of EVA film include heating grids for car windshields or photovoltaic cells in photovoltaic panels. Laminated glass with EVA is usually produced using a vacuum bag and high temperature in a horizontal position.

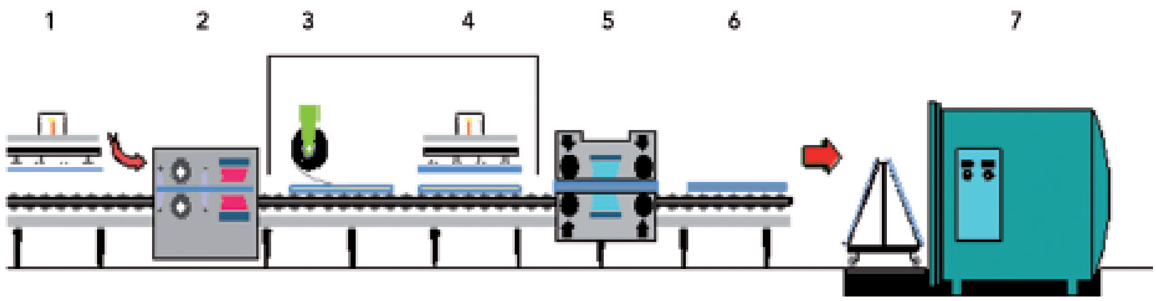


Fig. 1.3 Diagram of the laminated glass production process

Diagram of the MLM production process: 1 – glass loading, 2 – washing, 3 – PVB film application, 4 – placing the top glass, 5 – pre-pressing, 6 – transfer to the rack, 7 – autoclave

1.2.1. Interlayer materials – films for laminated products

MLM consist of two or more layers of glass (annealed or tempered) bonded together into a single compact unit using interlayers. The interlayer materials used are listed in Tab. 1.1 Types of interlayer materials for laminated glass and their susceptibility to delamination.

Polyvinyl butyral (PVB) is the most commonly used material for producing the interlayer film in laminated glass. PVB is a solid resin that is soluble in organic solvents (except hydrocarbons) and resistant to acids and alkalis. It has up to 20% free hydroxyl groups, which ensures good adhesive strength between the glass and the PVB layer based on the formation of hydrogen bonds. Better flexibility and adhesion of the PVB interlayer material is achieved by adding plasticizers such as adipic acid or polyethylene glycol. During the lamination process, the individual layers of glass with the PVB film are subjected to a pressure of 1.2 to 1.4 MPa at a temperature of 135 to 150 °C in an autoclave, ensuring the required adhesion between the individual layers.

MLM consist of two or three sheets of glass bonded together, usually with a strong adhesive film. However, this adhesion hinders the recycling process due to the difficulty of separating the inorganic glass from the organic polymer phase – softened PVB. Today, the issues associated with separating this system are well understood, with extensive practical application. It is therefore possible to obtain clean glass, but the polymer is often contaminated with glass or other foreign substances to such an extent that it is unsuitable for further use and usually ends up in landfills, as it cannot be incinerated due to its high glass content. [3]

On the other hand, the glass surface can be considered a much more complex chemical system where polar silanol groups (-Si-OH) predominate – these groups form on the surface through water absorption followed by a hydrolytic reaction to form the Si-O-Si bond. The glass surface may also be covered, to some extent, with water or another substance that has come into contact with it. When these two substances come into close contact, the chemically similar alcohol groups of PVB and the silanol groups on the glass surface combine to form a reversible but dense network of weak hydrogen bonds and a certain proportion of chemical bonds. For this process to take place, the PVB material must be flexible and adapt to the shape so that it perfectly fills the microscopically rough surface of the glass (Fig. 1.5).

Tab. 1.1
Types of interlayer materials for laminated glass and their susceptibility to delamination

Interlayer materials	Properties	Suscep-tibility
Polyvinyl butyral (PVB) (thermoset)	PVB is the most commonly used interlayer material. Its properties are described in detail below.	Yes
Resins	Their mechanical properties deteriorate when exposed to ultraviolet radiation	Yes
Polyurethanes	Problems with thermal expansion of the material	Less
Ionoplast (thermoset)	Used to make SentryGlas®	Less
Ethylene vinyl ace-tate (EVA)	Although it is less susceptible to delamination, EVA does not withstand impact loads as well as PVB	Less

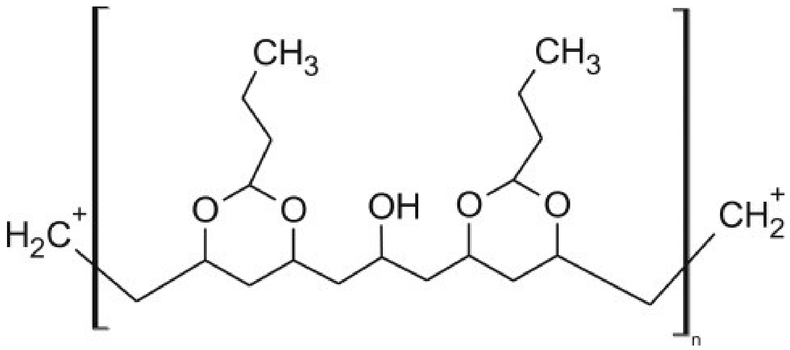


Fig. 1.4 Chemical structure of PVB [3]

In an autoclave, at a given pressure and exposure time, this process must run at sufficiently high temperatures to ensure that the process is completed and the maximum degree of adhesion is achieved, depending on the type of glass and the film used.

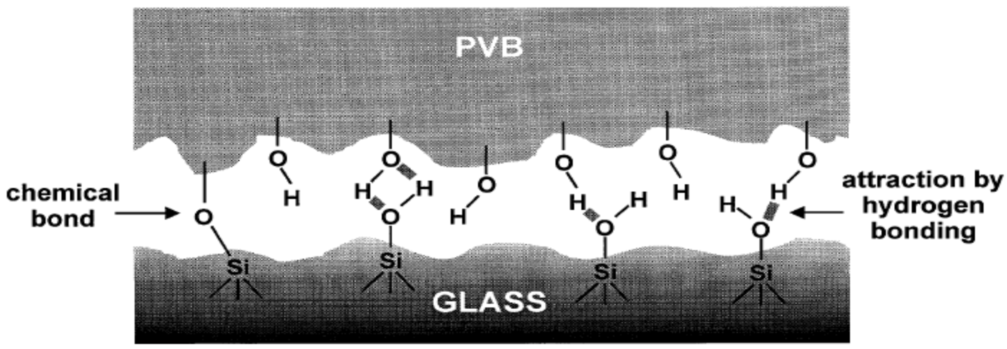


Fig. 1.5 Mechanism of bond formation in a glass-PVB system

1.3. Car glass

Laminated glass for cars must now serve more purposes than it did in the recent past. It is not just other car parts that are evolving – even a seemingly simple component like glass has not escaped evolution of its own. It is now common for laminated car glass to be heated, tinted and tempered, and incorporate various sensors. In addition to providing enhanced safety (they must prevent a person from flying through the glass or objects (rocks, ice, etc.) from entering the vehicle's interior; upon impact, they must not shatter into sharp fragments that could endanger the occupants), windshields also serve the following equally important functions:

- Noise reduction in the cabin
- Reflection of solar radiation
- Glass heating – removal of frost
- Equipped with sensors – rain, light, antenna, sensor for toll registration, etc.

Laminated glass for vehicles is also manufactured in various thicknesses, among other things. Suitable for products ranging from car windshields with a typical thickness of approximately 5 mm to high-speed train engine windshields with a thickness of up to 40 mm.

According to available data, the car manufacturers VW, PSA, JLR, and KIA in Slovakia damage a total of approximately 4,000 windshields per year during vehicle assembly, which amounts to a weight of 52,000 kg. They are collected by waste collection companies and delivered to the processor, Auto Glass Recycling s.r.o. in Šelpice.

Another source is authorized scrap car processors. The number of windshields should correspond to the number of dismantled cars. This includes all glass panels, i.e. windshields and side windows, as well as laminated rear windows found in newer models. If approximately 50,000 old cars are scrapped each year, that comes to a total of 700,000 kg, assuming a weight of 14 kg/1 pc.

The largest "source" is garages that replace damaged glass. According to internet data, there are approximately 1,200 garages in Slovakia, of which about 120 specialise in glass replacement, with general dealership and independent garages also providing the service. Specialised garages replace between 500 and 1,000 units per year, while general garages replace between 50 and 200 units per year. Visiting every garage would take several months and involve unnecessarily high costs, and even that would not provide accurate data. The estimated amount of laminated car glass is approximately 3,500 tonnes.

1.4. Sheet glass in the construction industry

Laminated sheet glass ls currently widely used, particularly in the construction industry, due to its suitable properties:

- It breaks safely – glass fragments remain adhered to the middle layer, reducing the risk of cuts and puncture wounds.
- When installed properly, laminated glass usually remains in the frame even after it breaks.
- Provides protection against vandalism, intentional physical assault, and even firearms.
- Significantly reduces noise.
- Used for entire walkable floors.
- Used for entire vertical surfaces.

- Blocks UV radiation.
- Provides thermal insulation.

1.4.1. Types of laminated glass produced

- Laminated glass with PVB film is the most common safety glass (e.g. Connex).
- Laminated glass with EVA film is suitable for interiors and design applications.
- Acoustic laminated glass has a special film for noise dampening.
- Safety and bulletproof glass are types of glass that can withstand impacts.
- Antibacterial or decorative laminated glass.

Flat glass accounts for a significant portion of industrial glass waste. Pure flat glass is not produced in Slovakia. It is imported and then processed into safety or insulating glass. Approximately 1,300 thousand m² of insulating safety glass is produced in Slovakia, with triple-pane insulating glass accounting for about 30% In addition, approximately 3.6 million m² of glass is imported and glass wholesalers supply an additional 1 million m², part of which is used to produce insulating glass and part for direct processing into interior products for glaziers and the furniture industry. Consumption can be estimated to be at least 4 million m², which, assuming a thickness of 4 mm, amounts to 40,000 tonnes.

In addition, approx. 300,000 m² of insulating glass is imported, which is either directly installed into buildings or exported outside Slovakia with finished products. Of the imported flat glass, 80% is used in buildings in the form of windows and doors and interior glass.
20%, i.e. 8 thousand tonnes is technological waste. If we assume that 25% of insulating glass is used in refurbishment, the amount of glass waste generated from window replacement annually is 325,000 m², weighing approximately 5 thousand tonnes, if the glass is 3 mm thick. The total available flat glass waste in Slovakia is 13,200 tonnes.

A significant source of laminated sheet glass waste in Slovakia are the producers and processors themselves. 3 million m² of flat glass is imported to Slovakia annually. The largest processors include: GLASKO Prešov, AGC Trenčín, IZOGLOBAL Martin, GLASSOLUTIONS Nitra, SAINT GOBAIN Bratislava, WINDOWGLASS Dunajská Streda, Reflex Glass (Poprad), RPN – Sklo, and Glass LPS. Production waste represents approx. 2600 tonnes.

1.5. Photovoltaic panels in the energy sector

Since time immemorial, people have sought to extract energy from natural sources for their own benefit. Wood was the primary source of heat and light, wind was used to propel ships, the power of rivers propelled mills, the sun's rays were used to dry crops and heat water. These primitive forms of using renewable energy were the basis for technological research into their more efficient utilisation. The massive use of fossil fuels such as oil, coal and wood during the Industrial Revolution in the 18th and 19th centuries temporarily halted the development of technologies for more efficient utilisation of renewable energy. Fortunately, humanity realised the negative impacts of fossil fuel use, such as air pollution and global warming, early enough and began investing in renewable sources. There is a growing awareness that there is plenty of energy in the Earth's ecosystem; our task is simply to find more efficient and effective conversions from one form of energy to another. Energy from the sun is ecological and inexhaustible. It is up to us to find more efficient forms of its conversion into heat or transformation into cold or electricity.

One of these technologies for transforming and harnessing solar energy is photovoltaics. It is the most dynamically developing form of renewable energy transformation among all forms of renewable energy sources (RES). However, it should be noted that with the development of photovoltaic technologies, great attention must be paid to the recovery of waste PV panels that have reached the end of their life cycle. The aim of the presented article is to focus attention on the state of research, production and use of photovoltaic (PV) panels, as well as on the necessity and complexity of recovering waste from these PV panels.

1.5.1. State of PV panel production and electricity production from photovoltaics

The cumulative global capacity of photovoltaic power plants has doubled over the last 10 years. By the end of 2024, it reached 615 GW [1]. The International Technology Roadmap for Photovoltaic (ITRPV) predicts, according to IRENA, an installed capacity of photovoltaic power plants in 2050 of 4,500 GW [5] (Fig. 1.6). Installations of photovoltaic PV panels are growing extremely fast. This number is expected to increase to 5.5–6 million tonnes by 2050.

International Renewable Energy Agency (IRENA)

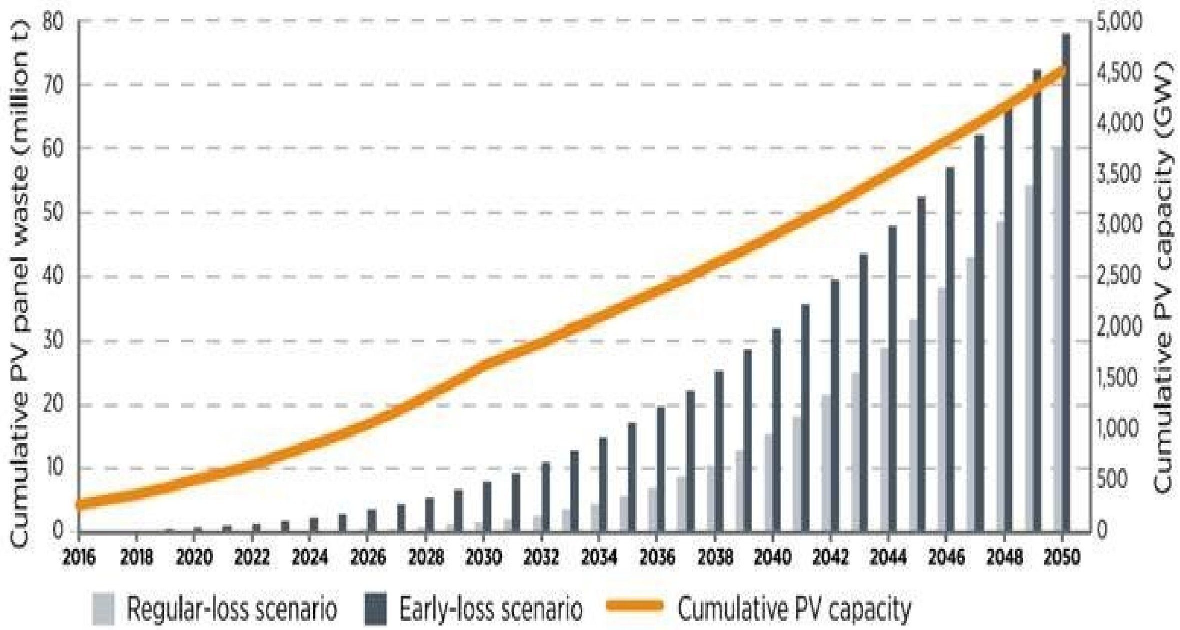


Fig. 1.6 Estimated cumulative global volumes of waste from photovoltaic modules at the end of their life cycle according to IRENA/Task12 [6]

PV panels have a life cycle of 25–30 years [6], and taking into account their introduction, these quantities are considered negligible compared to other types of waste according to WEEE.

1.5.2. Principle of photovoltaics

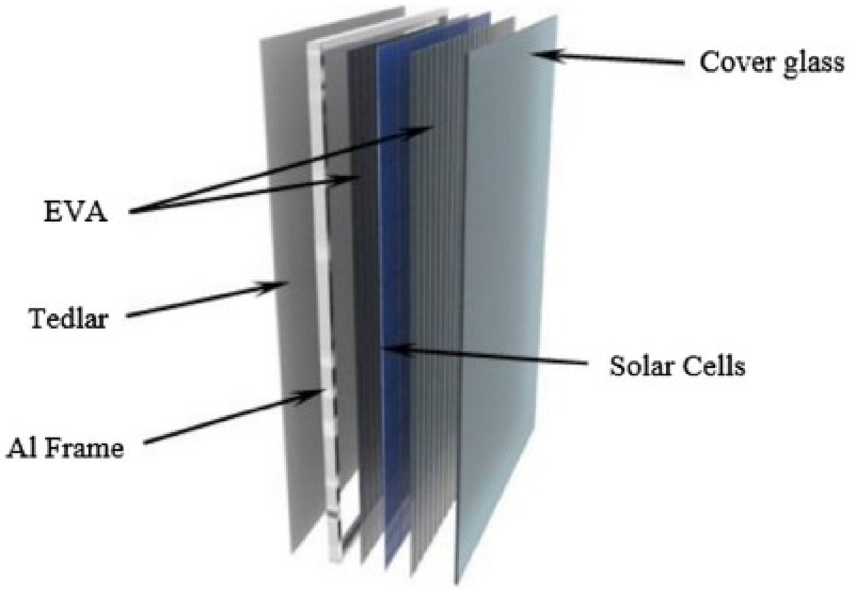


Fig. 1.7 Exploded view of a typical c-Si panel [4]

Photovoltaic systems can be divided according to the technology and materials used in solar cells. In general, photovoltaic cell technologies are divided into three generations [4]:

- First generation – includes traditional panels with a crystalline silicon (c-Si) base structure (Fig. 1.7), such as monocrystalline silicon (sc-Si) and polycrystalline silicon (mc-Si) cells.
- The second generation is based on thin-film solar cells containing amorphous silicon (a-Si), cadmium telluride (CdTe), and cadmium sulfide (CdS), copper indium gallium selenide (CIGS)/copper indium selenide (CIS), gallium arsenide (GaAs), and silicon-based tandem/bridge modules.
- The third generation includes innovative technologies without silicon and new equipment concepts, such as organic/semi-organic photovoltaic (OPV) panels, perovskite solar cells (PSC), dye-sensitized solar cells (DSSC) and quantum dots (QD) [4].

Crystalline silicon PV panels dominate the market with a share of over 90% and remain the technology with the highest return on investment. According to IRENA (2016), PV panels made from monocrystalline silicon (sc-Si) have a 51% share of the photovoltaic market, while multicrystalline silicon (mc-Si) %, CdTe and CIGS 2 have a share of 41% and 5% respectively %. [5] One problem that hinders faster and more extensive deployment of third-generation PV panels is the toxic elements used (Cd in CdTe) and/or critical elements (In, Ga in CIGS and CIGS).

The design of a PV panel must protect the system from external influences, such as wind, rain, temperature and humidity, and prevent corrosion. PV panels are made of thin silicon wafers – cells with a thickness of approximately 200 microns, with the ability to convert sunlight into electric current. The cells are encapsulated from the bottom and top into an EVA film, which allows light to pass through well from the active side and simultaneously connects the cell to the top glass and from the bottom side to the backsheet made of polyvinyl fluoride (PVF) or polyethylene (PET).

The cells are connected to each other in series into modules with copper (Cu) strips, and silver (Ag) is used for surface electrical contacts (clips). Typically, 60 or 72 cells are connected in one panel. A typical crystalline silicon (c-Si) PV panel contains approximately 75% of the total weight from the module surface (glass), 10% polymer (encapsulation and bottom film), 8% aluminum (mostly frame), 5% silicon (solar cells), 1% copper (interconnectors) and less than 0.1% silver and other metals (mostly tin and lead) (Fig. 1.8) [5].

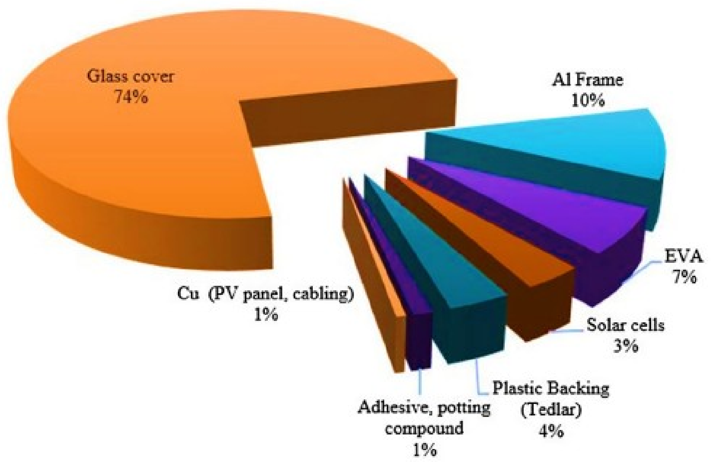


Fig. 1.8 Weight distribution of a PV panel

1.5.3. State of legislation in the EU and Slovakia

In total, only about 10% of photovoltaic modules are recycled worldwide. The main reason is a lack of regulation. The situation is better in the European Union. Since February 2014, the collection, transport and recycling of photovoltaic panels that have reached the end of their life cycle have been regulated in every EU country. Directive (WEEE) 2012/19/EU, [7] established mandatory recycling targets based on module weight from 2016 and also expresses the intention to increase the collection rate. From 2018, it requires a weight recovery to material recycling ratio of 80%/75 and currently this ratio is 85%/80 %. Economic analyses show that even a 90% material recovery is not sufficient compared to production costs [4].

In Slovakia, the Ministry of Economy of the Slovak Republic launched the first call for proposals to support the construction of new facilities for electricity production from RES. The purpose of this call is to increase electricity production from RES in accordance with the requirements of the Integrated National Energy and Climate Plan.

According to data from 2020, the total installed capacity of photovoltaic power plants in Slovakia was approximately 550 MW. An approximate "conversion" of this number into tonnes of future photovoltaic waste shows that in the future there will be around 55,000 to 70,000 tonnes of future e-waste from photovoltaic panels. The situation with the collection and recovery rate of waste PV panels in Slovakia is evident from Tab. 1.2. We conducted a similar analysis of the situation in the Czech Republic (Tab. 1.3).

Tab. 1.2
Situation with the collection and recovery rate of waste PV panels in Slovakia

	Recovery (t)	Recovery rate (%)	EU target (%)	Preparation for re-use and recycling (t)	Preparation for re-use (t)	Preparation for re-use and recycling rate (%)	EU target (%)
2019	24.6	88.57	85	24.6	0	88.57	80
2020	38	91.26	85	38	0	91.26	80
2021	30	90.57	85	30	0	90.57	80
2022	62	89.14	85	62	0	89.14	80

Tab. 1.3
Situation with the collection and recovery rate of waste PV panels in the Czech Republic

	Recovery (t)	Recovery rate (%)	EU target (%)	Preparation for re-use and recycling (t)	Preparation for re-use (t)	Preparation for re-use and recycling rate (%)	EU target (%)
2019	4.9	93.6	85	4.9	0	93.10	80
2020	40.3	87.68	85	40.3	0	87.35	80
2021	102.5	98.07	85	102.5	0	96.77	80

1.6. Volumes of waste from PV panels and their recycling

Due to the growth of the global photovoltaic energy market, the volume of PV panels reaching the end of their life cycle will, in the near future, with some delay, mirror the production of PV panels. The life cycle of PV panels is 25 years and is defined by a 20% drop in performance. The technical life cycle can therefore be even longer. However, they will become obsolete sooner, as installation areas will be increasingly scarce and the electrical power of new PV panels is growing rapidly, so replacing the panel with a more powerful one even before the end of its life cycle will prove more efficient. As a result, methods for recycling solar modules are being developed worldwide with the aim of reducing the impact of PV waste on the environment. PV panel recycling should ensure the sustainability of the long-term supply chain [2], thereby increasing recovery and energy payback time (EPBT) and the recovery of recycled materials, while reducing CO_2 emissions.

The International Renewable Energy Agency (IRENA), [6] predicted in 2016 that the global volume of waste from photovoltaic modules would range between 1.7–8.0 million tonnes by 2030 and between 60–78 million tonnes by 2050.

Therefore, companies manufacturing photovoltaics (e.g. First Solar, Pilkington, Sharp Solar and Siemens Solar) are investing in research into the recycling of PV modules at the end of their life cycle [4].

1.6.1. Possible recycling methods

The current standard c-Si module is connected by two layers of EVA, which bond the layers. For this reason, recycling PV panels is a relatively complex task, as these materials need to be separated. After separating the materials/layers of the solar module, it is possible to recover metals such as lead, copper, gallium, cadmium, aluminum and silicon and reuse them in new products.

So far, the most common methods for recycling c-Si PV panels are based on mechanical, thermal and chemical processes.

The report [2] considers the recycling of two main classifications of PV cell technologies:

- Crystalline silicon (c-Si), which is the dominant cell technology of existing and currently sold modules
- Compound PV cell technology, which includes thin-layer modules such as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS)

Recycling technologies for c-Si PV modules and compound PV modules (CdTe and CIGS) have different characteristics due to differences in module structure and the metals they contain. One important difference is that the goal of removing the encapsulating layer from the laminated structure of compound PV panels is to recover both the cover glass and the substrate glass, which has a semiconductor layer, while the goal for c-Si modules is the separation and recovery of glass, Si cells and other metals.

The recycling processes for c-Si PV panels can be roughly divided into those that remove the encapsulating layer from the module's laminated structure and those that recover metals from Si cells. Removing the encapsulating material from the laminated structure is one of the most difficult tasks, and there are some processes, such as thermal, mechanical and chemical. Recovering metals from silicon cells can be achieved through chemical approaches, such as etching; another viable method is processing in the metal refining industry.

As for the recycling of composite photovoltaic modules, the processes are roughly divided into those that remove the encapsulating material from the laminated structures and those that recover metals and substrate glass.

1.6.2. Analysis of possible solutions for processing old PV panels

Recycling silicon from used PV panels is still in the initial stage, but significant progress has been made in the development of innovative technologies. With the growing demand for renewable energy, the need for efficient and sustainable recycling of photovoltaic panels will also grow.

Recycling silicon from used photovoltaic panels presents several challenges:

- Complex panel structure – photovoltaic panels consist of multiple layers of materials, including glass, metal and polymers, which need to be separated before silicon extraction.

- Contamination – silicon in photovoltaic panels is often contaminated with other materials, such as metals and polymers, which can affect its purity and value.
- High energy consumption – traditional silicon recycling methods require high temperatures and energy input, making them environmentally unsustainable.

The photovoltaic panel recycling process involves several consecutive steps, with panel-specific differentiation being performed at the beginning of the process. If the panel is damaged and can no longer be used for the purpose for which it was produced, the first separation step follows – removal of the photovoltaic panel frames. The material recovered from this part of the process is aluminum. The second step of the process is glass decomposition. Glass decomposition can be performed in three ways – chemically, thermally or mechanically. In mechanical glass decomposition, the recovered material is crushed glass, created by breaking the PV panel.

Glass decomposition is followed by film decomposition. The film can be separated chemically – by leaching or etching, thermally – cold or hot, or using the third method, i.e. mechanically – e.g. using a hot knife technique or a laser.

Decomposition of the remaining parts of the PV panel is also possible chemically, thermally or mechanically.

The entire recycling process with individual steps is shown in the following Fig. 1.9.

To address future waste from photovoltaic modules at the end of their life cycle, recycling technologies must be available. In general, sustainable waste management offers opportunities known as 3R: "reduce, reuse and recycle".

As part of the preparation for future mass waste processing, several technologies are being developed to introduce and achieve a higher rate of recovery/recycling, improve the quality of recovered materials, as well as increase cost-efficiency. It is clear that for different types of panels, it will be necessary to use different processing technologies with a combination of various processes in individual processing steps.

So far, the most common known technologies for recycling c-Si PV panels are based on mechanical, thermal and chemical processes [8].

All technologies involve the removal of the frame and power terminal blocks in the first step.

Currently, we can divide recycling technologies after the removal of the aluminum frame and terminal block into three basic groups:

1. Mechanical disintegration of the entire PV panel and subsequent separation of individual components
2. Delamination of the bottom underlying layer and any subsequent decomposition and separation of silicon and metallic materials from the encapsulated substances
3. Decomposition of the top glass, subsequent decomposition and separation of silicon and metallic materials from the encapsulated substances

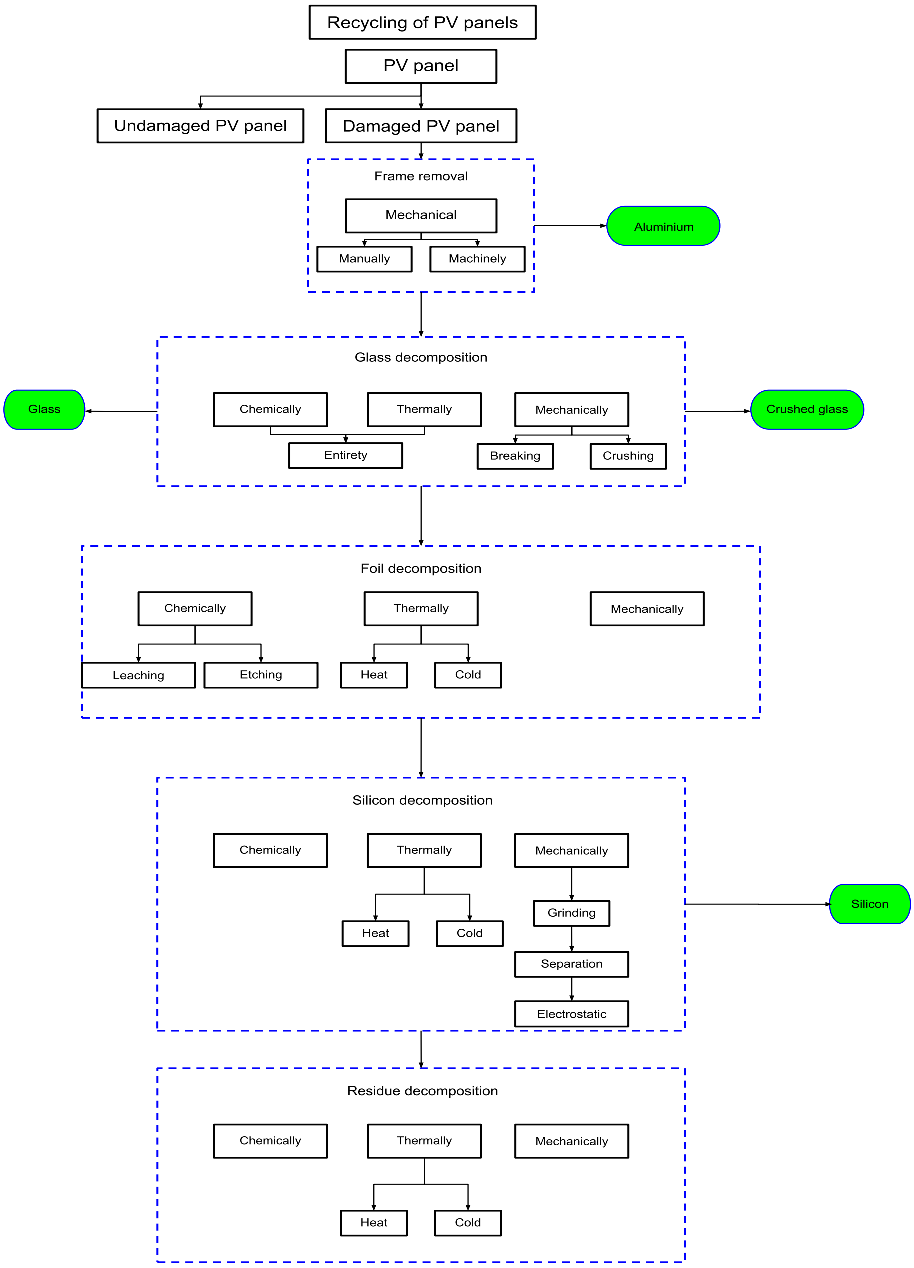


Fig. 1.9 Flowchart of the PV panel recycling process

Individual technologies differ in price and efficiency of recovering individual components. The types of processed PV panels have a significant impact on the technology used (Fig. 1.10).

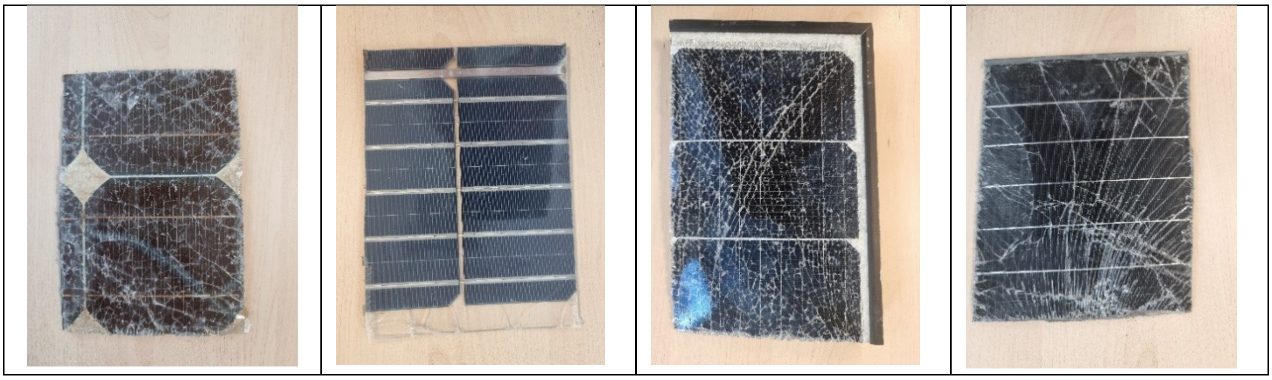


Fig. 1.10 Various sizes and shapes of photovoltaic cells

Glass decomposition can be performed in three ways – chemically, thermally, or mechanically. One of the methods of mechanical decomposition of the EVA film is the so-called hot knife method [6]. The process of mechanical and thermal delamination of encapsulated substances from glass is performed by applying high temperature of a hot knife to the bond between glass and film. This temperature causes the melting of the EVA film and its subsequent decomposition.

The mechanical process involves crushing, scraping off the glass or layers and cutting the encapsulating layer. Metals are subsequently recovered from the crushed materials through additional processes. Although the conventional mechanical method is the least energy-intensive, it is characterised by low processing performance, high dustiness and low yield and purity of the recovered components.

The thermal process is essentially a combustion process without or with an underlying layer based on fluoride. The EVA film or the bottom underlying layer are completely decomposed in an exhaust silencer and then the liquid is released and burned. The expected recovered materials are glass, silicon cells and electrode strips. For mass processing, it will be necessary to introduce countermeasures for the formation of gaseous fluorine in order to increase its economy and efficiency. A possible solution is to burn this gas and use the heat to heat the combustion chamber.

The chemical process is based on the application of solvents to remove the encapsulating substance from laminated structures with the aim of separating silicon wafers and other metals from the remaining mixture. For example, etching with hydrofluoric acid or alkaline hydroxide is used. It is a promising process that will allow the recovery of silicon cells. However, it is currently very lengthy and therefore not suitable for mass processing of PV panels. Problems also include gases generated in the process as well as the processing of hazardous waste chemicals.

The research results of the most important studies and works presented here represent the current possibilities of introducing chemical processes for recovering silicon from photovoltaic panels.

The main findings for chemical processing can be summarized as follows:

1. Efforts have been made to formulate a universal composition of the etching solution, but the results have shown that modification of the solution is necessary for different types of PV cells.
2. Many solvents dissolve non-crosslinked EVA when heated to 80 °C, and as for cross-linked EVA, trichloroethylene appears to be the most effective solvent when heated to 80 °C.
3. O-dichlorobenzene (O-DCB) is the most effective solvent for the regeneration of PV cells through ultrasonic irradiation.
4. The dissolution of trichloroethylene (TCE) and benzene is reduced due to pyrolysis and pyrolytic reaction at 70 °C.
5. The use of HF and HNO_3 is necessary for removing metallic impurities containing silicates.

Chemical processing of PV panels involves a number of disadvantages that are fundamental to its use in the recycling process, while significantly limiting the use of chemical processing. The biggest negatives of chemical processes for separating and purifying silicon include:

- Hazardous gaseous and liquid emissions and waste substances
- Working with hazardous solvents and acids
- The need for a closed-loop material processing cycle, which places heavy demands on recycling equipment
- Energy intensity – many procedures require higher temperatures.
- Time-consuming – chemical processes generally require long reaction times.
- Legislative restrictions for processors

1.7. Innovative method of PV panel processing

High purity of Si can be achieved by decomposing the panel layer by layer. The base panel remains intact.

The basic scientific hypothesis that we adopted for mechanical decomposition is that instead of crushing the panels, we will perform the decomposition layer by layer so that the remaining part of the panel always remains intact.

Basic scientific hypothesis

Ensure the separation of Si without crushing the PV panel.

Based on this scientific hypothesis, we created a conceptual design of the technological process (Fig. 1.11) [14].

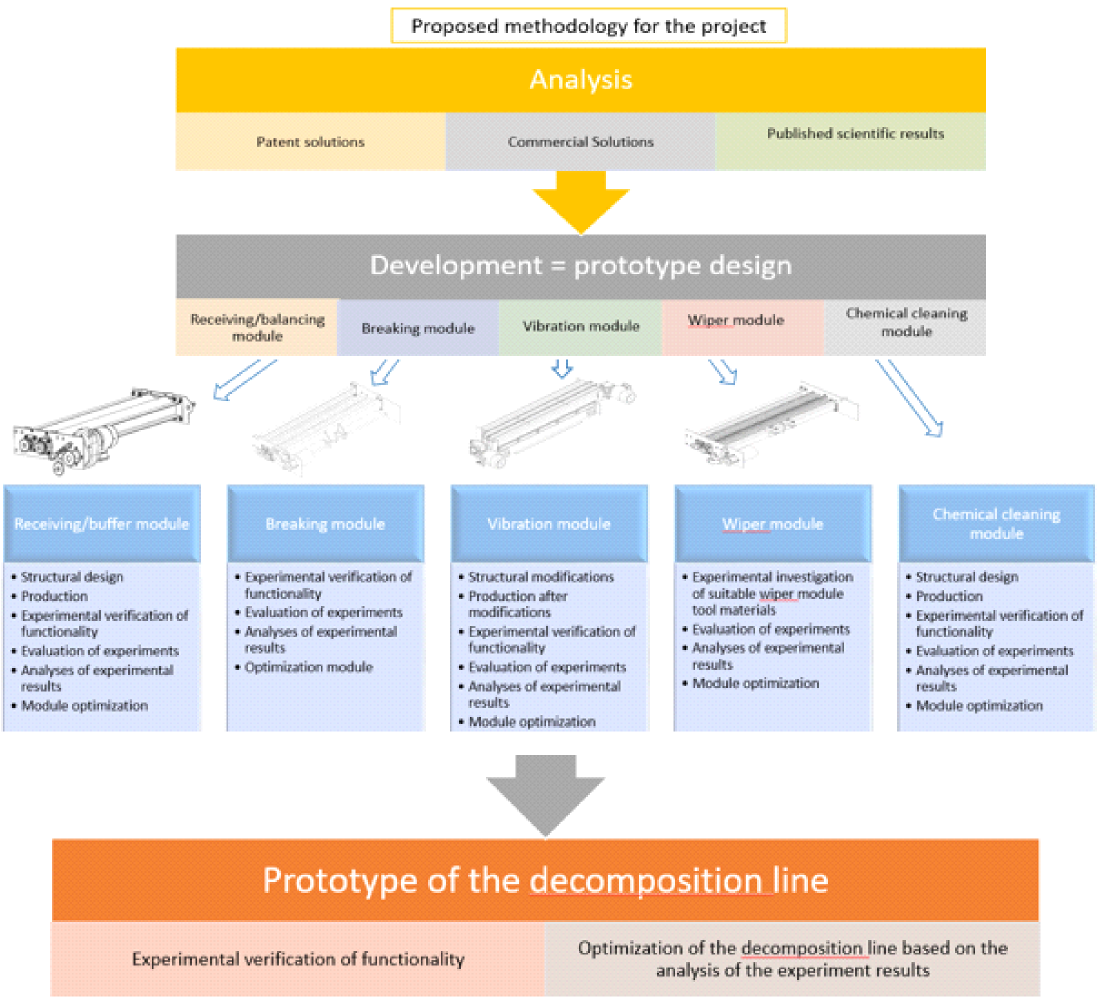


Fig. 1.11 Modular structure of the glass decomposition line [14]

1.7.1. Glass removal

For this technological step, we used an original technological module produced according to our patent SK288900 “Method for high-efficiency decomposition of laminated waste glass and modular line”.

The requirement was to develop a technologically acceptable and economically efficient technology for small and medium-sized outputs with an annual capacity of 1,000–2,000 kilograms. The goal of our experimental work was to research and verify various principles of disintegration.

In the design, we started from the basic technical hypothesis that, after the technological decomposition process, the proposed technology should meet the requirement of a “compact film”. In our opinion, this way we will achieve the highest level of purity of the individual fractions. This means designing a technology with no glass waste disintegration during the decomposition process. Within this process the glass is separated by its breaking and subsequent stripping and scraping off of the glass fragments in such way that the foil remains intact, if possible.

The structure of the designed technological equipment for the processing of waste laminated glass is based on the fact that it consists of a multi-stage set of variable modules. Thanks to this important feature it is possible to process bonded sheets of glass of various thicknesses, dimensions or even multiple laminated glass on a single equipment. This way it is possible to create new variable configurations for the specific requirements of individual customers. The individual modules are able to work independently as well as together with the smooth flow of technology. Their mutual movements and cooperation may be connected thanks to the frequency-controlled drives of individual rollers as well as the frequency of the applied industrial vibrator. On the one hand, individual customers will get their machines made to measure, and on the other hand, the module design enables a wide application of these machines in the processing of waste bonded glass, especially in the construction and automotive industry.

In the minimum configuration (Fig. 1.12), the line consists of one breaking module where the glass is broken in a transverse and longitudinal direction between two pairs of breaking profile rollers. The second module of the line is the shaking vibration module where the broken and still undivided glass is shaken between the vibration tool with pyramid-shaped points. The last module of this minimum configuration is the scraping module where the PVB film is mechanically cleaned by the effect of various frequencies of scraping roller rotations.

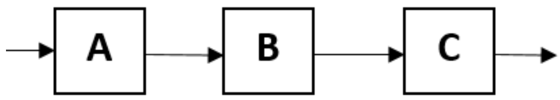


Fig. 1.12 Minimum line configuration
A – breaking module, B – vibration module, C – scraping module

For thick and multiple-layered laminated glass, it is possible to install some modules more times in a row (Fig. 1.13). In order to increase the processing capacity and the purity of the produced film, the line configuration is completed with the receiving table and washing module where the PVB film is washed in the warm water solution.

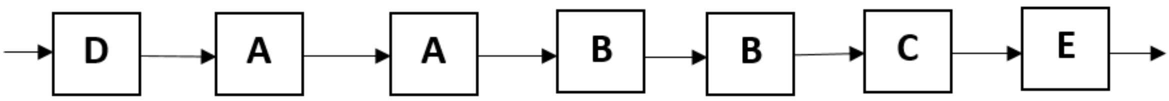


Fig. 1.13 Example of extended line configuration
D – initial module, A – breaking module, B – vibration module, C – scraping module, E – washing module

The evaluation of experiments relies on a suitable choice of method and technology determined based on the laboratory experiments performed. Based on the results of the experiments performed, we decided to design a functional model with a combination of mechanical and thermal principles. When the glass is heated to a temperature of approximately 120–140 °C, the Van der Waals forces between the glass and the film decrease significantly, increasing the efficiency of decomposition.

The first model (Fig. 1.14), which we proposed for production for the proposed line, was a model for scraping glass from the film. Upon entering the model, the material is first heated and then enters the roller system. The roller system breaks the multi-layer composite material in the longitudinal and transverse directions. In the third part, the cracked glass is peeled off the film. Convex and concave rollers are alternately slid onto the first pair of rollers, which ensure transverse cracking of the processed panel. The module is then equipped with a system of vertically moved pairs of rollers, which ensure longitudinal cracking of the processed panel. The last pair of cylinders has discs with scraping elements mounted on it (Fig. 1.15). The produced functional module is shown in Fig. 1.15. Testing is currently underway on the functional model.

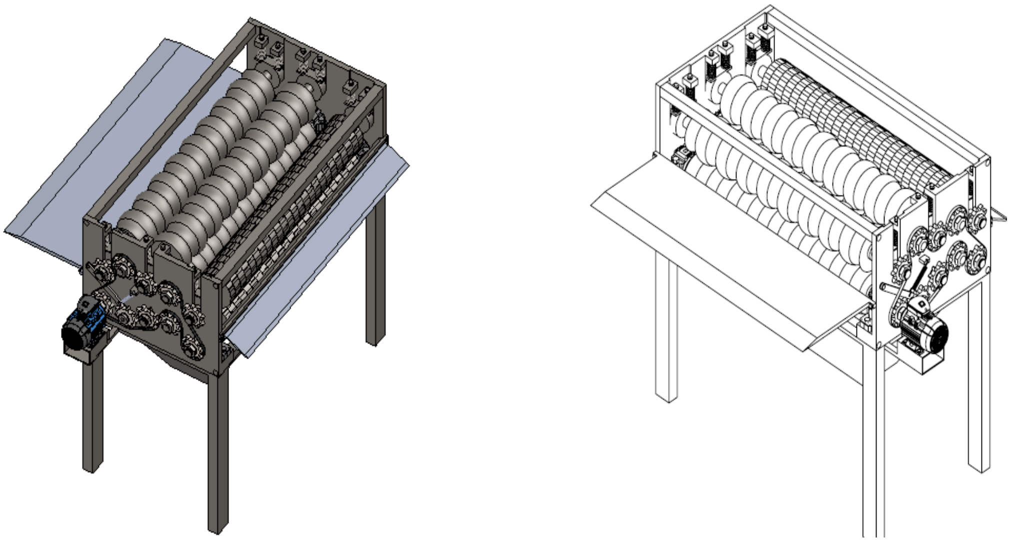


Fig. 1.14 3D multiple arrangement of breaking pairs in combination with a scraping pair of discs

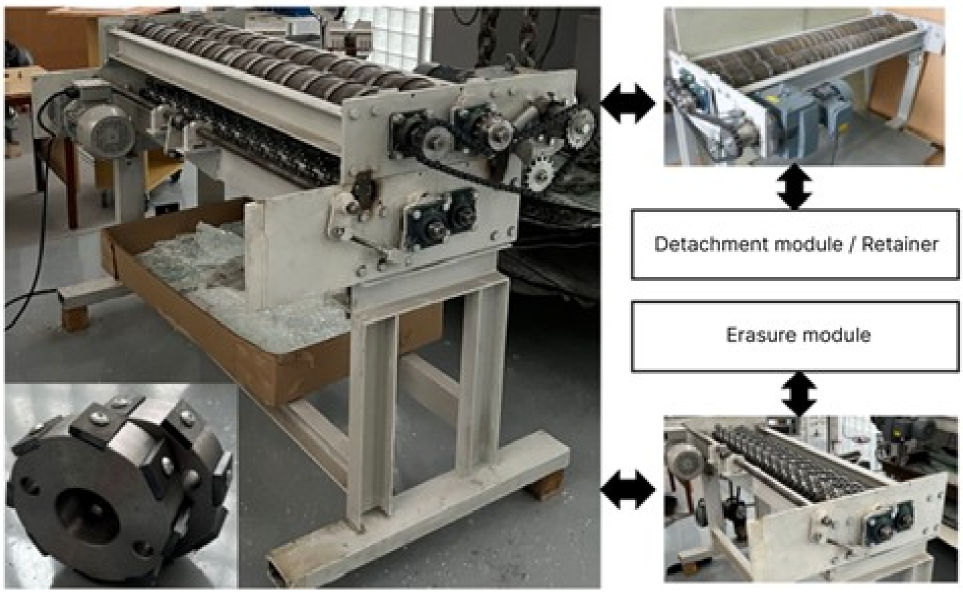


Fig. 1.15 Measuring equipment for the experiment – scraping module

Fig. 1.16 shows PV panels with glass, a view of the discs with scraping elements, and a view of the PV panel strips after the glass has been removed.

		
View of panels without frames	Glass removal	Panels without the top glass layer

Fig. 1.16 Glass removal equipment

The following Fig. 1.17 shows the separated and sorted glass and a detailed view of the panel without the top glass layer.

	
Example of sorted glass fractions	Detail of the sheet after glass re-moval

Fig. 1.17 Individual components after glass removal

1.7.2. Experimental verification of possible Si recovery technologies

The basic starting point of this decomposition is that we have a panel without a frame, glass and electrical box. The results of the analysis of the PV sheet without glass are shown in Fig. 1.18.

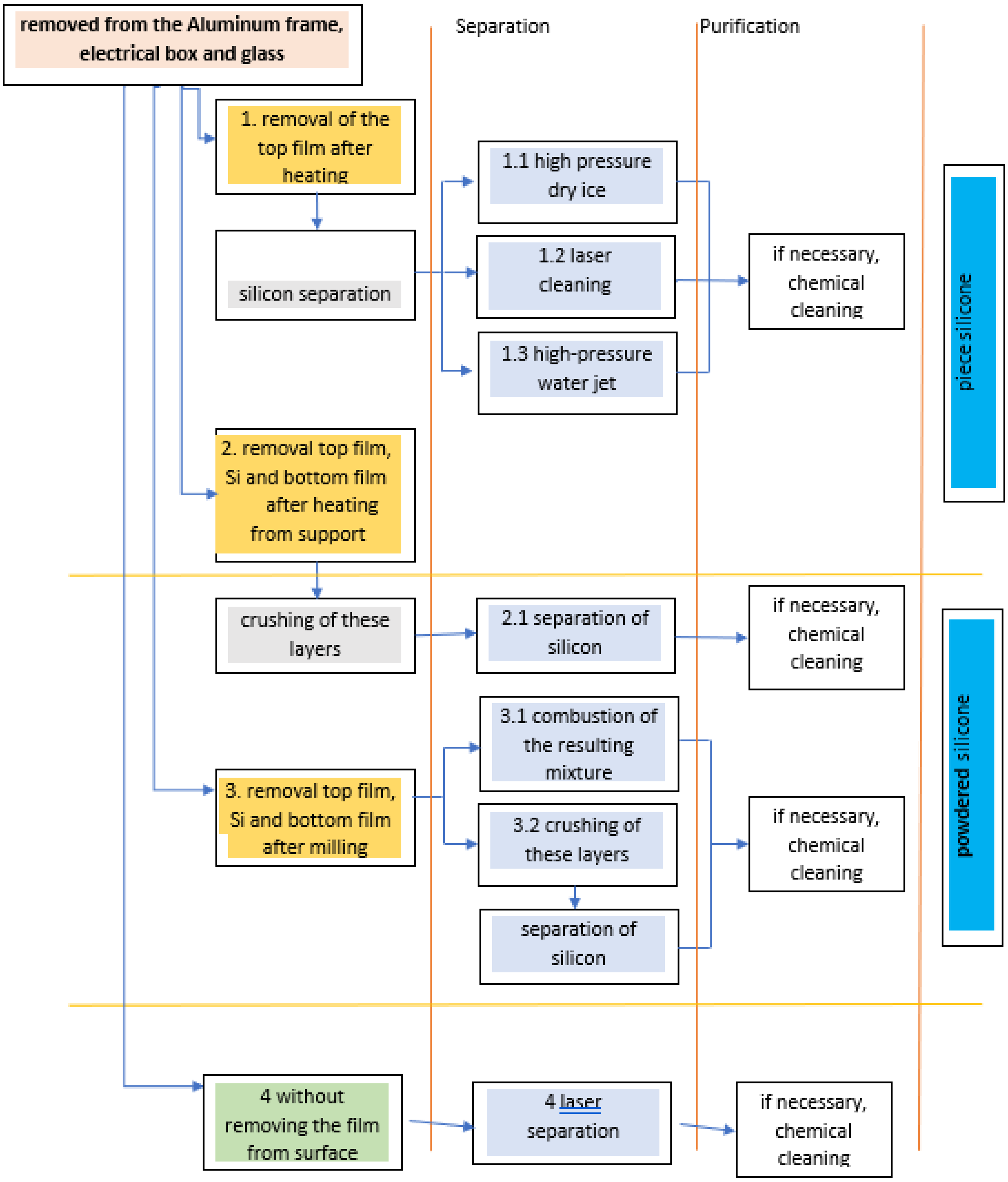


Fig. 1.18 Basic structure of silicon decomposition technologies

1.8. Removal of encapsulating film

1.8.1. Removal of the top encapsulating film

In our experiments, after removing the top film, we also performed a laser separation test of silicon (V 1.2). However, the test result was negative. The silicon did not separate during the test, it was only surface-cleaned and subsequently baked into the bottom supporting plastic base.

Problem: Precise setting of the thickness of the removed layers for different types of panels.

1.8.2. Removal of film + Si

Laser technology

Variant 2 assumes the removal of the top and bottom film together with silicon by milling or grinding. During silicon separation using laser technology, the top and bottom film evaporate. The released silicon falls freely into the collection container.
Detailed tests confirmed the possibility of delamination of all three layers at once (EVA+Si+EVA).

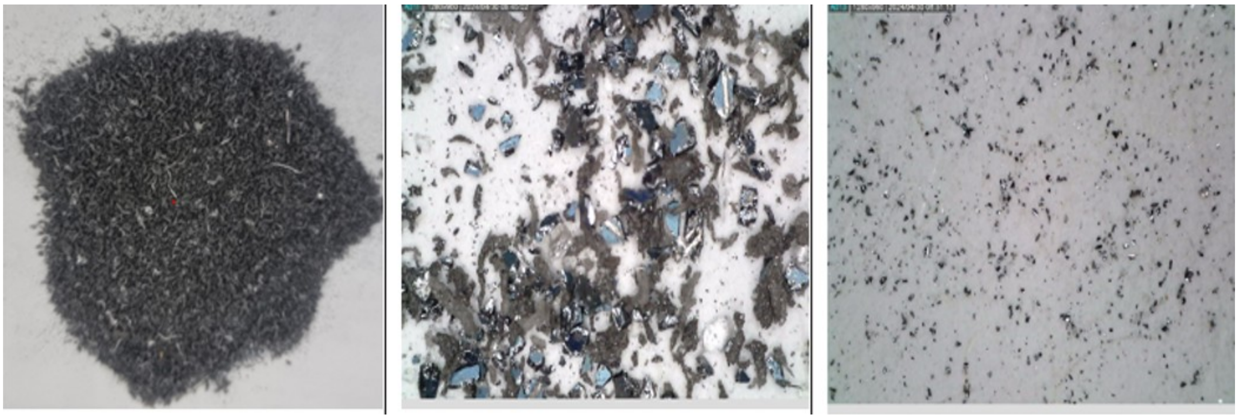
However, repeated tests (Fig. 1.19) showed some problems with the proposed technology:

- Poor performance of the applied technology and high energy intensity
- The technology is very sensitive to the precise setting of the laser gun distance (set equipment power, distance and angle setting of the laser head from the panel, speed of the delaminated sheet).
- A disadvantage of the tested technology is that when the type of delaminated panel changes, all parameters change.
- If the top layer of the EVA film of the panel is damaged, the silicon was not removed there.

The results of the removed components are shown in Fig. 1.20.

	
Laser device	Process of removing all three layers

Fig. 1.19 Application of laser for removing all three layers

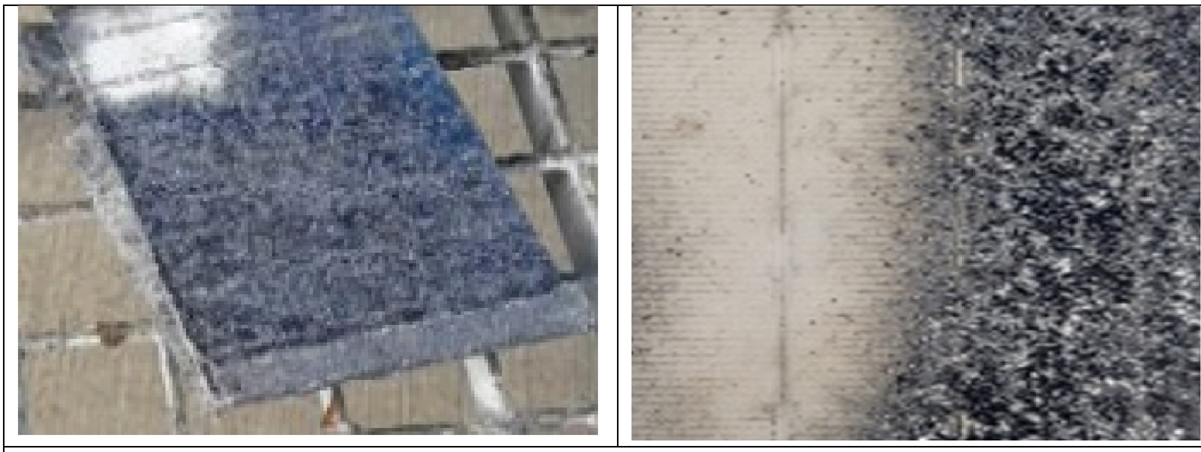


Fraction 1+	Fraction 0.5–1	Fraction 0–0.5 mm

Fig. 1.20 Sorted components by size after separation

Dry ice application

The process and view of the resulting backsheet of the PV panel is shown in Fig. 1.21



View of the process	View of the backsheet

Fig. 1.21 Removing 3 layers with dry ice

High-pressure water jet

The process and view of the resulting backsheet of the PV panel during water jet application is shown in Fig. 1.22

Fig. 1.22 Removing 3 layers with a water jet

Warm water is used for removing the encapsulating film and Si, which circulates in the system after filtration. The technology does not endanger the environment and is not energy-intensive. The technology removes piece fractions of the film.

1.8.3. Application of mechanical technologies

We also tested mechanical technologies for removing EVA film with Si. For these experiments, we designed a test module that allows testing grinding, milling or brushing technologies on a single module (Fig. 1.23). After milling, the film is removed in large pieces; during grinding and brushing, a fine to powdery fraction of EVA film with Si is created.

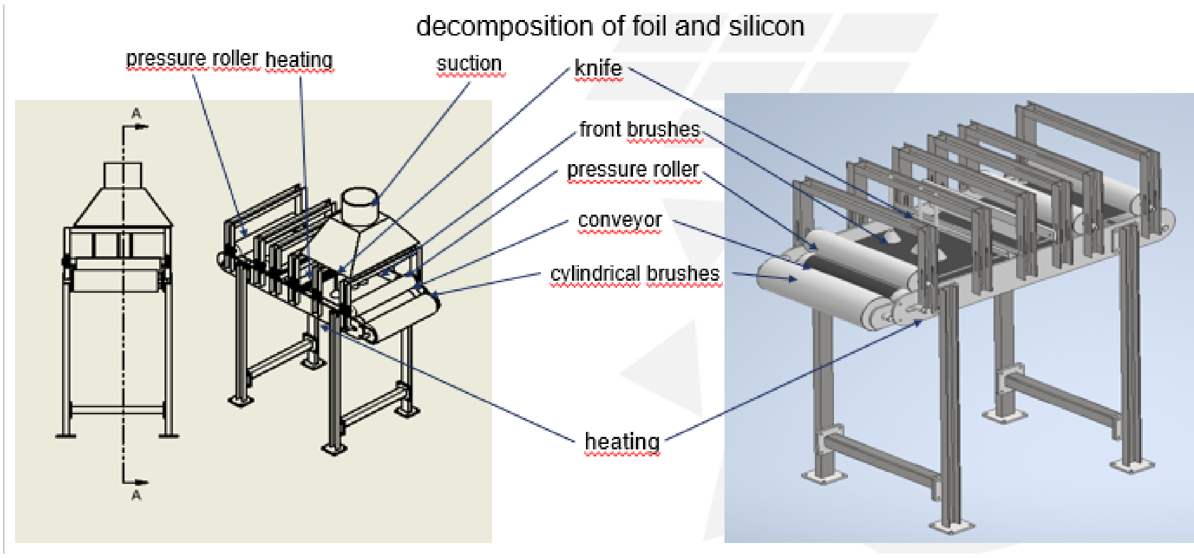


Fig. 1.23 Experimental stand – film and silicon decomposition

Based on the results of mechanical tests, we designed a technological procedure for the mechanical removal of the encapsulating film with silicon (Fig.1.24). This procedure takes into account different types of processed panels. The type of PV panel is scanned at the entrance to the line. The first step involves the removal of the aluminum frame and electrical box. In the second step, the glass is removed. The panel is then further processed according to type in one or the other line.

In the first line, the encapsulating film with Si is removed by milling. This method produces larger fragments of EVA film, which include electrical conductors separated on an electrostatic separator. After separating the conductors, this mixture enters the depolymerisation chamber (Fig. 1.25), where, at a temperature of approximately 550 °C, the EVA film evaporates and only silicon remains. In the last step, this silicon is rinsed in hydrochloric acid.

In the second line, the encapsulating film with Si is removed by brushing. This method produces a small to powdery fraction of EVA film. This fraction, together with pieces of electrical conductors, is placed into the depolymerisation chamber. After the depolymerisation process is finished, the Si is separated. In the last step, it is chemically cleaned in hydrochloric acid.

1.9. Overall concept of Si extraction

1.9.1. Modular design of the technological line

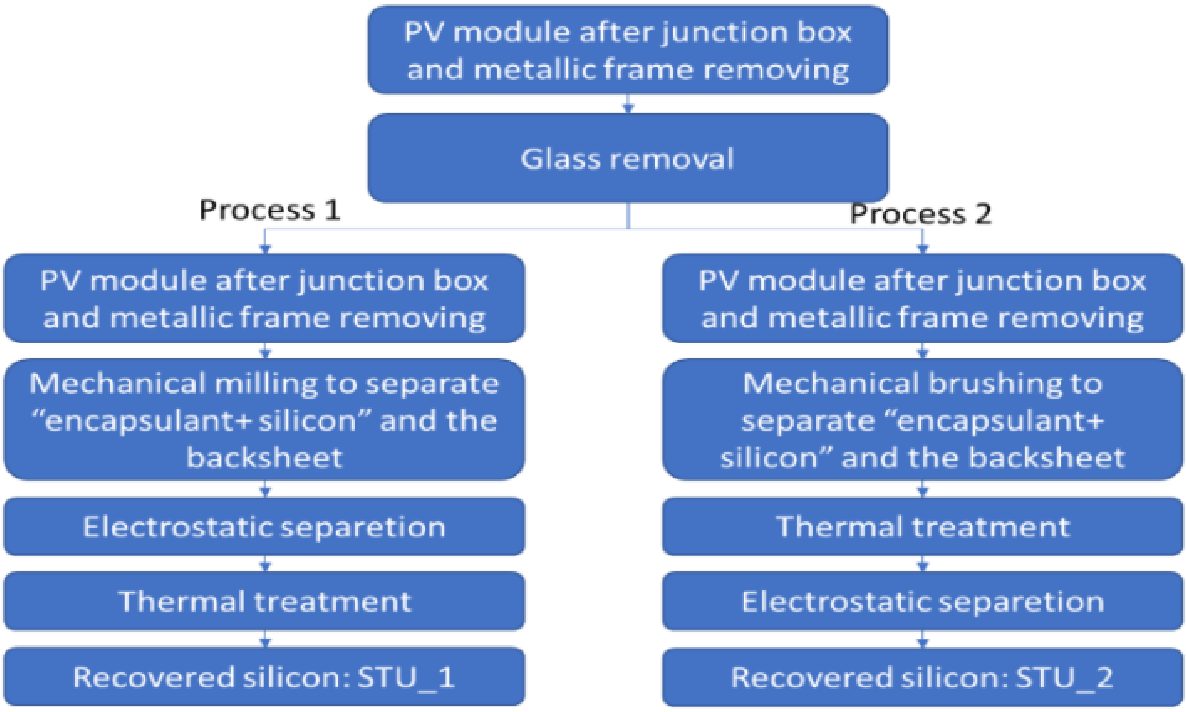


Fig. 1.24 Design of the technological procedure for Si separation

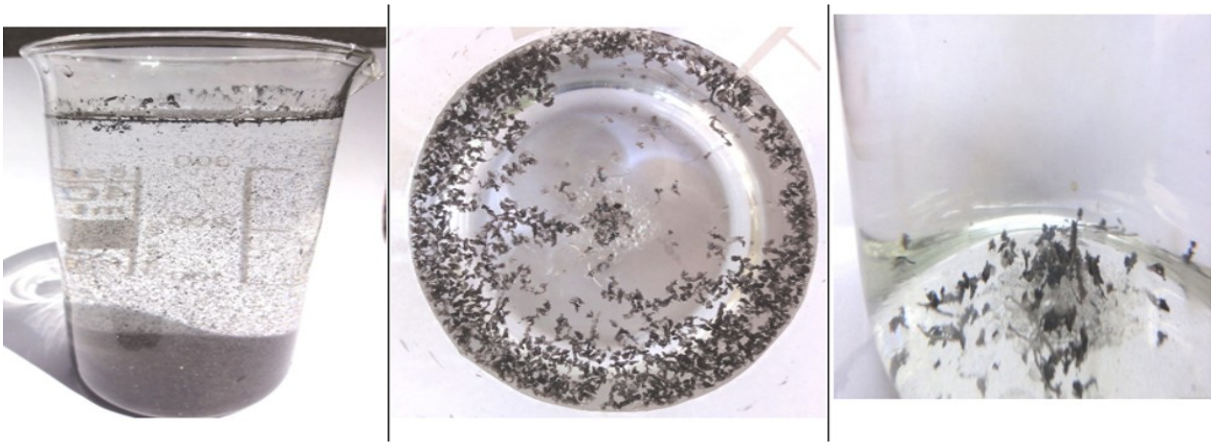
View of the depolymerisation column

View into the chamber

Fig. 1.25 Depolymerisation of EVA film

Fig. 1.26 Cleaned silicon

In our research, we also considered other methods of Si separation. It is also possible to separate silicon from EVA after brushing by a combination of flotation (Fig. 1.27) and then in an electrostatic separator. However, the purity of the obtained silicon was not at the required level.



Fraction after grinding	*Detail of the fraction*	*Silicon*

Fig. 1.27 Flotation method for Si and EVA film

When designing the technological line, we set basic requirements that the line must meet:

Original – based on the analysis of existing technologies, it can be stated that there is no mechanical processing technology that would process PV panels by removing individual layers without the need for crushing the panel.

Universal – EVA film and Si can be removed using various mechanical methods (milling, grinding, brushing, knife removal), each layer separately (EVA, or Si) or EVA+Si together.

Highly efficient – the efficiency of silicon recovery is at least 90%,

Continuous – By gradually arranging individual modules that are connected by conveyors, it is possible to achieve a fully continuous process of PV panel processing.

Modular – unified connecting elements of individual modules allowing their easy interchangeability. The technological line can be designed in both horizontal and vertical arrangements.

Variable – simple change of technology configuration in individual process steps depending on the type of processed PV panels.

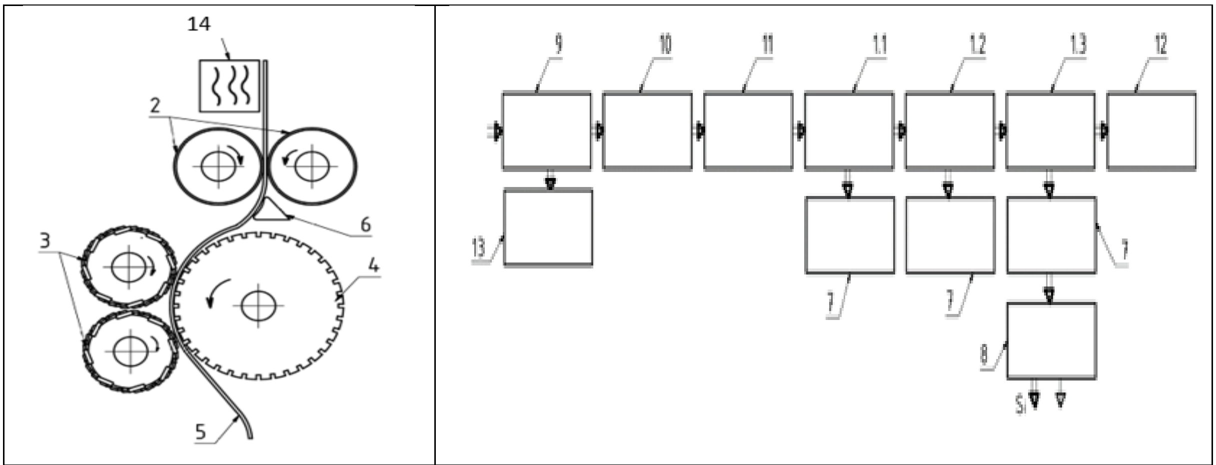
High-performance – increasing the line’s performance by duplicating critical modules.

Ecological – with the required Si quality, it is not necessary to apply chemical processes; the use of the technology does not cause environmental pollution.

1.9.2. Patent protection of the proposed solution

Based on the acquired knowledge, we have prepared and made two patent applications:

2) PP 64-2025 “Efficient silicon extraction by delamination of individual layers of photovoltaic panels and chemical-thermal decomposition of EVA film”. The application was made on 28/5/2025.
https://wbr.indprop.gov.sk/WebRegistre/Patent/Detail/64-2025?csrt=2768809193907261388, (Fig. 1.28)

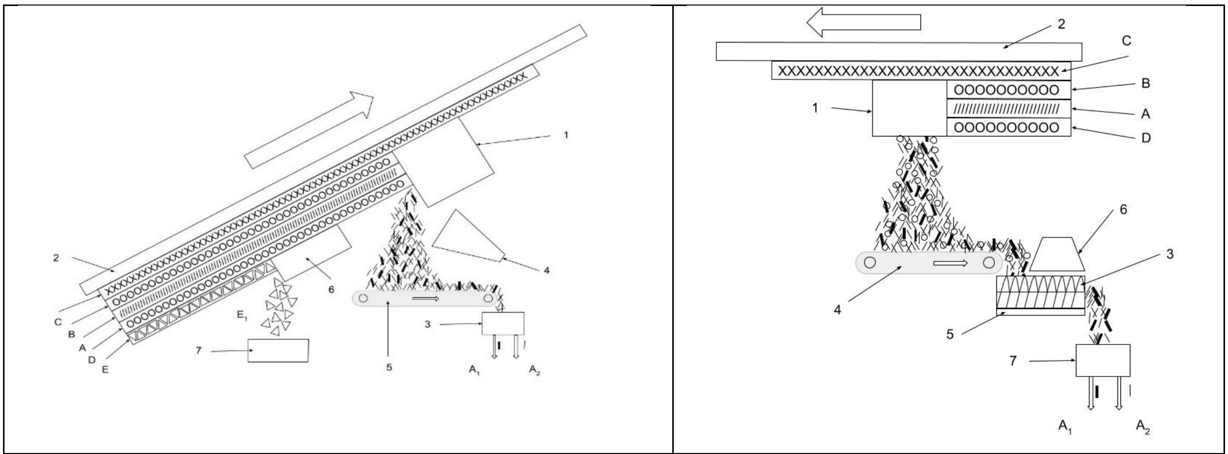


1. Combined module	6. Guiding bar
1.1Combined module for glass removal	7. Collection box
1.2 Combined module for polymer film removal	8. Separator
1.2Combined module for the removal of the silicon semiconductor layer	9. 8.1 Thermal separator
1.4 Combined module for the removal of the polymer film and silicon semiconductor- layer	10. Receiving/diagnostic module
2. Feeding/breaking rollers	11. Disassembly module for the electronic accessories
3. Scraping roller, scraping blade	12. Disassembly module for the metal frames of the photovoltaic panels
4. Pressing roller	13. Output of the line
5. Photovoltaic panel	14. Repair module
	15. Thermal module

Fig. 1.28 Patented solution for thermal-mechanical removal of EVA film and Si

The decomposition line for highly efficient decomposition of photovoltaic panels contains sequentially arranged combined modules (1) for removing layers of glass, polymer film and silicon semiconductor layers. All combined modules (1) have a thermal module (14) the input to develop a temperature of 130 to 150 °C, and a pair of feeding/breaking rollers (2) with shaped profiling, followed by at least one scraping roller (3) and a pressing roller (4). Collection boxes are attached to each combined module. The axes of the scraping rollers (3) and the pressing roller (4) are moved relative to the axes of the pair of feeding/breaking rollers (2) in such a way that they create a curved trajectory for the moving sheet of the photovoltaic panel (5). A guide bar (6) is inserted between the feeding/breaking rollers (2) and the pressing roller (4).

1) PP 102-2024 "Method of highly efficient decomposition of the silicon semiconductor layer from photovoltaic panels and decomposition equipment" The application was made on 12/12/2024. See: https://wbr.indprop.gov.sk/WebRegistre/Patent/Detail/102-2024?csrt=12685596007246113160, (Fig. 1.29)



1. technological unit	6. glass delamination module	B underlying polymer film
2. input conveyor	7. container of glass fragments	C photovoltaic panel carrier
3. separation module	A the semiconductor silicon layer	D cover polymer film
4. suction device	A1 silicon fragments	E glass layer output conveyor
	A2 metal connecting wires	E1 glass fragments

Fig. 1.29 Method of highly efficient decomposition of the silicon semiconductor layer

The principle of the method of highly efficient decomposition of the silicon semiconductor layer from photovoltaic panels stripped of electronic accessories, frames, glass layer and cover polymer film is that in the first step, the cover polymer film (D), the semiconductor silicon layer (A) and the underlying polymer film (B) on the carrier (C) of the photovoltaic panel are continuously exposed to the action of a laser beam from at least one laser head in a laser module. The laser beam has a pulsed character with a frequency of at least 130 kHz and a pulse duration of at least 250 ns, and an energy of up to 0.05 mJ/cm². Subsequently, due to the thermal energy of the laser beam, the cover polymer film (D) and the underlying polymer film (B) are evaporated, and the silicon fragments (A1) together with the metal connecting wires (A2) of the semiconductor silicon layer are released from the carrier (C) of the photovoltaic panel, and during the application of the laser beam to the cover polymer film (D), the semiconductor silicon layer (A), and the underlying polymer film (B), the vapours from the evaporated cover polymer film (D) and underlying polymer film (B) are captured by a suction device. In the second step, the released silicon fragments (A1) are separated from the metal connecting wires (A2) in a separation module.

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https://wbr.indprop.gov.sk/WebRegistre/Patent/Detail/642025?csrt=2768809193907261388

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[11] http://us.agc.com/sites/default /files/pdf/high/4.%20Glass%20Pocket%20Guide%20All%20About%20Glass.pdf

[12] patent SK288900 „Method for high-efficiency decomposition of laminated waste glass and modular line"

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[14] Šoo,Ľ. a kol.: Recyklácia vrstveného skla - Analýza technických a technologických možností. Správa UNIVNET 2020, p. 42.

2. Development of Moulded Thermal Insulation Elements from Waste Polyurethane Foam

2.1. Sources and volumes of waste polyurethane foam

Polyurethane (PUR) foams are widely used in various areas of industry and products due to their exceptional properties, such as low density, excellent mechanical properties, low thermal conductivity, or high sound absorption capacity. They are porous, light materials with excellent performance properties. Based on these properties, PUR foams have the highest share of application in mattresses and furniture (31%), then in cars and other means of transport (approximately 24%), in packaging materials, construction, electronics, footwear and elsewhere. Their extensive use, mainly in furniture and cars, is therefore the primary factor driving market demand. The growing demand of the construction industry for polyurethane foam stems from its key role in increasing energy efficiency, improving interior comfort and contributing to sustainable construction practices. With the development of construction standards, tightening of regulations and more intensive focus on energy-efficient and ecological buildings, it is expected that their use as a reliable insulation material will continue to grow significantly in the construction industry.

In 2022, the volume of PUR foam on the market reached 15.5 million tonnes, recording a growth of 6.9%. in the 2019–2022 period. The size of the global PUR foam market in 2025 was 50.47 billion USD and should reach 95.15 billion USD by 2033, with an estimated annual growth rate of up to 8.3% (Fig. 2.1). It is expected that the market will be driven by the growth of the appliances market and cold chain infrastructure. Another driving force of the polyurethane foam market is the growing demand from other industrial sectors, primarily the automotive industry, construction and furniture. In 2025, the soft foam segment accounted for as much as 59.12% of the market.[1]

Fig. 2.1 Trend of global PUR foam market development[1]

With these huge volumes of annual PUR foam production comes a huge environmental challenge to develop new technologies for material recovery of current and future waste PUR foam. Individual sources of polyurethane waste as well as the situation with their subsequent management are shown in Fig. 2.2 [2].

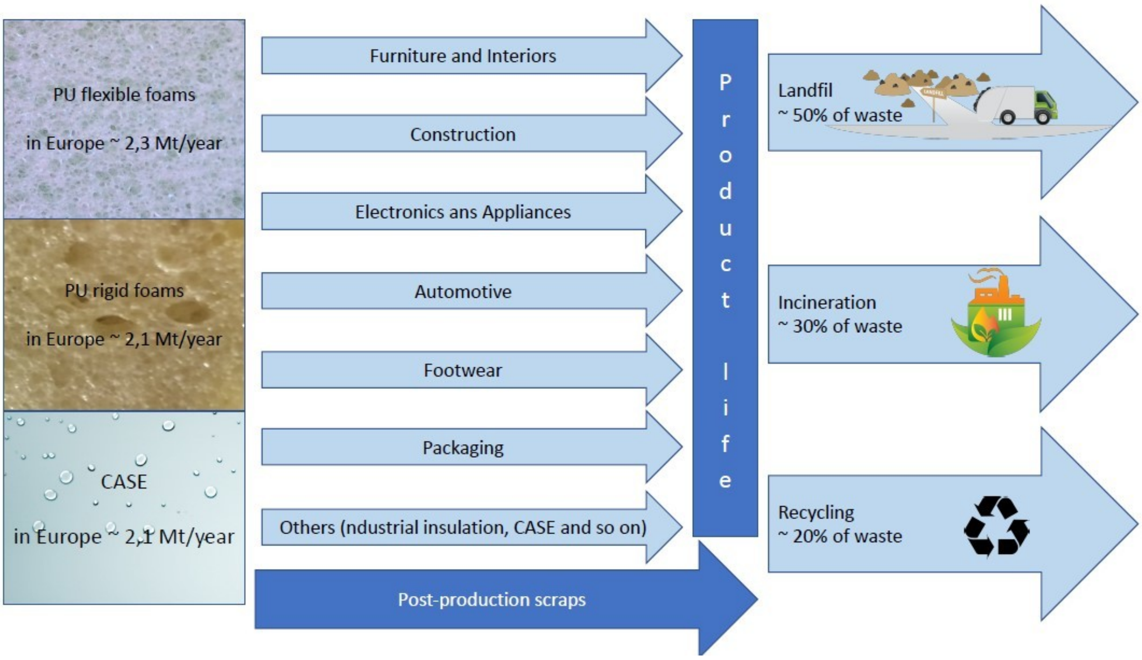

Fig. 2.2 Life cycle and waste management of polyurethanes (PU) in Europe[2]

The implemented project is focused on the efficient design of the treatment of PUR waste, especially from old vehicles. Polyurethane foams are used in cars as seat fillers, headrests, roof upholstery, door trim, carpet pads, noise and vibration insulation for engine compartments, etc. As the output is to be an optimised design of the technology of material (or energy) recovery of waste – polyurethane foams, it is necessary to quantify the quantities of this problematic waste from old vehicles in the Slovak Republic. In 2023, 33,597 old vehicles were processed in Slovakia, with a decrease in the number of processed old vehicles in the last 5 years [3]. Based on an average vehicle weight of 1,400 kg and a percentage by weight of PUR foam in cars of 1.75% it is possible to conclude that 823 tonnes of this problematic waste will be generated from old vehicles in 2023 alone.

However, in terms of designing and optimising a technology suitable for the treatment and recycling of such waste from old vehicles, two objectives need to be pursued:

- Recycling of pure PUR foam from seats
- Recycling of PUR foam from other parts of vehicles with an integral surface layer, i.e. PUR foam injected directly into moulded parts, upholstery with adhesive surface layer – textile, leather, artificial leather (armrests, door upholstery, roof, etc.).
- A highly investment-efficient technology for recycling PUR foams from old vehicles for the volumes of waste raw material in Slovakia.

2.2. Characterisation and areas of application of polyurethane foams

PUR foams have been used since the 1940s and are now a fundamental material with a wide range of applications in many industries. The reaction of isocyanates with alcohols produces so-called urethanes (Fig. 2.3). These are esters of carbamic acid [4].

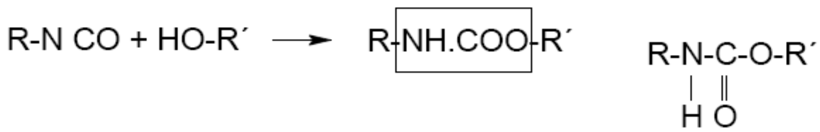

Fig. 2.3 Diagram of the reaction of isocyanate with alcohol to form urethane.

Polyurethane (PUR) foams account for about 33 % of total polyurethane production. They are used in the automotive industry for the production of seats, mattresses and furniture. They are also used in the construction industry. The fact that they are commonly used both in industry and as consumables raises the issue of waste disposal and recycling. There is also the possibility of waste in the production, where it can reach up to 10 % of the total foam production. PUR can be used as foams, elastomers, varnishes, adhesives, elastic fibres or artificial leather. From these forms, the greatest demand is for foams.

Soft (flexible) foams are produced with a density range from 15 kg m-3 to 70 kg m-3, hard ones with an even wider range from 10 kg m-3 to 600 kg m-3 [5]. Hard foams are prepared in closed or open moulds. They are mostly used as insulation material in construction and engineering (pipes, refrigerators, cars), as well as in aircraft as radar covers. It is not only the good insulating properties of hard PUR foams but also their mechanical resistance that are exploited. Soft foams are prepared exclusively in blocks. They are used for the production of mattresses, for textile lamination, for packaging purposes (impact protection) and for the production of insulation and sealing sheets. Foam rubber, an integral soft PUR foam, has seen significant application in the furniture industry. It is characterised by higher density on the surface (skin) and reduced density in the middle, especially in flat products. The density transition from the edge to the middle is smooth, which distinguishes these materials from, for example, sandwich composites. PUR foams are used as seals, thermal insulation and construction material. All applications of PUR foam represent either a current or future source of waste.

Polyurethane foams should be distinguished in terms of mechanical properties into hard (e.g. refrigerator insulation, insulation in construction, insulation boards, sandwich building elements, etc.) and flexible (e.g. automotive seats, upholstery, mattresses, carpet pads, packaging material, etc.). Depending on which category a particular waste PUR foam falls into, it is possible to design a suitable technology for its subsequent processing and use.

2.3. Framework objectives of research on the recovery of waste PUR foams

The development of an effective technology for the recovery of PUR foams is preceded by an extensive professional analysis of technological possibilities and recycling procedures and an assessment of the suitability of individual processing approaches, taking into account the estimated volumes, the state of waste PUR foam (especially soft) and the costs of transporting this waste to the processing site. The practice of recycling pure polyurethane is widespread and technologically manageable. A significant problem is the recycling of polyurethane foam that has an integral surface layer (furniture parts, car upholstery, etc.). This problem is not currently addressed. At the same time, for the conditions and annual quantities of waste PUR foam in Slovakia, it is necessary to effectively design and optimise a technology that would allow material recycling of both types of waste.

The conducted experimental research focuses on the mechanical recycling of waste PUR foams and the development of an efficient technology for their processing, and the production of moulded thermal insulation elements. The goal is to design a comprehensive, efficient and optimised technology, including equipment for the material recovery of waste PUR foams from old vehicles, which will allow:

- processing pure polyurethane foam,
- processing polyurethane foam with an integral surface layer,
- processing these two types of waste together,
- producing both flat and moulded recycled products,
- producing thermal insulation elements using a dry method,
- will be a cost-effective technology for local processing of smaller volumes of waste.

2.4. Expert analysis of approaches to the processing and recovery of waste polyurethane foams

The development of an optimal technology for the recovery of PUR foams is preceded by an extensive professional analysis of technological possibilities and an assessment of the suitability of individual processing approaches, taking into account the estimated volumes and the state of waste PUR foam. The practice of recycling pure polyurethane foam from seats is widespread and technologically manageable. A significant problem is the recycling of polyurethane foam from other parts of vehicles, which has an integral surface layer. This problem is not currently addressed. At the same time, for the conditions and annual volumes of waste PUR foam from old vehicles in Slovakia, it is necessary to effectively design and optimise a technology that would allow material recycling of both types of waste.

Research, studies and testing have led to a number of areas and methods of recycling and uses of polyurethane that may be economically and environmentally feasible [6]. The four main categories [7] are: mechanical recycling, advanced chemical and thermo-chemical recycling, energy recovery and recycling of the product itself. Each method provides unique benefits that are particularly suited to specific applications or requirements [8,9]. Mechanical recycling (i.e.

material recycling) involves physical treatment. Chemical and thermo-chemical recycling (i.e. raw material recycling) involves chemical treatment that transforms this waste into input products, i.e. chemicals for the chemical industry. The energy recovery of this waste involves the full or partial oxidation of the material [10], the production of heat and power and/or gaseous fuels, oils and coal, except for by-products such as ash which must be disposed of [12]. Due to the typically long service life of products containing polyurethane, a fourth option – product recycling or so-called closed-loop recycling – is limited [11,13], as markets are changing rapidly and the concept of downcycling or open-loop recycling applies strongly to chemical-based products such as polyurethanes. Therefore, mechanical, chemical and thermo-chemical recycling and energy recovery are the only three ways to effectively recycle polyurethane [14].

Regardless of the recycling technology used, two factors play a key role in determining the technical and economic feasibility of recycling polyurethane materials:

increasing the density of the bulk polyurethane foams, enabling cost-effective transport from the collection point to the recycling plant,

size reduction of polyurethane products (mattresses, car seats, insulation boards, etc.) suitable for further processing in the selected recycling process. The size of the suitable fraction of such waste may vary depending on whether mechanical recycling, chemical processing or energy recovery will follow.

2.4.1. Mechanical recycling

An important and first step is to process the waste materials into smaller particles, which are then easier to process. This can be flakes, pellets or dust, depending on the type of PUR that is recycled. For polyurethane foams, recycling by grinding is used. The resulting dust can be reused as a filler in the production of new PUR foams. In other cases, waste material is shredded [15].

Fraction size adaptation

Many disintegration technologies have been developed in order to process various types of waste polyurethane materials into smaller particles. The required fraction size for downstream processing of polyurethane ranges from particles smaller than 200 µm for reuse as fillers in polyurethane, to larger pieces for chemical processing or energy recovery.

Grinding

It is a technological process where the waste material is essentially broken down by grinding. This creates fine dust, optimally ranging from 100 to 200 micrometers. It is then used as a filler in the production of PUR foams and elastomers. This technology is successfully used in the recycling of polyurethane foams from car seats.[15]

Two-roller grinding process

Flexible PUR foam is best processed on this equipment. [15] For this processing method, it is necessary to have at least one pair of rollers. They rotate in opposite directions and each at a different peripheral speed. The shear forces generated in the very narrow gap between the rollers turn the polyurethane foam into a fine powder with a typical particle size of less than

0.1 mm. This fine powder is sieved and stored in silos. It is then transported by screw conveyors and mixed with polyol. This mixture is conveyed to the mixing head, where it reacts with isocyanate and then poured to form a flexible foam slab. Up to 30% recycled polyurethane powder can be added with this technology.

When grinding flexible PU foams, the best result can be achieved by grinding between two rollers, while for hard PU foams, a particle size of less than 85 micrometers can be achieved with ball mills. A crucial factor that limits the amount of waste PU foam recycled by grinding is the viscosity of the polyol and fine particle mixture that can be processed by the process equipment. In practice, it is possible to process a mixture of 15 wt% regranulate from grinding if MDI polyol is used, and up to 25 wt% if TDI polyol is used [8].

A major problem of grinding processes in waste treatment is their economics. Grinding waste PU foam to a size of less than 100–125 μm is no exception. However, one advantage compared to other (mineral) filling materials is that PU powder has a density similar to the new foam that is being produced. Overall, the recycling process with a recycled polyurethane mass fraction of 7–10% in the new PU foam shows a cost saving of approximately 7.02–8.2 %, while the mechanical properties compared to 100% new PU foam are almost unchanged [16]. In addition, recycled hard PU powder is an excellent material for absorbing oil spills [7].

Precision knife mills

Special types of knife mills are used, with a large number of static and rotating knives. In these plants, screens are also used which are designed so that subsequent grinding of the cut material occurs in the chamber of the mill. Both flexible and hard polyurethane foam materials are ground to particle sizes of less than 0.25 mm in this way. [15]

Pellet mill

This process uses two or more metal rollers that push the processed material through a metal perforated matrix [15]. Depending on the type of foam and the technological conditions of the pelletising process, the product can be fine polyurethane powder or compact pellets. These are suitable for energy use, as they suit the transport systems of combustion plants.

Impact disc mill

The grinding of reaction-injected polyurethane materials (hard PU foams) takes place in two stages. In the first stage, the material is granulated by a knife mill to a particle size of approximately 3 mm and then, in the second stage, the material is ground to powder by an impact disc mill. The typical output is a fine fractional composition, where up to 40% is made up of particles smaller than 200 μm. Subsequently, the material is sorted through sieves and the larger fraction is returned to the grinding process.

Cryogenic grinding

Due to the elastic nature of flexible polyurethane foams, grinding these materials to a fine fraction is often very difficult, especially when the material is heated during grinding. Therefore, it is very effective to cool this material below the embrittlement temperature, e.g. with liquid nitrogen.

Recycling with re-bonding

Recycling by bonding with the addition of a binder is one of the most widely used recycling processes. It has been in use for 30 years. It consists in a method of processing foam flakes obtained from recycling foam waste, e.g. by regrinding. The flakes are blown from hoppers into drum mixers, which consist of a drum and an agitator. Here, the flakes are mixed with glue. The resulting mixture can be dyed and then compacted with a conveyor press. Stabilisation is carried out with the help of steam. With this procedure we can obtain new properties of PUR, e.g. higher density. It also includes high flexibility and wide variability in the mechanical properties of the finished products. This technology allows obtaining high-quality moulded parts from bonded materials for the modern age.[15]

Adhesive pressing

Adhesive moulding consists of layering polyurethane crumb and adhesive and then curing under the influence of temperature and pressure [13]. Moulded parts for the automotive industry, such as mats or spare tyre covers, are produced using this method. Adhesive moulding is applicable to many types of plastic waste and their mixtures. This probably oldest method of recycling PUR foams allows producing mats, carpet underlays, parts of sports hall floors or sound insulation in cars. The crumbled PUR foam with a particle size of approximately 1 cm can be reassembled into a compact unit by the addition of MDI diisocyanate and subsequent compression moulding under temperature in the range of 100–200 °C and pressure of 3–20 MPa. The result is PU moulded parts, building boards with excellent water and moisture resistance, or insulation panels for use in new refrigerators and freezers. Waste PUR foam processed into blocks and then cut is used in carpet mats, parts of sports hall floors and furniture. Material recovery of the enormous amount of PU flexible foam (sponge) from old vehicles can satisfy a large part (in the USA, almost 50%) of the carpet underlay market [8]. This recycling method is also very interesting for PUR foam from construction waste, but the processing method is more complicated and often impossible due to the flame retardants contained in this material [7].

Moulding under pressure

The moulded parts contain 100% recycled material. This pressure forming method, which primarily uses reaction-injected polyurethanes as recycled raw material in the moulds, is capable of producing high-quality recycled products. The recycled raw material is ground to fine particles and subjected to high pressures and temperatures to create a solid material that is ideal for many automotive applications. Pressure forming [17] involves forming polyurethane particles at temperatures and pressures high enough (180 °C, 35 MPa) to generate shear forces needed to melt and bond the individual particles together, without the need for additional binders. This technology focuses on the production of upholstery from the processing of polyurethane and polyurethanes obtained from old vehicles. Parts molded from recyclate achieve guaranteed mechanical properties that may in fact be better than new polyurethane material. The technology is suitable for the production of rigid and complex three-dimensional parts, such as pump and motor casings. The method successfully utilises the recycling of reaction-injected polyurethanes in the production of automotive parts.

Injection moulding

Injection moulding technology enables partial recycling of polyurethane. One method (Bayer high-temperature pressing) processes granular polyurethane with a grain size of 250 to 1,000 μm at a temperature of around 180 °C and pressures greater than 35 MPa, making it possible to produce thermoformed products such as various automotive parts [18]. Injection moulding technology primarily allows processing mixtures of polyurethane and other thermoplastics. It consists in melting granulate from waste plastics, including the fine fraction of PU, in the extruder chamber by external heating and subsequent injection of liquid plastic into the mould. Injection may use a single extruder, with the raw material consisting of a homogenised mixture of thermoplastics. Dual injection moulding with two (or more) extruders enables the recycling and reuse of waste thermoplastics and thermosets. The raw material is mixed before entering the mould. The advantages of this technology lie in the increased mechanical properties of the product, in the higher surface quality, and in the possibility of any colour of the product.

2.4.2. Chemical processing

Hydrolysis

Hydrolysis is a decomposition reaction in which water is consumed. Polymers containing hydrolysable ester, amide and nitrile groups, and the conditions where these groups are formed by oxidation[20], are susceptible to degradation by water. The process takes place in an environment without the presence of oxygen. During the process, the polymer degrades into oils, gases and solids. The heating medium is superheated steam [15].

The industrial hydrolysis process is used for flexible PUR foams and utilises superheated steam heated to around 230–315 °C. [21,22] Superheated steam is generated by an electric boiler and superheater and provides both heat and water vapour to the reaction for the decomposition of polyurethane and urea bonds. Waste foam is fed directly into the reaction chamber and comes into direct contact with the superheated steam. No additional chemical additives are used here to improve the cost-effectiveness of the process. The resulting polyol will be in a dry state and free of contaminants. [21] This method therefore provides a relatively pure polyol without the need for further comprehensive purification.

Complete decomposition of polyurethane foam during hydrolysis can be achieved, depending on the structure of the specific material, in approximately three hours, which involves not only high energy consumption but also low production of recyclate per unit of time. The recyclate is used in the production of PUR foams with a ratio of 5% recycled polyol to 95% “virgin” polyol. [21]

Glycolysis

Glycolysis is a chemical reaction in which polyurethane reacts with diols at temperatures above 200 °C [20]. Currently, this method is the basic process for controlled recycling of polyurethane. Flexible polyurethane foams contain repeating urethane and urea groups. Heating in the presence of glycol and catalysts leads to a reaction that produces liquid products at room temperature [15]. The resulting polyols can be used as a replacement for up to 70% of virgin polyol [22].

The actual process takes place by heating ground PUR residues in a high-boiling glycol with a catalyst. Temperature is important during the reaction. If it is lower than 180 °C, the catalyst has lower activity. Conversely, if the temperature is higher than 220 °C [15], undesirable reactions occur. Due to the catalyst, it is important to avoid the formation of aromatic amines. After the reaction is complete, the material is cooled. It is then filtered. The entire process takes about 8 hours [15].

Alcoholysis

Alcoholysis is a chemical decomposition reaction similar to hydrolysis, in which alcohol plays a similar role to water in hydrolysis. Polyurethane foam reacts with alcohol under pressure and at a raised temperature. The alcoholysis agent is usually methanol or ethanol due to its low cost. Due to the low boiling point, it is necessary to conduct the process at raised pressure in the presence of a catalyst. This produces original polyols along with urethane products. The individual parts are then separated so that they can be further processed and reused. [15].

Alcoholysis products dissolved in excess alcohol can be used as heating liquids for direct combustion.[15,23]

2.4.3. Thermal-chemical processing

Pyrolysis

Pyrolysis, or thermal depolymerisation, generally takes place in an inert atmosphere with the aim of converting the polymer into a liquid and gaseous phase. The pyrolytic process can therefore be used to obtain a liquid product for further processing.

The initial pyrolysis reaction is the decomposition of urethane back into isocyanate and hydroxy compounds. Further increasing the temperature leads to the cleavage of urethane into alkyls and carbamic acid. The last controllable reaction is the decarboxylation of carbamic acid to form the corresponding amine and release CO_2. At temperatures above 300 °C, radical reactions begin to take place, resulting in a wide spectrum of products rich in alkyls and aldehydes.[24]

Gasification

Gasification is an exothermic reaction that produces heat. Other products of gasification are fly ash and gas (so-called synthesis gas). It contains a large amount of explosive gases such as H_2 and CO. In this process, waste polyurethane is heated to a temperature of 1,200 to 1,500 °C at a pressure of 2 to 8 MPa and combined with atmospheric oxygen. The cycle time is only a few seconds, resulting in 98–99%-nej conversion to gas and slag. Synthesis gas is further processed in the refining industry for the production of methanol, ammonia and oxo-alcohols. [20]

Hydrogenation

Hydrogenation can be understood as a compromise between gasification and pyrolysis. Through the action of heat and high-pressure hydrogen, we obtain gaseous and liquid products. Hydrogenation is one step ahead of pyrolysis, and the production of gases and oils through a combination of heat, pressure and hydrogen is purer. For this method to be feasible, two problems need to be solved – the purity of gases and oils obtained through pyrolysis and hydrogenation, and the associated costs of producing usable products. These can serve as fuel or as chemicals for further processing.[15]

Energy recovery

Polyurethanes are petroleum products, which means that they allow energy recovery. In some cases, they can be comparable to coal. Combustion can reduce the volume of solid waste and dependence on coal. It can also help preserve natural resources. [15] Further, adding PUR foam can increase the uniformity of temperature distribution during fluidised bed combustion and stabilise the combustion process.[25,26]

Energy recovery is often considered the only suitable method for recovering material for which material recovery is not economically viable. This approach currently applies, for example, to waste from polyurethane-laminated wood, foam rubber covered with artificial (or genuine) leather, fabrics, fibres or to composite materials. Material recycling is also very difficult for materials containing flame retardants. Combustion of polyurethane foams leads to a reduction in landfill volume by up to 99%. Combustion of polyurethane foams significantly reduces the landfilling of the material, i.e. by up to 99%, while simultaneously eliminating CFCs and other harmful foam blowing agents [8]. The presence of flame retardants complicates the combustion process, and the effect of these substances on the combustion process is currently receiving much attention [27].

2.5. Research into an effective technology for dry pressure moulding of recycled PUR foam

The development of an effective technology for the recovery of PUR foams is preceded by an extensive professional analysis of technological possibilities and recycling procedures and an assessment of the suitability of individual processing approaches, taking into account the estimated volumes, the state of waste PUR foam (especially soft) and the costs of transporting this waste to the processing site. The practice of recycling pure polyurethane is widespread and technologically manageable. A significant problem is the recycling of polyurethane foam that has an integral surface layer (furniture parts, car upholstery, etc.). This problem is not currently addressed. At the same time, for the conditions and annual quantities of waste PUR foam in Slovakia, it is necessary to effectively design and optimise a technology that would allow material recycling of both types of waste.

The conducted experimental research focuses on the mechanical recycling of waste PUR foams and the development of an efficient technology for their processing, and the production of moulded thermal insulation elements. The goal is to design a comprehensive, efficient and optimised technology, including equipment for the material recovery of waste PUR foams from old vehicles, which will allow:

- processing pure polyurethane foam,
- processing polyurethane foam with an integral surface layer,
- processing these two types of waste together,
- producing both flat and moulded recycled products,

- producing thermal insulation elements using a dry method,
- will be a cost-effective technology for local processing of smaller volumes of waste.

Experimental research has shown that the technology of dry pressure moulding of PUR foam is highly effective, meeting the requirements and complying with the given constraints, while also allowing material recycling for the reuse of PUR in various industrial fields. The technology is based on moulding recycled material (fractionally adjusted PUR foam) into the shape of the future shaped element. The mould is filled with the right amount of recyclate to achieve the required final density of the element. Subsequently, the material thus moulded is subjected to heating with a residence time. The simplicity of the technology requires very detailed research and optimisation of individual parameters (fractional composition of flakes, their density during moulding, pressing pressure, heating temperature, heating residence time and others) to achieve the required and guaranteed quality of the moulded elements (strength, density, thermal resistance, etc.).

The technology makes it possible to demonstrably recycle pure PUR foams as well as PUR foams with an integral surface layer. It enables the production of inherently flat insulating products, as well as shaped elements without the addition of binders or other chemical additives. Pressed products contain 100% recycled material. The products will see wide application due to their variability of shapes and guaranteed mechanical and thermal insulation properties.

The conducted experiments include research into the influence and optimisation of pressing temperature, pressing pressure and heating residence time on the qualitative parameters of the final product, defined primarily by density. The aim is to define specific technological parameters of the recycling process and their suitable combinations to allow successful and efficient production of moulded products, primarily as thermal insulation elements. However, the possibilities of applying recycled materials from waste PUR foam produced through this technology are wide (e.g. thermal and sound insulation in construction, impact acoustic insulation under parquet and laminate floors, underlays for carpets, acoustic filling in white goods, acoustic and thermal filling for door and window systems, acoustic filling in extraction and ventilation systems, thermal insulation of pipe systems, and others).

2.5.1. Used material

Within the experimental development of technology for the application of material recycling of waste PUR foams, especially from old vehicles, the aim is to define suitable (optimal) technological conditions for the production of shape-complex and precise elements.

In the proposed method of hot pressing (moulding) of PUR recyclate without the addition of adhesive, it is important to heat the shredded material to a temperature of 180 to 220°C, when this flexible PUR foam softens, the edges of the individual flakes are melted and the pressure can make the particles bond.

The decisive technological parameters investigated in the experiments were the effect of pressing temperature, pressing pressure and residence time. The other parameters were kept constant during the experiments: the shredded fraction (Fig 2.4) with the fractional composition shown in Fig. 2.5, the shape of the mould or the shape element.

Technological waste from PUR foam production was used for the experiments. The material was shredded in the form of flakes and had a fraction size of 2.0–15.0 mm (Fig. 2.4). To determine the fractional composition of the material, fractional analysis was performed on a Retsch Vibratory Sieve Shaker AS 200 digit and the material was divided into 5 fraction sizes. The fractional composition of the material is shown in
Fig. 2.5.

Fig. 2.4 PUR foam flakes

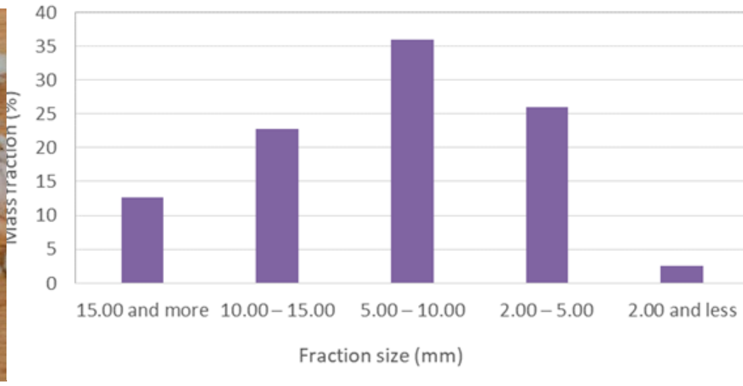

Fig. 2.5 Fractional composition of PUR foam flakes

2.5.2. Applied experimental research methods

For an exact evaluation of the qualitative indicators of moulded elements, samples in the shape of a cuboid with a base area of 50x100 mm were created using the dry pressure moulding technology, with their height depending on the setting of individual variable parameters of the experiment. For the experiments, a mould (Fig. 2.6) was made to allow the simultaneous production of 4 samples. The samples were produced by filling a preheated mould (Fig. 2.7) with 25 grams of PUR flakes, closing it and loading it with the chosen pressing pressure (Fig. 2.8). The filled mould was heated in a muffle furnace at a temperature and for a heating period according to the experiment plan. After the mould is emptied (Fig. 2.9), the whole procedure is repeated under precisely defined experimental conditions.

Fig. 2.6 Mould and weights for the production of experimental samples

Fig. 2.7 Filling the mould with material

Fig. 2.8 Loading samples with different pressing pressure

Fig. 2.9 Removing finished samples from the mould

The aim of the experiments is to define the optimal ranges of technological parameters of dry moulding under pressure and to determine the marginal values of the parameters' intervals in their individual combinations. The pressing temperature interval has critical limits based on PUR's state transition temperatures. Therefore, the following are the variable parameters of the process:

- Pressing pressure (2.0 kPa, 4.0 kPa, 6.0 kPa, 8.0 kPa),
- Heating temperature (200 °C, 225 °C, 250 °C),
- Heating period (10 min., 15 min., 20 min., 25 min., 30 min.).

Optimisation of the examined parameters is evaluated in terms of the qualitative parameters of the samples: sample density, shape accuracy, stability, compressive strength and thermal resistance. The experiments include 60 different combinations of technological parameters. For the sake of a sound statistical evaluation of the experiment, 10 samples of moulded shaped elements were produced for each combination of technological parameters (a total of 600 samples).

2.5.3. Results of experimental research on element density

The density of recycled PUR foam products produced by the pressure moulding technology depends on the pressing pressure, heating temperature and heating period. The given intervals of the variable technological parameters were chosen on the basis of an analysis of the properties of the moulded material and an analysis of the results of published scientific papers. Representative samples from each experimental setup are shown in Fig. 2.10. The results of the experiments show that with the defined intervals of the variable technological parameters, the magnitude of the loading pressure has the greatest effect on the increase in the density of the samples (Fig. 2.11). The absolute values resulting from the experiments with the same intervals of the variables (Tab. 2.1) show that it is the heating temperature that has the least effect on the density of the samples. Test samples achieving different quality were produced for all combinations of the variable technological parameters.

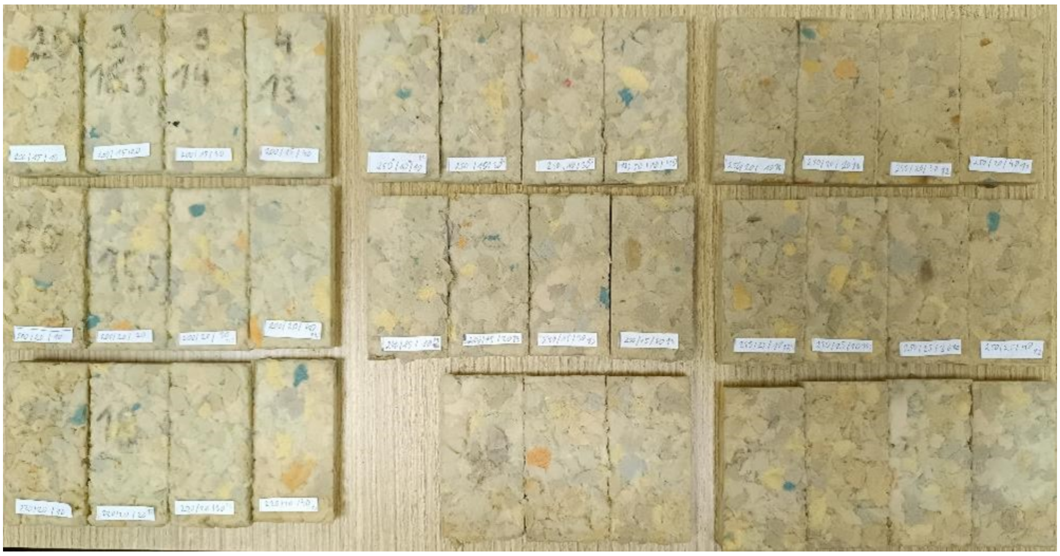

Fig. 2.10 Test samples produced using different combinations of technological parameters

Fig. 2.11 Dependence of sample height (and thus density) on the magnitude of the loading pressure

The results in Tab. 2.1 show that the change in density in relation to the heating period is nearly linear at each temperature. The experiments have shown that in the examined temperature range, the heating period has a significant effect on the cohesiveness and dimensional stability of the sample. As the moulded material is a thermal insulator, the required heating period allows its volumetric overheating and the melting of the contact points between the individual flakes. The necessary heating period depends on the heating temperature. As the temperature increases, the minimum period required for a cohesive and stable sample to form decreases.

The experiments also showed the time limits for the length of heating of the material. At temperatures of 200 °C and 225 °C, it is not possible to produce a cohesive and dimensionally stable sample with an endurance time of less than 15 minutes. The material does not overheat sufficiently and does not melt. The samples were not sufficiently cohesive and showed significant dimensional instability after removal from the mould. On the other hand, moulding at 250 °C has an upper endurance time limit of 25 minutes. With prolonged heating, degradation of the moulded material and caking occurred. Samples produced within the above limits showed good dimensional precision and stability, differing in their density.

Tab. 2.1
Average density values of samples made using different combinations of technological parameters

Heating temperature 200 °C					
Heating time (min)	10	15	20	25	30
Pressure (kPa)	Density (kg.m^{-3})				
2,00	Incoherent, unstable in shape	102,10	104,30	107,11	108,49
4,00		131,00	138,93	142,85	147,82
6,00		148,43	157,85	160,65	163,09
8,00		158,31	166,40	171,24	173,98
Heating temperature 225 °C					
Heating time (min)	10	15	20	25	30
Pressure (kPa)	Density (kg.m^{-3})				
2,00	Incoherent, unstable in shape	99,17	116,20	125,33	128,67
4,00		133,55	140,14	147,05	148,15
6,00		148,60	159,78	163,25	166,88
8,00		161,84	172,60	173,18	174,87
Heating temperature 250 °C					
Heating time (min)	10	15	20	25	30
Pressure (kPa)	Density (kg.m^{-3})				
2,00	110,4865	118,00	128,90	129,38	Material degradation, sintering
4,00	136,2667	141,33	143,77	146,86	
6,00	151,4286	158,46	160,67	163,68	
8,00	165,60	164,00	174,36	175,83	

An interesting result of the research is the effect of the individual technological parameters on the percentage increase in density. Fig. 2.12 shows the results of PUR foam moulding at the lowest examined pressing pressure, i.e. 2 kPa. The results show a significant effect of the heating period as well as heating temperature.

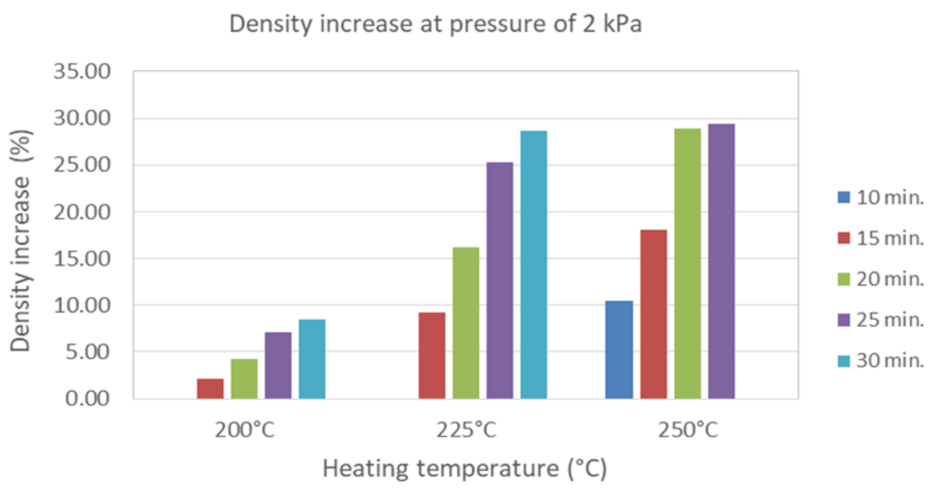

Fig. 2.12 Effect on density change depending on temperature and heating period at 2 kPa pressing pressure

On the other hand, the results of moulding at 8 kPa pressing pressure shown in Fig. 2.13 show that a change in heating temperature has a minimal effect on the change in density of the samples. At this level of pressing pressure, only the heating period has a significant effect on the density change. It is clear from these results that a detailed energy analysis will be necessary for practical applications, as both temperature and heating periods significantly affect the cost-effectiveness and competitiveness of the overall technology.

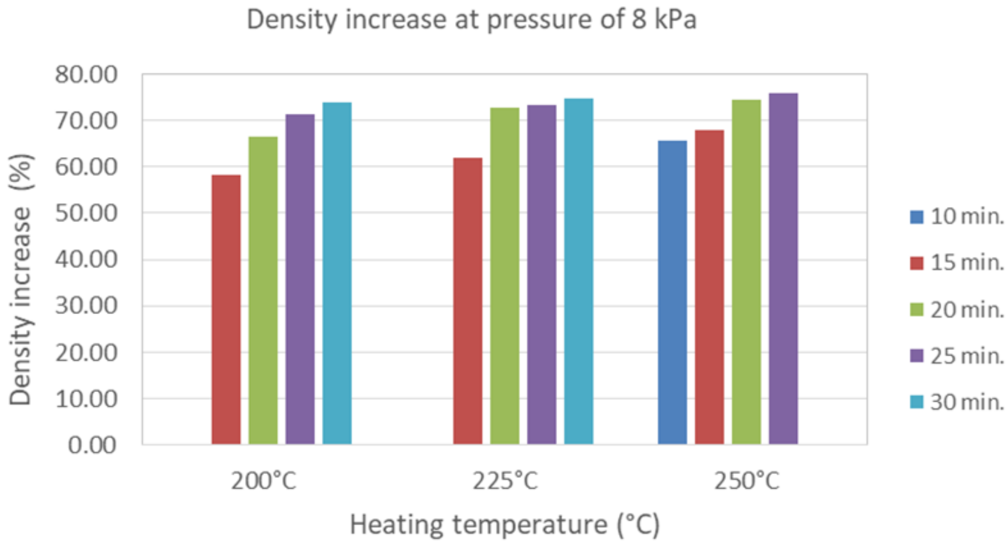

Fig. 2.13 Effect on density change depending on temperature and heating period at 8 kPa pressing pressure

The resulting density of the samples represents a fundamental physical parameter influenced by the technological parameters in a non-linear way. Considerable attention should be paid to the study of the results of density increase caused by the variation of the individual parameters. A more comprehensive picture of the increase in density due to an increase in pressing pressure as well as extended heating periods at 250 °C is shown in Fig. 2.14.

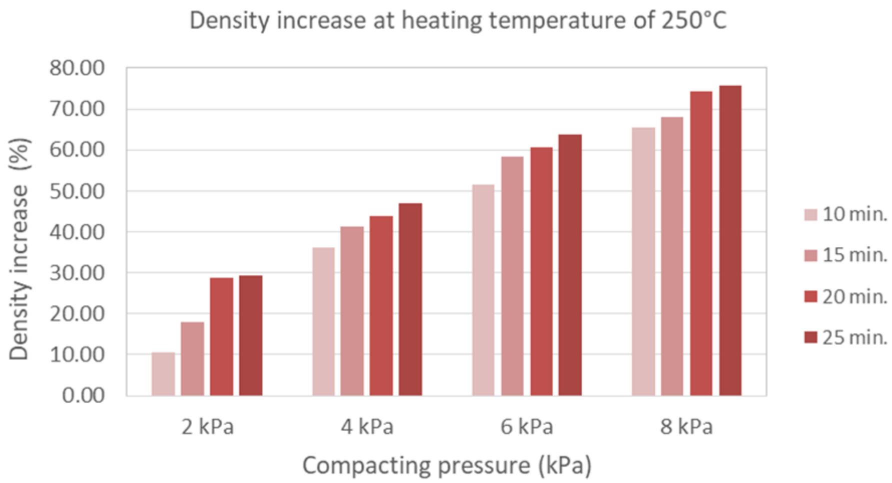

Fig. 2.14 Effect on density change depending on pressing pressure and heating periods at a heating temperature of 250 °C

Fig. 2.15, 2.16 and 2.17 show the density change depending on the change in moulding pressure and material heating period at different heating temperatures. The results show that the change in density in relation to the heating period is nearly linear at each temperature.

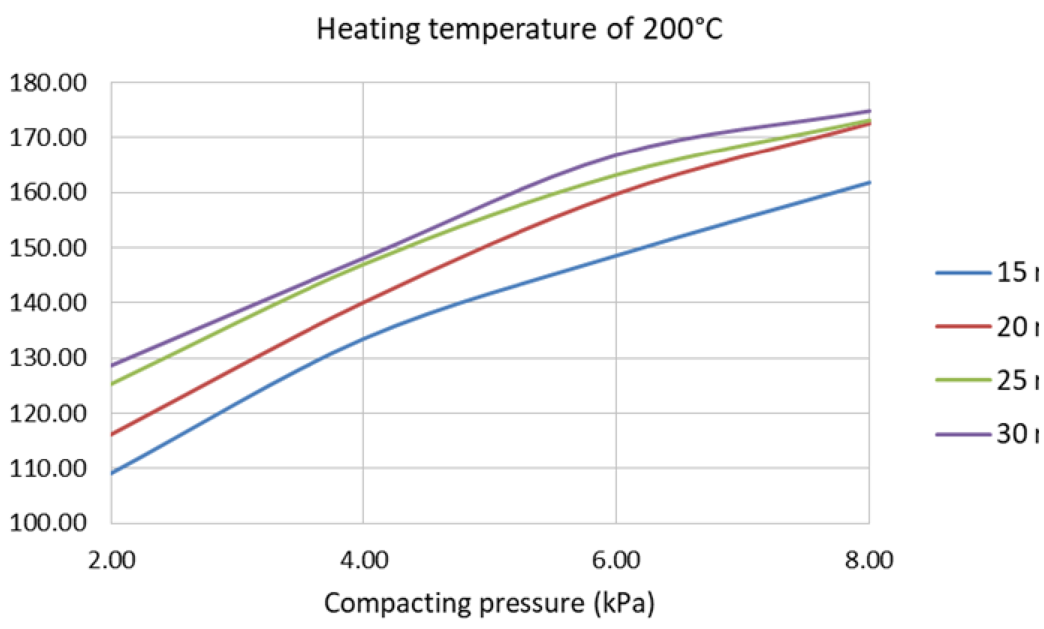

Fig. 2.15 Density change depending on moulding pressure and heating periods at a heating temperature of 200 °C

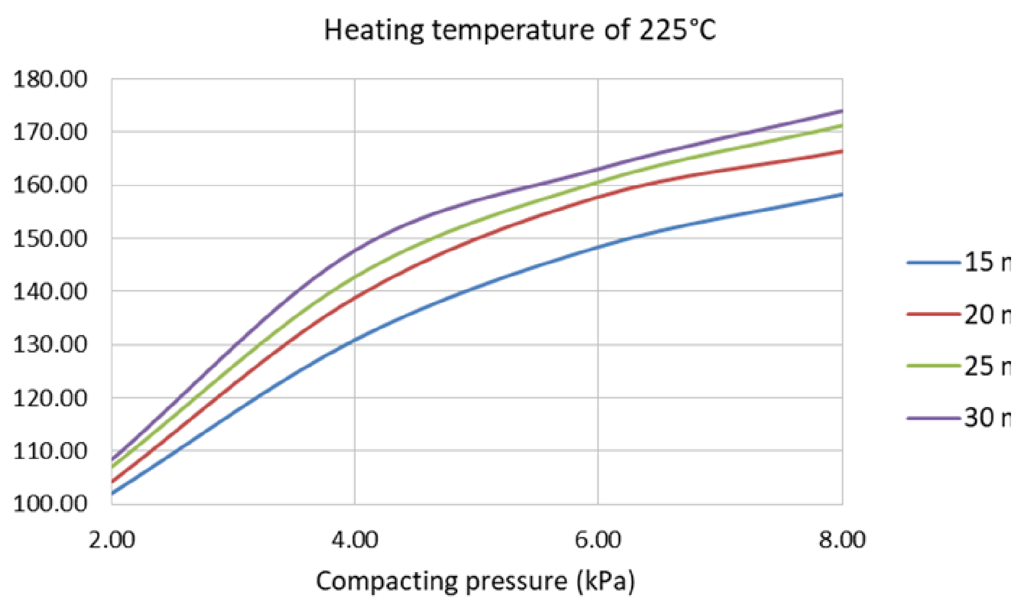

Fig. 2.16 Density change depending on moulding pressure and heating periods at a heating temperature of 225 °C

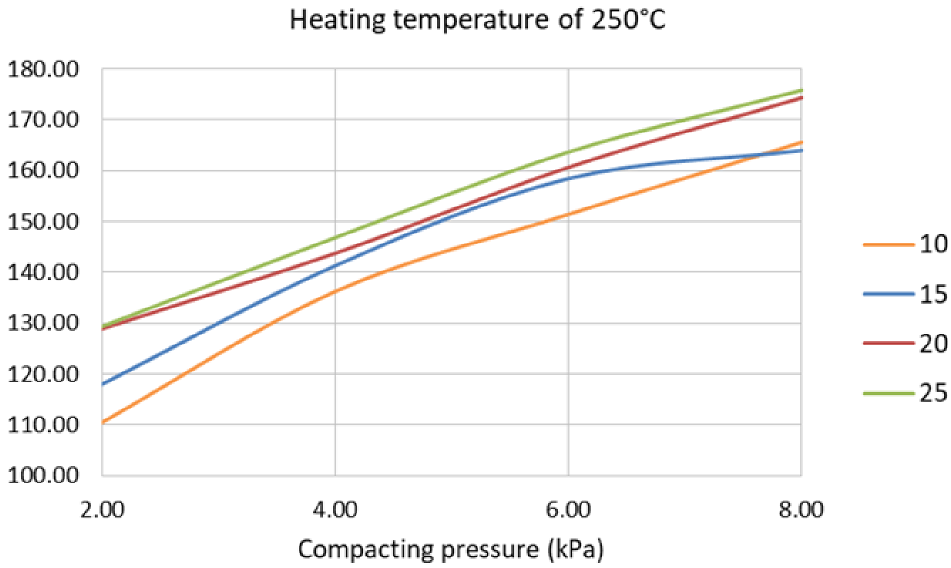

Fig. 2.17 Density change depending on moulding pressure and heating periods at a heating temperature of 250 °C

The experimental research has shown that in the examined temperature range, the heating period has a significant effect on the cohesiveness and dimensional stability of the sample. As the moulded material is a thermal insulator, the required heating period allows its volumetric overheating and the melting of the contact points between the individual flakes. The necessary heating period depends on the heating temperature. As the temperature increases, the minimum period required for a cohesive and stable sample to form decreases.

For recycled element production, processors need to consider whether it is more cost-effective to use a higher heating temperature with a shorter heating period to achieve the required density of the elements, or vice versa. This factor is shown in Fig. 2.18, which compares the density change at the limit values of heating temperature and heating period for different moulding pressures. It is clear from the diagram that to achieve the required density of the elements, it is more cost-effective to use a higher moulding pressure and, at the same time, to ensure dimensional precision and stability, a higher pressing temperature and a shorter residence time.

What is also interesting is the comparison of the density change of the examined samples moulded at constant pressure depending on the heating period at different heating temperatures. It is clear from Fig. 2.19 that as the heating temperature increases, the density of the samples also increases at the same heating period. However, it can also be stated that the most significant changes in density depending on the heating period occur at a temperature of 200 °C.

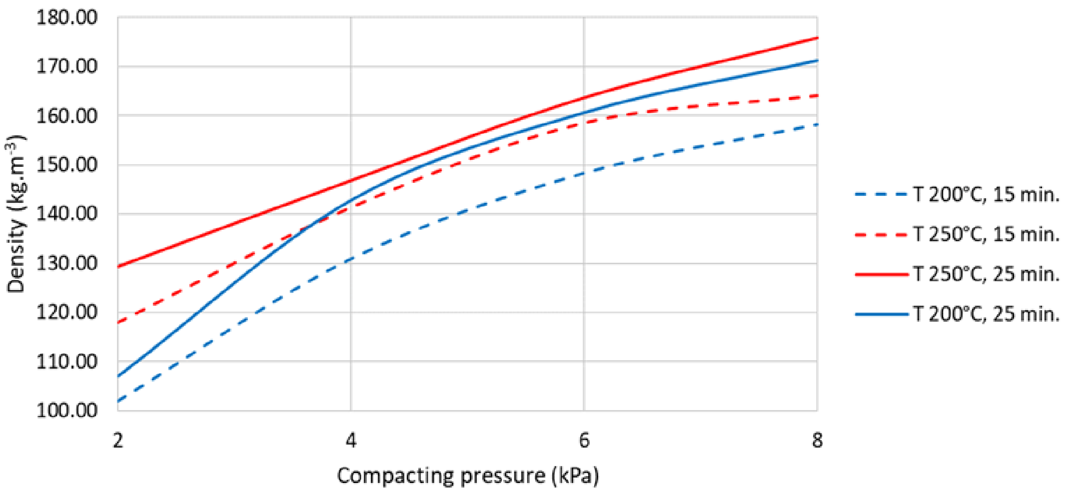

Fig. 2.18 Comparison of the density change at the limit values of heating temperature and heating period for different moulding pressures

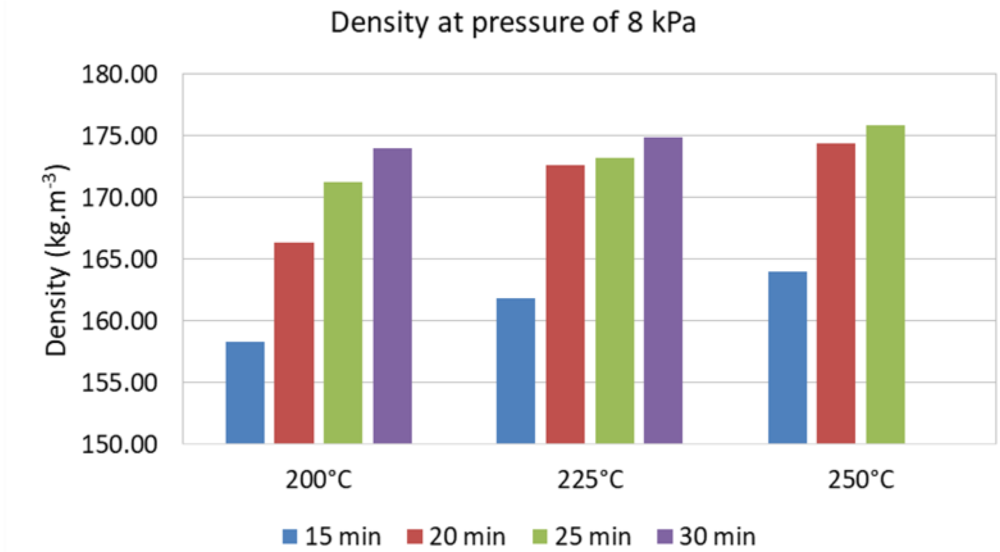

Fig. 2.19 Density change of the examined samples moulded at constant pressure depending on the heating period at different heating temperatures.

2.5.4. Research on the resistance of elements under cyclic compressive loading

A set of extensive measurements of the compressive resistance of PUR foam samples according to the ISO 3386-1 standard demonstrated the mechanical stability of the elements even under cyclic loading. This test is important for verifying the stability of the connection and the strength of the contacts of individual PUR recyclate flakes even under mechanical cyclic loading. The method consists of placing the sample between two flat surfaces – a static and a moving plate (Fig. 2.20). Due to the action of the moving plate, the sample is pressed to the appropriate thickness value. During the test, the load on the sample is measured in 4 cycles. The sample is pressed by 70% of its original thickness for the first three cycles, and by 40% for the fourth cycle. At this point, the value of the pressing force is recorded and the value of the compressive stress can be defined from the corresponding relationships. A graph of the moulded PUR foam sample test at a temperature of 225 °C, a pressing pressure of 2 kPa and a heating time of 20 minutes is shown in Fig. 2.21.

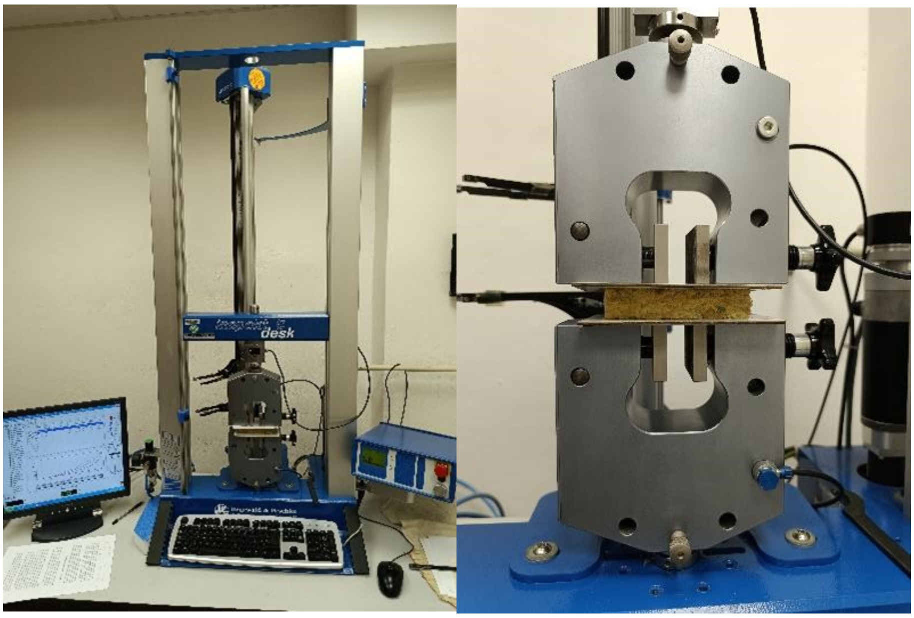

Fig. 2.20 Measuring setup for the compression strength test (according to ISO 3386-1)

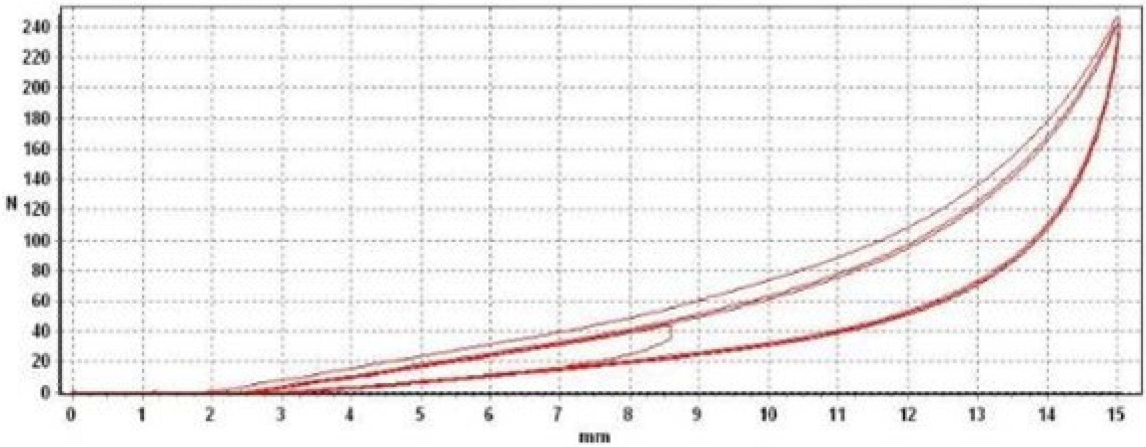

Fig. 2.21 Graph showing the result of the cyclic compression resistance test of the sample (according to ISO 3386-1)

The tests of mechanical properties of elements made of recycled PUR foam according to ISO 3386-1 (tensile strength, flexural strength, cyclic compressive strength) will be used to define optimal technological requirements for the elements under development depending on their required functional properties, and for the subsequent structural design of experimental equipment for the production of such specific moulded elements.

2.6. Development of moulded thermal insulation elements from recycled PUR foam

Polyurethane foam has excellent thermal insulation properties. These can be quantified by means of the thermal conductivity coefficient. The lower its value, the better the material works as thermal insulation. The undertaken development of an efficient technology for the production of moulded elements is based on optimising technological parameters in relation to the resulting density and strength. However, in the development of thermal insulation elements, the thermal conductivity coefficient is a fundamental quality parameter. The experiments showed that for PUR foam recycling, its value can be controlled precisely by changing the density of the elements. Therefore, it is necessary to take into account the results of thermal conductivity coefficient measurements when optimising the technology being developed.

2.6.1. Experimental research on the thermal conductivity coefficient

The ISOMET 2114 instrument was used to measure the thermal conductivity coefficient. It uses the principle of direct measurement of heat transfer properties of a wide range of isotropic materials. A needle probe for soft materials was used for the measurement. The instrument applies a dynamic measurement method, which allows a significant reduction in measurement time compared to steady-state measurement methods, with sufficient accuracy. During the measurement, the needle probe was inserted into the measured sample. To ensure maximum measurement accuracy, the sample was placed in a thermally insulated environment. The process of measuring the thermal conductivity coefficient with the ISOMET 2114 instrument is shown in Fig. 2.22. For a correct statistical evaluation of the experiment, the coefficient was measured on every produced sample.

Fig. 2.22 Measurement of the thermal conductivity coefficient with the ISOMET 2114 instrument

The results of the experimental measurement of the effect of density on the thermal conductivity coefficient are shown in Fig. 2.23. The graph shows a linear change in the thermal conductivity coefficient value with respect to the change in sample density. In the measured density interval with an increase from 100 kg.m-3 to 175 kg.m-3, the thermal conductivity coefficient increases from a value of 0.42 to a value of 0.47. With increasing density, the porosity of the material is reduced and thermal conductivity increases. Therefore, when thermal insulation elements are produced, it is necessary to optimise the values of variable technological parameters to achieve minimum element density, but with sufficient strength. The experiments proved a linear dependence between density and the thermal conductivity coefficient, allowing the production process to be set so as to achieve guaranteed thermal insulation properties of these recycled elements.

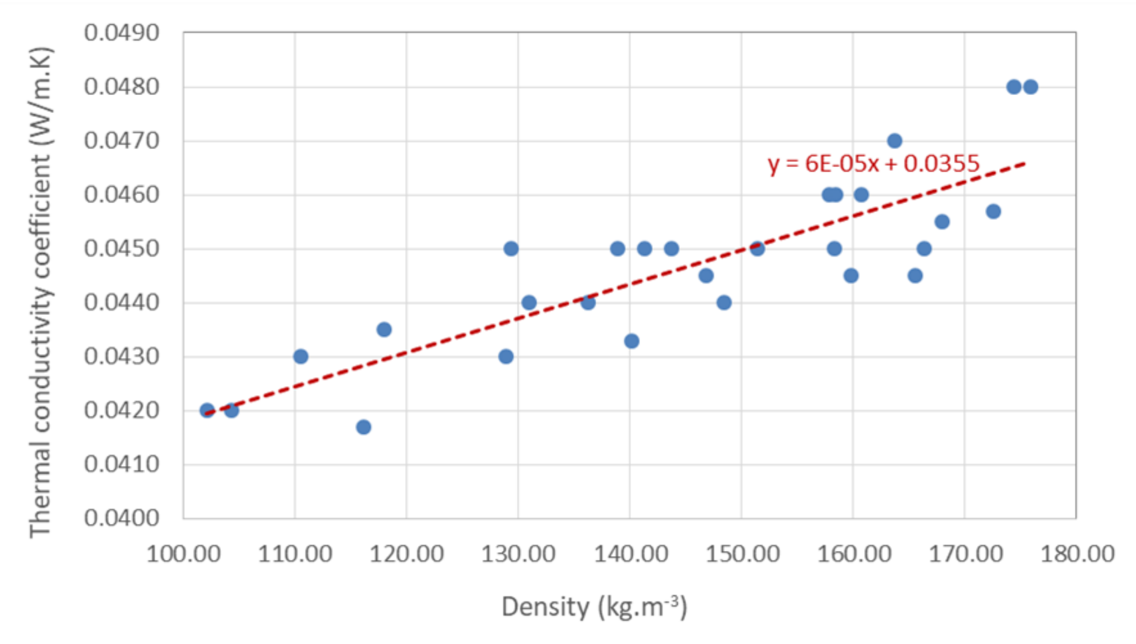

Fig. 2.23 Effect of density change of elements in the thermal conductivity coefficient of thermal insulation

2.6.2. Development of moulded thermal insulation elements

Based on the achieved laboratory results of the experimental research on the technology of dry pressure and temperature moulding of recycled PUR foam, pilot production tests of new moulded products with excellent thermal insulation properties suitable for high-temperature pipes and fittings were carried out. Fig. 2.24 shows the given moulded part of pipe thermal insulation (without film / with aluminum film) and Fig. 2.25 shows a the given moulded thermal insulation element for a valve. The developed technology does not limit the production of moulded elements in any way. On the contrary, it allows creating any shapes and dimensions. More complex moulded elements can be produced cyclically. Simpler ones (hollow cylindrical elements, plates, profile elements) can be produced continuously. Both approaches are currently being tested.

Fig. 2.24 Moulded part of pipe thermal insulation (without film / with aluminum film)

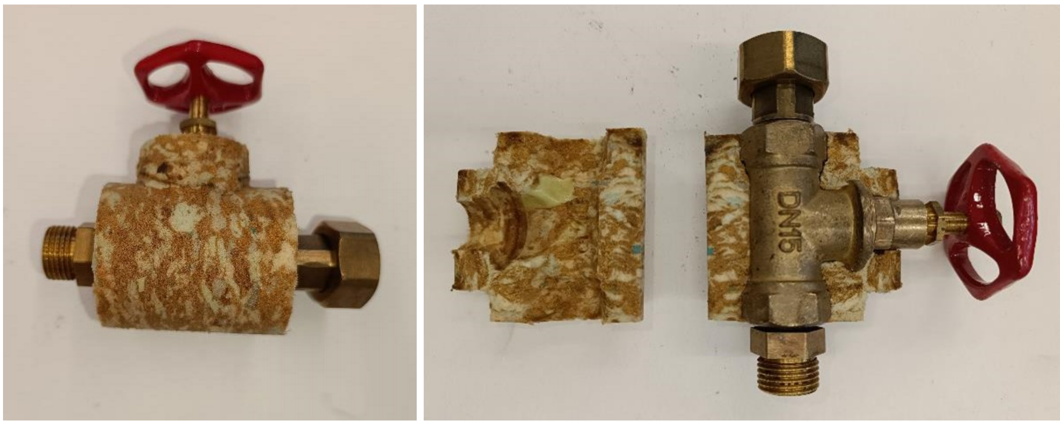

Fig. 2.25 Moulded thermal insulation element for a valve

The experimental production of moulded thermal insulation elements took place under laboratory conditions while maintaining optimal technological conditions based on the conducted experimental research. The volume of the mould was filled with PUR foam recyclate with suitable fractional composition and appropriate weight to ensure optimal mechanical and thermal insulation properties of the element. Laboratory production was carried out by cyclic filling, i.e. the elements were moulded in cycles. The experimental moulds used are shown in Fig. 2.26 and Fig. 2.27.

Fig. 2.26 Pipe insulation element

Fig. 2.27 Moulded fitting insulation element

2.6.3. Development of technology for continuous production of pipe insulation

The development of new products from recycled PUR foam through the developed pressure and temperature moulding technology also includes the development of new production infrastructure. A technological process for the continuous production of pipe insulation is being developed, based on the achieved results of the experimental research. An equipment design principle (Fig. 2.28) was proposed for this process which will allow the continuous production of 'endless' pipe insulation. The design is based on a mechanical principle that takes into account all technological parameters, allowing their control and optimisation. The laboratory equipment will be tested, and after subsequent optimisation, a production technology with a modular design will be developed which will allow changing the basic dimensions of the thermal insulation (pipe diameter, insulation thickness).

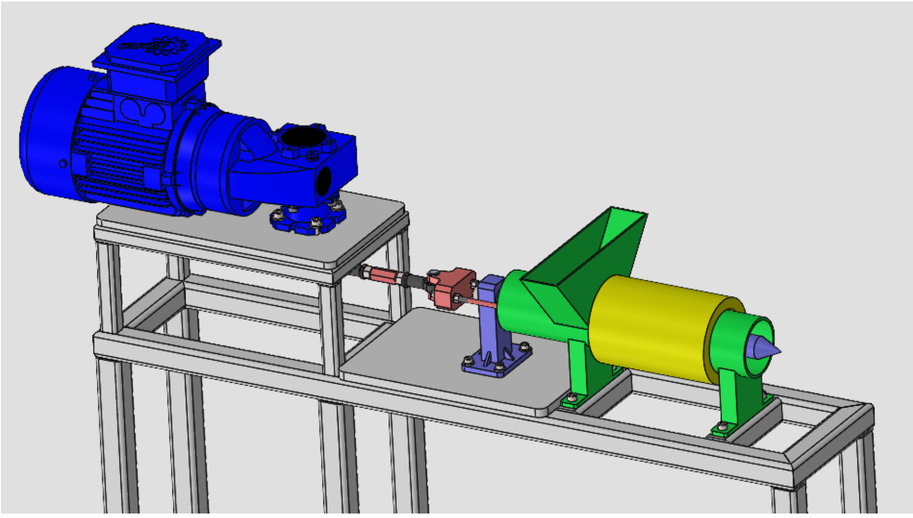

Fig. 2.28 Laboratory equipment for continuous production of pipe insulation

2.6.4. Development of coating for moulded thermal insulation elements

As it has already been noted, elements made from waste PUR foam are characterised by excellent thermal insulation properties. Due to the high critical softening temperature of PUR foam, these insulation properties are maintained up to temperatures exceeding 200 °C. Moulded elements have high application potential, especially in thermal energy, as insulation for hot water and steam pipes, valves and other fittings. However, elements are only guaranteed to have these thermal insulation properties in a dry state. To prevent water absorption, various surfaces of insulation elements were developed during the research, as shown in Fig. 2.29:

- Without coating
- Plastic film (PE, LDPE, PVC, etc.)
- Aluminum film

Surfaces without coating are intended for dry environments. Plastic coatings are developed for humid environments or for potential contact with liquid. Each type of plastic coating is intended for a different type of environment ambient temperature. The surface with aluminum film is developed to improve the thermal insulation properties of these elements. Testing of the properties of these coatings is currently underway, as well as the development of a continuous technology for applying these coatings during the element production process.

Fig. 2.29 Various surfaces of insulation elements

2.7. Conclusions on the achieved research results and further course of the research

The work is dedicated to the development of an efficient technology for the material recovery of waste polyurethane foam. The technology enables the production of new moulded products from 100% recycled PUR foam (Fig. 2.30). The results of experimental research demonstrated the high efficiency of the developed technology for moulding PUR foam under pressure with simultaneous heating. The effect of fundamental technological parameters (heating temperature, pressing pressure and heating time) on the resulting density and strength of the moulded elements was studied. Measurements objectively proved that the level of pressing pressure has the greatest effect on the increase in sample density. The heating period has a limiting effect on the formation of cohesive bonds and thus on the strength of the elements, while also affecting material degradation individually depending on the heating temperature used. The research results showed that to achieve the required density of the elements, it is more cost-effective to use a higher moulding pressure and, to ensure shape accuracy and stability of the elements, a higher pressing temperature and a shorter residence time. These results are of fundamental practical importance when setting the optimal combination of parameters for the recycling technological process and offer a basis for the cost-effective optimisation of the process.

The development of moulded thermal insulation elements is based on examining the effect of their density on the thermal conductivity coefficient. The research also revealed the possibility of optimising production technological parameters in relation to the thermal insulation properties of the products. The work also presents the results of the development of moulded thermal insulation parts as new products from recycled PUR foam. The added value of the developed parts lies in the application of specific coatings with the aim of ensuring or increasing the performance properties of these parts. The presented research demonstrated that the developed technology enables the successful and efficient production of moulded (not only thermal insulation) parts from 100% recycled PUR foam. The excellent acoustic, damping and thermal insulation properties of this material applied to moulded elements make it suitable for a wide spectrum of industrial applications, whether as acoustic or thermal insulation for piping systems, fittings and HVAC.

Fig. 2.30 New moulded products from 100% recycled PUR foam

2.8. Environmental impact of recovery

Polyurethane (PUR) foam is one of the important polymeric materials used in many industry sectors, especially in construction, the automotive industry and furniture and thermal insulation manufacturing. Their popularity stems from favourable properties, such as low density, good insulation capabilities, mechanical resistance and a long life cycle. On the other hand, the growing production of polyurethane materials also leads to an increasing amount of waste, which represents a significant environmental burden, especially in the case of its landfilling.

According to available data, the annual consumption of polyurethanes in Europe is approximately 3.7 to 3.8 million tonnes, with approximately 70% of this production consisting of various types of polyurethane foams. This means that more than 2.5 million tonnes of PUR foam is produced annually in Europe [28]. After the end of the product life cycle, a significant amount of waste materials is generated. It is estimated that approximately 25–30% of polyurethane foam production becomes waste during the product life cycle, which represents more than 700 thousand tonnes annually in the European Union [28].

As for waste management, a significant portion of PUR foams is still disposed of by landfilling. According to analyses of the European market, approximately 25–30% of waste polyurethane foams are deposited in landfills, while the remaining part undergoes energy recovery or recycling [29]. In absolute values, this means that approximately 180 to 200 thousand tonnes of polyurethane foams end up in landfills annually in Europe alone. This method of waste management is the least suitable solution in terms of environmental protection because PUR foams have very low biodegradability and can persist in landfill environments for decades to centuries [30].

A significant problem with landfilling PUR foams is also their low bulk density. Although the weight proportion of the waste may not be extremely high, its volume is significant. Polyurethane foams thus take up a large amount of landfill space and contribute to the faster filling of landfills. In addition, they may contain various additives used in production, such as flame retardants, catalysts or stabilisers. In landfill conditions, their gradual release and potential contamination of soil or groundwater may occur [30]. Another environmental factor is that the production of polyurethanes is mainly based on petrochemical raw materials, especially polyols and isocyanates. Their production is energy-intensive and associated with greenhouse gas emissions. Landfilling waste PUR foams thus means a loss of material potential that could be reused within the material cycle. Therefore, with circular economy principles mind, it is inefficient to deposit this material in landfills without further use.

Material recovery of PUR foams represents an environmentally more favourable alternative. Recycling allows reducing primary raw material consumption, while limiting the amount of waste deposited in landfills. Mechanical or chemical recycling processes can transform waste polyurethane foams into secondary raw materials, which can be used, for example, in the production of new insulation materials, composite products or construction components [31].

One environmental benefit of recycling PUR foams is also the reduction of the carbon footprint of the production process. Reuse of the material means a reduced need for the production of new petrochemical raw materials, thereby reducing energy consumption and CO_2 emissions associated with the production of primary polymers. Recycling also contributes to more efficient resource use and supports the implementation of circular economy principles for polymer materials.

Waste PUR foams placed in landfills take up a huge volume. Without material and energy recovery, waste PUR foams from old vehicles alone would represent huge volumes of waste in landfills. The average density of PUR foams used in cars is about 30 kg.m-3 – with a weight of 1,135 tonnes in 2022, the volume of this landfilled waste would take up 37,833 m^3 in 2022 alone. For the 2004–2014 period, this waste from old vehicles alone, without further use, would amount to around 162 thousand cubic metres.

The proposed technology of material recovery of PUR foam from old vehicles does not pose a risk to the environment, as there are no chemical reactions or pollution of the environment by solid dusts, liquids or gases.

For these reasons, the material recovery of waste PUR foams represents an important tool for reducing the environmental impact associated with their disposal. In addition to reducing the volume of waste in landfills, it allows more efficient use of material resources and contributes to the more sustainable operation of industrial production processes. With the growing production of polyurethane materials, the development of recycling technologies and PUR waste recovery systems will therefore play an increasingly important role in modern waste management.

In conclusion, the proposed and verified technology for material recycling of waste PUR foam forming under pressure is suitable for the production of shaped precision elements with a wide application not only in the automotive industry under appropriate technological conditions. The excellent acoustic, damping and thermal insulation properties of this material implemented in the form of shaped elements predestine it for a wide range of applications in practice. This method of recovering waste polyurethane foam materials, not only from old vehicles, has a very positive economic and environmental effect.

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3. Implementation and Research on Noise Absorbers as a Potential for Reducing Traffic Noise

3.1. Introduction

Despite existing European and national legislation targeting noise control, public interest and concern over noise remains high. EU Directive 70/157/EEC on the determination and management of environmental noise aims to create a quieter and more pleasant environment for Europe's citizens within the framework of “Sustainable Development in Europe”. The harmful effects of environmental noise are diverse and can manifest themselves in different ways. We can talk about health effects, quality of life effects, but also financial effects on the health of those affected affected [1].

A significant part of the European population is exposed to levels of traffic noise that are harmful to health. The latest estimates show that approximately 112 million people – more than 20% of Europe’s population – are exposed to long-term noise from road, rail and air traffic that exceeds the threshold values set in the END (European Noise Directive). However, the latest scientific evidence suggests that health effects occur even at noise levels lower than the threshold values. This means that, in fact, many more people are exposed to traffic noise that poses a risk to health. Taking these lower recommended values into account, it is estimated that approximately 150 million people – more than 30% of the population – are exposed to long-term unhealthy levels of traffic noise [4].

The problem of noise pollution is widespread in all European countries. Road traffic is identified as the main source of environmental noise, especially in densely populated urban areas. According to the END threshold values, road traffic is responsible for exposing approximately 92 million people to harmful day–evening–night noise levels and 58 million people during the night. For comparison, railway noise affects 18 million people during the day, evening and night, and 13 million at night, whereas noise from air traffic affects approximately 2.6 million people (day–evening–night) and less than 1 million during the night [4].

In 2025, the research team focused on **verifying the effectiveness of an innovative noise absorber in a selected motorway section.**

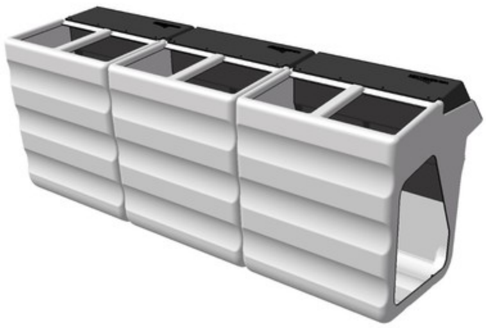
The work and research were divided into three consecutive stages, namely:

1. **Securing** and **installing** an innovative noise absorber on a selected noise barrier.
2. **Measuring noise levels** in the selected motorway section before and after the installation of the absorber.
3. **Evaluation of results** and formulation of conclusions from the testing.

3.2. Securing and installing an innovative noise absorber on a selected noise barrier

The innovative noise absorber is installed on noise screens and noise barriers as an additional product to increase noise damping. The noise absorber is installed on the top part of the noise screen, only increasing the height of the screen by 20 cm. The noise absorber is made of pure PP and HD-PE plastic. Its advantages include low weight, long life cycle and resistance to graffiti, which ensure easy installation and maintenance. The design of the individual types of materials in each module allows easy recycling of the material. There are no metals inside, which means that thre is no need for grounding cables [2,3,5].

The design and material of the noise absorber (low weight) are adapted for minimal impact on the foundations of existing and new noise barriers (Fig. 3.1).



Source: Authors.

Fig. 3.1 Noise absorber

The innovative noise absorber works on the basis of acoustic interference. It main application is traffic noise damping, as it is characterised by a specific frequency range. The noise absorber reduces noise spreading through and over noise barriers and acts as if the walls were 1–2 m higher. This effect means that noise barriers could be built lower or the damping of noise barriers could be increased without the wall being high and appearing intrusive (Fig. 3.2).

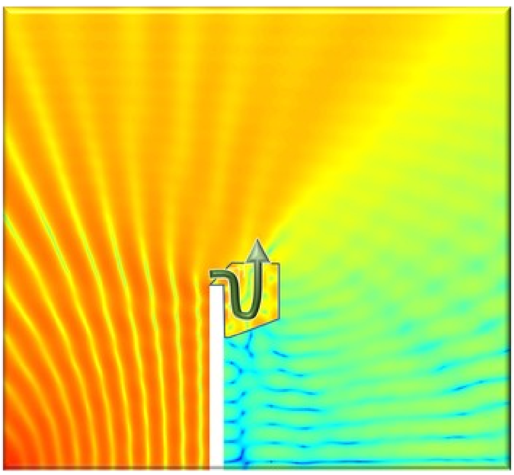


Fig. 3.2 Effect of the noise absorber on a noise barrier [6]

3.2.1. Innovative noise absorber – Waverbreaker

It is an innovative traffic noise absorber that uses destructive interference to reduce noise spreading through a noise barrier. This design solution passively generates "counter-noise" or "anti-noise", which reduces noise on the receiver's side. It is a lightweight product with minimal impact when installed on existing noise barriers.

The absorber consists of an acoustic insert and an acoustic box, which together radiate sound waves that meet the direct sound that passes over the absorber and the noise barrier. This creates acoustic interference and reduces noise in the frequencies that are most disturbing, annoying, etc. It is a completely passive absorber and does not need any electrical power to operate. It can be applied to both existing noise barriers and newly constructed noise barriers.

It is a traffic noise absorber that uses destructive interference to reduce noise propagating through a noise barrier.

The noise absorber consists of modules with a width of 500 mm. The acoustic insert is pre-installed in the acoustic box for quick on-site installation. Fig. 3.3 shows the individual types of modules.

Right module Middle module Left module

Fig. 3.3 Overview of 3 types of modules

For the entire installation, it was necessary to plan and determine in advance how many modules (right, left and right) would be part of the delivery, based on the linear design of the noise barrier and any necessary adjustments. A view of the system of seven consecutive modules is shown in Fig. 3.4.

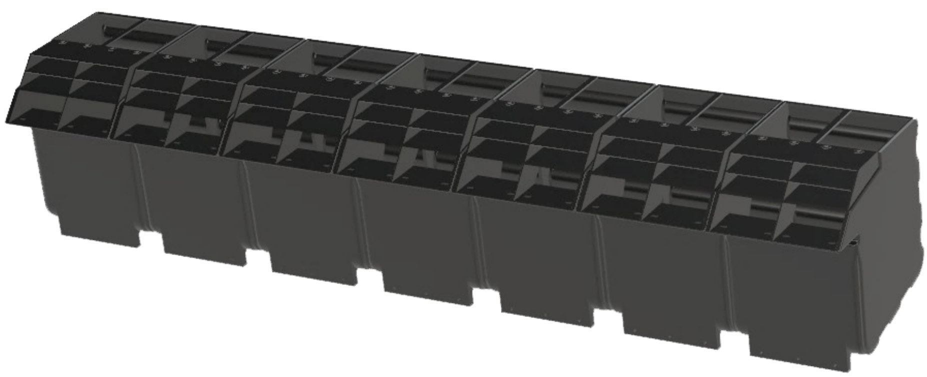
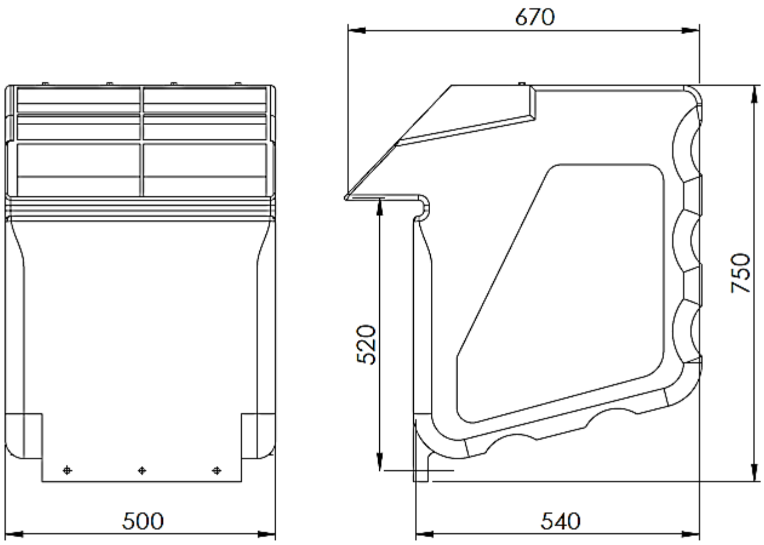


Fig. 3.4 Overview of 3 types of modules

The innovative noise absorber consists of two modules made of high-density polyethylene (PE) and polypropylene (PP) with 100% recycled content [1]. Because similar types of plastics are used instead of a combination of different materials, such as plastic and metal, recycling is simpler and more efficient in this case, as it is not necessary to separate the materials first. This product meets today's environmental requirements. The standard colour of the product is dark grey-black, and the life cycle of the material in its original colour is estimated to be 50 years. The dimensions of the noise absorber are shown in the following Fig. 3.5. The weight is approximately 8 kg.



Source: Authors.

Fig. 3.5 Dimensions of the noise barrier

3.2.2. Supply of the innovative noise barrier

The innovative noise barriers were delivered to the SSÚD Beharovce site on 13/06/2025. It was transported by lorry from Sweden, and upon arrival the delivery was organised so that it would be possible to seamlessly continue with the next installation steps. After unloading, the absorbers were stored in a container, which ensured protection of the components against weather conditions and mechanical damage, as well as well-arranged storage of the material before installation on the noise barrier.

The delivery included approximately 200 absorbers. An initial inspection of the delivered quantity and condition was then carried out (visual inspection of the packaging and modules), as well as logistics preparation for moving the absorbers to the installation site. The process of assembling and placing the container is shown in Fig. 3.6, and a view of the container contents with the stored noise absorbers is shown in Fig. 3.7.

Such prepared storage allowed continuous removal of modules according to the installation schedule and minimised downtime during the installation.

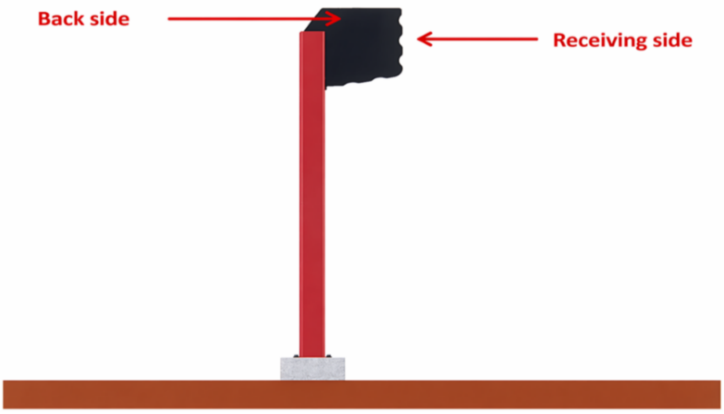
Fig. 3.6 Assemby of the container at the SSÚD Beharovce site

Fig. 3.7 Contents of the container with noise absorbers

3.2.3. Installation of the innovative noise absorber

The researchers working on the research task prepared a detailed procedure for the assembly and disassembly of the innovative noise absorber on the selected noise barrier, which is included and documented in in the work [11].

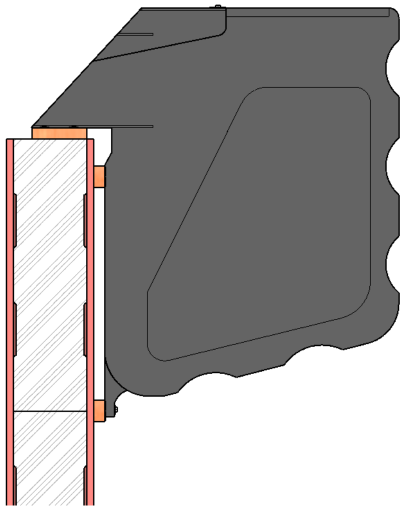
The method of mounting the individual modules is schematically presented in Fig. 3.8.



Source: Authors.

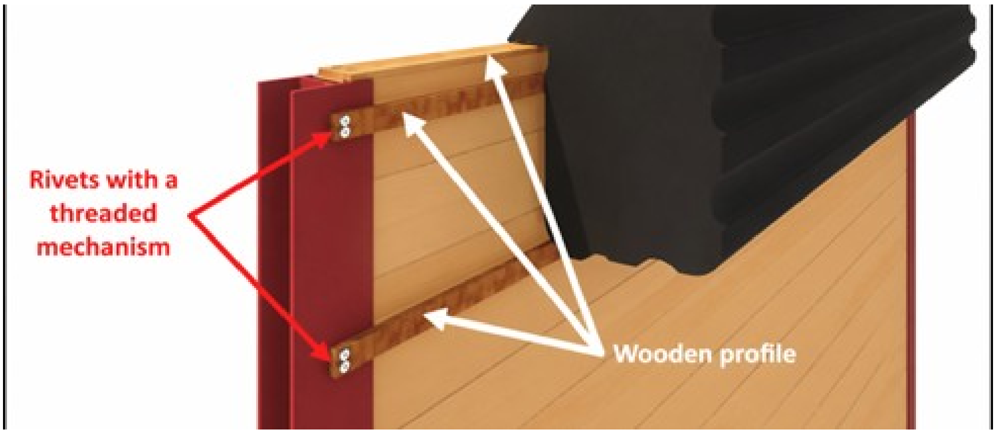
Fig. 3.8 View of the method of mounting the modules to the noise barrier

A view of the installed noise absorber on the noise barrier, including the mounting profiles, is shown in Fig. 3.9 and 3.10.



Source: Authors.

Fig. 3.9 Cross-section drawing of the noise absorber on the noise barrier element



Source: Authors.

Fig. 3.10 View of the installed noise absorber on the noise barrier with mounting profiles

The photographs in Fig. 3.11–3.13 document the preparation and subsequent installation of the innovative noise absorber on the noise barrier:

Fig. 3.11 – View from the terrain of the noise barrier wall and the prepared noise absorber modules laid along the wall before installation.

Fig. 3.12 – Side view of the noise barrier wall with the noise absorber already installed on the upper edge. The absorber forms a continuous band of modules along the length of the wall.

Fig. 3.13 – Aerial view of the test section.

Fig. 3.11 Absorbers prepared for installation

Fig. 3.12 Installed noise absorbers on the noise barrier

Source: Authors.

Fig. 3.13 Aerial view of the installed noise absorbers

3.3. Measurement of noise levels in the selected motorway section

The researchers working on the research project focused on measuring the noise level in a selected motorway section (D1 Jablonov – Studenec) without the innovative noise absorber installed and with the innovative noise absorber installed, and on evaluating the performed tests (measurements).

3.3.1. Development of the methodology for measuring and assessing the effectiveness of the noise absorber

The noise burden in an outdoor environment caused by road transport on roads can be determined by measurement or by calculation using mathematical modelling of sound propagation. Measurement determines the noise burden, or the values of the determining measures of road traffic noise at a local, precisely defined place. For the sake of an objective determination of road traffic noise burden in relation to health protection, the procedures and methods for obtaining noise data are defined by the relevant legislation [9,10]. For the measurement, the standards addressing this matter are also taken into account – STN ISO 1996-1 and STN ISO 1996-2 [7,8]. Calculation, similarly to measurement, can determine the noise burden at a local place, as well as the spatial noise burden in the surroundings of a larger section or sections of the monitored road. In designing the methodology for assessing the effectiveness of the innovative noise absorber, all methods and principles for measuring traffic noise set out in the relevant legislation and technical standards were observed. The measure used to evaluate noise in an outdoor environment from traffic on a road is the equivalent A-weighted sound level for a specified time interval T, $L_{Aeq,T}$. The equivalent A-weighted sound level can also be determined on the basis of measuring equivalent sound pressure levels in fractional octave (most commonly third octave) bands for the specified time interval. For the sake of an objective determination of noise in an outdoor environment caused by traffic on a road, in accordance with legislation on the protection and promotion of public health, $L_{Aeq,T}$ values are used for the following time intervals: day (from 06:00 to 18:00), evening (from 18:00 to 22:00) and night (from 22:00 to 06:00), referred to as reference time intervals.

The effectiveness of the innovative noise absorber will be evaluated by noise measurements on a selected road section. The following part of the report describes the individual procedures and methods that form a comprehensive methodology for assessing the effectiveness of the innovative noise absorber.

3.3.2. Selection of the road section

The first step in assessing the effectiveness of the noise absorber is choosing a suitable road section with a noise barrier wall, since the innovative noise absorber is installed on a noise barrier. For measurement, it is appropriate to choose a road section without significant elevation changes and with sufficient traffic intensity. Another requirement is a good condition of the road surface and a good technical condition of the noise barrier.

The D1 Jablonov – Studenec motorway section near the village of Studenec was chosen for the measurement. A satellite view of the selected motorway section is shown in Fig. 3.14. The length of the noise barrier along the selected section is approximately 290 m with a height of 3 m. It stretches along the left-hand unpaved hard shoulder of the motorway. A view of the selected motorway section and the noise barrier is shown in
Fig. 3.15.

Fig. 3.14 Satellite view of the selected motorway section

Source: Authors.

Fig. 3.15 View of the selected motorway section

3.3.3. Description of the noise barrier design

The load-bearing system of the noise barrier consists of vertical posts made of rolled HEB 160 profiles, installed in a modular step according to the type of infill: at 2.0 m for glass-combi elements and at 4.0 m for aluminum absorptive panels. The vertical posts are anchored into the substructure. The substructure of the noise barriers installed on a bridge consists of a raised bridge kerb. The substructure of the noise barriers installed in the ground consists of Ø 400 L 4000 mm piles with reinforcement and pile caps [6].

After the construction of the load-bearing system, panel-type infill elements were inserted between the posts. The prefabricated base is placed on polycarbonate supports. The joint between the prefabricated base and the pile cap is filled with Styrodur and sealed. The terrain around the noise barrier is adapted so that the bottom edge of the base is always below the ground level.

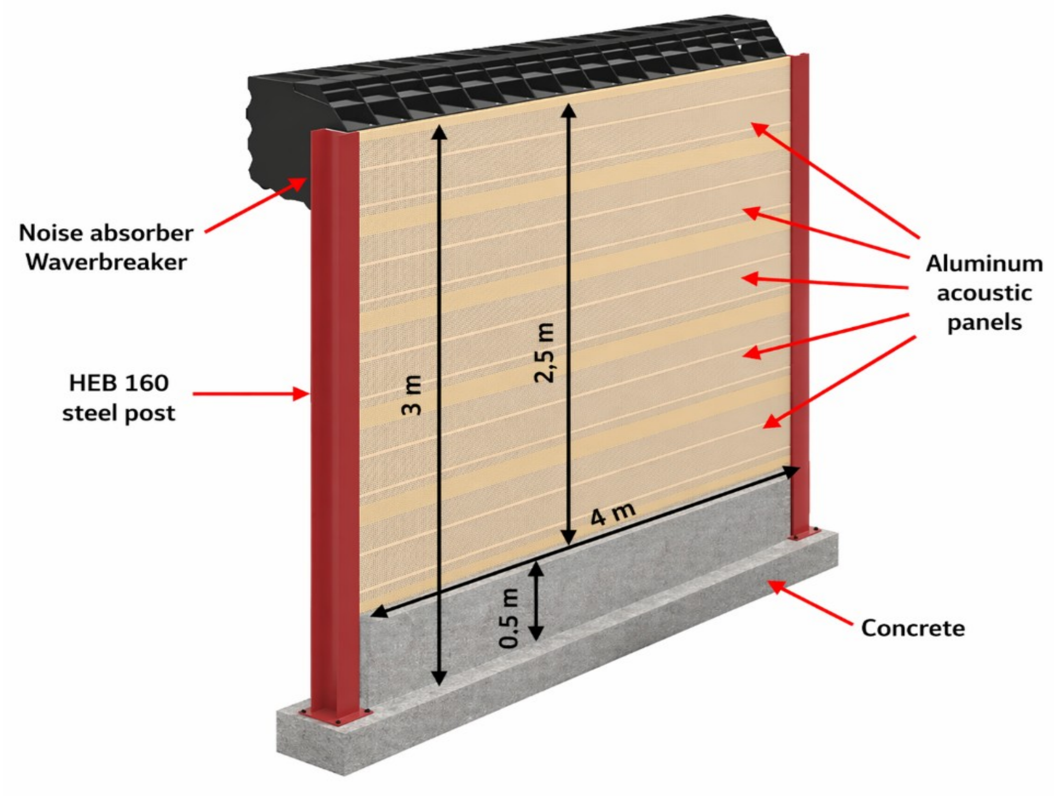
On the ground:

1) Reinforced concrete base with a structural height of H = 0.65 m

2) Aluminum single-sided absorptive panels H = 2.5 m

The steel structure posts are anchored using bonded anchors.

Individual noise absorbers were installed on the structure. These absorbers will be placed on the top of the noise barrier. The placement of the noise absorber on the existing noise barrier is shown and described in Fig. 3.16.



Source: Authors.

Fig. 3.16 Placement of the innovative noise absorber on the noise barrier

3.4. Experimental measurements

3.4.1. Objective of the measurement

The objective of the measurement was to assess the effectiveness of the innovative noise absorbers installed on the noise barrier in the selected motorway section. Effectiveness was assessed using noise measurements at selected measurement points. The assessed value for traffic noise measurement is the equivalent A-weighted sound level for a specified time interval T, $L_{\mathrm{Aeq,T}}$.

3.4.2. Description of the measurement conditions

Noise absorbers were installed on the existing noise barrier. The noise barrier has a total length of approximately 290 m. Noise absorbers were installed on the noise barrier over a total length of 100 m. A view of the installed noise absorbers is shown in Fig. 3.17 and 3.18. The measurements were performed on 29–30 October 2025 on normal working days. The measurements were performed over 24 hours.

Fig. 3.17 View of the installed noise absorbers in the given section

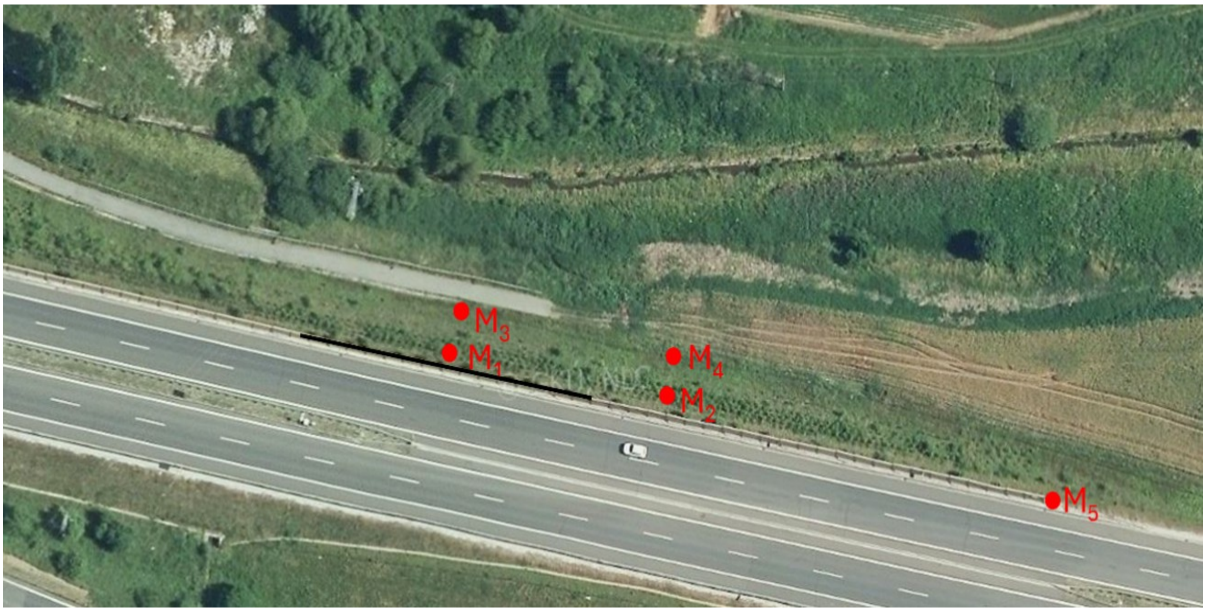
Fig. 3.18 View of the installed noise absorbers in the given section – rear view

3.4.3. Measurement method

1. To describe traffic noise in a protected outdoor environment, the values of equivalent A-weighted sound pressure levels $L_{Aeq,T}$ are determined by direct measurement for a measurement time interval $T = 1$ hour.
2. The traffic noise measurement included determining the intensity and composition of road traffic at 1-hour intervals.
   a) The traffic noise measurement was performed over 24 hours – measurement of hourly equivalent A-weighted sound pressure levels to determine the time dependence of the traffic noise level on the hourly intensity and composition of road traffic for the corresponding reference time interval.
3. The measuring microphone (sound analyzer) was mounted on a tripod at the required height and placed at the selected measurement point, with the main axis of sensitivity oriented perpendicular to the road.
4. The measuring microphone (sound analyzer) must not be exposed to excessive vibrations, strong magnetic or electric fields, or unsuitable meteorological conditions during the measurement.
5.

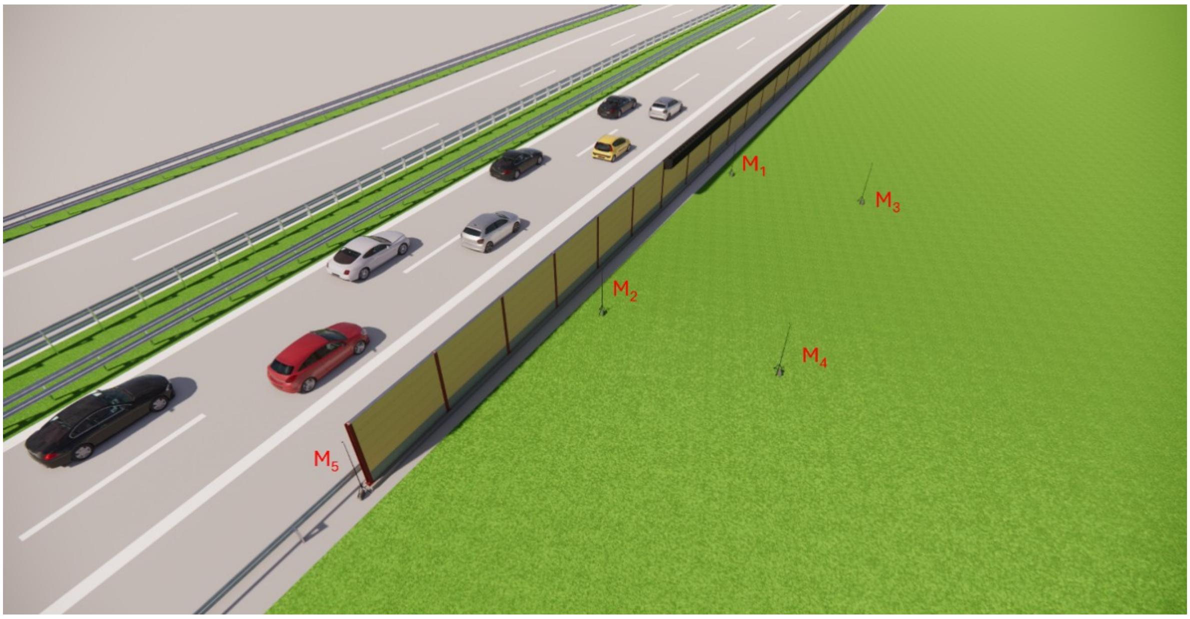
3.4.4. Selection of measurement points

To assess the effectiveness of the absorber, traffic noise measurements were performed on the selected motorway section. Measurement points were selected behind the noise barrier at two distances and at locations with installed noise absorbers, as well as in the section behind the noise barrier. Traffic noise measurements were also performed at the beginning of the section with the noise barrier along the hard shoulder of the adjacent traffic lane. This measurement point was chosen with the aim of understanding the acoustic situation in the given section. The locations of the measurement points are shown in Fig. 3.19 to 3.21.



Source: Authors.

Fig. 3.19 Satellite view of the locations of measurement points



Source: Authors.

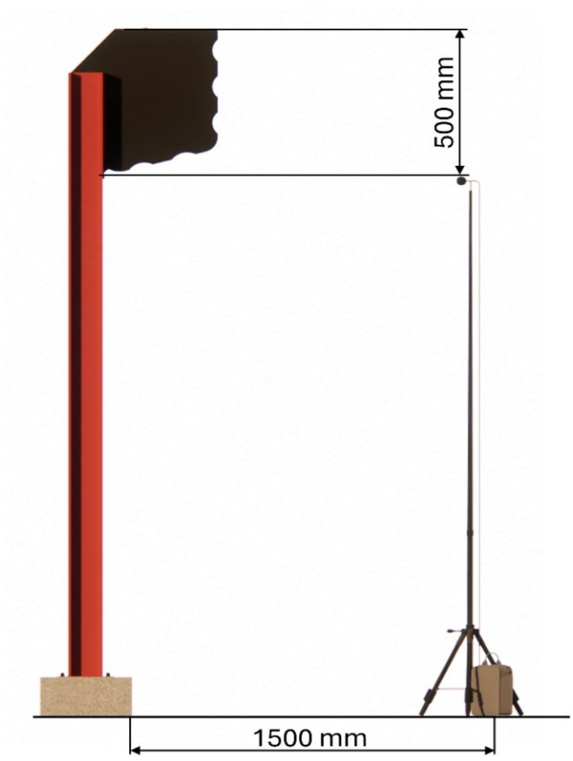
Fig. 3.20 Visualisation of the location of measurement points

Source: Authors.

Fig. 3.21 Location of measuring points in the selected motorway section

Measurement point M1 – was located at a distance of 1.5 m behind the noise barrier with installed noise absorbers, at a height of 0.5 m below the upper edge of the noise barrier with the microphone oriented perpendicular to the axis of the road. A view of the measurement point is shown in Fig. 3.22 and a visualisation of the measurement point location is shown in Fig. 3.23.

Fig. 3.22 View of measurement point M1

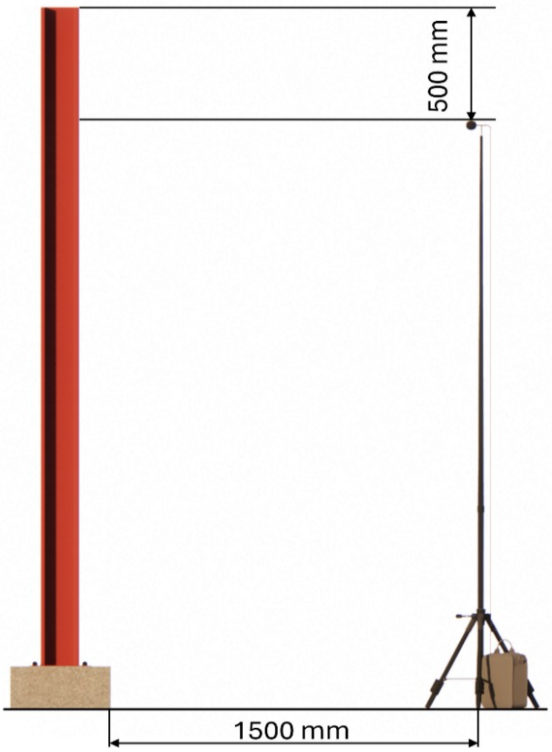


Source: Authors.

Fig. 3.23 Visualisation of the location of measurement point M1 behind the noise barrier

Measurement point M2 – was located at a distance of 1.5 m behind the noise barrier without noise absorbers, at a height of 0.5 m below the upper edge of the noise barrier with the microphone oriented perpendicular to the axis of the road. A view of the measurement point is shown in Fig. 3.24 and a visualisation of the measurement point location is shown in Fig. 3.25

Fig. 3.24 View of measurement point M2



Source: Authors.

Fig. 3.25 Visualisation of the location of measurement point M2 behind the noise barrier

Measurement point M3 – was located at a distance of 8 m behind the noise barrier with installed noise absorbers, at a height of 0.5 m below the upper edge of the noise barrier with the microphone oriented perpendicular to the axis of the road. A view of the measurement point is shown in Fig. 3.26.

Fig. 3.26 View of measurement point M3

Measurement point M4 – was located at a distance of 8 m behind the noise barrier without noise absorbers, at a height of 0.5 m below the upper edge of the noise barrier with the microphone oriented perpendicular to the axis of the road. A view of the measurement point is shown in Fig. 3.27.

Fig. 3.27 View of measurement point M4

Measurement point M5 – was located at the beginning of the noise barrier at a height of approx. 2.5 m above the road with the microphone-oriented perpendicular to the axis of the road. A view of the measurement point is shown in Fig. 3.28.

Fig. 3.28 View of measurement point M5

3.5. Traffic intensity count

Simultaneously with the measurement of traffic noise levels at the corresponding measuring point, a traffic intensity count was carried out on the selected motorway section in both directions during specified hours. The traffic intensity count was carried out in at the noise barrier near the village of Studenec. The count was carried out based on provided video recordings of passages through the location from NDS a. s., Bratislava. A view of the traffic count location is shown in Fig. 3.29.

Fig. 3.29 View of the traffic intensity count location in the given motorway section

Road traffic intensity in each direction is recorded for the following categories:

– PC (passenger cars + lorries up to 3.5 t),
– L (lorries over 3.5 t),
– BUS (buses) and
– MOTO (motorcycles).

The results of the traffic intensity count during noise measurements are presented in Tab. 3.1.

Tab. 3.1
Results of traffic intensity count

Direction	Towards Poprad				Towards Prešov			
Time	PC	L	BUS	MOTO	PC	L	BUS	MOTO
06^{00}–07^{00}	419	57	0	1	403	118	0	0
07^{00}–08^{00}	551	102	1	0	499	113	1	0
08^{00}–09^{00}	650	119	3	0	517	129	0	2
09^{00}–10^{00}	733	93	3	0	558	128	0	0
10^{00}–11^{00}	861	119	1	0	546	87	3	0
11^{00}–12^{00}	582	106	1	0	437	83	2	1
12^{00}–13^{00}	622	109	1	0	525	93	0	1
13^{00}–14^{00}	614	95	3	0	575	75	4	0
14^{00}–15^{00}	662	86	4	0	611	79	1	1
15^{00}–16^{00}	729	80	4	1	665	79	0	0
16^{00}–17^{00}	707	55	1	0	672	62	3	0
17^{00}–18^{00}	578	45	0	0	572	71	0	0
18^{00}–19^{00}	463	66	2	0	545	47	3	0
19^{00}–20^{00}	307	69	2	0	446	57	2	0
20^{00}–21^{00}	149	43	2	0	388	53	3	0
21^{00}–22^{00}	101	32	0	0	293	42	1	0
22^{00}–23^{00}	56	24	0	0	212	52	1	0
23^{00}–24^{00}	42	17	0	0	131	37	0	0
00^{00}–01^{00}	26	29	0	0	60	38	1	0
01^{00}–02^{00}	32	20	1	0	51	29	1	0

02^{00}–03^{00}	33	23	0	0	47	46	1	0
03^{00}–04^{00}	50	28	2	0	43	53	5	0
04^{00}–05^{00}	84	45	2	0	48	65	0	0
05^{00}–06^{00}	215	41	0	0	191	101	0	0
TOTAL	**9,266**	**1,503**	**33**	**2**	**9,035**	**1,737**	**32**	**5**

3.6. Noise measurement results

The following table, Tab. 3.2, shows the results of noise measurements at individual measurement points.

Tab. 3.2
Results of noise level measurements at each measurement point

Measuring point	**M1**	**M2**	**M3**	**M4**	**M5**
Measurement time	With noise absorber 1.5 m behind NB	Without noise absorber 1.5 m behind NB	With noise absorber 8 m behind NB	Without noise absorber 8 m behind NB	At the beginning of the barrier
11:00–12:00	**62.2**	**63.8**	59.4	58.9	79.2
12:00–13:00	**62.7**	**63.9**	60.9	60.6	79.1
13:00–14:00	**62.4**	**63.6**	60.8	61.7	79.3
14:00–15:00	**62.7**	**64.0**	61.6	62.4	79.5
15:00–16:00	**63.2**	**65.5**	62.1	62.4	79.7
16:00–17:00	**63.2**	**65.4**	63.0	62.8	79.6
17:00–18:00	**62.6**	**64.8**	61.3	60.9	78.8
18:00–19:00	**61.8**	**63.6**	60.8	59.8	78.5
19:00–20:00	**61.2**	**62.9**	59.1	59.6	77.4
20:00–21:00	**59.3**	**60.5**	57.6	57.8	75.1
21:00–22:00	**57.9**	**59.1**	54.6	56.7	73.7
22:00–23:00	**55.9**	**56.8**	53.6	54.0	71.4
23:00–24:00	**54.3**	**55.4**	52.7	52.6	70.3
0:00–1:00	**54.5**	**55.6**	52.8	53.0	70.1
1:00–2:00	**54.1**	**55.4**	52.8	53.2	69.6
2:00–3:00	**54.4**	**55.9**	52.6	53.4	69.8
3:00–4:00	**54.6**	**56.3**	53.1	53.5	70.4
4:00–5:00	**57.1**	**58.7**	55.8	56.2	72.8
5:00–6:00	**58.7**	**60.5**	56.4	57.6	74.6
6:00–7:00	**61.9**	**63.8**	60.9	61.7	77.9
7:00–8:00	**62.7**	**64.5**	61.6	62.0	78.9
8:00–9:00	**63.1**	**65.1**	62.1	62.5	79.6

9:00–10:00	**63.0**	**65.3**	61.3	62.0	79.6
10:00–11:00	**63.2**	**65.9**	61.4	61.7	80.1

3.7. Mathematical model of noise emission propagation

The CADNA (version 3.6.117) software product, set up to apply the relevant methodologies, was used to create the mathematical model.

For the prediction of equivalent noise levels, the NMPB Routes 96 methodology with the French standard XPS 31–133 was used to calculate traffic noise from road transport.

To give an idea of the noise emissions around the assessed motorway section, we present the values of the equivalent noise level at some calculation points, see
Tab. 3.3 to 3.5. A graphical representation of the calculated equivalent noise level values at different traffic intensities and at different distances is shown in Fig. 3.30 to 3.32.

The specific values of equivalent levels in the entire area of interest for each variant are evident from the graphical presentations. Noise isophones are at a height of 1.5 m above the terrain and are color-coded with a 5 dB step (Fig. 3.33, 3.34 and 3.35).

Tab. 3.3

Calculated L_{Aeq} values at calculation points – without NB

Calculation point	**Distance of the calculation point [m]**	**Equivalent A-weighted sound pressure level L_{Aeq} [dB]**		
		Traffic intensity[vehicles per hour]		
		1,600	**900**	**350**
V1	1.5	80.1	77.4	71.5
V2	8	75.9	73.2	67.5
V3	50	65.7	63.6	58.4
V4	100	60.0	58.2	53.2

Tab. 3.4

Calculated LAeq values at calculation points with NB

Calculation point	**Distance of the calculation point [m]**	**Equivalent A-weighted sound pressure level L_{Aeq} [dB]**		
		Traffic intensity[vehicles per hour]		
		1,600	**900**	**350**
V1	1.5	65.9	62.9	56.8
V2	8	62.0	58.9	52.8
V3	50	53.5	50.2	43.8
V4	100	48.3	45.1	39.0

Tab. 3.5

Calculated LAeq values at calculation points with NB and noise absorber

Calculation point	**Distance of the calculation point [m]**	**Equivalent A-weighted sound pressure level L_{Aeq} [dB]**		
		Traffic intensity[vehicles per hour]		
		1,600	**900**	**350**
V1	1.5	63.2	61.2	55.9
V2	8	59.1	57.0	51.6
V3	50	49.6	47.4	41.7
V4	100	44.0	41.9	36.4

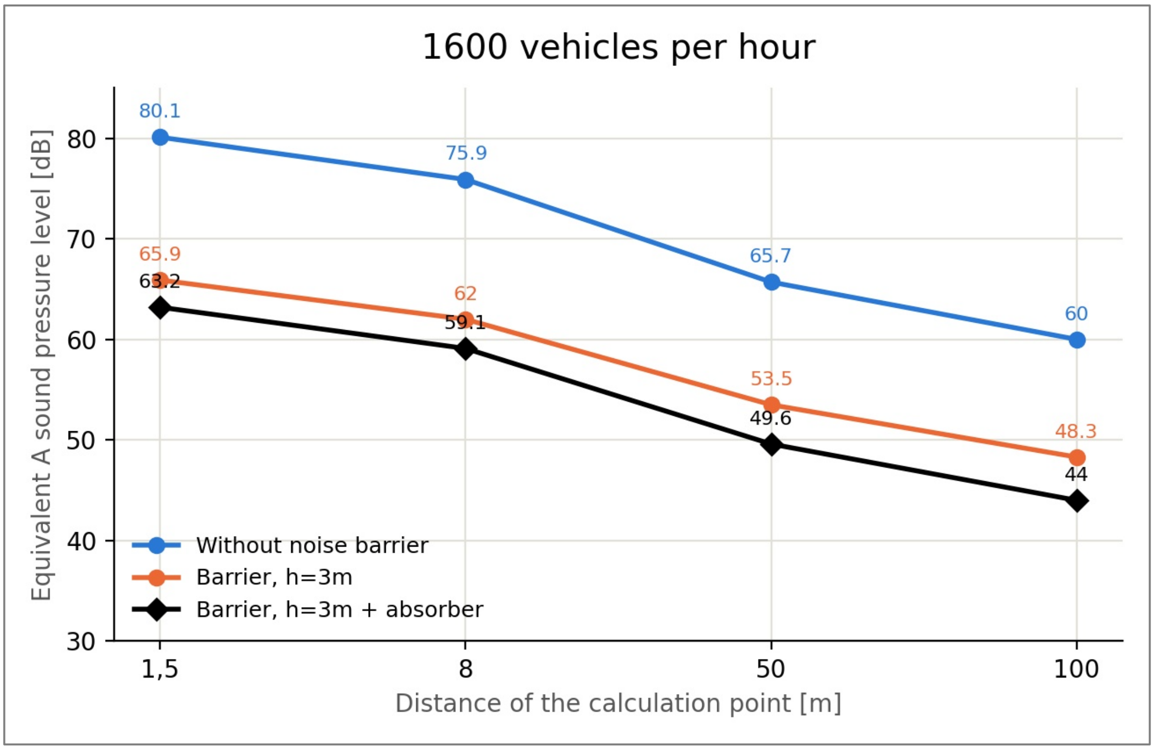


Fig. 3.30 Comparison of calculated equivalent noise levels at an intensity of 1,600 vehicles per hour

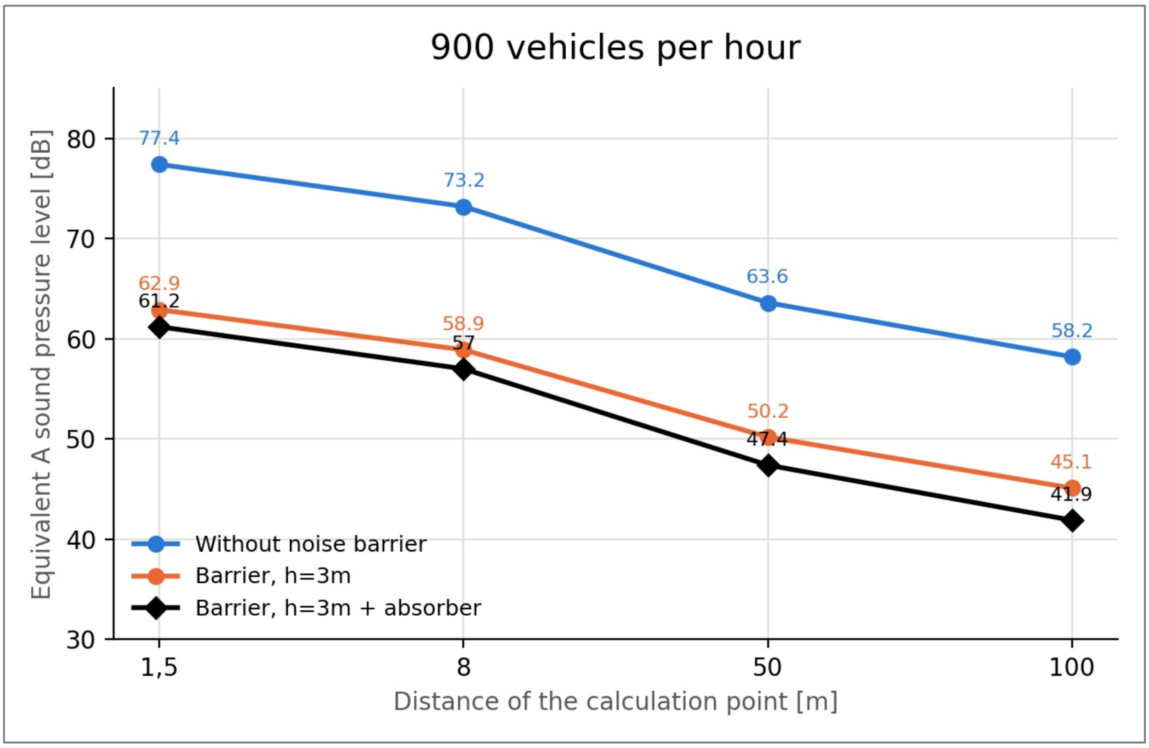


Fig. 3.31 Comparison of calculated equivalent noise levels at an intensity of 900 vehicles per hour

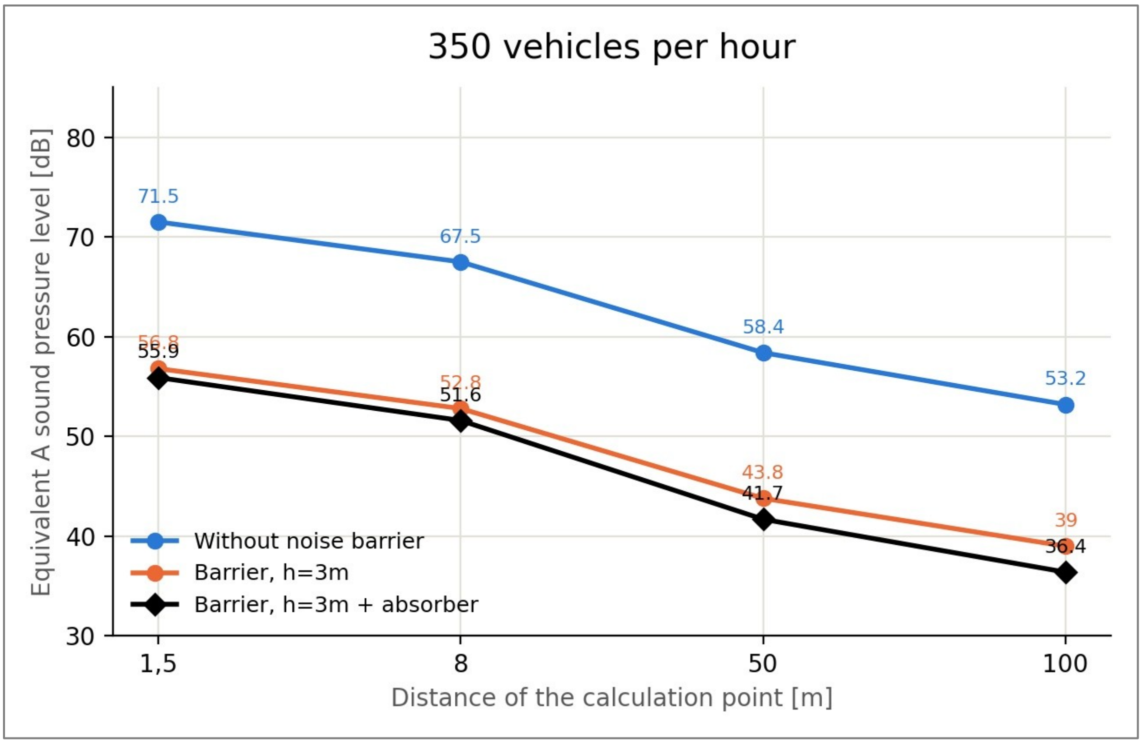
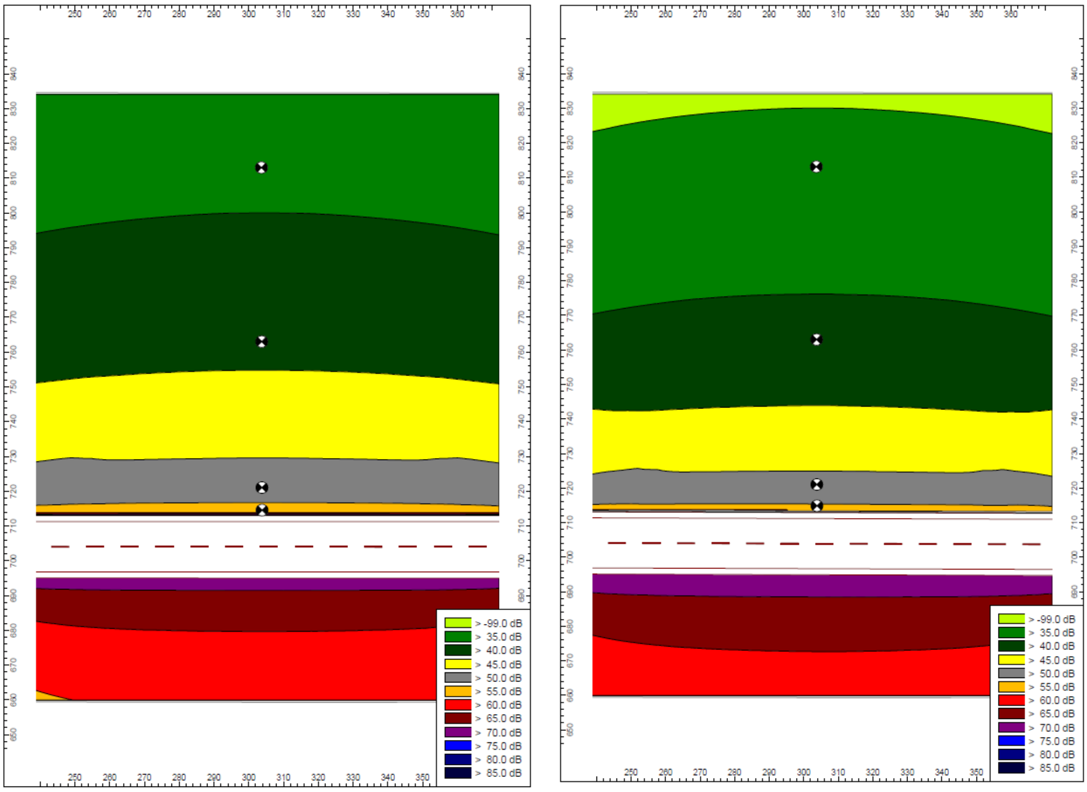


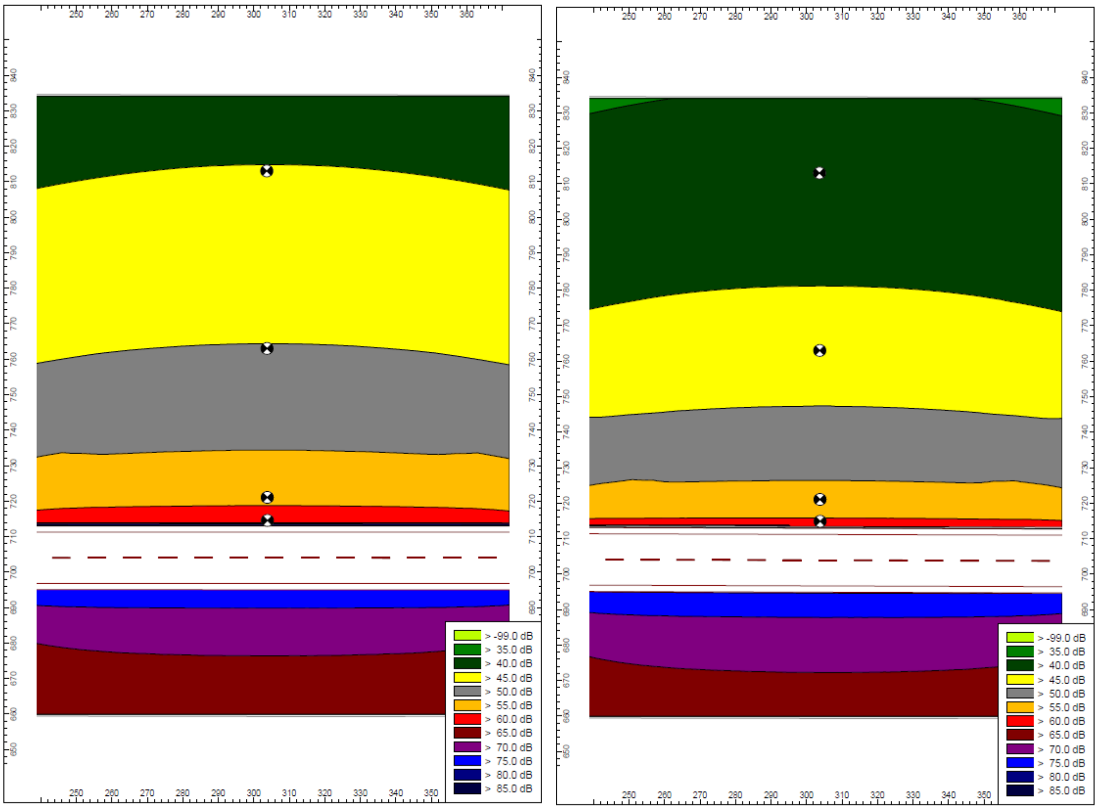
Fig. 3.32 Comparison of calculated equivalent noise levels at an intensity of 900 vehicles per hour



a) Without absorber b) With absorber

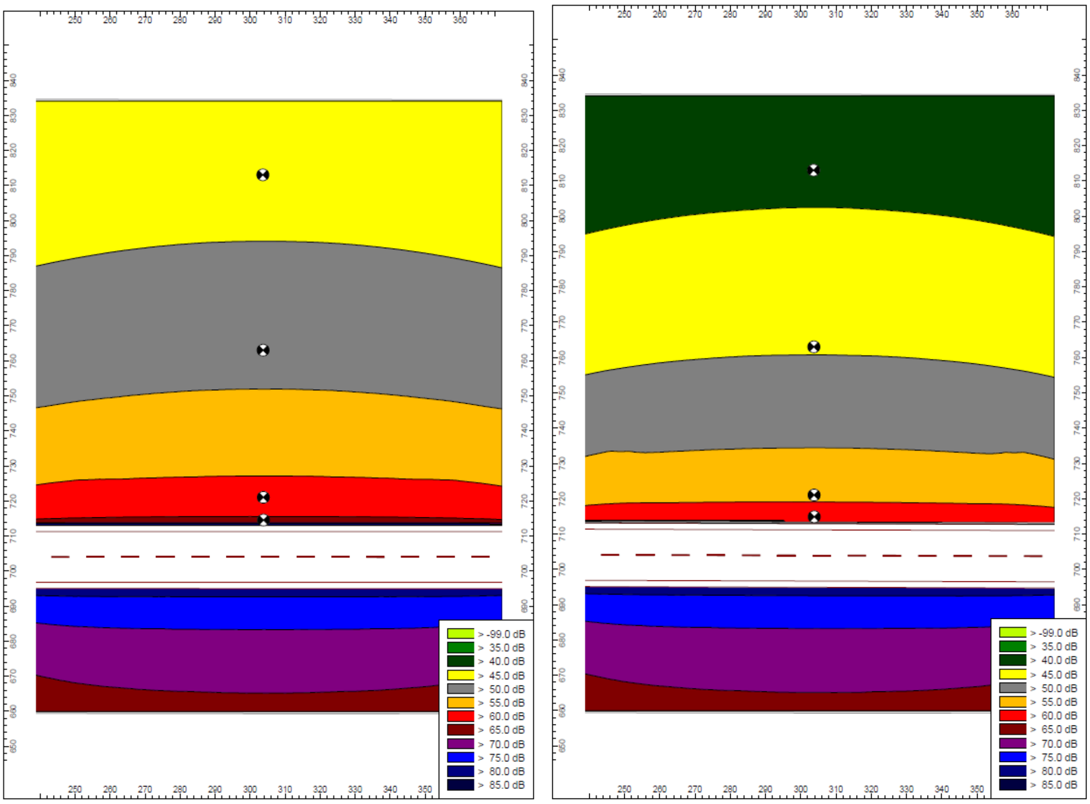
Source: Authors.

Fig. 3.33 Noise map – propagation of noise emissions at an intensity of 350 vehicles per hour



a) Without absorber b) With absorber

Fig. 3.34 Noise map – propagation of noise emissions at an intensity of 900 vehicles per hour



a) Without absorber b) With absorber

Fig. 3.35 Noise map – propagation of noise emissions at an intensity of 1,600 vehicles per hour

3.8. Assessment of the effectiveness of noise absorbers

Measurement points M1 and M2 located 1.5 m behind the noise barrier are decisive for assessing the effectiveness of the installed noise absorbers, with one measurement point located behind a noise barrier with installed noise absorbers and the other behind a barrier with installed noise absorbers. The effectiveness of the noise absorbers can be assessed based on the difference in measured noise levels at these measuring points. The differences in noise levels are shown in Tab. 3.6 below. A graphical presentation of the absorber effectiveness depending on traffic intensity and measured noise levels is shown in Fig. 3.36.

Tab. 3.6

Assessment of the effectiveness of installed noise absorbers

	M5	**M1**	**M2**	**Differ-ence**	**Traffic intensity**		
Measurement time	At the begin-ning of the barrier	With noise ab-sorber 1.5 m behind NB	Without noise absorber 1.5 m behind NB		Passenger cars	Lorries	Total
11:00–12:00	79.2	**62.2**	**63.8**	**1.6**	1,020	192	1,212
12:00–13:00	79.1	**62.7**	**63.9**	**1.2**	1,148	203	1,351
13:00–14:00	79.3	**62.4**	**63.6**	**1.2**	1,189	177	1,366
14:00–15:00	79.5	**62.7**	**64.0**	**1.3**	1,274	170	1,444

15:00–16:00	79.7	63.2	65.5	2.3	1,395	163	1,558
16:00–17:00	79.6	63.2	65.4	2.2	1,379	121	1,500
17:00–18:00	78.8	62.6	64.8	2.2	1,150	116	1266
18:00–19:00	78.5	61.8	63.6	1.8	1,008	118	1,126
19:00–20:00	77.4	61.2	62.9	1.7	753	130	883
20:00–21:00	75.1	59.3	60.5	1.2	537	101	638
21:00–22:00	73.7	57.9	59.1	1.2	394	75	469
22:00–23:00	71.4	55.9	56.8	0.9	268	77	345
23:00–24:00	70.3	54.3	55.4	1.1	173	54	227
0:00–1:00	70.1	54.5	55.6	1.1	86	68	154
1:00–2:00	69.6	54.1	55.4	1.3	83	51	134
2:00–3:00	69.8	54.4	55.9	1.5	80	70	150
3:00–4:00	70.4	54.6	56.3	1.7	93	88	181
4:00–5:00	72.8	57.1	58.7	1.6	132	112	244
5:00–6:00	74.6	58.7	60.5	1.8	406	142	548
6:00–7:00	77.9	61.9	63.8	1.9	823	175	998
7:00–8:00	78.9	62.7	64.5	1.8	1,050	217	1,267
8:00–9:00	79.6	63.1	65.1	2.0	1,169	251	1,420
9:00–10:00	79.6	63.0	65.3	2.3	1,291	224	1,515
10:00–11:00	80.1	63.2	65.9	2.7	1,407	210	1,617

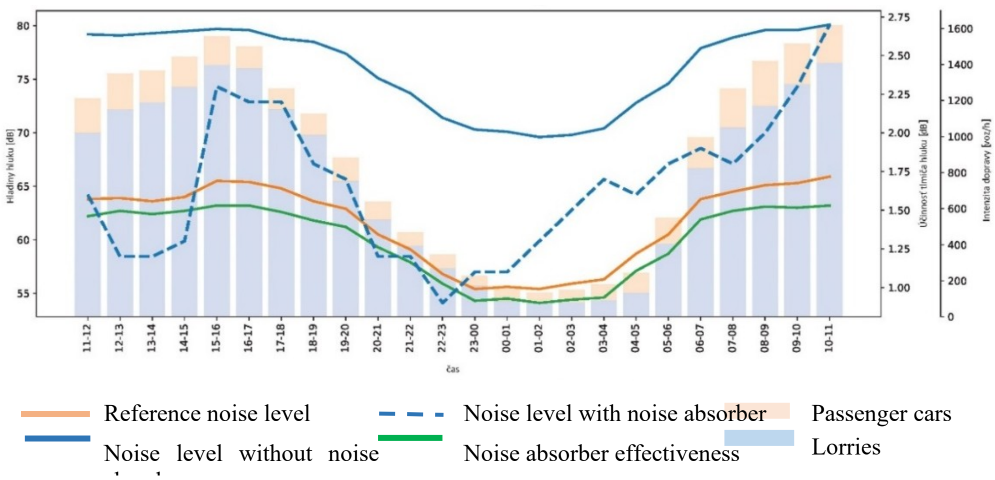


Fig. 3.36 Graphical representation of the noise absorber effectiveness during noise measurement Experimental measurements

3.9. Conclusion

Based on the noise measurements performed at measuring points M1 and M2, the efficiency of the installed noise absorbers can be assessed based on the difference in noise levels. The difference in noise levels with and without the noise absorber ranges from 0.9 to 2.7 dB during the hours. It is clear from the presented results that the effectiveness of the absorbers increases with increasing traffic intensity. The flow of passing cars also affects the effectiveness of the noise absorbers, as their response is delayed. We can assume that with higher traffic intensity, the effectiveness of the noise absorbers will also increase. The expected absorption of the noise absorbers depending on the increase in traffic is shown in Table 3.7 and is presented in Fig. 3.37.

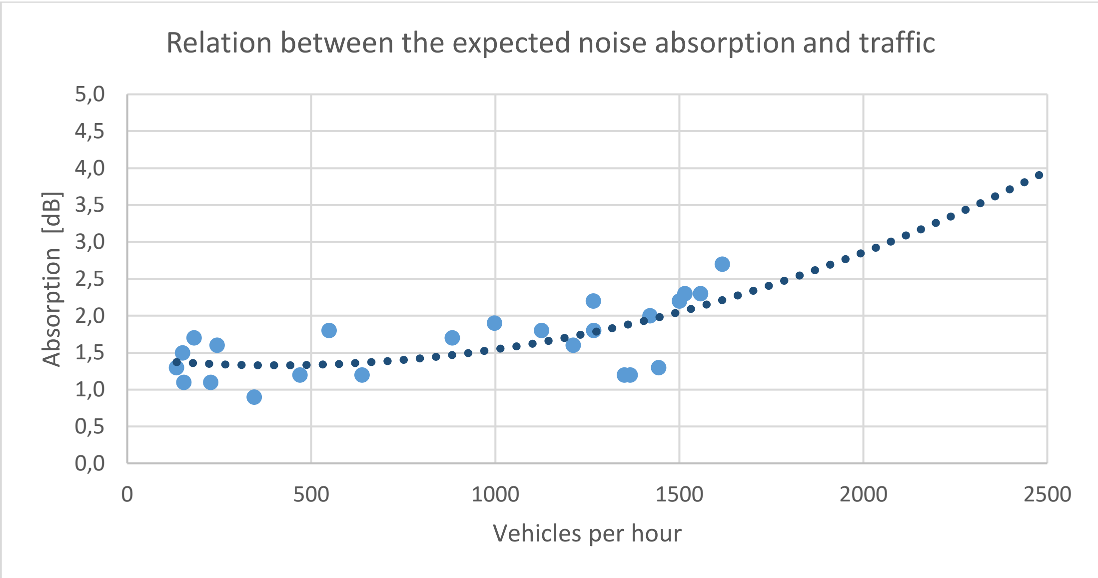


Fig. 3.37 Expected absorption of noise absorbers

Tab. 3.7
Expected absorption of noise absorbers

Number of vehicles	Absorption[dB]	
	During 24 hours	During the day, 6:00–18:00
15,000	1.6	1.8
20,000	2.2	2.5
25,000	2.8	3.2
30,000	4.0	4.6

The experimental measurements demonstrated the objective effectiveness of the innovative noise absorbers. Based the analysis of the measurement results and mathematical modelling, we can state the following facts:

– The noise absorber, with its height of 20 cm above the noise barrier, constitutes, in the specific case of installation on a 3 m high noise barrier, an equivalent of its height

increase of approximately 0.6 m to 1.0 m, or the wall could be reduced by approximately 0.6 m to 1.0 m.
- With an increase in traffic intensity, an increase in the effectiveness of the noise absorber is also expected.
- Noise absorbers can be installed during full operation without the need for any traffic restrictions, without the use of heavy machinery, and in a very short time.
- The lifespan of the extensions is declared by the manufacturer to range from 25 to 50 years, depending on the design. The design of the extensions allows their partial or complete removal and reuse. It is therefore an effective technology in places where, due to time constraints or for technological reasons, it would not be possible to replace existing noise barriers.
- The extensions are manufactured from partially or fully recycled plastics; their transport, installation, and maintenance allow significant savings compared to conventional noise barriers, and especially when taking into account the costs and necessary technologies for alternative heightening of existing walls using conventional methods, they represent a dramatically resource-efficient, ecological, and CO_2-neutral path to rapid and effective noise reduction on existing transport routes.
- The solution demonstrated the possibility of an acoustically effective, economically and environmentally efficient alternative solution to the noise problem on transport infrastructure. Applying this extension allows achieving a significant improvement in noise protection while minimising costs and time compared to conventional replacements and reconstructions of existing noise barriers.

The latest EC implementation report states that the implementation of noise reduction measures proposed in some local and national action plans would be highly cost-effective. A study commissioned by the EC [4] found that for every euro invested in specific noise reduction measures, there is a return of 10 euros in the form of social benefits. This suggests that if authorities in member states adopt these measures, they not only address health risks but also create long-term benefits for society. Therefore, noise reduction can also bring economic opportunities and help establish manufacturers and industry in the EU as leaders in green innovations.

The fact that the national motorway operator Národná diaľničná spoločnosť, a.s. in Bratislava, together with the research and educational platform UNIVNET, intensively supports solving the issue of reducing noise emissions generated from traffic demonstrates alignment with the goals of the European Commission related to methods for reducing traffic noise.

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4. Possibilities of Waste Textile Energy Recovery

Reasons why waste textiles are also treated as fuel:

- The production of new cars generates a large amount of textile waste from synthetic and natural textiles in the form of rejects, offcuts, etc. The average proportion of technical textiles in a car is shown in Fig. 4.1. [26]
- The disposal of end-of-life vehicles is also a large source of textile waste of similar composition, with the only difference being that the textile is often contaminated, degraded by solar radiation and heat, or has an increased moisture content (depending on the storage and processing of scrap cars).
- Municipal waste is also a large source of textile waste; from 2025, EU member states have an obligation to introduce separate collection of textiles, so the volume of flows that cannot be reasonably materially recovered (especially mixtures, damaged and heavily soiled pieces) will grow.

Energy recovery of textile waste is often problematic mainly due to the variety of composition (fibres + dyes + finishes + prints + additives) and due to halogens and metals, which affect the production of HCl/HF, corrosion and the binding of metals to fine ash fractions.

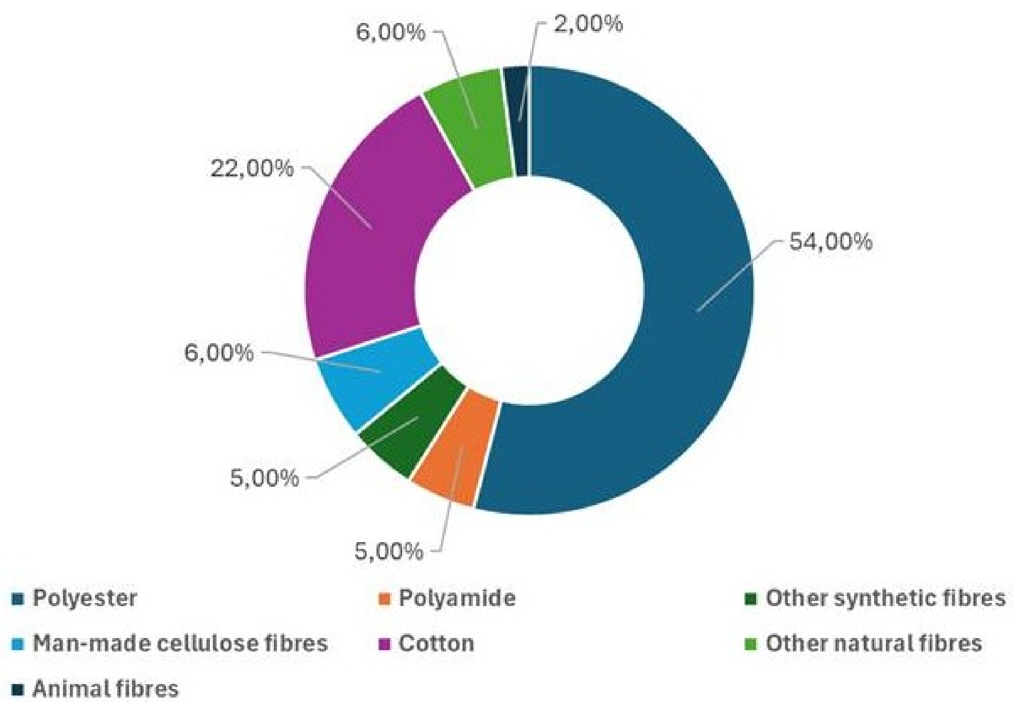

Fig. 4.1 Average proportion of technical textiles in a car [26]

In cars, textiles are generally found in 3 forms: woven fabrics, knitted fabrics and especially non-woven textiles (felts, needle-punched mats, acoustic layers). In terms of materials, it is polyester (PET), polyamides (nylon 6/6,6) and polypropylene (PP) that dominate, and locally also rayon, aramid, glass fibres and natural fibres in mats.

1) Safety textiles:
   a. Airbags: dense fabrics, most commonly made of nylon 6,6, or also nylon 6 or polyester, often coated for low gas permeability.
   b. Seat belts: woven straps made of special high-strength polyester (PET) yarns.
2) Interior – comfort and decorative layers:
   a. Seat covers and upholstery: woven or knitted fabrics (often polyester or mixtures), very often with surface treatments and coatings (e.g. PVC/PU systems for abrasion, cleaning, flammability).
   b. Headliner, A/B/C pillars: typically polyester mats laminated with polyurethane foam and other layers (adhesive 'low-melt' fibres, films).
   c. Acoustic and thermal insulation in the cabin and boots: predominantly non-woven textiles (polyester, PP) and, depending on the application, also mixtures with glass fibre.
3) Floor, boot, wheel arches – large volumes of non-woven textiles: carpets, floor coverings, boot linings, wheel arch felts: often needle-punched non-woven textiles made of PP/PET (and in some systems also nylon fibres), usually multi-layered (fibres + binder/latex/foam + backing).
4) Textiles outside the interior – reinforcements and technical fabrics: tyre cords: reinforcing textiles made of polyester (PET), nylon, rayon, and aramid (plus bonds/adhesive systems for bonding with rubber).
5) Natural fibres in cars (mainly as mats/composite carriers, not 'clothing' textiles): in some interior parts (acoustic fillings, load-bearing mats for panels), such as kenaf/jute/flax/cotton, are used as a component of non-woven mats or hybrid layers with PP/PET.

For mapping the input raw material, it is worth recording whether it is:

- PET-dominant (belts, part of carpets/non-woven textiles),
- PA-dominant (airbags, some carpets),
- PP-dominant (non-woven textiles, acoustics, parts of carpets),
- and especially the presence of foam/adhesives/laminations (PU, latex, coatings), plus glass fibres and any halogens from surface treatments (due to HCl/HBr and ash content).

Many textiles (especially synthetic fibres) have a calorific value in the order of tens of $MJ.kg^{-1}$. In several studies on the energy use of waste textiles, the calorific value of this material as fuel is around 20 $MJ.kg^{-1}$ with low Cl and Hg emissions, which is acceptable in terms of SAF parameters (SAF – solid alternative fuel[1], also referred to as RDF – refuse derived fuel, and SFR – solid recovered fuel). Dziok et al. [7] [8] point out the topicality and importance of solving the problem used textiles management.

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[1] SAF – solid alternative fuels are primarily used as a substitute for fossil fuels (coal, coke, etc.) in industry, e.g. cement plants, lime plants or heating plants. It is produced from waste that could not be materially recovered; it is produced by sorting and mechanical processing (removing metals, impurities, drying and shredding) and subsequent mixing with a suitable auxiliary fuel, e.g. wood chips. The advantage is mainly the reduction of the industry's carbon footprint, the reduction of the amount of waste, and the reduction of dependence on fossil fuels. SAF represents a more ecological alternative, as instead of landfilling, the mixture of waste is energetically recovered.

One of the possibilities is recycling, but these processes are characterised by a high environmental burden and the obtained products are of lower quality, they are not always suitable for reuse. Used textiles can be successfully used for the production of SAF. This type of fuel is standardised by the STN EN ISO 21640:2021 standard. An analysis of used textiles made from fibres of various origins was performed in the study. These were acrylic, cotton, linen, polyester, wool and viscose. The authors performed energy analyses and analyses focused on specific chemical elements on the examined samples, especially on the mercury and chlorine content. SAF made from used textiles is characterised by acceptable parameters for energy use: calorific value of 20 $MJ.kg^{-1}$ (SAF class 1–3), mercury content below 0.9 $\mu g_{Hg}.MJ^{-1}$ (SAF class 1), and chlorine content below 0.2% (SAF class 1). The chemical composition of some types of textiles can limit their energy use; wool, for example, contains 3.0 to 3.6% sulfur, acrylic has a high nitrogen content, which affects SO_2/NO_x emissions and the need for additional flue gas cleaning. As for replacing conventional fossil fuels with SAF produced from used textiles, it is possible to replace, for example, 3% of consumed coal for energy purposes (in the case of Poland). The reduction of carbon dioxide emissions by replacing coal with alternative fuel obtained from used textiles will depend on their composition. For natural and artificial cellulose fibres, an emission factor equal to that for plant biomass can be assumed; for synthetic fibres, the emission factor was estimated at 102 and 82 $g_{CO2}.MJ^{-1}$ for polyester and acrylic, respectively.

We distinguish two types of solid alternative fuel: RDF (refuse derived fuel) and SRF (solid recovered fuel). Both fuels are types of fuels made from waste, i.e. SAF, which serve as a substitute for fossil fuels. The origin of the waste from which SAF is made affects the final properties of the product; RDF mainly comes from municipal waste, whereas SRF mainly comes from industrial waste. The main difference between them therefore lies in the level of processing, quality, purity and calorific value. SRF is a high-quality, refined fuel meeting strict standards, whereas RDF is less processed, coarser waste.

Main differences between RDF and SRF:

- Processing and purity:
    - RDF undergoes a less intensive process (shredding, separation). It contains more mixed municipal waste, including biodegradable materials.
    - SRF undergoes strict separation, drying and cleaning. Non-combustible substances (glass, metals) and moisture are removed from it.
- Calorific value:
    - RDF has a lower and more variable calorific value (approximately 8–12 $MJ.kg^{-1}$).
    - SRF has a high and stable calorific value (approximately 12–20 $MJ.kg^{-1}$).
- Standards:
    - RDF is often produced according to the requirements of a specific end-user.
    - SRF must meet strict European standards, especially EN 15359, which define quality classes.

- Use:
    - RDF is used mainly in gasification plants or large waste incineration plants. Due to its high quality, SRF is suitable for cement plants, where it replaces coal and coke.

- Due to its high quality, SRF is suitable for cement plants, where it replaces coal and coke.

- Humidity:
  - RDF tends to have more moisture (20–30%).
  - SRF tends to have less moisture (often even below 15%).

4.1.1. Main methods of energy recovery from waste textiles

1) **Direct incineration or co-incineration** (Waste-to-Energy plants, heating plants, cement plants). Directly in waste incineration plants or as co-incineration (e.g. in cement kilns) after processing into RDF/SRF. In the EU, operation is bound by the requirements of the Industrial Emissions Directive and BAT conclusions for waste incineration (2019/2010) [9] – it addresses limits and monitoring of NO_x, SO_2, HCl, HF, Hg, dioxins/furans, dust, etc.
2) **Production of SAF – especially SRF** (mechanical processing + quality specification). The usual industrial production process for high-grade SRF is: sorting → shredding/cutting → separation → homogenisation → densification (bales/pellets/briquettes) → delivery as SRF. STN EN ISO 21640:2021 defines the system of SRF specifications and classes.
3) **Gasification** (syngas). For textiles, there are already experimental studies on the use of gasification. Garcia-Monforte et al. [9] focused on comparing the effect of a gasification atmosphere consisting of air, CO_2 and a mixture with steam at an operating temperature of 900 °C. The steam component increased the production of H_2 and CO, but also increased the formation of tars (which necessitates the cleaning of synthesis gas). The presented calorific values of the produced gas are in the order of 9–10 $MJ.m^{-3}$.
4) **Pyrolysis and co-pyrolysis** is a reasonable method of energy recovery from waste textiles, especially as part of broader waste management schemes and the subsequent market for pyrolysis products. For textiles, issues of pyrolysis oil, gas and solid residue yield and the effect of fibre mixtures and additives on the distribution of pyrolysis product yields are typically addressed. Dziok et al. [8] published a study on the co-pyrolysis process of car tyres together with the addition of cotton and polyester textiles. The effect on the properties of co-pyrolysis products was examined. The addition of textiles led to a reduction in the yield of solid residue and a significant decrease in the formation of pyrolysis oil, along with an increase in the volume of released pyrolysis gas. The production of by-products in the form of aqueous fraction and sediments increased with the addition of both cotton and polyester textiles. The addition of textiles led to an improvement in the quality of the solid residue further used as fuel (reduction of ash and sulfur content and increase in calorific value), but the sorption properties deteriorated. The addition of textiles caused a reduction in the calorific value of the pyrolysis oil, but a decrease in sulfur content was also observed. The calorific value of gaseous products also decreased significantly. The advantage of using cotton was the introduction of biogenic carbon into the products, which can contribute to the reduction of carbon dioxide emissions.

4.1.2. Emissions and risks specific to waste textile energy recovery

The greatest risk in energy recovery from textiles is its chemical composition, not so much the main component (e.g. polyester, cotton, etc.) but the presence of additives (dyes contain a whole range of metals, flame retardants and chemical stabilisers are used in textiles).

Metals in textiles are not destroyed by incineration; a portion can be transferred to the gas phase and subsequently condense or adsorb onto fine particles (also relevant for solid pollutant particles, also referred to as PM – particulate matter, in flue gases and for ash processing).

Textiles with brominated or chlorinated flame retardants increase the risk of forming brominated and mixed dioxins or furans under unsuitable conditions; emphasis is placed on high-quality combustion and subsequent effective flue gas cleaning.

4.1.3. Composition of textile waste and its properties

When researching the energy recovery of waste textiles, it is necessary to perform an initial fuel characterisation for the individual fractions that make up the waste. In addition to standard chemical analyses (volatile and non-volatile combustible substance, ballast, content of main elements important for energy – C, H_2, S, N_2, O_2) and energy analyses (calorific value and heat of combustion, moisture), it is also necessary to focus on the content of other chemical elements, such as chlorine, mercury, bromine and other selected metals.

An example of textile waste composition analyses, which determined the content of moisture, ash, volatile substances, carbon, hydrogen, chlorine and sulfur, as well as the lower calorific value. The analyses are based on specialised literature (e.g.[8]) and were confirmed by our own research, as shown in Tab. 4.1. These analyses involved clean, uncontaminated substances, which can be observed, for example, in the evaluation of moisture, which was very low. When the moisture of textile waste from scrap cars and from separated textile from municipal waste was evaluated, the moisture was significantly higher and varied, so such waste was not considered in the initial analyses. The ash content of the textile waste samples is very low, which points to the suitability of this material for energy recovery. The most significant is the evaluation of the calorific value, which is very favourable for synthetic materials, above 21 $MJ.kg^{-1}$, whereas it is lower for natural materials – but still positive in comparison, for example, with the calorific value of municipal waste. An important parameter for the characterisation of textile waste is the content of selected chemical elements, which can be judged as toxic or may cause problems during the later processing of the main products and by-products of textile waste energy recovery. The content of some significant chemical elements is shown in Tab. 4.2. Their content is not high, nor does it pose a risk in that it would pose a direct threat to human health, e.g. when clothing is worn or during skin contact with car seat upholstery, but with a large amount of processed waste, their content accumulates (because as mentioned above, metals in textiles cannot be destroyed by the action of heat and they pass into, for example, flue gases, ash or pyrolysis products).

Tab. 4.1
Characterisation of input materials for textile waste energy recovery [8]

	Humidity [%]	**Ash content** [%]	**Volatile substances** [%]	**C** [%]	**H** [%]	**S** [%]	**Cl** [%]	**Calorific value** [$MJ.kg^{-1}$]
Polyester	1.2	0.4	89.06	63.0	5.06	0.04	0.044	21.905
Cotton	3.9	1.3	82.07	42.5	7.61	0.03	0.03	14.809

Tab. 4.2
Content of selected chemical elements in textile waste [8]

	Hg	**As**	**Cd**	**Co**	**Cr**	**Cu**	**Mn**	**No**	**Pb**	**Sb**	**Ti**	**V**	**Zn**
	[$\mu g.kg^{-1}$]	[$mg.kg^{-1}$]											
Polyester	17	< 1.0	< 0.06	0.621	1.45	7.60	1.26	1.58	2.99	156	< 1.0	< 0.50	12.2
Cotton	4.0	< 1.0	< 0.06	< 0.10	0.94	4.42	4.01	1.22	3.00	< 1.5	< 1.0	< 0.50	9.54

4.2. Pyrolysis of textile waste

If we only focus on the pyrolysis processing of textile waste in the study, there are practically three recovery regimes that can be distinguished – each of them has different requirements for sorting the input raw material, processing operating temperature, gas cleaning and operational cost-effectiveness.

4.2.1. Pyrolysis for fuel fractions

Pyrolysis for fuel fractions (pyrolysis oil and gas) – a ‘robust’ regime, suitable for industrial processing of large quantities of diverse textile waste, but the quality of the output pyrolysis oil varies. Typical conditions: operating temperature of 400–600 °C, inert reactor atmosphere (most often N_2), residence time in the work area according to the type of pyrolysis reactor (screw, rotary kilns or fluidised beds are used).

For pure and mixed textiles, the yields of pyrolysis oil, gas and solid residue are monitored in published laboratory studies, and their composition is evaluated. With increasing operating temperature, the proportion of pyrolysis gas generally increases (especially for polyester and mixtures), which can also be seen in the data of studies dedicated to the processing of cotton, polyester and their mixtures with a ratio of 45% cotton and 55% polyester at operating temperatures of 425/500/575 °C. [2]

Technical risks for textile pyrolysis:

- The variability of the composition of textile waste (fibre + dyes + finishes + elastane + prints) results in an unstable composition of the pyrolysis oil.
- Halogens (Cl, Br, etc.) and some added additives cause corrosion and toxic pyrolysis by-products.

- N-fibres (e.g. acrylic/PAN, polyamides) cause the formation of HCN, NH_3, which are toxic and impose requirements for additional cleaning of the pyrolysis gas. The formation of HCN is commonly observed during the pyrolysis of nitrile and similar materials.

A scientific study by authors Arjona et al. [2] is focused on pyrolysis of pure cotton, polyester and a mixture of 55% polyester and 45% cotton as a sustainable approach to managing textile waste and recovering resources (fuels for energy and the chemical industry). Pyrolysis was carried out in a tubular reactor at temperatures of 425 °C, 500 °C and 575 °C. The resulting fractions of solid residue, pyrolysis oil and gas were quantified and characterised. Highest pyrolysis oil yield (more than 45%) was achieved using pure cotton; the pyrolysis oil was formed primarily from the heavy fraction of heating oil. In contrast, pure polyester and cotton-polyester mixtures produced a predominantly gaseous fraction (more than 50%) with hydrogen as the main component. The solid residue, especially after processing cotton waste at an operating temperature of 575 °C, showed a significant carbon content (75.6%) and textural properties suitable for use in the form of an adsorbent. The study focused on processing textile waste separated from municipal waste, but the findings demonstrate the potential of pyrolysis for energy recovery and supporting the circular economy in textile waste management.

The study also summarises the results of the elemental and closer analysis of the input textile waste, as shown in Tab. 4.3. Elemental analysis showed that the textile waste samples consisted mainly of carbon (the most important energy carrier) and oxygen. Cotton contained 41.57% carbon and polyester contained 60.15%. carbon. Cotton contained 49.39% oxygen and polyester contained 33.80%. oxygen. A significant amount of hydrogen and a low ash content (below 2%). were also found. The nitrogen and sulfur content was negligible. More detailed analysis confirmed that the textile waste consisted mainly of volatile substances (over 82%, which is advantageous for pyrolysis processing).

Tab. 4.3
Characterisation of input materials for textile waste energy recovery [2]

					Elemental analysis [%]				
	Humidity [%]	**Volatile substances [%]**	**Fixed carbon [%]**	**Ash content [%]**	**C**	**H**	**N**	**S**	**O**
Cotton	3.72	87.76	6.90	1.61	41.57	6.02	0.66	0.75	49.39
Polyester	0.00	84.05	14.12	1.83	60.15	4.22	0.00	0.00	33.80
Cotton/polyester	2.52	82.70	13.04	1.71	48.78	5.63	0.23	0.23	43.65

4.2.2. Pyrolysis as a method of chemical recovery

Pyrolysis as a method of chemical recovery – high selectivity; however, this recovery method requires clean waste streams, and the processed waste can no longer be considered a waste mix but rather a polymer raw material.

Polyester (PET) – pyrolytic processing leads to products such as benzoic acid or aromatics. PET can be directed by pyrolysis towards relatively valuable aromatic products; the literature includes studies aimed at obtaining benzoic acid, which depends significantly on the operating temperature, residence time and the catalyst used.

The authors Diaz-Silvarrey et al. [6] focused their research on obtaining benzoic acid from PET waste (plastic bottles and packaging material from the food industry) and polyester fibres. To obtain products with added value from waste, other versatile alternatives such as pyrolysis should be used. Thermochemical conversion is considered a promising approach to obtaining benzoic acid, a precursor in the food and beverage industry, unlike its current production process from fossil fuels. This study examined the effect of operating conditions, i.e. temperature, residence time, [16] mass ratio of plastic waste and catalyst, and the effect of volatile interactions on the yield and properties of the obtained pyrolysis product. Zirconium sulfate was used for catalytic pyrolysis, which has favourable properties due to its high acidity and environmentally friendly synthesis. The research results showed that by pyrolysing PET and polyesters at an operating temperature of 450–600 °C and a residence time of 20 seconds, it was possible to obtain up to 27–32 wt.% of benzoic acid. By increasing the catalyst/plastic waste ratio to 10 wt.%, only 26 wt.% of benzoic acid was obtained, but an increase in other valuable pyrolysis products, i.e. light hydrocarbons (with carbon numbers C_1 – C_3), was observed, which were obtained in the pyrolysis gas.

As described above, if the waste pyrolysis process is aimed at a specific end product, it is necessary to know the process operating conditions in detail. For example, the authors Perez et al. [25] focused on evaluating the effects of various conditions of pyrolytic processing of polyester waste. The study provides an in-depth examination of the primary decomposition of polyethylene terephthalate (PET) through pyrolysis using an experimental-analytical work procedure that integrates design of experiments, micro-pyrolysis coupled with comprehensive two-dimensional gas chromatography, and multidimensional data analysis to verify intrinsic kinetic conditions and understand evolving product distributions for mapping key reaction pathways. Among all the parameters examined, pyrolysis temperature was the only statistically significant factor affecting product yield ranging from 58.78 to 84.26 wt.%. In contrast, the other parameters, whether sample mass or carrier gas flow rate, did not have a significant effect on product yield in the evaluated experimental environment. At 600 °C, the main pyrolysis products were benzoic acid (up to 20.20 ± 1.46 wt.%) and CO_2 (up to 21.28 ± 1.46 wt.%), which can be formed by decarboxylation reactions.

Polyamide 6 (nylon-6) pyrolytic processing leads to products such as ε-caprolactam[2] (monomer). For polyamide 6 (PA6), pyrolysis or depolymerisation towards ε-caprolactam already looks very attractive, but selectivity depends on catalysis and control of conditions. Several studies are focused more on chemical recycling using suitable catalysts at low temperatures [15]. The selection of a suitable catalyst and the method of its use are the most important. In

[2] -caprolactam is a cyclic amide (lactam) of ε-aminocaproic acid, which appears as a white, hygroscopic solid. It is a key industrial raw material, produced in volumes of millions of tonnes per year, used almost exclusively for the production of polyamide 6 (nylon 6). Key properties and uses: a colourless to white crystalline substance. The main component in the production of nylon 6, which is used to make fibres, carpets, technical plastics and films. It is produced by cyclisation, for example from hexamethylenediamine or other precursors. It is a substance with high water solubility, which is important in its processing.

this study, the authors introduce a simple and efficient methodology to achieve recycling of polyamide 6 (PA6) to ε-caprolactam (CPL) in a closed loop through rational catalyst design. In pyrolytic processing of nylon, the advantage of vacuum pyrolysis for rapid removal of volatile products is often discussed (reduction of secondary reactions in the primary pyrolysis gas).

'Chemical' pyrolysis works optimally when monomaterial inputs are available (for example, only polyester or only polyamide). Mixed textile waste, such as clothing combining materials like polyester/cotton, polyester/elastane, nylon/elastane, etc., make efficient processing of waste using this technology impossible and rapidly reduce selectivity.

Catalytic pyrolysis represents a promising method of transforming waste into valuable chemicals, offering a path towards a more sustainable circular economy[13]. In this study, catalytic pyrolysis of low-density polyethylene (LDPE) under MW irradiation was carried out. The effect of different types of catalysts (HZSM-5, Ga/ZSM-5, Ga/Ni/ZSM-5, Ga/Co/ZSM-5 and Ga/Cu/ZSM-5) on product yield and distribution (pyrolysis oil/gas/solid residue ratio) was examined. The results showed that the Ga/ZSM-5 catalyst provided the maximum liquid oil yield, approximately 41%. Ga/Ni/ZSM-5 performed excellently in the production of long-chain olefins, making up approximately 27% of the liquid fraction. Ga/Co/ZSM-5, however, led to the production of heavier pyrolysis oil containing nearly 25% long-chain paraffins, making it unsuitable for the production of high-value chemicals. In contrast, the Ga/Cu/ZSM-5 catalyst produced pyrolysis oil rich in aromatic hydrocarbons, with benzene derivatives making up approximately 90% of the liquid oil fraction, proving to be a suitable catalyst. The use of the HZSM-5 catalyst could yield an 86.4% naphtha fraction. The study also showed that the Ga/Cu/ZSM-5 catalyst generated the largest amount of hydrogen and synthesis gas, as determined by MicroGC analysis of gaseous products. This catalyst also exhibited the highest coke deposition (1.35%) after the reaction, which is attributed to its high content of aromatic hydrocarbons in the pyrolysis oil and maximum hydrogen release. The properties of the fresh and used catalyst were also compared to get a clear picture of catalyst activity and correlate the effects of metal doping on product distribution. These findings highlight the potential of microwave-assisted catalytic pyrolysis, especially with the Ga/Cu/ZSM-5 catalyst, for the efficient conversion of waste into valuable chemicals, thereby contributing to sustainable resource use and environmental protection.

4.2.3. Pyrolysis focused on solid residue

Pyrolysis focused on solid residue ('char' or 'biochar') and its subsequent activation – this approach is particularly suitable for cellulosic textiles. For textiles such as cotton or viscose, directing pyrolysis in this direction is often more suitable than focusing on pyrolysis oil, which is highly oxidised. After activation, the carbon residue is used in sorption applications. For this method of textile waste recovery, it is critical to monitor the composition of the raw material in terms of ash content, metal content and halogens (due to the later use of the activated material and the leachability of halogenated compounds).

In a study by Rubi et al. [27], cotton textile waste underwent slow pyrolysis in a fixed-bed reactor at different operating temperatures (350 °C to 550 °C), yielding a carbon residue as a precursor for the production of activated carbon. The carbon residue was then chemically activated using H_3PO_4 at different impregnation ratios and subsequently heat-treated, resulting in activated carbon. The produced carbon residue and activated carbon were characterised using scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR). The results showed that the highest yield of carbon residue after pyrolysis (27.64 wt.%) was achieved at 450 °C, with the microporous structure increasing with increasing temperature. On the other hand, the micropores volume of activated carbon increases with increasing impregnation ratio. Finally, activated carbon exhibits an acidic surface with many oxygen-containing surface groups, making it a promising candidate for various applications in the chemical industry.

4.2.4. Risks associated with the pyrolytic processing of textile waste

Waste sorting and 'invisible' additives – the greatest process uncertainty in pyrolytic processing of textiles stems from flame retardants (often Br) and some surface treatments. During the thermal decomposition of halogenated additives, the formation of (poly)brominated dioxins and furans and their precursors is examined – the mechanisms and risks are well described in several studies. For example, Altarawneh et al. [1] study in their work the effect of brominated flame retardants on the formation of polybrominated dibenzofurans (PBDF) and polybrominated diphenyl ethers (PBDE) through the oxidation of monobromobenzene (MBBz). The study maps the reaction pathways and presents kinetic parameters for the formation of PBDF and PBDE from coupling reactions of the MBBz molecule and its derived ortho-bromophenoxy (o-BPhxy) radical using quantum-chemical calculations.

A study by Perenich and Tuazon [16] examined gases formed during the combustion of carpets made of nylon, acrylic or acrylic/modacrylic fibres. Infrared spectra of carpet fibres were obtained after pyrolysis of the samples. The results showed that hydrogen cyanide, carbon dioxide, carbon monoxide, acrylonitrile, acetylene, ethylene, methane and ammonia were released during the reaction. Each of these substances is life-threatening; each of the specific toxic substances formed during combustion can be fatal if present in sufficient quantity. The research also showed that the cumulative and synergistic effects of these gases can cause weakness and death.

Based on the study of the available literature, important conclusions can be drawn for the application of pyrolysis in textile waste processing: without analysis of the chemical composition of the input material, especially the Cl and Br content, and without adequate gas purification (alkaline neutralisation by scrubbing + sorption on activated carbon), pyrolytic processing is risky.

Textile waste mixtures, such as cotton/polyester, do not behave as a linear sum, which essentially means that in real textiles, clothing and mixtures, the composition of products and the decomposition process differ from that of pure fibres. A study by Sakurai et al. [30] examined pyrolytic processing of textile waste; waste clothing made of polyester, cotton and common mixed textiles was used as experimental samples. Pyrolysis characteristics were examined using thermogravimetric analysis (TGA) and laboratory pyrolysis experiments. The thermogravimetric (TG) curve showed that pyrolysis of polyester and cotton started at 255.1 °C and ended at 471.7 °C. Laboratory pyrolysis experiments were then performed at heating temperatures of 400, 500, 600 and 700 °C. The pyrolysis products were characterised by analysing the formed solid residue (consisting mainly of carbon), pyrolysis oil and gas. The solid residue from the pyrolysis of polyester and cotton showed a high calorific value. Analysis of the composition of the pyrolysis oil showed the presence of substances with a phenyl structure derived from polyester, with benzoic acid being an important component of the pyrolysis oil. This composition was characterised by significant production of polycyclic aromatic hydrocarbons, even at pyrolysis temperatures below 700 °C. The main components of the pyrolysis gases were CO_2 and CO. The study's conclusions indicate a link between the effect of operating temperature and the chemical composition of the pyrolysis products. A mechanism was proposed in which interactions between hydroxyl groups in the molecular structure of cotton and benzene rings in the molecular structure of polyester during pyrolysis lead to the formation of CO. These findings contribute to the development of recycling technologies for the utilisation of textile waste as a future source of energy and chemical raw material.

The choice of pyrolysis reactor type based on the requirements for the final product has a fundamental impact on the process.

- Screw reactor, rotary reactor – slow or medium-fast pyrolysis, heterogeneity of the input material is tolerated, but the quality of the resulting products corresponds to this.
- Fluidised bed – fast pyrolysis, better heat and mass transfer, the resulting pyrolysis oil has stable properties (if a stable supply of single-type textile waste is ensured).
- Catalytic pyrolysis (extensive research on used catalysts) – tends to produce aromatics, but the demands on the purity of the input material increase, catalyst deactivation may occur, and the content of halogens and metals is undesirable.

4.3. Design of a pyrolysis processing procedure for textile waste

4.3.1. General procedure

1. Classification of the input raw material according to fibre type (cotton, viscose, polyester, PA6, PAN, acrylic and their mixtures), it is also necessary to focus on the content of elements such as chlorine, bromine, nitrogen, sulfur, metals, etc. (at least by using XRF or IC methods).
2. TGA or DTG analysis together with isoconversional kinetics for a quick overview of temperature windows optimal for pyrolysis.
3. Py-GC or MS method for mapping output products (mainly when processing polyester and PA6, where it is possible to target the pyrolysis processing process at specific valuable chemicals.
4. For the final pyrolysis gas, the concentrations of at least these components should be monitored: CO, CO_2, H_2 and CH_4/C_2+, and, compulsorily, HCN/NH_3 for N-textiles.
5. If previous analyses have shown a need to address emerging halogens or FR, it is necessary to think about gas cleaning and neutralisation from the beginning of the process (neutralisation of acid gases + sorption of organohalogens). [16]

If we focus our research only on textile waste from the automotive industry, it is key to first distinguish which point in the industrial production chain the waste comes from, because this determines whether the pyrolysis can be chemically targeted at a specific chemical product (monomers, chemicals, etc.), or robust instead – focused on processing diverse waste while focusing on the production of pyrolysis oil and solid residue with an emphasis on further processing – cleaning and neutralisation.

a) If the pyrolysis is focused on waste generated during production (cuttings, trimmings from airbags, belts, upholstery, carpets, etc.), we know its material composition and the waste is often significantly more homogeneous (e.g. PA66 airbag fabric, PET belts, PP/PET non-woven textiles, carpet systems). In such a case, it makes sense to fractionate the waste according to the specific polymer and choose a different pyrolysis or thermochemical strategy for each. Some production wastes are inherently a mixture, for example, the composition of automotive carpets is usually a mix of nylon 6/6,6, PP, PET, PE, acrylics, often with latex, binders and backings.
b) If the pyrolysis is focused on processing waste from scrap cars, it is often a heterogeneous mixture with an unclear chemical composition and proportions of individual components, also referred to as ASR – automotive shredder residue. ASR typically makes up 15–25% of the vehicle's weight after the removal of fluids, dismantling and separation of metals; it is a mixture of plastics, rubber, foams, textiles and inorganics [16]. In thermochemical processing of ASR, pyrolysis and gasification are generally considered new technologies. In this case, the pyrolysis focuses mainly on the production of pyrolysis oil with a great emphasis on the pre-treatment of the input raw material, taking into account potential corrosion, formation of halogens, the possibility of metal content and risks associated with the formation of PCB or PAH. Pyrolysis uses medium temperatures (400–600 °C) and an oxygen-free environment for the chemical decomposition of ASR. Gasification of ASR takes place at higher temperatures (> 700–800 °C) and air is typically used as the gasifying agent, which causes certain problems in terms of produced emissions. Data on the typical composition and properties of ASR are shown in the following tables, as obtained from the available literature. Each of the studies is focused on the contents of various ASR elements; comparison or observation of the dispersion of values for specific wastes is possible.

Tab. 4.4
Typical composition and properties of ASR – main elements

% wt, dry state	[16]	[31]	[27]	[20]	[18]	[3] [28]	[20]	[5]	[20] [21]	[31]
C		50.8	56.6	17.5	60.2	32.8–45.1	44.5	30.0		39.7
H		6.5	7.9	2.1	6.6	4.1–6.1	5.3	3.7		4.6
N	0.9	3.0	2.7	0.5	1.7	0.6–3.1	4.5	1.7		0.92
O (diff)			21.4	17.4	7.8		6.9	7.0		11.8
S	0.6	0.3	0.2	0.25		0.2–1.0	0.2	0.3		0.25

Cl	1.8	3.7		0.05	2.5	0.1–3.4	0.5	1.4	0.5–2.0	
Al	2.0					0.74–10.5			0.7–3.0	
Ba	0.58	0.5								0.0012
Ca	4.0									
Cu	1.1	1.6				0.5–7.1	1.2		0.37–2.6	
Fe	14.1					0.9–15.7	25.7	13.0	3.3–18	
K	0.27									
Mg	0.87								0.05–0.8	
Mn	0.10								0.036–0.11	
L	0.71									
P							0.7			
Pb	0.51	0.14				0.22–0.65	0.2		0.11–1.1	0.01
Si	7.70						2.1	9.5		
Ti							0.9			
Zn	0.90	1.2				0.8–6.1	1.9			

Tab. 4.5

Typical composition and properties of ASR – minor elements

mg/kg	[16]	[28] [3]	[22]	[20] [21]	[32]	[31]	[3] [3]
As				20–50	57–63	11	< 2
Ag						< 6	
Br							< 20–90
Cd	61	50–80		<85	14–200	160	< 0.4–3
Co				< 33			< 1
Cr	1,200	50–660	800	1,000–1,800	247–770	280	8–39
F			500				< 30
Hg	2.1			< 4.9	0.7–15	1.6	< 0.1
No	1,200	130–930		400–1,500			4–24
Sb				180–3,200			< 3–43
Se						5.8	
Sn	67			130–400			123–220
V				< 150			< 1–1

[3] Dry PU foam obtained from seats from scrap cars

Tab. 4.6
Typical composition and properties of ASR – other properties

	[27]	[18]	[22]	[4] [28]	[20] [21]	[32]	[31]	[16] [17]	[3] [4]
Moisture (% wt)	1.3	0.8	2.2		2–5		27.3		0.25–3.6
Volatile substances (% wt, dry)	74.4	61.3	54.2				52.4		
Ash (% wt, dry)	12.1	0.8	36.2		28–61		43.2		
PCBs (mg/kg)						1.7–320		5–14	< 50
PAHs (mg/kg)								10–36	
PCDD/F (μg/kg)								0.014	
Calorific value (MJ/kg)			16.7					7–26	
Heat of combustion (MJ/kg)	28.3	28.7			9–20		18.2		25.3–26
Density (kg/m^3)			359	283–563			380		

4.3.2. Process design of a pyrolysis processing procedure for textile waste

Recommended architecture for pyrolysis processing of textile waste from automotive production:

1. Forensic characterisation and quick classification of the input raw material – minimum requirements before process design:
   a. Polymer composition of the input raw material: NIR/FTIR analysis or DSC/TGA analysis as a check.
   b. Elemental analysis: CHNS-O + analysis of Cl and Br content (IC after combustion or XRF analysis).
   c. Ash and metal content: ash at 550–815 °C + XRF/ICP for hazardous elements (Cu, Zn, Pb, etc.).
   d. For ASR waste, the literature reports wide ranges of components it may contain (plastics/textiles/rubber/inorganics), and it is precisely this variability that determines the choice of pyrolysis regime.
2. Pre-treatment of the input raw material (absolutely crucial for automotive waste)
   a. For production waste: remove metal parts (use of metal detectors) and dust, or simple sorting into PA/PET/PP streams.

[4] Dry PU foam obtained from seats from scrap cars

b. For ASR and textiles:
  i. Mechanical shredding + sorting of fractions + separation of metals and minerals; the goal is a stable bulk mixture for continuous feeding.
  ii. An interesting concept is torrefaction as pre-treatment, which can reduce the problem of 'impurities' and corrosion during subsequent ASR pyrolysis.

3. Choice of pyrolysis regime according to the goal
   a. Regime R1: 'robust mode' – production of pyrolysis oil and gas (PP/PE mix + residue):
      i. The operating temperature is typically 450–550 °C; this is the preferred temperature window for high oil yields in PP waste streams.
      ii. For automotive production waste, this usually means: polyolefin input material (PP/PE) → output is pyrolysis oil and gas (used for heating the pyrolysis process) + solid residue.
   b. Regime R2: input is usually polyester/nylon (targeted chemicals) – suitable only after sorting the input material:
      i. For synthetic textiles, it is helpful to follow trends in catalytic and chemical decomposition, because it often makes more sense to decompose PET/PA more selectively than to produce unspecified pyrolysis oil.
      ii. For nylon, the advantage of vacuum pyrolysis for the extraction of volatile products (reduction of secondary reactions) is often discussed. *Note:* airbags are often PA66, where the 'monomer' loop is more complex than for nylon-6; sorting into nylon-6 vs PA66 is therefore essential.
   c. Regime R3: processing of ASR waste into products (if the waste is a heterogeneous mixture):
      i. For ASR pyrolysis, a temperature window of 400–600 °C is commonly stated.
      ii. There are also science articles focused on low-temperature pyrolysis at temperatures of 300/400/500 °C, focused on energy + metal sorting, where the dominant product is solid residue at lower temperatures.
   d. Processing of primary pyrolysis gas and condensation – regardless of the type of pyrolysis reactor used, it is appropriate to use:
      i. A cyclone or hot filter (protection of condensation from dust and aerosol from solid residue).
      ii. Multi-stage condensation – separation of condensate into heavy and light fractions.
      iii. Removal of acidic compounds, for example by scrubbing the primary pyrolysis gas (if the content of Cl and Br elements is not negligible).
      iv. Sorption on activated carbon.
      v. Pyrolysis gas to be used for thermal afterburning, oxidation or as fuel for the process (but only after stabilising its composition).
      vi. For ASR, the production of PCBs/PAHs and contaminants in the solid residue is also addressed; in scientific studies, this is considered a fundamental environmental issue.
      vii.

4.4. Energy recovery of waste from car seat covers

4.4.1. Input analysis of car covers

Samples of car covers were obtained from various sources, from car recyclers in the Žilina region. To ensure a representative set of samples, a diverse range of types and materials of car covers was obtained. The car cover materials were carefully disassembled to separate various components, such as foam, fabric and plastics. Each component was then cleaned, removing any impurities or residues. Elemental analysis techniques were used to assess the composition of the car cover materials. Thermogravimetric analysis (TGA) provided information on thermal stability and decomposition properties. Data obtained from elemental analysis were analysed using appropriate software, and the results were compared with known material databases for identification and quantification of components. CHNS analysis determined the content of basic elements (carbon, hydrogen, nitrogen sulfur) in each sample.

Fig. 4.2 Shredded car cover sample

Fig. 4.3 Shredded car cover samples before weighing

CHNS analysis and thermogravimetric analysis (TGA) of car covers

Thermogravimetric analysis (TGA) examines the thermal behavior of solid materials through controlled heating of the sample while continuously measuring its weight. This method provides important information about the thermal stability of the material, including decomposition temperature, weight loss and reaction kinetics. TGA analysis proves invaluable in assessing the quality of plastic waste from the automotive industry, refined fuel obtained from municipal solid waste, or industrial waste that replaces fossil fuels for energy production. TGA analysis results for plastic waste from the automotive industry usually reveal multiple stages of weight loss, which correspond to different materials present in the fuel, such as loss of moisture, volatile organic compounds and decomposition of materials such as plastics or paper. Component samples undergo mechanical shredding for analysis on instruments such as the LECO TGA 701 for moisture, volatile substances, fixed carbon and ash content, the LECO CHN628 for carbon, hydrogen and nitrogen content, and the LECO 628S module for sulfur content.

The particle size in all samples mostly ranged from 0.5 mm to 2 mm. Detailed results of the analyses are presented in Tab. 4.7 and Fig. 4.4. The elemental analysis included pre-weighed samples burned without atmospheric gases. The thermogravimetric analyzer monitored the weight loss of individual samples with increasing temperature. The samples were gradually heated at 107 °C (air atmosphere), 900 °C (nitrogen atmosphere) and cooled at 550 °C (air atmosphere). Standard methods for solid biofuels, which follow the STN EN ISO 18134, STN EN 18122, and STN EN ISO 18123 standards, were used in this examination.

Tab. 4.7
Results of the analysis of nitrogen, carbon, hydrogen and sulfur content of car covers

Sample	Nitrogen [%]	Carbon [%]	Hydrogen [%]	Sulfur [%]
Type 1	0.48	50.12	7.57	0.20
Type 2	0.40	54.89	7.80	0.26
Type 3	1.26	47.50	6.62	0.33
Type 4	0.29	59.60	9.89	0.31
Type 5	0.69	53.30	6.88	0.30

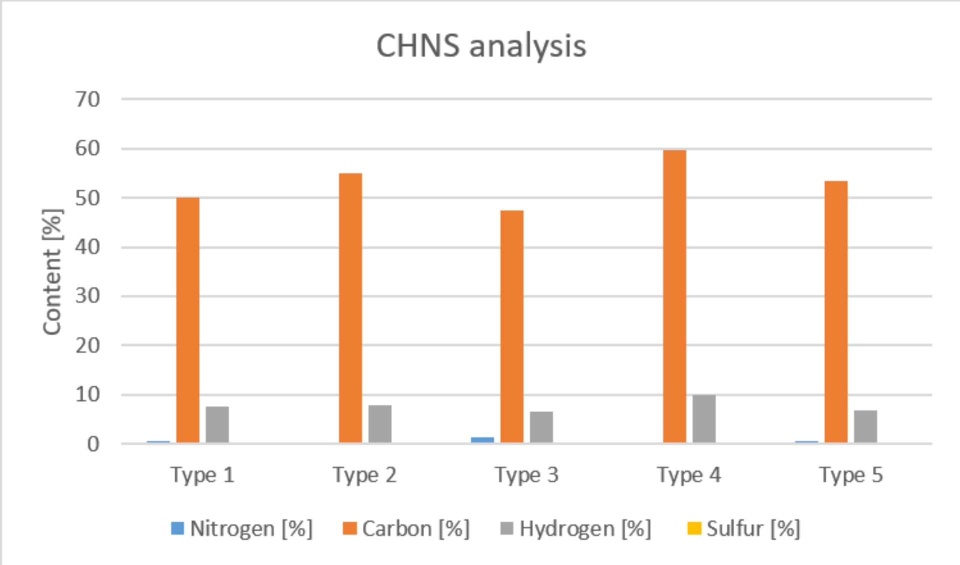

Fig. 4.4 Results of the analysis of nitrogen, carbon, hydrogen and sulfur content of car covers

We analysed the CHNS (carbon, hydrogen, nitrogen, sulfur) analysis results of five automotive plastic samples identified as Type 1 to Type 5. We focused on the content of carbon, hydrogen, nitrogen and sulfur, which are key to determining their properties and potential application.

We found that the Type 4 sample had the highest carbon content (59.6%) and hydrogen (9.89%), while the nitrogen (0.29%) and sulfur (0.31%). The Type 1, Type 2 and Type 5 samples had a carbon composition ranging from 50.1% to 54.89% and a hydrogen content ranging from 6.62% to 7.8%. The nitrogen and sulfur content in these samples was also low.

The Type 3 sample differed significantly in that it had the lowest carbon content (47.5%) and the highest nitrogen content (1.26%). The hydrogen content was 6.62% and the sulfur content was 0.33%.

Based on these data, we concluded that the Type 2 to Type 4 samples likely represent different types of polyolefins, such as polyethylene (PE) or polypropylene (PP), which are characterised by a high carbon and hydrogen content. The Type 3 sample, with a higher nitrogen content, could be polyamide (nylon) or another nitrogen-containing polymer.

It is important to note that these conclusions are only preliminary, and further analyses would be necessary for definitive identification.

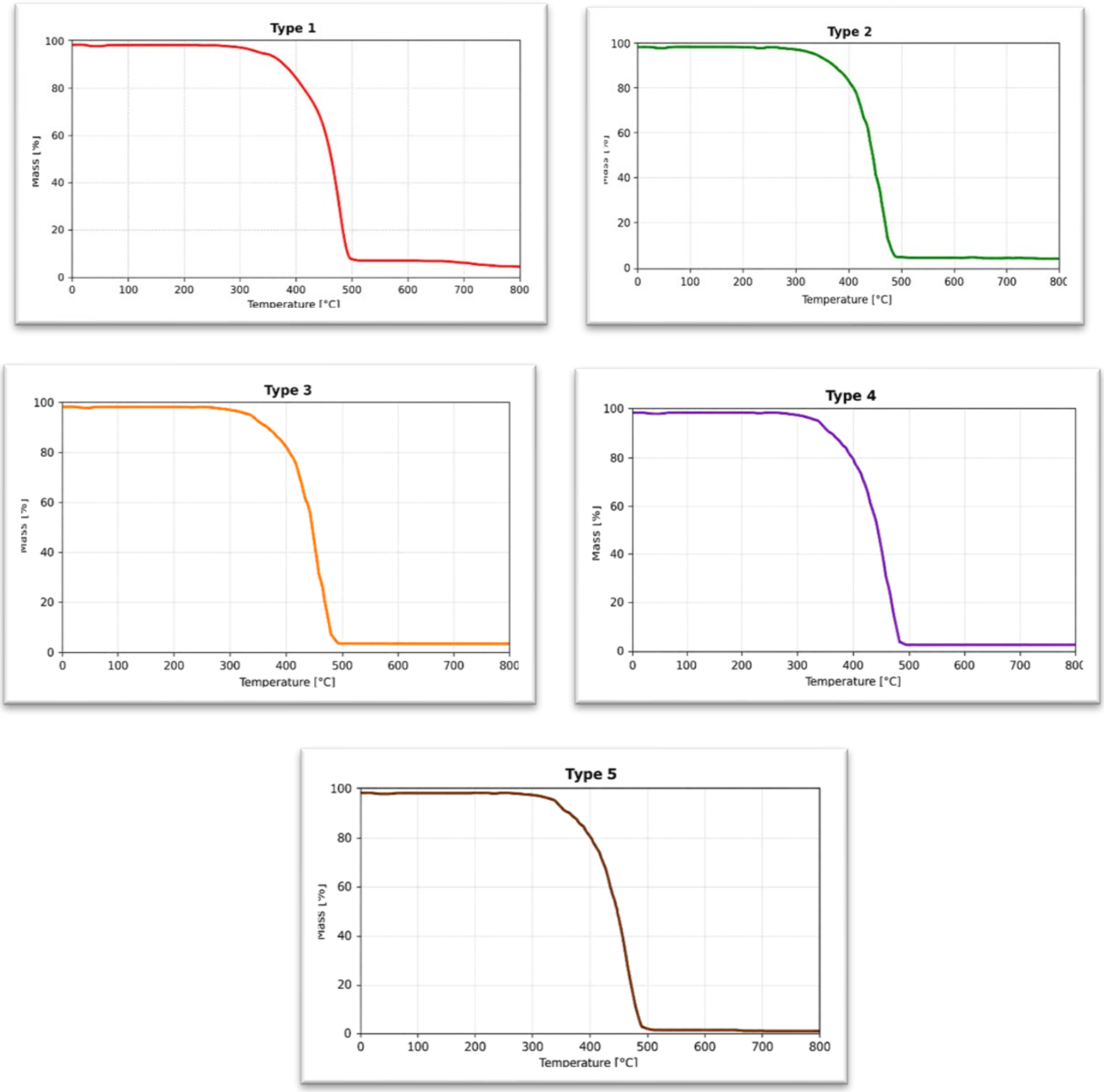

Fig. 4.5 TGA curve of an automotive seat sample

The analysis results consist of the arithmetic average of three measurements of the samples on each equipment unit. During the laboratory analysis, all standards necessary for the accuracy of the measurement were followed. Understanding the thermal properties of these materials is crucial for the development of efficient recycling processes. By knowing the relevant decomposition temperatures of the materials, recycling facilities can optimise energy consumption and minimise emissions during processing.

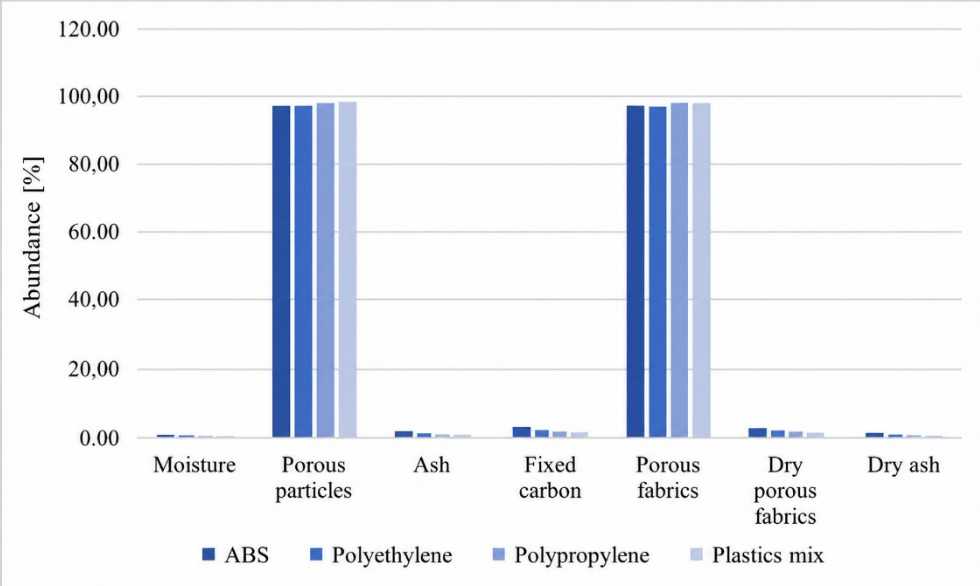

Fig. 4.6 TGA analysis of automotive textiles

The analysis of thermogravimetric (TGA) measurements of various automotive plastic samples revealed their thermal behaviour and composition.

The ABS sample shows a low moisture content (0.57%), which indicates that the material was sufficiently dried before analysis. The volatile substances content is very high (98.69%), which points to a high proportion of organic components that decompose at lower temperatures. On the other hand, the ash content is very low (1.42%), which indicates a minimal amount of inorganic substances, such as fillers or flame retardants. Fixed carbon makes up only 0.46% of the sample, which confirms the low content of organic components that resist high temperatures.

Polyethylene and polypropylene samples show similar results. The moisture content is low (0.52% and 0.42%), the volatile substances content is high (97.72% and 98.95%) and the ash content is low (0.64% and 0.20%). Fixed carbon makes up 2.16% in polyethylene and 1.26% in polypropylene, which again confirms the high content of organic components.

The plastic mixture sample shows similar results to polyethylene and polypropylene, with a low moisture content (0.35%), a high volatile substances content (98.85%) and a low ash content (0.25%). Fixed carbon makes up 1.25% of the sample.

A comparison of all samples shows that all analysed plastics are characterised by a high volatile substances content and low ash content, which indicates an organic nature. Differences in fixed carbon content among the individual samples may be caused by different polymer compositions and the presence of additives.

These findings are important for understanding the behaviour of these materials at high temperatures in, for example, recycling processes such as pyrolysis. The high volatile substances content shows that these plastics are suitable for pyrolysis because they easily decompose at high temperatures into gases and liquids that can be further processed. The low ash content is advantageous because it minimises the amount of solid waste generated during pyrolysis.

Calorific value of car upholstery

The calorific value of plastic waste from the automotive industry represents the energy released during combustion. Its remarkably high calorific value positions it as an alternative to traditional fossil fuels and represents a renewable energy source. This value, which ranges approximately between 18–24 MJ.kg^{-1}, significantly exceeds the value of municipal solid waste (MSW), which is normally incinerated. This difference highlights the potential of automotive plastic waste as a strong energy source offering an environmentally beneficial alternative. Its ability to release a significant amount of energy during combustion makes it an attractive prospect in the ongoing search for sustainable and cleaner energy solutions. In addition to addressing waste management problems, the utilisation of the natural energy content of automotive plastic waste contributes to the transition to more ecological energy practices, which is in line with broader environmental sustainability goals.

The heat of combustion was determined by the LECO AC 500 instrument by measuring the heat released after burning the sample. The calorific value was calculated from the heat of combustion based on equation (1) and equation (2).

$$\mathrm{LCV} = \mathrm{HCV} - r_{H2O}(W_p + 8.94 x_H) \quad (1)$$

$$x_H = H_h \cdot B_p \quad (2)$$

where r_{H2O} is the latent heat of vaporisation of water in MJ.kg^{-1}; W_p is the water content (kg.kg^{-1}); the conversion coefficient of hydrogen to water with a value of 8.94; H_h is the hydrogen content (kg.kg^{-1}) and B_p is the volatile matter content (kg.kg^{-1}) of the tested samples.

All measurements were repeated two to four times. However, five types of plastic samples were tested. The results of the calorific value analysis are shown in Tab. 4.8. The heat of combustion values ranged from 22.33 to 26.95 MJ.kg^{-1}. The calorific values ranged from 20.80 to 24.95 MJ.kg^{-1}. The obtained results were generally significantly higher compared to wood fuels.

Tab. 4.8

Results of calorific value and heat of combustion of a car seat

Sample	Heat of combustion [MJ.kg^{-1}]	Calorific value [MJ.kg^{-1}]
Type 1	24.29	22.55

Type 2	24.19	22.31
Type 3	22.33	20.80
Type 4	26.89	24.95
Type 5	24.07	22.45

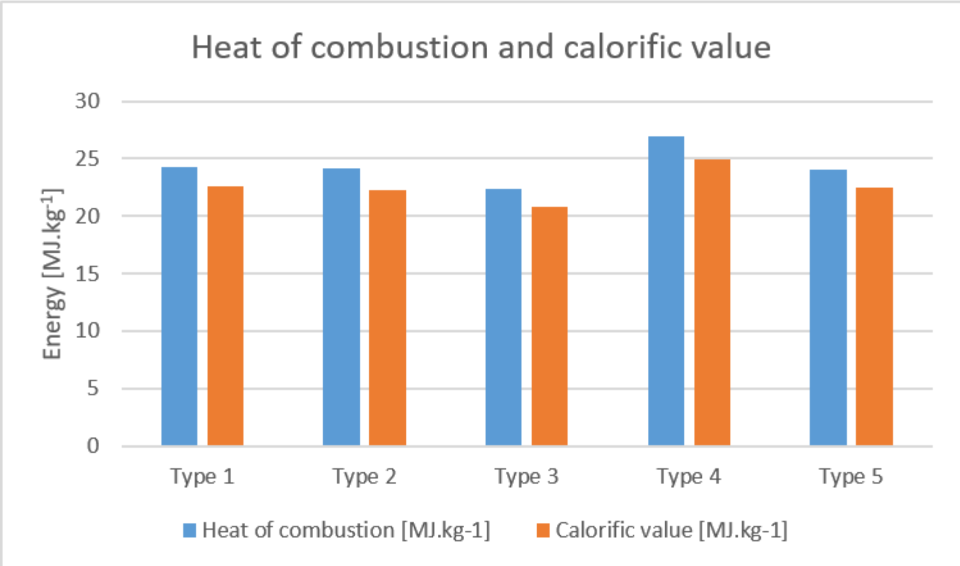

Fig. 4.7 Results of calorific value and heat of combustion of a car seat

The results of the elemental analysis are shown in Tab. 4.7. The nitrogen content ranged from 0.29 to 1.26%. The carbon content ranged from 47.50 to 59.60%. The hydrogen content ranged from 6.62 to 9.89%. The sulfur content ranged from 0.20 to 0.33%. The obtained carbon content results were generally higher compared to wood fuels. However, the nitrogen and sulfur content was higher, which is negative due to the formation of nitrogen or sulfur oxide emissions.

4.4.2. Pyrolysis of car upholstery

By performing initial tests, we determined the pyrolysis process setting parameters for the given car upholstery samples. Initial analyses of the examined samples included the following analyses: TGA, CHNS, calorific value and heat of combustion.

Sample preparation before measurement

After performing the initial analyses of the car upholstery textile materials, the samples were cut into smaller pieces suitable for loading into the pyrolysis reactor. Before pyrolysis, we collected a representative sample of car upholstery from various parts of the car. The sample contained various upholstery materials, such as fabric and leather seat covers, reinforcements and fillings, headliners and door upholstery. We thoroughly cleaned the textile materials of all dirt and foreign substances, such as dust, crumbs and other dirt. We ground them into small pieces with a size of approximately 2–3 cm. We dried the crushed materials in a dryer at a temperature of 40–50 °C for 6 hours until they reached a constant weight. After drying, we weighed the required amount of dried crushed material. The typical sample weight for the pyrolysis measurement ranged from 250 to 300 g. We placed the sample into a pyrolysis reactor, which is resistant to high temperatures and inert gases. Using this procedure, we prepared the car upholstery material sample for pyrolysis measurement and analysed the pyrolysis products in order to obtain information about the composition and properties of the material. Analyses of the obtained products included: TGA, CHNS analysis, calorific value and heat of combustion.

Measurement procedure

When setting up the pyrolysis equipment for car seat upholstery, we carefully considered several parameters. Based on an analysis of TGA curves, we set the pyrolysis temperature to 485 °C and the residence time after reaching the pyrolysis temperature to 15 min. to ensure effective decomposition of materials without excessive formation of undesirable products. The duration of pyrolysis can range from minutes to several hours, depending on the type of material and the required degree of decomposition.

We used an inert carbon dioxide atmosphere in the reactor to prevent oxidation and burning of the material. We chose a heating rate of 6.5 °C per min. to avoid uncontrolled decomposition or unnecessary prolongation of the process.

Fig. 4.8 Car upholstery material load

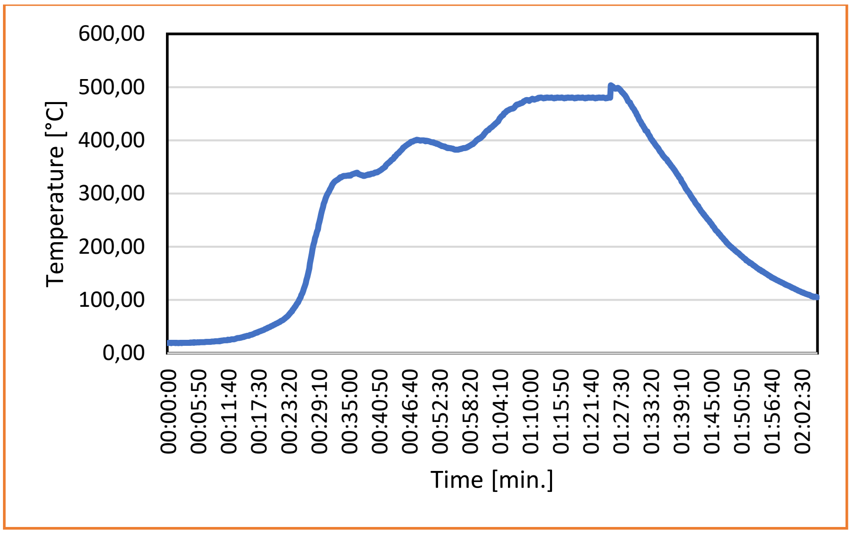

Fig. 4.9 Time and temperature profile of the measurement

Tab. 4.9
Pyrolysis measurement of car upholstery

Measurement	**1.**	**2.**
Load weight	285.5 g	271.4 g
Solid residue	51.39 g	50.48 g
Liquid	19.99 g	66.22 g
Gas	214.12 g	154.7 g
Measurement time	15 min	15 min

4.4.3. Car upholstery measurement results

Products obtained from processing car seat upholstery

According to the analysis of the TGA curves, we determined the pyrolysis temperature to be 485 °C and the residence time after reaching the pyrolysis temperature to be 15 min. After pyrolytic processing of the car upholstery, we also obtained a solid residue. This material represented a complex mixture of carbon and inorganic substances, with its exact composition depending on the original upholstery material and the conditions we set during pyrolysis. We further analysed the solid residue and found that we could use it in various ways. Given its carbon content, we tested it as a fuel with a lower calorific value. In addition, we examined its adsorption properties and found that it is suitable for capturing some pollutants. Another possible use was its application as a filler in composite materials.

The results of a spectral analysis revealed the presence of various organic compounds in the sample, with hydrocarbons and their derivatives making up the majority. In the area with the lowest retention time (1.92), there is 3-methyl-6-(1-methylethyl)-2-cyclohexen-1-one, which is a cyclic ketone with a double bond. This compound is probably responsible for the characteristic odour of the sample. In the portion between 2.24 and 2.67, there is a group of aromatic and aliphatic hydrocarbons. 1,4-dioxane (2.24) is a cyclic ether often used as a solvent. Benzene (2.54), toluene (2.67) and 2-methyl-1-decene (2.55) are typical components of petroleum products and may indicate the presence of fuel or other petroleum derivatives in the sample. Methyl benzoate (2.56) is an ester with a characteristic odour used in perfumery. In the portion between 3.15 and 3.9, there are other organic compounds with various functional groups. Cyclopentanone (3.15) is a cyclic ketone used as a solvent and intermediate in the production of plastics. 3-penten-2-one (3.48) is an unsaturated ketone that may be a decomposition product of some polymers. 2-propyl-1-heptanol (3.54) and 2,4-diethyl-1-heptanol (5.55) are fatty alcohols that may be found in some lubricants and oils. Diethylene glycol (3.57) is a dihydric alcohol used as a solvent and plasticizer. 3-cyanotricyclohex-3-ene (3.9) is a cyclic compound with a nitrile group that may be a decomposition product of some polymers. In the 4.65 portion, there is 4-methylidenecyclohexanone, which is a cyclic ketone with a double bond. This compound may also be a decomposition product of some polymers. In the 11.15 portion, there is diacetamide, which is an amide derived from acetic acid. This compound may be present in some adhesives and paints. In the 18.92 portion, there is trimethyl orthoformate, which is an ester of formic acid. This compound may be found in some solvents and paints. It is important to note that this analysis is only qualitative and does not provide information about the exact concentrations of individual compounds. For quantification, other analytical methods would be needed, such as gas chromatography with mass spectrometry (GC-MS).

Overall, the results of the spectral analysis suggest that the sample contains a mixture of various organic compounds, most of which are hydrocarbons and their derivatives. The presence of some compounds may indicate the origin of the sample (for example, petroleum products, plastics, adhesives, paints).

Fig. 4.10 Liquid phase of car seat upholstery

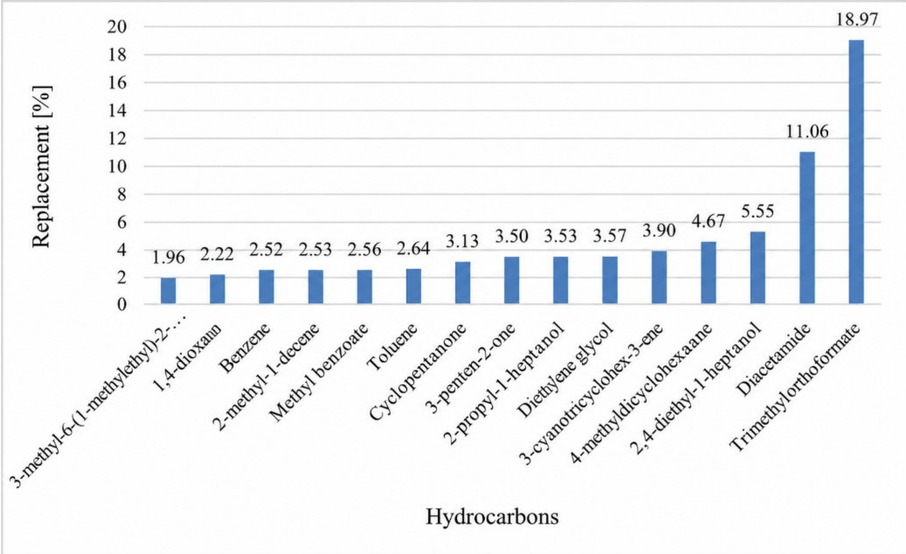

Fig. 4.11 Most abundant hydrocarbons in the liquid phase

During the pyrolysis of the car upholstery, we observed the formation of a gas phase, which represented an important product of the process. We found that the composition of this gas mixture depends on the type of material processed and the pyrolysis conditions used. The dominant components were often hydrogen, methane, carbon monoxide and carbon dioxide, but other hydrocarbons and gases were also present. The analysis of the results of the pyrolytic measurement of samples of synthetic car upholstery provides valuable information about the composition and energy potential of the gas phase formed during the process. The dominant components of the gas phase are carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and carbon monoxide (CO). Their abundance indicates that pyrolysis took place under incomplete combustion, which is typical for this process, in which organic materials decompose at high temperatures without access to oxygen.

The presence of ethylene (C_2H_4) and ethane (C_2H_6) in relatively high concentrations (7.62% and 6.40%) indicates that the input material contained polyethylene (PE), which is a common plastic used in car upholstery. Other hydrocarbons, such as propene (C_3H_6) and propane (C_3H_8), are probably products of the decomposition of other polymeric materials or the result of secondary reactions during pyrolysis.

Fig. 4.12 Combustion of pyrolysis gas in the afterburner chamber

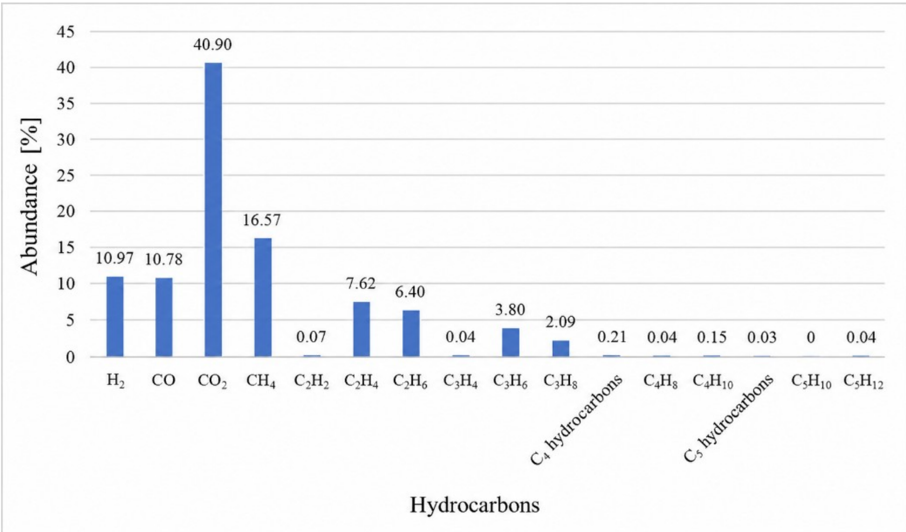

Fig. 4.13 Hydrocarbon content in the gas phase of car upholstery

The heat of combustion of 17.92 $MJ.kg^{-1}$ and the calorific value of 16.46 $MJ.kg^{-1}$ indicate a high energy potential of the gas mixture. These values are comparable to some conventional fuels, suggesting that the gas obtained through pyrolysis could be used as an alternative energy source. However, given the presence of carbon monoxide, which is toxic, the gas would need to be thoroughly cleaned before energy use. The gas density of 1.2731 $kg.m^{-3}$ is an important parameter for its storage and transport. This value is higher than the density of air, which means that the gas is heavier than air and will tend to sink. Overall, the results of the gas phase analysis confirm that the pyrolysis of synthetic car seat upholstery is a promising waste recovery method. The obtained gas has high energy potential and, after suitable treatment, could be used as fuel or as a raw material for the chemical industry. However, further research is needed to optimise the pyrolysis and gas cleaning process in order to minimise environmental risks and maximise process efficiency.

The solid residue from the pyrolysis of car seat covers, called char, represents a complex mixture of carbon and inorganic substances. Its composition depends on the original material of the covers and the pyrolysis conditions. The solid residue may contain various metals and other elements depending on the additives and dyes used in the production of the covers. The use of the solid residue is broad: it can serve as a fuel with a lower calorific value, as an adsorbent for capturing pollutants from gases or liquids, or as a filler in composite materials.

Fig. 4.14 Solid residue after pyrolysis of car seat covers

An EDXRF analysis of car covers shows a complex composition with various elements represented in different concentrations. The dominant components are antimony (Sb) and iron (Fe), which make up 1.48% and 1.49% of the total composition. Antimony is often used in car covers for its ability to improve corrosion and abrasion resistance, while iron can be part of pigments or other additives.

Calcium (Ca) and chromium (Cr), present in concentrations of 1.03% and 0.97%, are other important elements. Calcium can be part of fillers or stabilisers, while chromium is often used in pigments for its vibrant colour and resistance to fading. Chlorine (Cl), silicon (Si), phosphorus (P) and titanium (Ti) are present in smaller amounts, ranging from 0.58% to 0.80%. These elements can perform various functions, such as improving adhesion, hardness or weather resistance. Chlorine can also be part of solvents or other additives. Magnesium (Mg) and barium (Ba) are present in even smaller concentrations (0.33% and 0.27%), which suggests their possible role as trace elements or impurities. Their presence may be caused by the raw materials used or the production process. The presence of trace amounts of copper (Cu), sulfur (S), tin (Sn), zinc (Zn), potassium (K), silver (Ag), lead (Pb), nickel (Ni) and strontium (Sr), with concentrations below 0.10%, may be caused by contamination or natural occurrence in the materials used. Even though these elements are only present in small amounts, they can affect the properties of the covers, such as their corrosion resistance or colour fastness. Overall, this EDXRF analysis provides a detailed insight into the composition of car covers, which is important for understanding their properties, performance and potential environmental impacts.

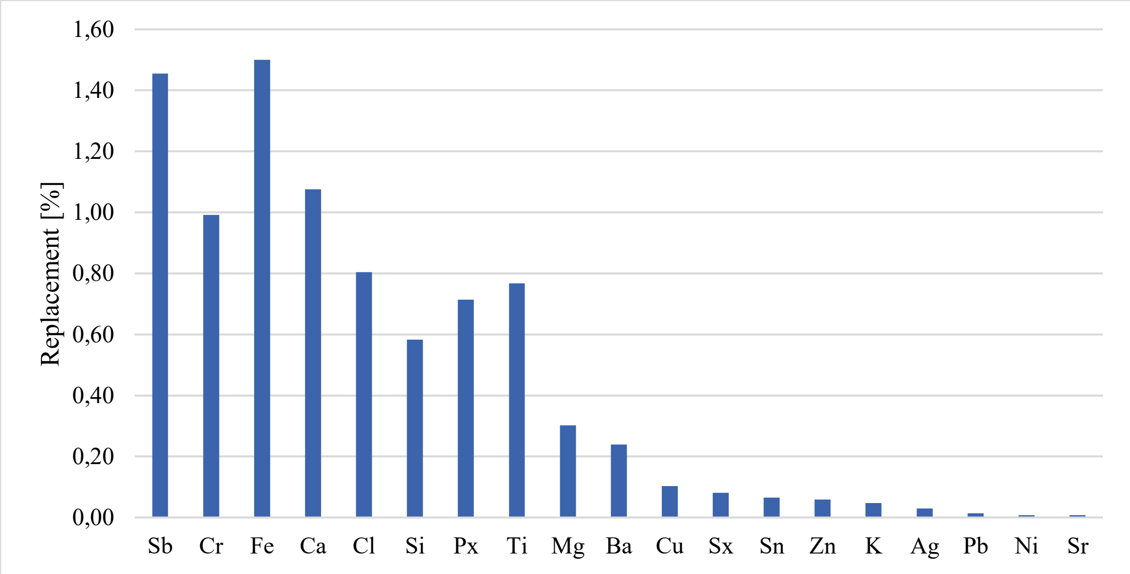

Fig. 4.15 Elemental composition of the solid residue of car seat covers [m/m%]

Results of measurements of the pyrolysis processing of car covers

The results of pyrolysis measurements, presented in graphs, show the yield of pyrolysis gas in relation to temperature ranging from 20 to 600 °C. The graphs show the maximum, minimum and average gas yield at a given temperature. It is clear from the graphs that at lower temperatures the product yield is relatively low, but increases significantly with increasing temperature. The average product yield curve is located between the maximum and minimum yield curves, which suggests that the yields can be affected by various factors, such as the composition of the input material, heating rate, or reaction conditions. Furthermore, in heterogeneous mixtures, various phenomena can occur, such as the mutual influence of the decomposition rate of individual components, the formation of new chemical compounds, or a change in the physical properties of the mixture during the process. The main input parameters by which the pyrolysis process is affected are:

- Initial temperature: the temperature at which the pyrolysis process begins
- Final temperature: the temperature at which the pyrolysis process ends
- Heating rate: the rate at which the temperature increases during the process
- Duration: the total duration of the pyrolysis process – residence time
- Activation energy: the energy required to initiate a chemical reaction
- Mixture content
- Heating power

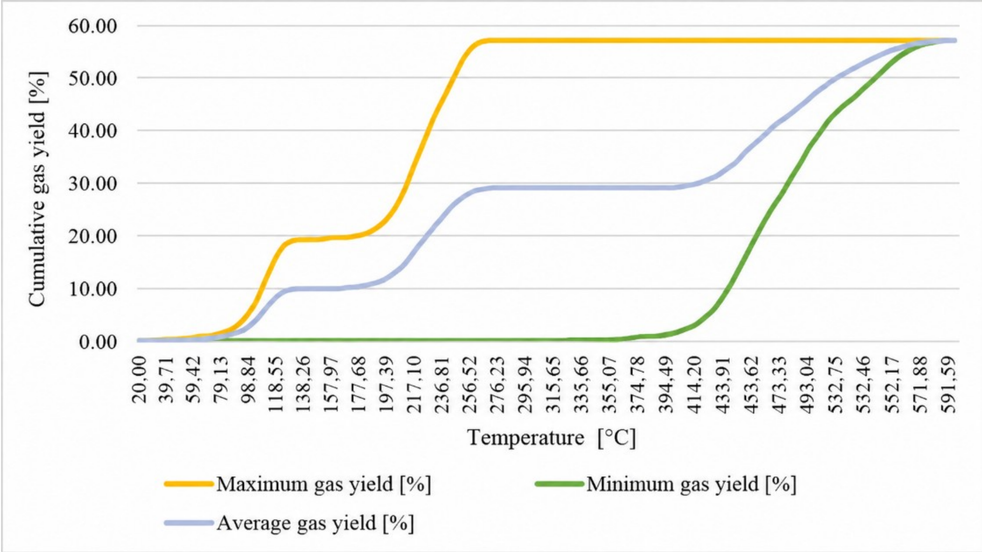

Fig. 4.16 Average pyrolysis gas yield in the temperature range of 20–600 °C

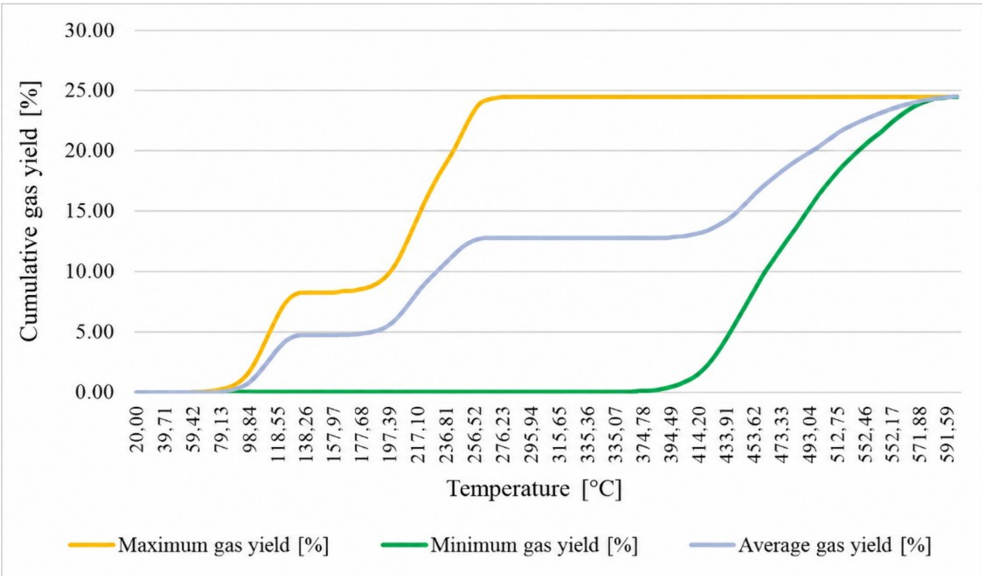

Fig. 4.17 Average pyrolysis liquid yield in the temperature range of 20–600 °C

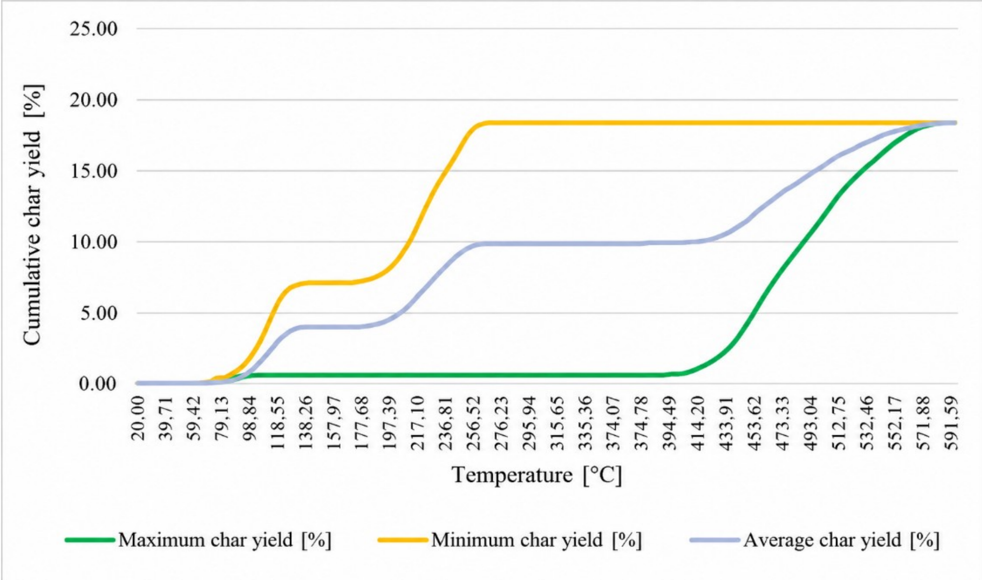

Fig. 4.18 Average pyrolysis residue yield in the temperature range of 20–600 °C

4.4.4. Conclusion

The utilisation of waste materials from the automotive industry represents an important topic in the context of responsible waste management and the development of technologies with a low environmental impact. Our research focuses on the energy recovery of waste from car covers using several analytical approaches, i.e. CHNS analysis, thermogravimetric analysis (TGA) and determination of calorific value and heat of combustion. The findings confirmed that the examined covers contain a high proportion of carbon and hydrogen, which points to their potential for energy utilisation – whether in the form of direct combustion or through pyrolysis, which allows the production of liquid and gaseous fuels. Elemental analysis also showed that the chemical composition of individual components of the covers varies. Samples containing polyolefins (e.g. polyethylene and polypropylene) showed a higher proportion of carbon and hydrogen, while materials with a share of polyamides had a higher nitrogen content. These differences are reflected not only in the calorific value but also in the process and mechanism of thermal decomposition. The calorific value of waste car covers was evaluated in order to determine their usability as an energy source. The determined values reached 20.80 to 24.95 $MJ \cdot kg^{-1}$, which represents a significantly higher level compared to the average calorific value of municipal solid waste (MSW), which is typically energy-recovered in incinerators.

In terms of practical application, several technological approaches are considered. Direct combustion is the most straightforward option, but it requires effective flue gas cleaning in order to limit emissions – especially nitrogen and sulfur oxides. An alternative with greater flexibility is pyrolysis, during which thermal decomposition of polymer components into liquid and gaseous fractions occurs; these products can then be used as fuels or raw materials in industrial and energy processes. Pyrolysis processing of car covers represents an efficient way of material and energy recovery of both plastic and textile components, resulting in three basic fractions: liquid product, gaseous product and solid residue. Characterisation of the products showed that the liquid phase contains a wide spectrum of hydrocarbons, which can be applied either directly as fuel or as a raw material base for chemical production.

The gaseous fraction was composed mainly of methane, hydrogen and carbon monoxide; its calorific value reached 16.46 $MJ \cdot kg^{-1}$. This indicates potential for utilising the obtained gas as fuel in industrial applications or for electricity generation, either alone or in a mixture with other gases. However, for practical application, gas treatment is key, especially the removal of undesirable components such as nitrogen and sulfur oxides, which can increase environmental burden. The solid residue was evaluated in terms of elemental composition and possibilities for further processing. The increased carbon content points to its potential for energy use in the form of solid fuel, albeit with a lower calorific value compared to the input material.

Compared to other waste management methods, such as mechanical recycling or landfilling, pyrolysis represents a technologically more promising recovery option. It allows the conversion of waste material into products usable for energy and raw materials, while limiting the need for its final disposal. Mechanical recycling of plastics from the automotive sector is often limited by the heterogeneity of the input material, the presence of additives and contaminants, which reduces the quality of the resulting recyclate. Landfilling, on the other hand, does not lead to material or energy recovery and, from a long-term perspective, represents an environmentally and spatially inefficient solution. A significant advantage of the pyrolysis process is its operational flexibility. By adjusting reaction conditions (temperature, residence time, heating rate), it is possible to influence the yield of individual fractions and preferentially increase the proportion of liquid product, gaseous phase or solid residue. In an environment of tightening environmental requirements and efforts to reduce CO_2 emissions, it is therefore necessary to develop technologies that enable effective waste recovery while reducing the consumption of primary raw material resources.

The performed analyses confirmed that car upholstery has relevant potential for energy recovery; for future application of the technology, several open questions need to be answered. A key challenge is the optimisation of pyrolysis operating conditions to suppress the formation of undesirable components while increasing the yield and quality of the target products. Equally important is the economy of the process. The logistics of collection, dismantling, separation and preparation of car upholstery can be costly, which directly affects the commercial feasibility of pyrolytic processing. For wider industrial implementation, the development of effective sorting and pre-treatment procedures for the input material is therefore essential. Finally, it is necessary to systematically address environmental aspects as well. Although pyrolysis reduces the amount of waste and allows the production of fractions usable for energy or raw materials, the technological chain must be designed so as to minimise emissions and the overall environmental burden within the entire process.

Energy recovery of waste materials from the automotive industry represents a technically promising approach that allows the use of secondary raw materials while simultaneously limiting the environmental burden associated with their final disposal. In this context, pyrolysis appears to be an effective technology, as it allows the conversion of plastic and textile components into products with usable energy value and potential for further processing. For further development, it will be crucial to focus on technical improvement of the process to increase processing efficiency and product quality stability, and to ensure economic feasibility while complying with strict environmental requirements. The results of the presented research can serve as a starting point for follow-up studies and the transition to practical applications in recycling and energy utilisation of plastic waste from the automotive sector.

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5. Utilisation of Rubber Waste from the Automotive Industry in Wood-Cement Boards

The term 'wood composite' is used to refer to a wide range of materials in which wood raw materials (fibres, chips, veneers, flour) are bonded with other wood or non-wood components using binders or matrices. The basic motivation for the production of wood composites is the efficient use of low-quality wood, wood waste or small-diameter wood, while simultaneously obtaining homogeneous and predictable properties that natural solid wood often fails to provide. Wood composites include a wide spectrum of products – from traditional panel materials such as particle boards (PB), medium density fibreboard (MDF), high density fibreboard (HDF), oriented strand board (OSB), plywood or fibreboards to modern materials such as hybrid composites and wood-plastic composites. These materials are classified according to the type of raw material (fibres, chips, veneers), binder (synthetic resins, polymers, mineral matrices), density, pressing method and end-use (Zanuttini and Negro 2021).

They are used in furniture making, interior and exterior construction, flooring, terraces, facades, walls, ceilings and even in products with high mechanical strength requirements (Stark and Cai 2021).

Composites created by combining wood and non-wood materials include:

- Wood-plastic composites
- Wood-rubber composites
- **Wood-cement boards** (boards bonded with a mineral or inorganic binder) (Stark and Cai 2021)

Wood-cement boards are a widely used construction material, valued especially for their good mechanical properties, dimensional stability and biological resistance. The size of the global wood-cement board market was estimated at 4,787.0 million USD in 2025 and is projected to grow at a compound annual growth rate (CAGR) of 5.10% during the forecast period (www.marketresearch.com).

5.1. Characteristics of wood-cement boards

Wood-cement boards are long-proven and economically efficient materials used mainly for cladding and lining structures. They are characterised by favourable thermal insulation and acoustic properties, high fire resistance, as well as resistance to biological degradation agents, including rot and insect infestation. Similar to natural wood, these panels also exhibit favourable elastic-mechanical properties and good machinability using common tools. Such materials also provide a wide range of surface finishes (Fig. 5.1.)

Fig. 5.1 Wood-cement boards with surface finish

The physical properties of composites with inorganic binders are significantly affected by the type and amount of binder used, the nature of the wood component, the water-to-cement ratio, as well as the resulting bulk density of the composite. According to available literature sources (Mayer et al. 2022), lightweight wood-cement boards made of wood wool with a bulk density of 360–570 kg·m^{-3} belong to fire reaction class B1, while heavy wood-cement boards with a density of 1000–1200 kg·m^{-3} are classified as classes B1 to A2.

As for the mechanical behaviour of wood-cement composites, the key parameters are mainly static bending strength and flexural modulus. The significant effect of bulk density on these properties can be explained by the optimal distribution of wood particles in the composite and their effective bonding with the inorganic matrix. This fact allows the use of wood-cement boards even in structures exposed to higher mechanical loads. The presence of fibre reinforcement also significantly improves bending strength. At a bulk density of 1200–1300 kg·m^{-3} and a wood component content of 20% wt. the bending strength reaches 10–13 MPa (Wolfe et al. 1996).

In this work, rubber granulate, waste from the automotive industry, was applied to wood-cement boards in a proportion of 10 and 20%. Rubber has several unique properties: excellent energy absorption, large elastic deformation, better sound insulation, durability and resistance to abrasion and rot (Yang et al. 2016, Fu 2003). However, the connection of the cement matrix, wood reinforcement and rubber granulate significantly changes the physical, chemical and thermal properties of the resulting material. It is therefore necessary to assess in detail to what extent the content of recycled rubber can affect the properties of this new material. The offered technical solution, which essentially means creating a new type of wood-cement board, eliminates the shortcomings of the currently recognised types of products. The main purpose of this type of wood-cement board made from quick-setting cement, wood wool soaked in water and recycled rubber granulate is to save resources by using secondary raw materials, i.e. rubber waste from the production and operation of cars. Such a solution helps to reduce the burden on the environment. The main advantages of these types of boards are their durability, fire safety and environmental friendliness.

A wood-cement board with the addition of recycled rubber consists of quick-setting cement, wood wool soaked in water, onto which a binder is applied, and recycled rubber granulate in a proportion of 10 to 20% wt. with a fraction of 1–3 mm. Rubber granulates can be used in the production of a wood-cement board with the addition of recycled rubber, for example, from old tyres (styrene-butadiene rubber – SBR) or from old seals and mats (ethylene-propylene-diene rubber – EPDM). After the individual materials are mixed, the mixture is poured into a mould, and then cold pressing under a specific pressure, temperature and for a specific period produces a wood-cement board with the addition of recycled rubber with defined properties suitable for practical use (Fig. 5.2).

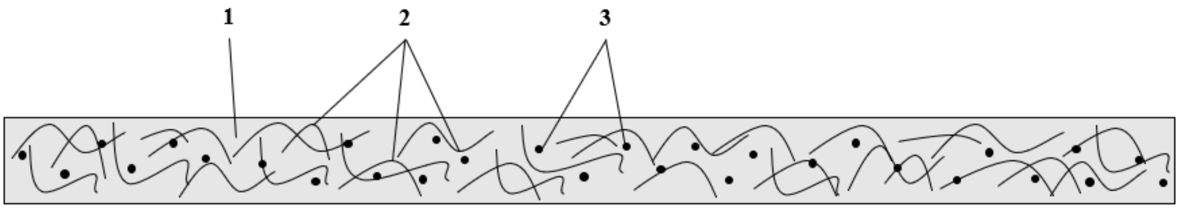

Fig. 5.2 Structure of wood-cement board, 1 – cement, 2 – wood fibres, 3 – rubber granulate

The offered technical solution for indoor and outdoor use ensures the ecological recovery of rubber waste without producing volatile organic compounds, helping to prevent the creation of landfills with adverse effects on the environment.

Construction, engineering and other industrial sectors can use the technical solution of the developed wood-cement board with the addition of recycled rubber indoors and outdoors. The above combinations of wood-cement boards with the addition of recycled rubber can be used in organic buildings, acoustic and thermal claddings, partition walls or flat roofs. The boards can also be used in humid conditions, such as ceilings in indoor swimming pools. The main advantages of these types of boards are their durability, fire safety and environmental friendliness.

5.1.1. Production of wood-cement boards

The wood-cement boards were produced using industrial technology on a production line of the company ELTOMATION (Barneveld, Netherlands), designed for continuous production of wood-cement boards. The production took place in cooperation with the company VERÓNY OaS, s.r.o., Krupina, Slovakia.

The basic wood-cement boards were produced with dimensions of 2.0 m × 0.5 m × 0.025 m (length × width × thickness) with an average weight of 14.42 kg. The raw material mixture consisted of wood wool (Fig. 5.3), Portland cement type AS 42.5 R and calcium chloride ($CaCl_2$), which was used as a chemical accelerator for cement hydration. The wood wool was prepared from dry spruce wood (Picea abies L.), dried naturally over a period of 2 to 3 months. The moisture coefficient of wet and dry wood wool reached a value of 1.14.

Fig. 5.3 Wood wool fed into the mixing drum

Material consumption per area unit was approximately 3.5 kg.m^{-2} of wood wool, 9.0 kg.m^{-2} of cement, 0.0075 kg.m^{-2} of calcium chloride and process water. The production process involved dosing calcium chloride onto the prepared wood wool, its subsequent transport to the mixing drum and the addition of cement together with water. After homogenisation of the mixture, a wood-cement mat with a width of 0.5 m was formed, cold-pressed with a weight of

1 t. After pressing, the mat was formatted to the final dimensions of the boards (Fig. 5.4) and moved to a warehouse, where curing took place under load for a period of approximately three weeks until the complete hardening of the cement matrix.

Fig. 5.4 Formatted wood-cement boards

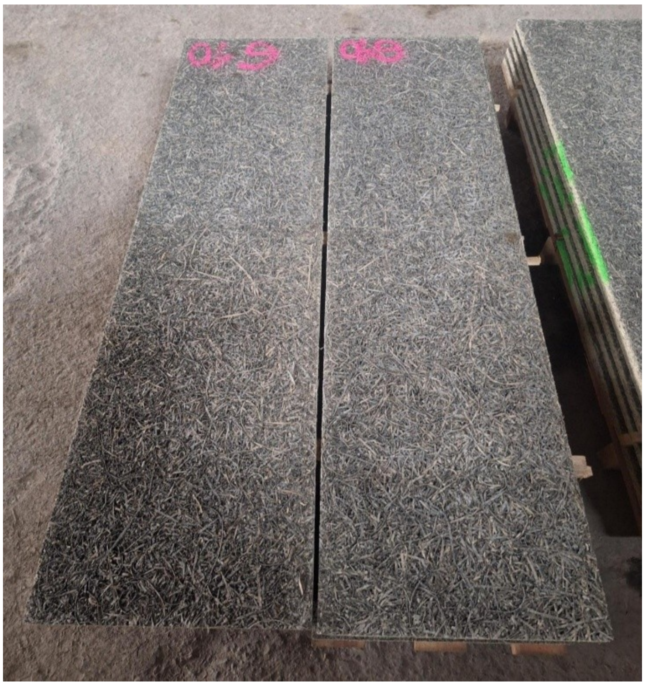

Fig. 5.5 Finished wood-cement board with 10% content of a mixture of seals and mats

The rubber granulate was introduced into the production process at the inlet of the wood wool into the mixing drum.

Wood-cement boards (Fig. 5.5) modified with rubber granulate from tyres (Tab. 5.1) were produced using identical technology. 14 kg and 28 kg of rubber granulate was used for the production of 10 pieces of boards with the stated dimensions. Due to the addition of rubber granulate, the weight of the other components of the mixture (wood wool, cement, water and calcium chloride) was proportionally adjusted to maintain a constant final weight of the boards (Čabalová et al. 2025).

Characterisation of the used rubber granulate from scrap cars

Two types of rubber granulate were used as a modifying and filler component of the wood-cement boards.

1. **Tyres** are characterised by high mechanical resistance, dimensional stability and the ability to withstand extreme temperature conditions. Approximately 50% of their composition consists of various types of elastomers. The dominant component of tyres is **styrene-butadiene rubber (SBR)**, which is widely used in the automotive industry, especially in the production of tyres, as well as sealing, insulating and hose elements.
2. The second type of rubber material came from a **mixture of vehicle seals and floor mats**. These components are characterised by strong anti-slip properties, mechanical resistance and the ability to protect the vehicle interior from dirt and moisture. Compared to textile floor coverings, they provide a higher level of protection with a longer lifespan. The main elastomeric component of this mixture was ethylene-propylene-diene rubber (EPDM), which is one of the most used synthetic rubbers in the automotive industry. EPDM is characterised by high resistance to heat, oxidation and weather, making it particularly suitable for outdoor applications such as door seals, protective mouldings and hoses exposed to climatic stress.

The granulate from waste rubber and tyres from scrapped cars was provided by AVE SK-Kechnec, a.s., Slovakia.

Tab. 5.1
Codes of wood-cement boards

REF	Reference wood-cement board
G-10	Wood-cement board with 10% rubber content
G-20	Wood-cement board with 20% rubber content
P-10	Wood-cement board with 10% tyre content
P-20	Wood-cement board with 20% tyre content

5.1.2. Thermal insulation properties of modified wood-cement boards

In the experiment, the thermophysical properties of the reference material (REF) and its modifications with the addition of 10% (G-10) or 20% (G-20) recycled rubber and 10% (P-10) and 20% (P-20) recycled tyres were analysed. The evaluated parameters were thermal conductivity λ and specific heat capacity c.

A stationary method was used for the measurement, where a stationary temperature field is created between the opposite surfaces of the material, and then the heat flow passing through the material is measured. A temperature difference of 20 °C at a mean temperature of 20 °C was used for all thermal conductivity measurements, and heating from 20 °C to 40 °C was applied for the heat capacity measurement. NETZSCH HFM 446 Lambda Eco-Line Medium equipment was used for all measurements, allowing measurements on samples with dimensions of 200 × 200 mm up to a thickness of 50 mm. This equipment measures in accordance with the DIN EN 12664, DIN EN 12667, DIN EN 12939, ISO 8301, ASTM C518 and JIS A1412 standards. All samples were conditioned before measurement at a temperature of 20 °C and a relative air humidity of 60%.

Four samples of each material type were prepared for the research. Four repeated measurements were performed on each sample. This meant that 16 values of the thermal conductivity coefficient were determined for each material type. The specific heat capacity was determined once for each sample. The measured data dispersion was up to 6.5% for thermal conductivity and up to 9.5% for heat capacity of the average values of the determined quantities, which, given the material structure, means and that these are acceptable values for a wood-based material. The resulting values of the repeated measurements show good repeatability.

Effect of additives on thermal conductivity

The average values of thermal conductivity show a clear trend of increasing thermal conductivity with an increasing proportion of additives. Tab. 5.2 summarizes the experimentally obtained data.

Tab. 5.2
Change in thermal conductivity of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Material	Proportion of additive	λ (W/m·K)	Change compared to REF (%)	Bulk density (kg.m^{-3})
REF	0%	0.076±0.002	–	468.9±24.5
G-10	10%	0.079±0.002	+4.0	449.9±30.9
G-20	20%	0.082±0.002	+8.7	477.5±27.7
P-10	10%	0.082±0.004	+7.9	487.2±49.4
P-20	20%	0.086±0.003	+13.5	526.8±7.1

The thermal conductivity of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%) is presented in Fig. 5.6.

It is clear from the results that the additive in the form of recycled tyres increases the thermal conductivity of the material more significantly than rubber. The tyre recyclate has a higher thermal conductivity (λ = 0.098 W/m.K) than the rubber recyclate (λ = 0.087 W/m.K), and it also has a higher bulk density (499 kg/m3 vs 465 kg/m3).

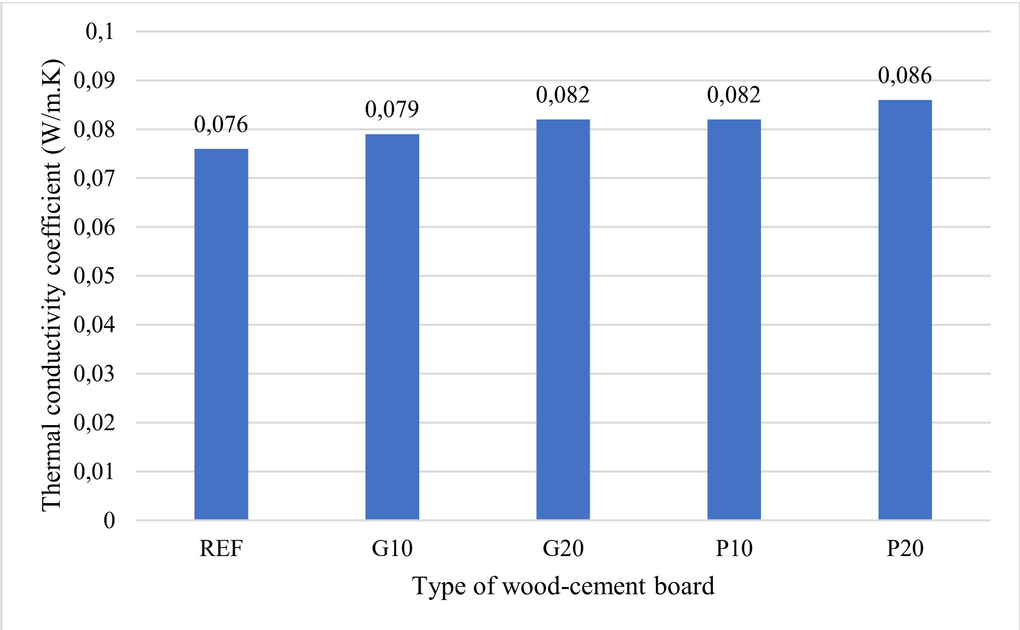

Fig. 5.6 Thermal conductivity of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Higher thermal conductivity in combination with higher bulk density ultimately causes a greater increase in thermal conductivity. The additives themselves have higher thermal conductivity than the reference material, so the increase in thermal conductivity of materials with added recyclates is logical and expected.

The increase in thermal conductivity is also caused by other effects:

- By a change in microstructure and a reduction in material porosity (air with thermal conductivity of approximately λ = 0.026 W/m.K in the pores is replaced by rubber, which has a significantly higher thermal conductivity).
- By improving the contact between wood wool and creating conductive 'bridges'; small particles of recyclate are coated with cement slurry during the production process (cement has λ = 0.6 – 1.0 W/m.K after hardening), which increases the proportion of cement in the final product and creates a greater number of connections, which ultimately increase energy transfer and thermal conductivity.
- By disrupting the optimal structure of wood wool bound with cement slurry, the additive particles are glued to the surface of the wood wool by the cement, and therefore the surface is covered by a thicker layer of cement with relatively high conductivity.
- By a higher proportion of the compact phase compared to air pockets.

The results suggest that the additive acts as a structure modifier with a slightly negative impact on the thermophysical properties of the material.

Relationship between bulk density and thermal conductivity

In addition to the effect of additives, the dependence of thermal conductivity on the bulk density of the material is also clear from the results. The general principle is that samples with higher bulk density exhibited higher thermal conductivity values. The trend of increasing thermal conductivity with bulk density is typical for wood and wood composites, where an increase in density is associated with a decrease in porosity and an increase in the proportion of the solid phase, which conducts heat more effectively than air pores. In this case, the air in the pores is replaced by recyclate and a larger proportion of cement in the mixture.

Fig. 5.7 shows the dependence of thermal conductivity on bulk density for all measurements on the analysed samples:

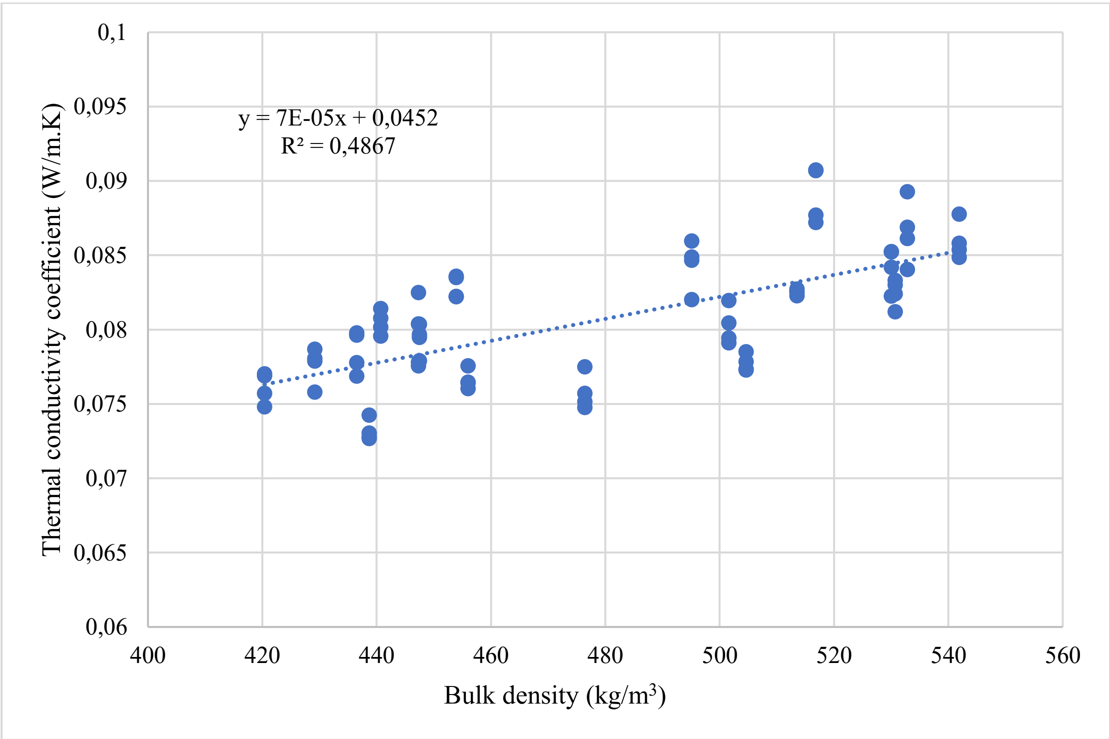

Fig. 5.7 Dependence of thermal conductivity on bulk density of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Heat capacity of the material

The average values of specific heat capacity do not vary significantly among the groups (Tab. 5.3), which suggests that the addition of recyclate does not have a systematic effect on the specific heat capacity of the material and its thermal accumulation. The high degree of variability in heat capacity is likely caused by the heterogeneity of the composite, the large dispersion of the bulk density of the samples and the different proportions of the individual components of the composite.

Tab. 5.3
Experimentally determined values of specific heat capacity of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Material	Heat capacity range (J/kg·K)	*c* (J/kg·K)
REF	1190–1390	1,274.5±72.1
G-10	1,220–1,310	1,253.0±38.1
G-20	1,208–1,341	1,263.0±54.9
P-10	1,202–1,268	1,226.5±25.0
P-20	1,235–1,348	1,309.0±52.4

The data confirm that there is no clear effect of bulk density on the heat capacity of the material. The trend is shown in the graph in Fig. 5.8.

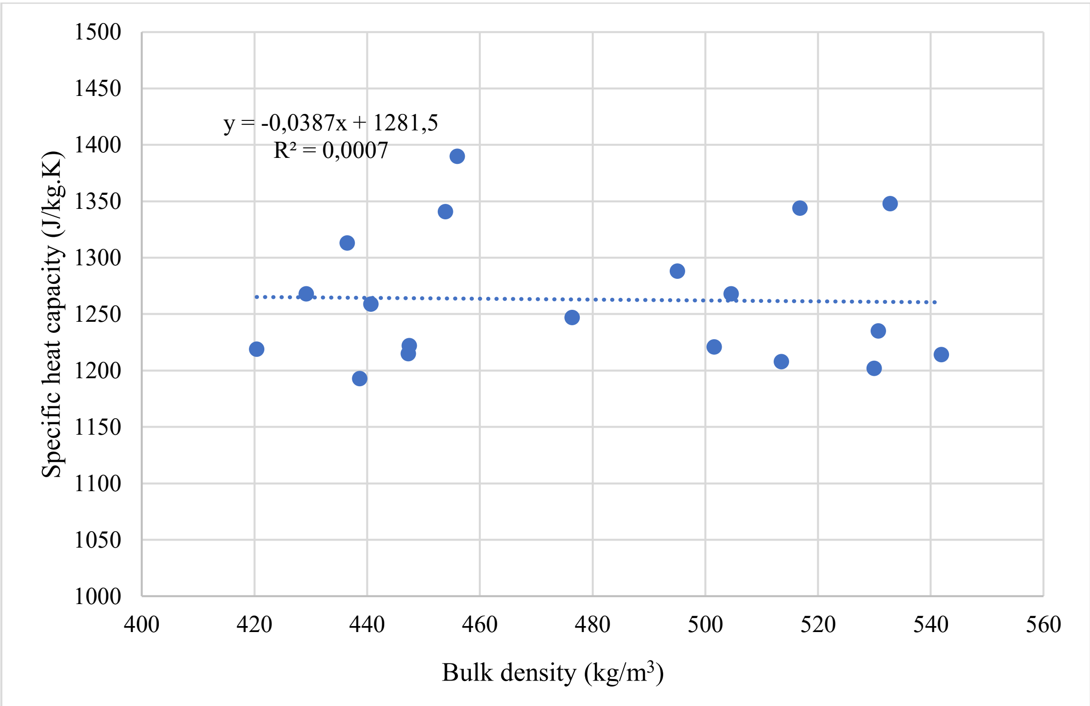

Fig. 5.8 Dependence of specific heat capacity on bulk density of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Heat capacity remains relatively stable and the differences are likely caused by the heterogeneity of the composite and the different wood wool/cement ratios.

5.1.3. Physical properties of modified wood-cement boards

Swelling and absorption in water

The procedure was performed according to STN EN 317. The test samples were measured and weighed in a dry state. The samples were then immersed in water at room temperature for 2 h, after which the dimensions and weight were recorded. They were then re-immersed for another 24 h. After the end of the period, they were measured and weighed again to determine thickness swelling and water absorption.

In general, the reference board (REF) had the highest water absorption and moisture content (Tab. 5.4).

Tab. 5.4
Absorption, swelling, moisture and density of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

	Absorption, %				Swelling, %				Initial moisture, %		Density (kg.m^{-3})	
	2H		24H		2H		24H					
Series	Average	St. dev.	Average	St. dev.	Average	St. dev.	Average	St. dev.	Average	St. dev.	Average	St. dev.
REF	43.15	6.209	47.39	5.583	1.257	0.827	1.481	1.443	11.52	1.647	398.8	49.51
P-10	31.82	3.849	35.48	4.776	0.859	0.400	1.297	0.441	11.52	0.668	506.6	104.36
P-20	34.13	2.120	36.26	2.659	1.438	0.324	1.637	0.410	10.35	0.899	487.6	87.34
G-10	32.38	1.759	35.00	2.734	1.271	0.486	1.572	0.463	10.91	0.763	500.9	78.03
G-20	36.02	1.795	39.66	3.300	0.861	0.330	1.020	0.532	9.80	0.735	520.3	92.44

The addition of recycled waste (tyre P, rubber G) generally led to a reduction in absorption compared to the reference (REF), both after 2 h and after 24 h. The most significant decrease in absorption was observed for a 10% dosage (P-10 and G-10; approximately 25% compared to REF), whereas at 20% the effect was weaker, especially for the rubber fraction (G-20), which showed the highest absorption among the mixtures with waste. In terms of waste type, for a 20% dosage, the results were more favourable for tyre (P-20) than for rubber (G-20), whereas for 10% the differences in absorption between P and G were small. The result is in line with the more hydrophobic nature of the additives, which reduces the overall ability of the composite to absorb water.

Swelling showed a non-linear dependence on the type and concentration of waste. Tyre at a concentration of 10% (P-10) reduced swelling (≈ −12% after 24 h). However, at 20% (P-20), there was an increase in swelling above the REF level (≈ +10% after 24 h), which indicates a limit dosage for which dimensional stability may deteriorate. For rubber, the effect was the opposite: G-10 was approximately at the REF level or slightly higher, whereas G-20 achieved the lowest swelling of all series (≈ −31% after 24 h), which points to a potentially favourable effect of a higher dosage of the rubber fraction on limiting swelling.

Equilibrium moisture content

Moisture content after conditioning was determined according to STN EN 322. The test samples were first weighed in their initial state. For samples with a polystyrene layer, the foam part was removed before testing. The samples were then dried in an oven (HS62A) at 104 ± 2

°C until a constant weight was reached. After drying, the dry weight was determined and the moisture content was calculated from the weight loss.

Equilibrium moisture content decreased with increasing waste concentration. Overall, the results show that a 10% waste addition is consistently favourable in terms of absorption, while dimensional stability (swelling) is more sensitive to the type and dosage of waste: tyre is more advantageous at 10%, while rubber at 20%.

Science literature states that moisture properties (amount and movement) depend on fibre orientation and the quality of the binder/coating. Berger et al. (2020) reported acceptable moisture behaviour of wood wool-cement boards with the addition of waste wood from pallets, which suggests that waste can be incorporated without deteriorating moisture properties. Rico (2002) discussed how fibre alignment affects water mobility and moisture distribution. Doudart de la Grée et al. (2014a, 2014b, 2014c) emphasised that coating thickness and binder type control water interaction and dimensional stability; inhibitory substances in wood (e.g. sugars and hemicellulose) can interfere with cement hydration, affecting moisture behaviour. Caprai et al. (2018) also showed that the hygroscopic behaviour of fibres affects the effective water-to-binder ratio, which subsequently shows in the development of porosity and material properties.

Density

The density of the test samples was determined by measuring dimensions with a caliper (volume calculation) and subsequent weighing on analytical balances (±0.001 g) according to STN EN 323.

The density trends in Tab. 5.4 support these observations. The reference sample had a medium density, while the series with added waste content achieved higher densities (around 500 $kg.m^{-3}$), which indicates a more compact structure. The type of waste did not have a significant effect on density. The density analysis was performed in more detail on samples intended for the evaluation of mechanical properties.

5.1.4. Mechanical properties of modified wood-cement boards

The results of the basic statistics (Tab. 5.5) clearly confirm the significant directional anisotropy of the wood-cement board: in the direction parallel to the board length ('Parallel') the average values of both modulus of elasticity and bending strength are higher than in the direction perpendicular to the board length ('Perpendicular'). This trend is consistent across all series and is typical for materials with a reference orientation of wood particles/structure formed during panel production. Density varies less between directions, and the directional effect is weaker compared to the mechanical properties.

Tab. 5.5
Basic statistics of the bending mechanical properties test of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

	Sample length	Parallel to the board (Parallel)		Perpendicular to the board (Perpendicular)	
	N	15		30	
Property	series	Average	St. dev.	Average	St. dev.
Density (kg.m^{-3})	REF	409.2	47.3	442.3	41.0
	P-10	496.6	98.7	496.6	45.0
	P-20	529.4	103.9	514.5	22.9
	G-10	499.4	89.9	480.5	18.3
	G-20	499.0	72.7	517.1	24.8
Modulus (N.mm^{-2})	REF	539.7	182.4	439.0	143.2
	P-10	945.7	469.6	570.8	152.1
	P-20	678.1	337.7	371.4	75.0
	G-10	806.5	427.7	438.6	95.6
	G-20	516.9	271.3	337.4	72.1
Strength (N.mm^{-2})	REF	1.97	1.36	1.13	0.39
	P-10	2.37	1.22	1.66	0.26
	P-20	1.71	0.81	0.96	0.16
	G-10	1.94	0.89	1.12	0.27
	G-20	1.33	0.77	0.89	0.22

Modulus of elasticity

In the 'Parallel' direction, the highest modulus is shown by series P-10 (945.7 ± 469.6 N.mm-^{2}), which represents an increase of +75.2% compared to the reference sample (REF) (539.7 ± 182.4 N.mm-^{2}). Series G-10 (806.5 ± 427.7 N.mm-^{2}) is higher than REF by +49.4%, while P-20 (678.1 ± 337.7 N.mm-^{2}) reaches +25.6%. By contrast, G-20 (516.9 ± 271.3 N.mm-^{2}) is slightly lower in the 'Parallel' direction than REF (-4.2%).

In the 'Perpendicular' direction, the picture is different: P-10 (570.8 ± 152.1 N.mm-^{2}) is still higher than REF (439.0±143.2 N.mm-^{2}) by +30.0%, but G-10 (438.6 ± 95.6 N.mm-^{2}) is practically the same as REF (−0.1%). For 20% addition, a decrease occurs: P-20 (371.4 ± 75.0 N.mm-^{2}) is lower than REF by −15.4% and G-20 (337.4 ± 72.1 N.mm-^{2}) by as much as −23.2%.

The bending modulus of elasticity showed similar dependencies. Waste type affected the modulus (F(1,258)=7.39, p=0.007), concentration had a strong effect (F(2,258) = 20.92, p = 3.80 × 10–9), and the orientation of the sample in the board was highly significant (F(1,258) = 75.54, p = 4.22 × 10–16). Samples tested parallel to the board direction exhibited a higher modulus than samples tested perpendicular to the board direction. The Concentration × Sample Direction interaction was significant F(2,258) = 8.13, p = 3.77 4.22 × 10–4. The other interactions were not significant (Fig. 5.9).

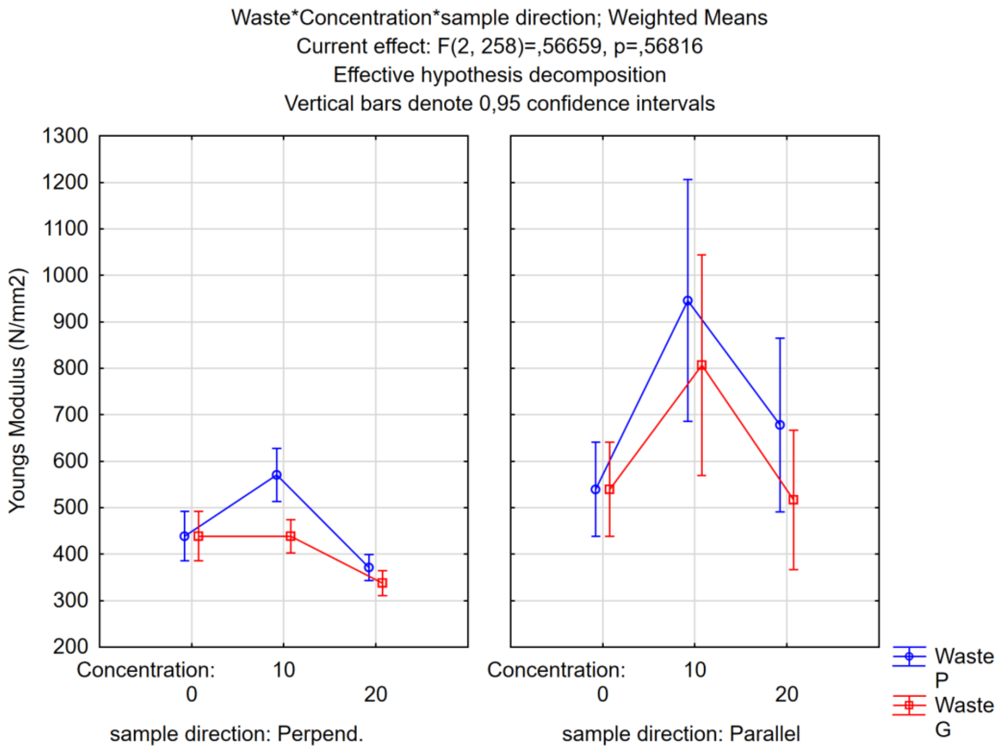

Fig. 5.9 Effect of factors on the modulus of elasticity of wood-cement boards with rubber content (10% and 20%) and tyres (10 % and 20%)

These trends are in line with published studies that emphasise the importance of density, geometry/orientation of wood wool and binder distribution. Ahmad et al. (2011) showed that bending properties strongly depend on board thickness and wood wool dimensions; finer fibres can improve coating and reduce the number of voids. Rico (2002) emphasised that the orientation of wood wool can significantly control bending behaviour, with alignment parallel to the loading direction leading to higher strength. Karlinasari et al. (2011) report strong correlations between density and bending parameters (MOR/MOE). Doudart de la Grée et al. (2014a, 2014b, 2014c) also pointed out that mechanical properties are governed by the quality of the cement coating, compaction/packing of particles and binder distribution: optimised coating and dense packing improve strength, whereas poor distribution and higher porosity reduce performance. Similarly, Koh et al. (2024) showed that improved matrix chemistry and fibre treatment can increase adhesion and bending behaviour in geopolymer wood-wool boards, confirming again the importance of microstructure and inter-phase bonding.

In terms of differences between waste types at the same concentration, it appears that tyre rubber (P) is more favourable than rubber (G), especially at 10%. At 10% P-10 is higher than G-10 by +17.3% (‘Parallel’) and +30.1% (‘Perpendicular’). At 20% P-20 is higher than G-20 by +31.2% (‘Parallel’) and +10.1% (‘Perpendicular’).

Bending strength

Bending strength also shows significant directional dependence and also sensitivity to the type and amount of waste. In the ‘Parallel’ direction, REF has 2.0 ± 1.4 N.mm^{-2}. Series P-10

(2.4 ± 1.2 $N.mm^{-2}$) is higher than REF by +20%, G-10 (1.9 ± 0.9 $N.mm^{-2}$) is slightly lower (-5%) and P-20 (1.7 ± 0.8 $N.mm^{-2}$) decreases to -15%. The most significant decrease is in G-20 (1.3 ± 0.8 $N.mm^{-2}$), which is lower than REF by -35%. In the 'Perpendicular' direction, REF has 1.1 ± 0.4 $N.mm^{-2}$. P-10 (1.7 ± 0.3 $N.mm^{-2}$) shows significant improvement (+54.5%), while G-10 (1.1 ± 0.3 $N.mm^{-2}$) is practically at the REF level (≈0%). With 20% addition, a decrease occurs again: P-20 (1.0 ± 0.2 $N.mm^{-2}$) is -9.1% and G-20 (0.9 ± 0.2 $N.mm^{-2}$) -18.2% compared to REF.

The orientation of the sample length within the board (perpendicular vs. parallel) was significant for bending strength (sample direction $F(1,258) = 71.20$, $p = 2.34 \times 10\text{-}15$). Waste concentration was also significant ($F(2,258) = 13.64$, $p = 2.34 \times 10–6$). With increasing waste content, strength generally decreased, but series P-10 was an exception. This is apparently due to the significance of waste type $F(1,258) = 7.65$, $p = 0.00610$). The other interactions were not significant (Fig. 5.10).

When P is compared with G at the same concentration, the difference in strength is most significant at 10%: P-10 is higher than G-10 by +26.3% ('Parallel') and +54.5% ('Perpendicular'); at 20% concentration, P-20 is higher than G-20 by +30.8% ('Parallel') and +11.1% ('Perpendicular').

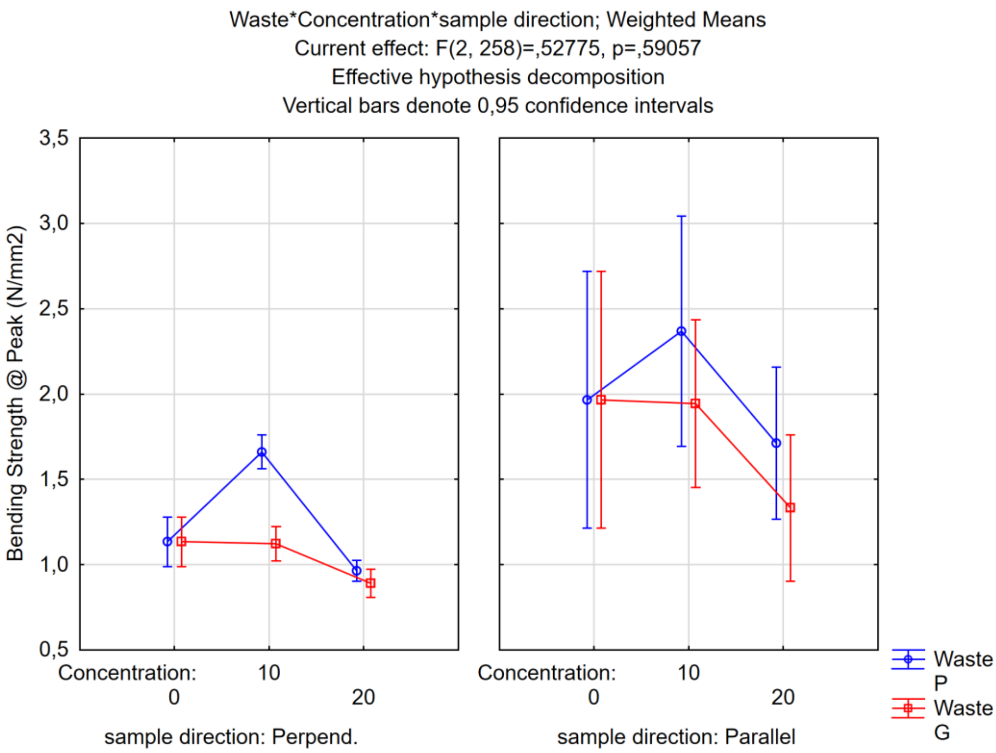

Fig. 5.10 Effect of factors on the bending strength of wood-cement boards with rubber content (10% and 20%) and tyres (10% and 20%)

Density

Density increases with the addition of waste in both directions, with the differences between directions being smaller than for the mechanical properties. In the 'Parallel' direction, REF has 409.2 ± 47.3 kg/m³, while additions increase the density to P-10 496.6 ± 98.7 (+21.4 %), P-20 529.4 ± 103.9 (+29.4%), G-10 499.4 ± 89.9 (+22.1%) and G-20 499.0 ± 72.7 (+22.0%).

In the 'Perpendicular' direction, REF has 442.3 ± 41.0 kg/m³ and again the additions increase the density: P-10 496.6 ± 45.0 (+12.3%), P-20 514.5 ± 22.9 (+16.3%), G-10 480.5 ± 18.3 (+8.6%) and G-20 517.1 ± 24.8 (+16.9%).

For density, the dominant main effect was concentration $F(2,258) = 59.24$, $p = 6.73 \times 10$-22, while waste $F(1,258) = 0.87$, $p = 0.351$ and sample direction $F(1,258) = 1.49$, $p = 0.224$ were not significant. Among the interactions, concentration × sample direction were significant $F(2,258) = 3.42$, $p = 0.0341$.

The density of wood-wool cement boards (WWCB) was in the typical range for this type of composite (300–500 $kg \cdot m^{-3}$; Ashori et al., 2011). Ahmad et al. (2011) report a density of approximately 490 $kg \cdot m^{-3}$ for WWCB of similar thickness. The addition of waste material caused a statistically significant increase in density ($F(2,258) = 60.76$, $p < 0.001$). However, further increases in waste content did not lead to further statistically significant changes in density. The type of waste did not have a significant effect on density ($p = 0.321$), which suggests that boards with different rubber waste did not differ significantly in this parameter.

From a practical point of view, it is important that the increase in density is not automatically accompanied by an increase in modulus or strength. For example, P-20 and G-20 have a higher density compared to REF, but their mechanical parameters (especially in the 'Perpendicular' direction) decrease. This suggests that with a higher dosage of waste, the proportion of weaker interfaces/defects likely increases or the cohesion of the matrix deteriorates to the effect that it outweighs the 'compaction' effect.

Summary of mechanical properties

- The best contribution to mechanical properties (both modulus and strength) is achieved by series P-10 in both directions, with the improvement being particularly significant in the 'Parallel' direction for strength (+54.5% vs REF).
- With 20% addition, the effect worsens: P-20 and especially G-20 show a decrease in both modulus and strength (most significantly in the 'Perpendicular' direction).
- The directional effect ('Parallel' > 'Perpendicular') is dominant for both modulus and strength, while density is less directionally sensitive.
- The dispersions (SD) are large at times, which is consistent with the heterogeneity of wood-cement composites; therefore, it is fair to always interpret the differences while stating the direction and variability.

Evaluation of testing of modified wood-cement boards

In this work, wood-cement boards based on wood wool were prepared, modified by the addition of ground automotive waste based on tyres (P) and rubber (G) with dosages of 0%, 10% and 20%.

Based on the experimental evaluation of the thermophysical properties of the modified wood-cement boards, it can be stated that the addition of 10% and 20% rubber granulate and tyre granulate affects the thermal insulation properties of the wood-cement boards, with the changes having a clear but mild character. Average values of thermal conductivity (λ) showed an increasing trend with increasing content of the additives. The reference material reached a value of $\lambda \approx 0.076$ W/m·K, while the modified boards ranged from 0.079 to 0.086 W/m·K. The increase in thermal conductivity was approximately 4% to 13.5% depending on the type and amount of the addition. The tyre fraction increased thermal conductivity more significantly compared to rubber granulate, which is related to its higher intrinsic thermal conductivity and higher bulk density.

The increase in thermal conductivity can be explained mainly by:

- A reduction in the porosity of the material and the replacement of air ($\lambda \approx 0.026$ W/m·K) with a material with higher conductivity
- An increase in the proportion of the compact phase (cement and recyclate)
- The creation of conductive bridges in the microstructure of the composite

Despite this slight deterioration in thermal insulation parameters, all modified boards retained thermal conductivity values typical for lightweight wood-cement materials and remain suitable for applications in construction.

The specific heat capacity (c) did not differ significantly among the individual series. The values ranged approximately from 1226 to 1309 J/kg·K, with no systematic effect of the type or concentration of the additive on the material's ability to store heat being proven. The differences were attributed mainly to the natural heterogeneity of the composite.

Overall, it can be stated that the addition of recycled automotive waste does cause a slight increase in thermal conductivity, but without a fundamental negative impact on the thermal insulation potential of the material. Modified wood-cement boards retain favourable thermophysical properties, while offering an environmental benefit in the form of secondary raw material recovery.

The results of **physical** tests showed that the addition of recycled fractions generally reduces absorption compared to the reference, both after 2 h and after 24 h of immersion. The most significant reduction in absorption was achieved with 10% addition (P-10, G-10), while for 20% the effect was weaker, especially for the rubber fraction (G-20), which showed higher absorption among the modified mixtures. Swelling behaviour was non-linear and dependent on the type and dosage of waste: the tyre fraction at a concentration of 10% reduced swelling, but even 20% showed an increase in swelling above the reference level; conversely, for rubber, the lowest level of swelling was achieved at 20% which suggests a potentially favourable effect of a higher dosage of the rubber fraction on limiting dimensional changes. The initial (equilibrium) moisture content tended to decrease with increasing waste concentration, with the lowest values observed for G-20.

Mechanical tests in three-point bending confirmed significant anisotropy of the board: samples cut parallel to the length of the panel achieved a higher modulus of elasticity and higher bending strength than samples cut perpendicular to the length of the panel. Among the modified mixtures, series P-10 appeared to be the most advantageous in terms of bending parameters, showing an improvement in both modulus and strength (in both cutting directions) compared to the reference. On the contrary, a dosage of 20 showed a decrease in mechanical parameters – more significant for the rubber fraction (G-20) – which suggests the existence of an optimal dosage of the addition and also points to the sensitivity of the mechanical response to the type of filler and its content. The observed trends are consistent with literature, which emphasises the decisive effect of wood wool orientation, the quality of the cement coating and the microstructure on the moisture and mechanical behaviour of composites.

From a practical point of view, the results show that recycled fractions from automotive waste can be integrated into wood-cement boards with a favourable effect on selected physical properties (especially absorption), but mechanical properties may suffer at higher dosages and require optimisation of the composition. It appears promising to verify mainly (i) the stability of properties during long-term cyclic wetting/drying, (ii) the effect of the morphology of granulation and waste surface treatment on adhesion in the matrix and (iii) the relationship between filler distribution, porosity and panel anisotropy.

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6. Elimination of Losses, Operating Materials and Associated Hazardous Waste During the Operation of Air Conditioning in Industrial Buildings Using Industrial IoT and Smart Industry

6.1. Introduction

Description of the current situation of medium-sized manufacturing enterprises, industrial facilities, current technology, ventilation, cooling, forced ventilation, unused waste heat and unnecessarily high service costs.

HVAC control (direct, M&R, temperature) = need to streamline the cost structure – HVAC, standard model, introduction of a control model based on complex internal environmental indicators.

Objective: The need to streamline the Slovak industrial environment (SME) and capacity with regard to Slovakia's decreasing competitiveness, and energy and ESG challenges.

- Approximately **70% of production 'accommodation' capacity** (halls, facilities, primary production processing units) is older than **12 years.**
- There is a need (domestic manufacturers and foreign investors) to revise and invest in upgrading production halls – primary technologies such as ventilation, cooling, M&R, heat, HSE, compressed air and others are near the end of their lifespan and are inadequate for the new energy reality (prices in industry soaring by 170% and ESG-EU ETS legislation). From 2019, new industrial buildings have been built to a high quality standard corresponding to new requirements and standards.
- Manufacturing enterprises face cost and competitive challenges (external competition, Slovakia's internal cost environment with inflationary pressures – it is not always possible to fully transfer costs to prices) and work with single-digit margins. This situation does not create cash flow for the necessary investment in the restoration of production buildings (for example, costs for replacing ventilation and cooling with upgraded M&R reach as much as 35% of the cost level in 2015 for the total construction of the hall = ROI is 8 years or more).
- According to the average cost structure of an industrial enterprise, costs for so-called facility – buildings, halls, ESG, waste management, safety, recycling and related energy for heat production, cooling, compressed air and others – range between 5%-8% of industrial sales prices. It does not seem much, but with single-digit margins from sales prices, it is one of the essential items that affects the competitiveness of the enterprise.

In this work, we will focus on real solutions and experience from the industry from the perspective of a plant manager – how it is possible to work efficiently with a relatively low budget to eliminate losses and waste heat/cooling even with older technology and reduce the generation of associated waste and service costs using environmental real-time control and data prediction.

Ventilation systems in a manufacturing enterprise – play a key role in reducing waste/ losses – especially for air pollutants, heat and material losses.

a) Capture and control of pollutants in the air:
- Material losses (e.g. dust from powders that could otherwise be reused)
- Pollutants in the air that would require costly cleaning or would cause product contamination, health risks

b) Heat recovery and energy efficiency
- Modern ventilation systems often contain recovery units that recover waste heat from exhaust air.
- Using recovered heat to preheat supply air, process water or other systems – reduces energy waste.

c) Humidity reduction, dust control
- Proper airflow prevents condensation and mould growth, which can lead to product or packaging waste damage.
- Monitoring dust (particle size) can indicate a problem with filtration or instability of the production process = elimination of losses from production, cleaning and service work = waste.

d) Improvement of process stability
- By maintaining consistent air quality and temperature, ventilation systems help with process stability.
- Fewer fluctuations mean fewer products outside specifications – reduction of waste from rework or disposal.

e) Support for regulatory compliance
- Well-designed systems ensure that emissions remain within limits, thereby preventing fines or production shutdowns – both indirect forms of waste.

Example of existing ventilation/HVAC control.

Baseline state – industrial hall, 16y with M&R:

Traditional ventilation/HVAC control system:
- Uses pre-programmed timers, manual switches or basic sensors (such as temperature/humidity sensors) to turn on/off fans, vents and HVAC systems.
- Operators often adjust settings manually or based on fixed threshold values.
- Limited data analysis or adaptability.

Advantages:
- Simplicity: Easier installation and maintenance.
- Lower initial costs: Cheaper hardware and basic M&R software.
- Reliability: Fewer intelligent and sensory parts included in the technology; well understood by most technicians.

Limitations:

- Does not adapt to changing conditions effectively (e.g. weather, production increases and decreases, daytime).
- Energy waste: Systems may run unnecessarily or insufficiently.
- No predictive capabilities: Cannot predict ventilation needs based on data trends.
- Dependent on manual control: Requires constant monitoring and adjustment by a human.

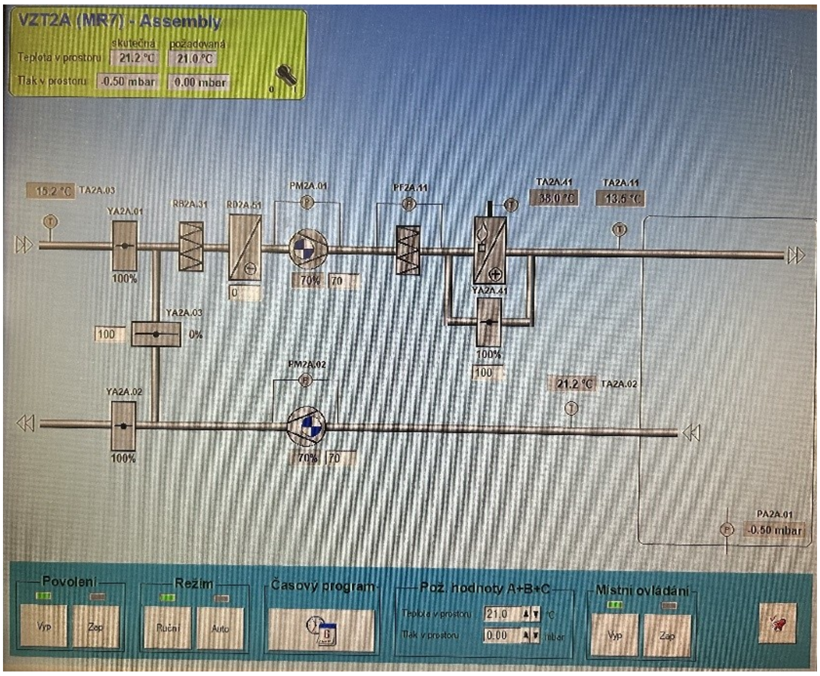


Fig. 6.1 Example (screenshot) from traditional M&R

HVAC control upgrade solution: Transitioning from traditional M&C to a Smart Industry Platform is not resource-intensive and has a maximum ROI of 2 years.

Uses sensors + AI algorithms to monitor and react in real-time to variables such as:

- Temperature, humidity, CO_2, dust, VOC, pressure
- Time of day, weather forecast, weather compensation
- It constantly learns and optimises airflow, energy consumption and climate balance.
- Can be connected to intelligent manufacturing systems (ERP, MES, WHM, measurement of process par.) or IoT devices

Advantages:

- Effects: Optimises ventilation, reduces energy costs and improves the plant environment.
- Predictive control: Anticipates environmental changes and reacts to actively operating technologies – producing emissions and data, and adapts proactively.
- Remote access: Can be monitored and controlled via an application or cloud dashboard.
- Automation: Reduces the need for human intervention.

Limitations:

- Requires investment in new control software = Smart Industry platforms, IoT sensors or cloud infrastructure. (However, costs are lower than for traditional M&C)
- Complexity: Requires technically skilled operators and training, working with data, and the ability to understand and follow real-time data.
- Dependence on data quality: Bad data = bad decisions.

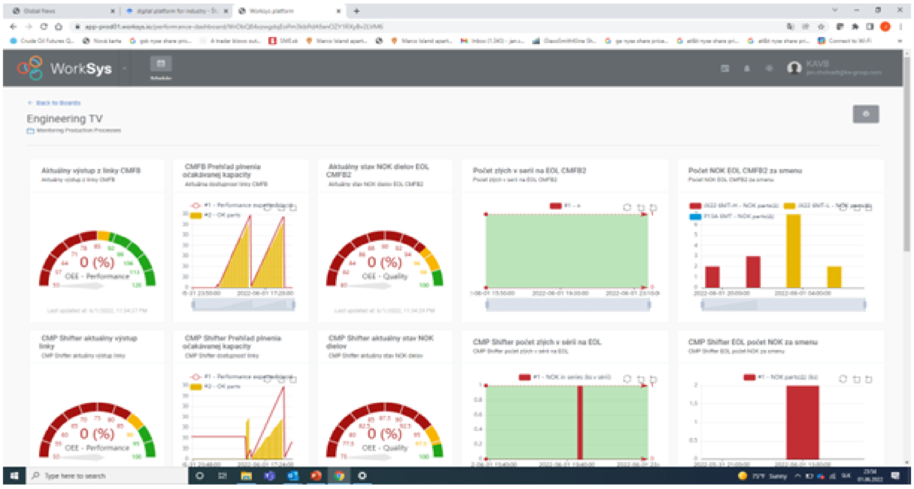
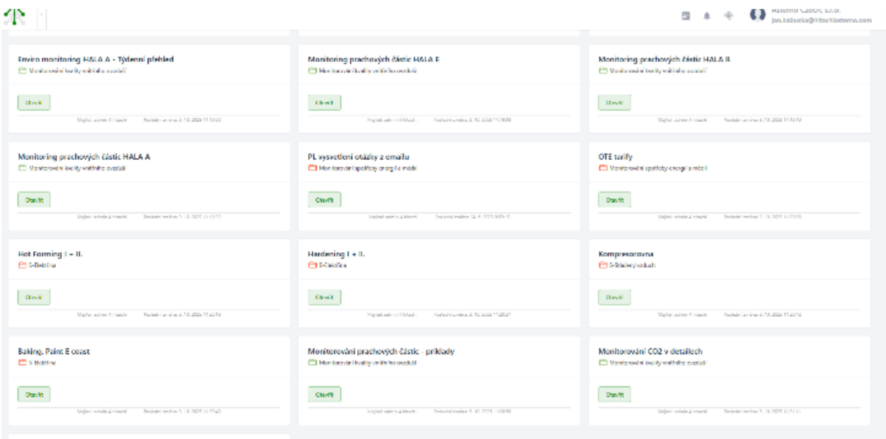


Fig. 6.2 Example (screenshot) of a Smart Industry platform integrating a multitude of process and facility data in one place



6.2. The need to manage and evaluate immediately, in real-time = highlighting the application of this solution as very effective. Real-time requires new technological and software elements – Smart Industry.

a) Technology:

- Ventilation with heat recovery (HRV) or ventilation with energy recovery (ERV): The system transfers heat between incoming and outgoing air, recovers heat from exhaust air and pre-conditions the supply air.

- Air handling unit (AHU): The air handling unit controls airflow, temperature and humidity in the system and, in conjunction with heat recovery, can further reduce the system's energy needs.
- Sensors and control elements: Modern systems are equipped with temperature, humidity, VOC, dust, CO_2 and airflow sensors to adjust operation in real time; it is necessary to supplement this with an analytical IoT industrial platform and control HVAC parameters according to the real-time status of the plant = production volume, energy price trends, employee numbers in halls = process capacity, elimination of unnecessary HVAC operation.

b) Optimal strategy:

- Integration of sensors and automated control systems = IoT Smart Industry platforms = low costs vs. upgrade of older M&C.
- Real-time monitoring: Continuously monitor indoor air quality (IAQ), CO_2 levels, temperature, humidity, dust and pressure using sensors. These data can help dynamically adjust ventilation speed and the heat recovery process; in combination with SPOT energy prices, you can prepare an energy-optimal ventilation setting.
- Demand-controlled ventilation (DCV): When levels, e.g. of CO_2 or occupancy are low, the system can reduce ventilation intensity. Similarly, if temperature or humidity fluctuates, ventilation works using AI elements to prevent overheating or overcooling.
- Heat recovery modulation: The heat recovery system is controlled by adjusting the level of heat exchange depending on the outside temperature, thereby preventing excessive use in mild weather conditions = elimination of energy costs, high operating hours and maintenance.

c) Efficient heat recovery:

- Heat accumulation: Heat accumulation solutions for storing excess heat off-peak (e.g. at night or during periods of lower demand) and releasing it during peak demand, ensuring consistent energy use – hot utility water using low spot prices or PV energy.
- Heat recovery efficiency: Choose heat exchangers that are highly efficient at heat transfer and allow airflows to maintain a suitable temperature without cross-contamination.

d) Seasonal settings:

- Winter and summer environment: In winter, it is important to gain as much heat as possible, while in summer, heat recovery can be minimised or even reversed if it is necessary to cool the supply air.
- Free cooling: In cooler seasons, the outside air may already have a pleasant temperature. Free cooling can bypass the heat recovery process and directly intake outside air if needed.

e) Correct sizing and layout:

- System sizing: The HRV or ERV system is correctly sized for the building's volume and occupancy.
- Dividing the layout into zones with individualised measured elements, which allows more precise control of airflow, heat and process extraction, especially with different temperature or humidity needs.
-

f) Maintenance and regular inspection

- Regular cleaning: Dust and dirt can accumulate in heat exchangers and reduce heat transfer efficiency. Regular cleaning of heat exchangers is essential to maintain efficiency.
- System and sensor calibration.

g) Energy recovery from exhaust air

- Preheating or precooling of supply air = utilisation of heat in production technology.
- Dehumidification: In humid environments, some ERVs have dehumidification properties that help reduce energy consumption by adjusting the indoor humidity level, thereby optimising the energy needed for cooling or heating.

h) Operator training and understanding of measured data:

- Operator training: Ensure that employees understand how the ventilation and heat recovery system works and know how to use Smart/AI analytics to optimise settings.
- Energy audits: Regular audits can help identify inefficiencies and areas where the system could be further optimised.

i) Reduction of energy costs and return on investment:

- Cost-benefit analysis: In the short term, you may need to invest in more advanced sensors, control elements and IoT software and smart systems, but in the long term, they lead to significant savings on energy bills and a more comfortable working environment.
- Green building certifications: Optimising ventilation with heat recovery can help earn points for certifications such as LEED or BREEAM, thereby increasing sustainability credibility and potentially providing tax benefits or subsidies.

j) Integration of IoT smart ventilation control with other building and plant systems:

- Smart building integration: The ventilation system can be integrated into the building's overall smart control system, including lighting, HVAC and energy management systems. This can optimise energy consumption across multiple systems based on overall building occupancy, weather conditions and production schedules.
- By carefully managing these factors, you can create a ventilation system that provides optimal air quality and comfort while minimising energy consumption and improving sustainability.

Analysis of a comprehensive data-driven Smart Industry platform – description, requirements, technology, solutions.

Technical platform requirements

The industrial IoT data and integration platform is a modern SaaS (Software as a Service) cloud platform that provides a centralised and flexible solution for collecting, managing and analysing operational data in companies. The system enables comprehensive monitoring and control of diverse processes in real-time – from energy management and production efficiency to tracking environmental indicators such as CO_2 emissions or temperature and humidity in the work environment.

The system is based on a modular architecture that allows scalable deployment according to customer needs. **The industrial IoT data and integration platform** is capable of integrating data from various sources – production equipment, sensor networks, ERP systems or environmental sensors – and categorising them over time. These data are then visualised using interactive dashboards, including 2D/3D views in the form of a so-called digital twin of the operation. The system supports both standardised and custom data formats, which ensures easy connection to the company's existing infrastructure.

Thanks to advanced analytics, the **industrial IoT data and integration platform** allows not only monitoring the current state but also predicting future developments and optimising resources. Users have access to clear charts, custom reports and alerts for deviations, and the ability to perform ad-hoc analyses. The platform thus helps reduce costs, increase efficiency and achieve sustainability goals.

The system is designed for rapid implementation – from a demo version for one week, through pilot deployment over 2–3 weeks, to full launch into live operation within 2–5 weeks. Updates take place without downtime or disruption to operations. The customer also has full control over which data points and devices they connect to the system.

The platform offers various licensing models adapted to the scale of use – from smaller installations to large company deployments. Technical and consulting support comes as standard, helping customers use and develop the system effectively. The **industrial IoT data and integration platform** thus represents a robust, clear and user-friendly solution for the digital transformation of a company.

Technology used

The system should be built on a microservices architecture running in a secure cloud environment in European data centres with a high level of security. A flexible and scalable infrastructure managed by Docker Swarm allows zero-downtime deployment of modules and efficient management of system operations.

Concept of using the platform as a core tool for the digitalisation (r)evolution

The system should be designed for Brownfield (a brownfield project – a project implemented on existing infrastructure, i.e. in an environment that is already functioning). Most often, this involves an upgrade, extension or integration. (note: It will handle Greenfield even more easily – a greenfield project, i.e. a project that starts 'on a green field', completely from scratch, without any existing infrastructure or technological limitations.)

Implementation into a brownfield is one of the critical processes of digitalisation for existing companies, for two reasons:

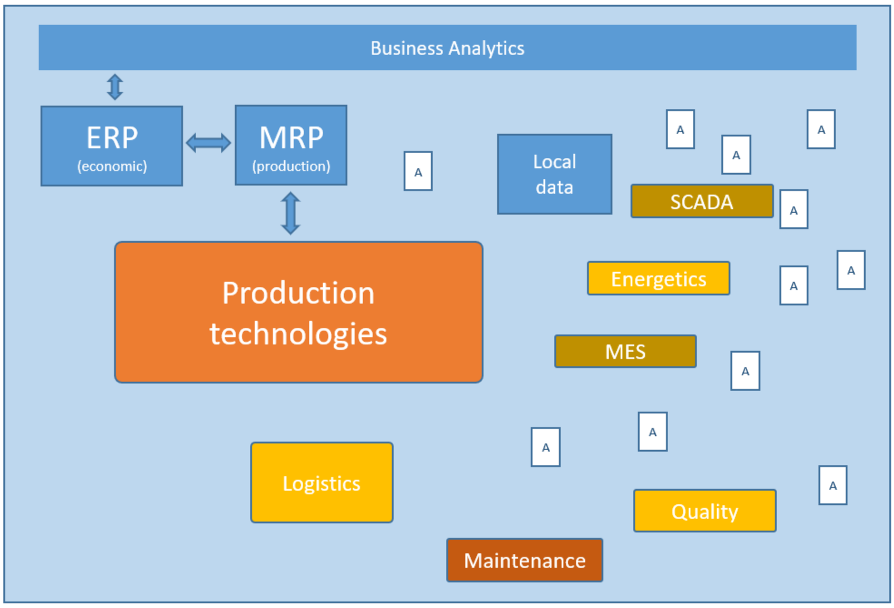
a) Technological complexity – various old and modern technology that needs to be data-connected
b) The economic and time demands of this process

A separate major challenge is connecting as large a part of the company as possible to the wider data environment as quickly as possible, including off-line collected and recorded structured data (e.g. XLSX, CSV, etc.).

This is best understood by viewing the individual phases of companies in the process of digitising production parts.

Phase 1 – Functional planning and basic production management

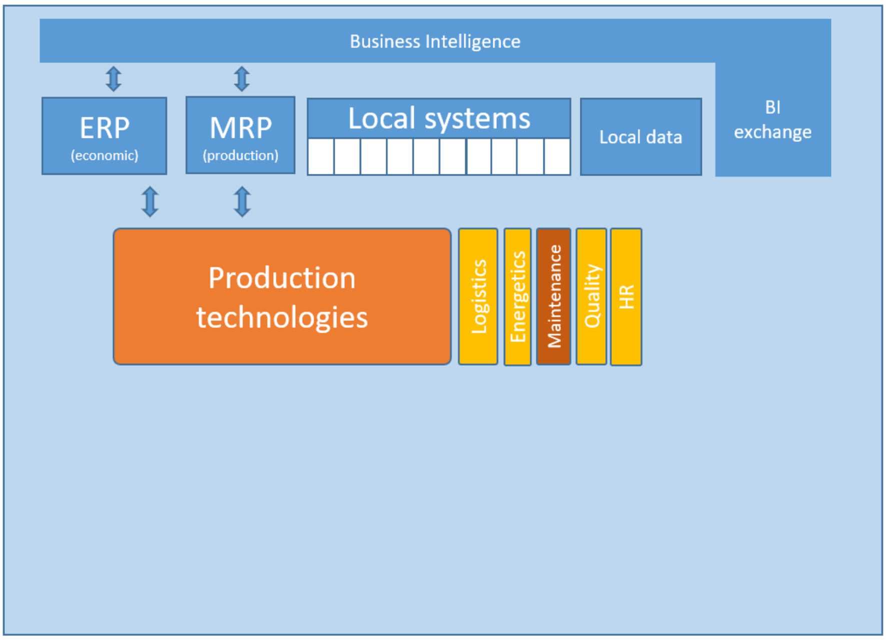
This is the most common state of current manufacturing companies, where, in addition to an economic system or ERP, they use production planning software (at least Excel) and narrowly specialised small software solutions supporting their basic production or process activities.



The primary goal in the digitisation process in this phase is to identify all quality data sources and prepare digital data for integration into a common location. This also represents an effective model for protecting investments.

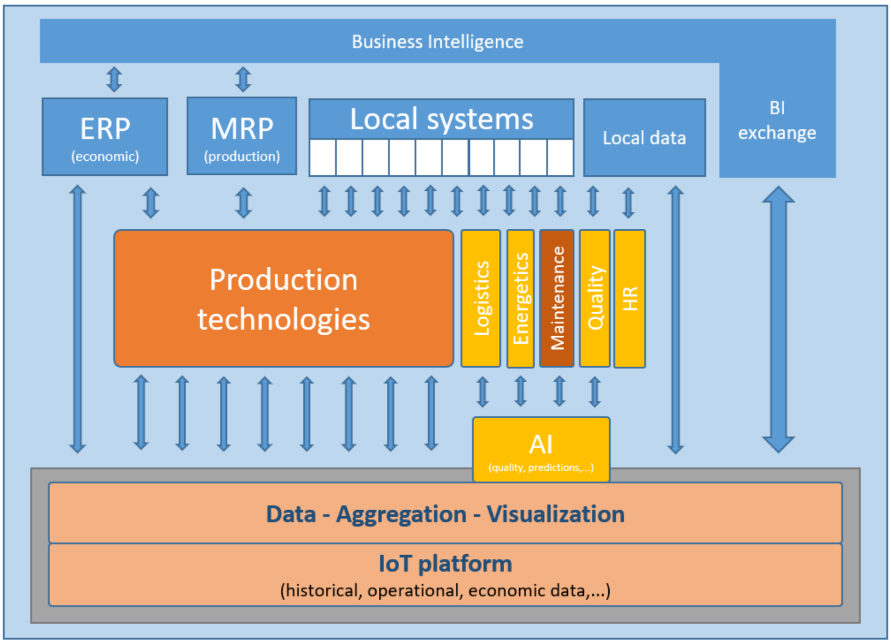
Phase 2 – Logical 'rearrangement' of existing systems

In this phase, a logical 'reorganization' of existing systems and their data outputs occurs, along with the identification of candidates for deeper operational data collection (MES, SCADA, PLC etc.). This is also suitable preparation for checking data outputs or even checking the efficiency of previously implemented production and operational procedures.



Phase 3 – Centralisation of data on a common data platform

Centralisation of data on a common data platform represents the dominant role for the industrial IoT data and integration platform.

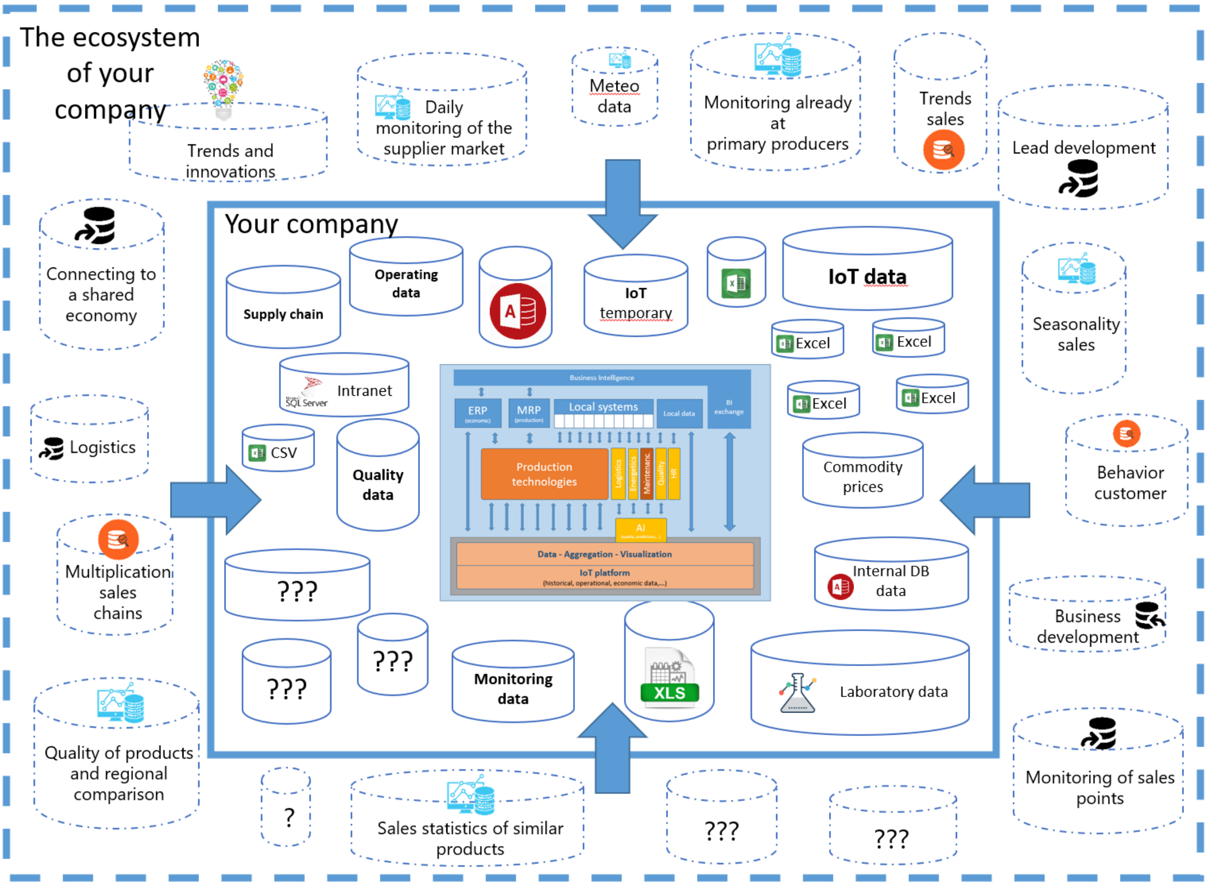


It is important to name the parts of this phase that should not be forgotten.

- **Connect all previously digitised processes for integration in one place.**
- **Interconnecting solutions (vertical) helps achieve further savings and efficiency.**
- **By interconnecting systems, it is possible to increase the number of automatable processes, even between individual departments or technologies.**
- **Create a system for more effective early warning.**

Phase 4 – Continue connecting additional external data inputs, including off-line local data sources.

In this final phase, it is important to gradually involve all internal and external sources that will help increase efficiency, reduce costs, and thus gain a competitive advantage. Thanks to the created early warning system, the risk of 'human-overlooked' deviations is significantly reduced – or completely eliminated – without the need to increase staff numbers.



User interface – access types, scalability

The industrial IoT data and integration platform offers a modern, clear and responsive user interface designed with ease of use, access security and a high degree of scalability for various types of users and devices in mind.

Access types

- **Web interface (browser-based UI)**
  - Main interface accessible via a secure web domain
  - Requires no installation, supports current versions of common browsers (Chrome, Firefox, Edge).
- **Mobile access**
  - Responsive interface display allows comfortable use even on tablets and smart phones.
  - For specific cases, it is possible to create simplified dashboards for operational access by workers directly in production.

- **External API access**
  - A REST API interface with authentication is available for integration with ERP, MES, SCADA or other systems.
- **Permission levels (RBAC)**
  - Role-based access control allows precise management of access according to roles.

Scalability

- **User scalability**

The platform allows the management of units from a few users up to dozens of separate teams and organisational units, with each having its own dashboards and access to specific data.

- **Functional scalability**

It is possible to gradually activate new parts of the system and digital entities (e.g. for energy, CO_2, machine data, climate variables, reporting, predictive models) without the need to change the basic architecture.

- **Data scalability**

The architecture is prepared for large volumes of data from thousands of sensor points, including historisation, aggregation and real-time analysis.

- **Multilingual scalability**

The system's multilingualism is designed as a key feature for use in an international or multilingual environment.

Functionalities and their use

Overview of key functions

Production dashboard – central production overview

The production dashboard is a key part of the industrial IoT data and integration platform, focused on the visualisation and management of production operations in real time:

- **Digital twin of operations** – The dashboard allows displaying operational points and areas on a 2D/3D or satellite map, taking into account the logical structure of the company (e.g. halls, production lines, departments, etc.).
- **Selection and filtering of points** – Users can selectively display specific data points by type (e.g. temperature, motion, consumption sensors).
- **Colour status indications** – Individual points are indicated by colours according to current operational values and defined limits, which facilitates the identification of deviations.
- **Real-time visualisation** – Data are updated online, thanks to which operators and managers gain an immediate overview of the performance of equipment and processes.
- **Logical dependencies** – The dashboard displays relationships between objects, which helps to better understand complex production processes and technological connections.

Summary of expected benefits:

- Intuitive visualisation of production processes with the possibility of quick problem localisation

- Real-time monitoring and early warnings of deviations
- Decision support through clear and customisable overviews.
- Digital twin as an alternative path to understanding and optimising operations

Studio – modelling and creation of a digital image

The studio should provide an advanced tool for configuring production directly by the user, without the need for programming:

- Allows creating and customising production centres ('work centres') or modifying existing objects simply, quickly and independently, which saves time and reduces implementation costs.
- It is a visual editor of operational units that can be controlled by the user: adding devices, setting their parameters, defining the logical structure and assigning data points.
- Thanks to the ability to configure an object 'in-app', it supports an iterative approach to the design of production processes, which means that modules and layout can be quickly changed based on user feedback or new requirements.

Summary of expected benefits:

- Speed and efficiency – Design and modifications without developers Users can add or modify operational centres themselves
- Lower deployment costs – Minimises the time needed for analysis, development and configuration – shortens implementation time
- Flexibility – The production environment can be easily adapted to changing requirements, new sensors, or production lines
- Sustainable management – Changes and updates can be performed without the need for intervention by external specialists

Performance dashboards – a key tool for monitoring performance, not just processes

Performance dashboards in the industrial IoT data and integration platform are a key tool for monitoring the performance of processes, equipment and operational units. This module is intended for both managerial and operational management and helps companies quickly evaluate efficiency, performance and deviations based on real-time data.

Expected main functions:

- **Creation of custom reports/boards** with the possibility of sharing them with other users.
- **Display of key performance indicators (KPIs):** for example, OEE (Overall Equipment Effectiveness), energy consumption per unit of production, machine time utilisation, performance of individual teams, CO_2 per product, etc.
- **Real-time & history:** combination of online data with historical trends allows immediate comparison of performance with previous periods.
- **Visual presentation of data:** graphs, bar charts, heat maps, percentage deviations, colour performance markers (e.g. green = OK, red = problem).
- **Filtering by time period, shift, operation or line:** managers can create their own performance views according to context (e.g. shift comparison, individual days, production centres).

- **Automated calculations:** the dashboard automatically calculates productivity, standard fulfilment and differences between plan and reality.
- **Export of data from individual KPIs** to Excel or CSV format for any local processing.

Summary of expected benefits:

- **Rapid detection of problems and bottlenecks** – allows immediate identification of performance drops without the need for detailed analysis.
- **Decision support** – provides reliable data for both operational and strategic decisions.
- **Increased transparency of production and other operational processes** – every team has a clear overview of performance 'in black and white'.
- **Employee motivation** – clear visualisation of results can act as a gamification tool and support team spirit.

Public API panel – a key tool for data sharing

The public API panel should represent an ideal and very user-friendly tool for creating secure data REST API interfaces directly from the application, without the need for programming. Sharing acquired and processed data in a data and integration platform naturally gives rise to the need for further sharing or collaboration with third-party tools – whether they are data and analytical tools, or inputs for more complex AI analyses.

Expected main functions:

- **Creation of custom API boards** with the option to share them with other users.
- **Setting access rights for third-party applications** directly from the data and integration platform environment, which allows secure and controlled data usage.
- **Graphical display of key performance indicators (KPIs) before the actual export** – all KPI data prepared for export are visualised as charts (similar to the Performance Dashboards section) so that the user can verify the scope and quality of the data shared via API.

Summary of expected benefits:

- Rapid preparation of REST API interfaces directly from the application environment – without the need for programming and thus without additional costs.
- Ability to effectively create ad-hoc API interfaces – suitable for both short-term and long-term integrations.
- Support for current security standards for REST API interfaces – ensuring data protection and access management according to modern standards.
- Online documentation with the option to verify API functionality via <u>Swagger</u>.
  <u>Swagger</u> is a tool (or a set of open-source tools) that is most commonly used today as part of the OpenAPI standard. Its main functions include:
- Provides a clear view of available API endpoints, including expected parameters and response types.
- Swagger UI allows sending requests (GET, POST, PUT, DELETE, etc.) directly from the browser and immediately monitoring responses in real-time.
- Allows verifying API functionality without the need to write test code, which significantly speeds up integration and testing.

Early warning system

The early warning system should serve as a powerful and flexible mechanism for monitoring specific data points or process states and reacting to predefined events (e.g. deviations, approaching critical values, outages).

Expected main functions:

- **Defining monitored parameters** – the user can select specific variables (e.g. temperature, energy consumption, pressure) that are critical for their operation.
- **Rules and conditions** – the system allows setting logic (greater than/less than, in range, growth/decline trend) for triggering actions.
- **Notifications and alarms** – when conditions are met, alerts are triggered, which can be delivered in the form of visual signalling, email or other notifications.
- **Automated reactions** – can trigger subsequent actions, such as logging, data export, API calls or even directly starting a process in a superior system.
- **Event history** – every event is recorded for the purposes of retrospective analysis and audit.

Summary of expected benefits:

- **Timely identification of problems** – detecting deviations before they cause outages or economic damage.
- **Operational automation** – the system actively reacts to defined states without the need for direct operator intervention.
- **Flexibility and scalability** – can be used for both simple and complex process logic.
- **Increased security and quality** – monitoring critical points minimises the risk of human error.

Logs – protocols

Logs represent a central mechanism for continuous recording of both system and operational events. They serve as a basic tool for monitoring, auditing and incident resolution.

Expected main functions:

- **Continuous recording** – all system and operational events are stored in a central database or file structure.
- **Event capturing** – actions such as user logins, errors, dashboard configuration changes, alert generation and their subsequent confirmations are written to the logs.
- **Web interface** – available for easy viewing and filtering of records based on selected criteria (time, event level, specific module, user).
- **Standardised log levels** – the system supports standard log categories such as INFO, WARNING, ERROR, DEBUG, which allows quick sorting and analysis.

Summary of expected benefits:

- Increased transparency – complete recording of events provides an overview of system and user behaviour.

- Audit and oversight – support for internal and external audits thanks to the retention of the history of all key operations.
- Effective incident resolution – quick search for the cause of errors or outages.
- Cybersecurity support – detection of suspicious activities and tracking of unauthorised access attempts.

Customisation options for specific operations

The data and integration platform should be designed with an emphasis on maximum flexibility and scalability, allowing its effective deployment in various types of industrial, logistics or energy operations – from smaller businesses to large production plants.

Thanks to the modular architecture and easily configurable environment, it should be possible to precisely adapt the system to the specific needs of the customer without the need for demanding custom development.

Customisation of structure and functions

System customisation options mainly include:

- Configuration of the digital twin of the operation – 2D/3D or satellite map, visualisation of points and process zones.
- Creation of custom dashboards and views according to departments, roles or device types.
- Defining relationships between data points – e.g. hierarchical structure line → machine → sensor.
- Setting custom metrics and KPIs – e.g. OEE, MTBF, consumption per product, shift efficiency.

Customisation without programming

- **Studio module** – allows users to define and edit production centres and data flows using an intuitive graphical editor.
- **Watchers and Alert Engine** – can be configured directly via the user interface without the need for writing code, even for more complex alert logic or rules.
- **Multi-language environment** – every user can set their preferred language, which simplifies work in an international environment.

Custom reports and outputs

- **Ability to define custom export formats and reporting templates**
- **Automatic sending of outputs** to specific users or departments
- **Division of reporting units** according to operational units, shifts, locations or production lines

The industrial IoT data and integration platform is a tool that fully adapts to the specific conditions of each operation. Whether it is production, logistics, energy or building management – the system can be easily adapted without the need for intervention in the platform's core. Thanks to this, it enables:

- Rapid deployment
- Low costs for modifications
- A high degree of usability across industries

The role of software in managing business processes

In a modern environment, where efficiency and flexibility play a key role, an industrial IoT data and integration platform becomes an important tool for managing, controlling and optimising business processes across the entire organisation.
Its role is not just data collection itself, but, most importantly, **the transformation of raw data into usable information** that supports daily decision-making at all levels of management.

Key benefits in process management

- **Complex integration**
  - Watchers can be run in parallel with piece or batch processes.
  - Thanks to data visualisation and KPI overviews, it is possible to immediately identify bottlenecks, losses or fluctuations in production.

- **Support for operational and tactical decision-making**
  - The system provides clear dashboards for both operators and managers, which help in making data-driven decisions.
  - It allows quick reactions to changes in operations, for example by redirecting capacity or changing priorities.

- **Streamlining resource management**
  - The data and integration platform helps optimise energy consumption, machine time, staff numbers and production material.
  - Using alerts and predictive analytics, it is possible to prevent losses, outages or waste.

- **Support for standardisation and quality**
  - It allows the setting and monitoring of standard operating parameters, thereby contributing to increased stability and quality of outputs.
  - It ensures traceability and an audit trail for retrospective evaluation of process changes.

- **Connection with other systems**
  - Thanks to an open API and support for integrations, the data and integration platform can be easily connected to ERP, MES, SCADA or custom applications.
  - This creates a connected ecosystem where data are available and usable across departments – from production to finance.

Types of processed data

List of supported data types and variables

The data and integration platform system should allow the collection and processing of a wide spectrum of data relevant for both operational and administrative parts of manufacturing companies. Thanks to its openness and modular architecture, it can cover the needs of various departments – from production through maintenance and energy to quality and reporting for management.

To fulfil what is expected of it, it should have at least the following technical features.

Tab. 6.1
Supported data types

Data type	**Use in a production environment**
Numerical data	Measurement of values from machines and sensors (e.g. temperature, pressure, power)
Logical data	Status indications: on/off, open/closed, OK/ERROR
Text data	Product codes, work procedures, shift logs
Timestamps	Machine start time, cycle length, occurrence of an event
Aggregated data	Daily summaries, averages, performance per shift or device

Tab. 6.2
Typical variables supported in a production operation

Area	**Typical monitored variables**
Production	Number of pieces, production cycles, run/downtime, failure rate
Machine data	RPM, vibrations, currents, motor states, operating temperatures
Energy	Consumption of electricity, gas, water, measurements at main nodes
Maintenance	Frequency of interventions, service times, predictive signals
Kvalita	Non-conformity rate, number of complaints, monitoring of parameter deviations
Logistics	Number of shipments, status of warehouse positions, equipment utilisation
Safety	Sensor status, emergencies, presence of persons
Environment	CO_2 emissions, noise, humidity, temperature, CO/VOC concentrations

Other special features

- **Real-time and historical data** – the ability to monitor both current status and long-term trends.
- **Conversion of quantities and units** – units can be customised or recalculated according to company standards.

- **Logical links between data** – e.g., conditions such as *'if machine is running + temperature above X'*.

Tab. 6.3
Data inputs – typical examples for a company

Source	Description
PLC / SCADA	Data from line and equipment control systems (e.g. Siemens, Schneider).
Sensors (analogue, digital)	Temperature, pressure, CO_2, humidity, currents, pulses.
ERP / MES	Data on production orders, shifts, reports.
CSV / REST API / MQTT	Data transfer from local systems or external cloud services.

The industrial IoT data and integration platform supports all key data types common in the operational parts of the company. Thanks to direct connection to physical devices, superior systems and cloud services, it provides a unified data environment that enables a detailed overview of the status of production, machines, consumption and processes – not only in real time but also from the perspective of long-term evaluation.

Input data formats (CSV, XML, JSON, direct API connection)

The industrial IoT data and integration platform should be designed as an open and flexible solution that supports a wide range of data formats and integration methods. It allows easy connection of various technological units, IT systems and external data sources – regardless of their original structure or manufacturer.

CSV (comma separated values)

- **The most frequently used format for both manual and automated data import**
    - Supports both single and batch import of time series, measurements or outputs from third-party systems (e.g. ERP, laboratory software)
- **Configuration options:**
    - Setting separators (comma, semicolon)
    - Custom column headers
    - Measurements over time (timestamp, values, units)

XML (eXtensible Markup Language)

- Suitable for **structured datasets** with multi-level records
- Allows connection to MES, SCADA or B2B data exchange systems
- Used, for example, for transferring batches, traceability or quality results

JSON (JavaScript Object Notation)

- **Standard for modern web and IoT applications**
- Ideal for connecting smart devices, API gateways and edge systems
- Supports:
    - Structured data points
    - Metadata and dynamic variables
    - Communication with cloud services

Direct API connection (REST API**)**

- **The most direct and efficient way of integration**
- Allows:
    - Bidirectional data transfer (push and pull)
    - Online connection of devices, PLC, SCADA, ERP and other applications
    - Triggering actions and synchronising states in real time
- API is secured using:
    - Authentication (token, key, OAuth)
    - Works with JSON format

  Interactive documentation (Swagger) is available

The industrial IoT data and integration platform allows combining multiple formats simultaneously – for example, direct API connection to SCADA and parallel import of historical data from CSV or JSON files.
This ensures high flexibility not only during the integration process but also later during actual operation.

Format	**Suitable for**	**Typical uses**
CSV	Fast import/export	Measurement results, laboratory data, manual records
XML	Structured data flows	Batches, production orders, multi-level data
JSON	Web and IoT systems	Smart devices, cloud integration
REST API	Online transmission and integration	SCADA, ERP, live communication

The industrial IoT data and integration platform thus ensures seamless integration of data from both older and modern systems with the goal of quickly centralising and visualising all important operational data – without the need for intervention in the original technologies.

Methods of data storage and structuring

The industrial IoT data and integration platform is designed as a powerful and scalable data platform that enables efficient storage, sorting, searching and analysis of operational data from various sources. Its architecture ensures that all data – regardless of origin – are organised with an emphasis on time, type, meaning and technical context.

Tab. 6.4
Data model structure (example)

Implementation	**Description**
Organisation	Customer instance, production plant or branch.
Operational units	Halls, production lines, devices, sensors – grouped within a so-called *digital twin*.

Implementation	Description
Data points	Individual measured or monitored variables, e.g. temperature, pressure, production cycles.
Groups and tags	Thematic or technical groupings of points, e.g. ‘energy’, ‘compressed air’, ‘quality’.

Each **data point** within the industrial IoT data and integration platform can have defined **metadata** that expand its meaning and increase usability:

- **Data type** – determines the character of the variable (numeric, logical, text, time).
- **Unit** – e.g., °C, kWh, m^3, pieces.
- **Category** – thematic or technical classification (e.g. energy, production, quality).
- **Time context** – timestamp, cycle, duration, measurement periodicity.
- **Logic and relationships** – calculations, derived values, rules or connections to other points.

Metadata defined in this way allow precise interpretation of data, their correct evaluation and simple integration into subsequent processes or visualisations.

Time series storage

- **Storage in time series** – every measured value is always firmly tied to a precise timestamp.
- **Support for various levels of granularity** – from seconds through minutes and hours to daily values.
- This approach allows **tracking the development of variables over time**, evaluating **long-term trends** and simultaneously running **predictive models** for early detection of deviations or process optimisation.

Logical structure and dependencies

- **Logical structure of operation** – data is stored and organised according to the hierarchy of operational units, for example, *production line → device → sensor*.
- **Relationships and dependencies between data** – individual data points can be logically connected, for example: *energy consumption depends on machine temperature*.
- **Incorporation into verticals (areas)** – each data point can be assigned to one or more functional categories, such as:
  - Energy
  - Production quality
  - Maintenance
  - Security monitoring
  - CO_2 and ESG
  - Other specific areas according to customer needs

History and archiving

- **Long-term data archiving** – the system allows storing extensive historical records with the possibility of fast retrospective searching.

- **Aggregation of older data** – to save storage space, it is possible to automatically convert detailed time series (e.g. minute-based) into aggregated intervals (hourly, daily).
- **Use of historical data** – archived data are a key input for:
  - regular reports and management outputs,
  - benchmarking between operations or time periods,
  - predictive models and analyses to support planning and maintenance.

Summary

The industrial IoT data and integration platform stores data in a way that is:

- **clear** – every value has a clearly defined place and meaning,
- **efficient** – optimised for both fast queries and complex calculations,
- **scalable** – ready to process millions of records daily,
- **secure** – with support for audit mechanisms and precise access control.

This data structure forms a reliable foundation for **advanced analytics, process automation and strategic management of production or operational processes.**

Integration with measuring devices

Overview of measuring technologies

The **industrial IoT data and integration platform** system should be designed as an open and flexible platform capable of working with a wide range of measuring devices and sensors. To achieve reliable and comparable results, it is important to choose suitable types of meters based on the measured medium, required accuracy, communication method and the environment in which they will be installed.

Recommendations for device selection with regard to accuracy, communication and service life

When selecting measuring devices and sensors for the **industrial IoT data and integration platform**, it is important to consider the following criteria:

- **Measurement accuracy**
  - Determine the required accuracy class according to the purpose of the measurement (e.g. billing measurement vs. technological monitoring).
  - Consider the meter's tolerance depending on the process dynamics (e.g. rapid consumption changes vs. long-term averages).
- **Communication interface**
  - Prefer devices with standardised protocols (Modbus TCP/RTU, MQTT, OPC UA, BACnet, M-Bus).
  - Assess the availability of network infrastructure (Ethernet, Wi-Fi, LoRaWAN, LTE/5G).
  - Verify the possibility of remote configuration and firmware updates.

- **Lifespan and reliability**
  - Select devices with high environmental resistance (IP rating, temperature range, resistance to vibrations or dust).
  - Prefer instruments with the possibility of long-term calibration or self-diagnostics.
  - Evaluate total operating costs (maintenance, spare parts, service support).

Recommendation: *In environments where meters already exist, it is appropriate to prioritise integration via interfaces and communication gateways to minimise equipment replacement costs while maintaining data accuracy and continuity.*

Methodology for initiating data collection

The methodology for initiating data collection in the **industrial IoT data and integration platform** is a key step for the successful digitalisation of operational processes. The goal is to correctly identify measurement points, ensure reliable device connection and set appropriate measurement intervals so that the data is accurate, consistent and usable for analysis.

Identification of measurement points in the operation

- Conduct an audit of the existing infrastructure and determine which devices or processes should be monitored.
- Set priorities according to importance – critical machines, energy-intensive technologies, safety elements.
- Define the type of measurement: energy consumption, technological variables (temperature, pressure, vibrations), environmental data (CO_2, humidity).

Design of the sensor connection architecture to the system

- Choose a suitable communication method (Modbus, OPC UA, MQTT, REST API, M-Bus).
- Assess the need for edge devices or IoT gateways for data collection and preprocessing.
- Design redundancy and security measures (VPN, encryption, RBAC).
- Optimise data flows so that they do not burden the internal network, but also allow real-time transmission.

Measurement intervals and accuracy requirements

- Determine the measurement frequency according to the process type:
  - **Critical processes** – interval in seconds
  - **Technological processes** – minute values
  - **Reporting and benchmarking** – hourly to daily summaries
- Define the measurement deviation tolerance according to the purpose (e.g. billing measurements must have higher accuracy than indicative ones).
- Implement data validation mechanisms (boundary checks, outage detection).

Testing and pilot operation

- Before deploying into full operation, verify the collection reliability on a pilot sample of devices.
- Evaluate data quality – consistency, completeness, accuracy.
- Optimise settings (intervals, transmission paths, aggregations) according to the pilot results.

This methodology ensures that data collection will not only be technically functional but also practically usable for decision-making and optimisation of production and operational processes.

Connection options for sensors and devices (IoT, Modbus, OPC UA, MQTT, etc.)

The industrial data and IoT integration platform should be designed as an open integration platform that allows the effective connection of modern IoT devices as well as traditional industrial technologies.

The system supports a wide spectrum of communication protocols and data formats, ensuring fast and universal integration into almost any operational environment – without the need for interventions or fundamental changes to the existing infrastructure.

Tab. 6.5
Direct connection of industrial devices

Protocol	**Use description**
Modbus TCP/RTU	Integration of standard PLCs, electricity meters, sensors, drives
OPC UA	Connection to SCADA, DCS and complex industrial networks
BACnet	Measurement and control systems in buildings (BMS)
KNX	Lighting, HVAC and building control
Others as needed	Also prepared for new types of devices and communication protocols

Data transmission via data gateways (EDGE Gateways)

The industrial IoT data and integration platform should also support data connection for older devices using local HW gateways. This model is also used for types of measurements that need to be read locally for security reasons (e.g. electrical energy monitoring).

- For older or non-networked devices, it is possible to use local IoT gateways that convert local data to standard protocols (e.g. MQTT, HTTP).

The industrial IoT data and integration platform enables simple and robust connection of diverse devices via commonly used industrial and IoT protocols. Regardless of the technology type or manufacturer, it is possible to integrate sensors, meters and control units into a unified system without the need to interfere with their function.

This significantly accelerates the digitisation of operations and enables centralised visualisation and data management across the entire company.

Compatibility with common measuring units (electricity meters, water meters, gas meters) and an overview of technical requirements (options).

The industrial IoT data and integration platform should be prepared for the fast and efficient connection of a wide range of standard measuring devices commonly used in manufacturing operations, administrative buildings and infrastructure applications. Thanks to the modular architecture and support for industrial communication protocols, high compatibility is ensured without the need for custom development.

Electricity meters

The system supports the connection of most modern electricity meters with a digital output:

- **Modbus RTU / TCP electricity meters** (e.g. Schneider, Socomec, Carlo Gavazzi, Janitza, Siemens)

- **Pulse outputs (S0)** – consumption measurement using pulse converters and counters
- **Measurement of network parameters:** e.g. voltage, currents, active and reactive power, power factor, frequency, kWh

Data from electricity meters are used in the system for consumption monitoring, cost calculations, overload, deviations and efficiency analysis.

Water meters

The **industrial IoT data and integration platform** enables the connection of water meters via various communication methods:

• **Pulse water meters** – with a pulse converter (e.g. 1 pulse = 1 liter)

• **Water systems with M-Bus or Modbus output**

• **Digital flow meters for precise flow and pressure monitoring**

Typical use: monitoring daily/instantaneous water consumption, leak detection, monitoring of technological or operational water.

Gas meters

For gas measurement, the industrial IoT data and integration platform supports:

- **Modules with pulse outputs** (e.g. Elster, Itron, Metrix)
- **Gas meters with a data interface** (Modbus, M-Bus, IoT converters)
- **Integration with pressure and temperature measurement** to calculate converted volume

Data from gas meters are used for cost monitoring, optimisation of boiler room operations, production equipment or heating.

Connection method

All measuring devices can be connected:

- **Directly via PLC/RTU with Modbus interface**
- **Via IoT converters with MQTT or http output**
- **Using an EDGE gateway with support for multiple inputs (pulse, RS485, M-Bus, analogue)**

Benefits of integration into the platform

- **Centralised overview of all energy sources in one place**
- **Possibility of automatic calculation of costs, efficiency and deviations**
- **Generation of reports, alerts and predictive consumption models**
- **Basis for energy management and ESG/ISO 50001 reporting**

The industrial IoT data and integration platform should be fully compatible with common measuring instruments used in electricity, water and gas services. It enables their simple connection, management and visualisation without complex modifications. This makes it an ideal platform for digital monitoring of energy and operational media in production, buildings and technological units.

Data processing and interpretation

Data analysis methods (statistics, comparisons, predictions)

The industrial IoT data and integration platform is not just a tool for data collection and visualisation, it is also a full-fledged analytical platform that enables advanced data processing in real-time and retrospectively. Its goal is to help companies transform raw data into understandable information that leads to informed decision-making, savings and increased performance.

Statistical analysis

The industrial IoT data and integration platform enables data processing using basic and advanced statistical functions:

- Average, minimum, maximum, median
- Standard deviation, dispersion
- Sums, occurrence counts, state counts
- Slow trends and seasonal fluctuations

Statistics can be displayed in graphs and interactive reports with export options.

Comparative analysis (comparison over time or between objects)

- **Inter-temporal comparisons**: performance comparison day vs. yesterday, shift vs. shift, month vs. month Month
- **Inter-object comparisons**: comparison of lines, machines, shifts, operations, branches
- **Benchmarking**: against planned values, limits or ideal parameters
- **KPI calculations**: e.g. consumption per piece, CO_2 per product, shift efficiency

Comparison results can be automatically highlighted (colours, alerts) or used as input for notifications.

Real-time and online monitoring

- **Real-time update of graphs and tables**
- **Automatic reactions to deviations and fluctuations** (e.g. Watchers)
- **Connection with the digital twin of the production process (Factory Dashboard)**

Users see the current status **without needing to refresh data** and can **react immediately to changes in operations.**

Predictive analysis

- Prediction of consumption trends, temperature, load or equipment performance
- Estimation of failures or exceeded limit values
- Possibility of implementing custom models (e.g. linear regression, decision trees, AI models)

Prediction results can be displayed as projections in charts or used for automatic alerts and planning.

Visualisations and interactive dashboards

- **All analytical outputs can be displayed in a graphical dashboard**
- **Possibility of combining different types of visualisation:** bar charts, line charts, tables, heat maps
- **Configurable panels according to user roles and needs**

Historical analyses and exports

- Retrospective evaluation of processes, shifts, failures, shutdowns
- Ad-hoc filtering and analysis by time windows, data types and users
- Exports to CSV, Excel, PDF or API connection to BI tools

The **industrial IoT data and integration platform** provides a comprehensive set of analytical tools for:

- Performance statistics
- Comparing operational data
- Trend prediction and optimisation
- Evaluating efficiency and quality

Thanks to these functions, the **industrial IoT data and integration platform** becomes an intelligent data layer that connects data collection with decision-making – and thus contributes to the company's true digital transformation.

Visualisation and reports - settings and customisation options

The industrial data and integration IoT platform should offer a user-friendly and fully customisable visualisation and reporting system that allows various users – from operators to management – to quickly get an overview of process status, equipment performance or resource consumption. The visual interface is designed to reflect the organisational structure as well as the specific needs of the operation.

Real-time data visualisation

- Display of current data point values in the form of:
  - Charts (line, bar, pie, histograms)
  - Heat maps
  - Gauge elements and indicators
- Visualisations can be customised with colours, scaling, ranges, axis selection and thresholds.
- Updates occur in real time without the need for manual refreshing.
- 2D/3D digital twin – interactive map of the operation with status markers.

Creation of custom dashboards

- **Drag & drop editor** allows every user to create their own reports without programming.
- The user can define:
  - Layout of graphical elements
  - Selection of monitored data points
  - Time range (hours, days, weeks, months, years)
  - Filters by machines, halls, shifts or products, etc.
- **Boards/reports/panels** can be saved, shared or assigned to a user based on editing permissions.

Customisation options

Reports can be customised according to:

- user types (e.g. production manager, energy manager, quality, maintenance),
- locations and operations,
- time requirements (shift, day, month),
- formal requirements (e.g. export for ISO, ESG, internal audit).

Possibility to add custom calculations, notes, comments and, for example, a company logo.

Summary

An industrial IoT data and integration platform should provide a comprehensive and fully customisable tool for visualisation and reporting, which:

- takes into account the special characteristics of the operation,

- enables automation of outputs,
- supports better decision-making based on data.

The system should be designed so that every user can customise the outputs to their needs without IT or developer intervention.

Real examples of processing and practical application

Example – Ventilation and cooling control based on comparison and evaluation of environmental indicators.

Ventilation and cooling control based on comparison and evaluation of environmental indicators – deviation / upgrade / from traditional M&R.

Task:

Monitoring of temperature, humidity, VOC, CO_2 and the amount of solid particles in the production hall – goal – savings of at least 30% on HVAC cooling and heating with new Smart Industry logic added to older M&R (investment in new M&R = ROI 7 years)

Need to monitor, visualise and then control the level of environmental variables in a production hall with an area of approximately 6 000 m², where air is regularly exchanged. The hall is 16 years old, the M&R system is prone to failure and the control units are poorly supported by the manufacturer, including the ventilation units.

Solution from the digitisation Smart IoT platform:

Based on the request, combined special sensors for temperature, humidity, VOC, CO_2 and dust (IoT Sensor Box Enviro) were installed in the production hall area – with the possibility of data transmission via electrical infrastructure, then to the cloud via mobile data – without the need for investment in IT infrastructure.

Findings from measurements:

According to the data, it was found that individual measured variables change significantly depending on production load, the number of people in individual work areas and external conditions. Even though it felt like some values exceeded critical limits, measurements revealed that the values were still within normal ranges and in compliance with OHS (occupational health and safety) = measured dust, CO_2, humidity and VOC.

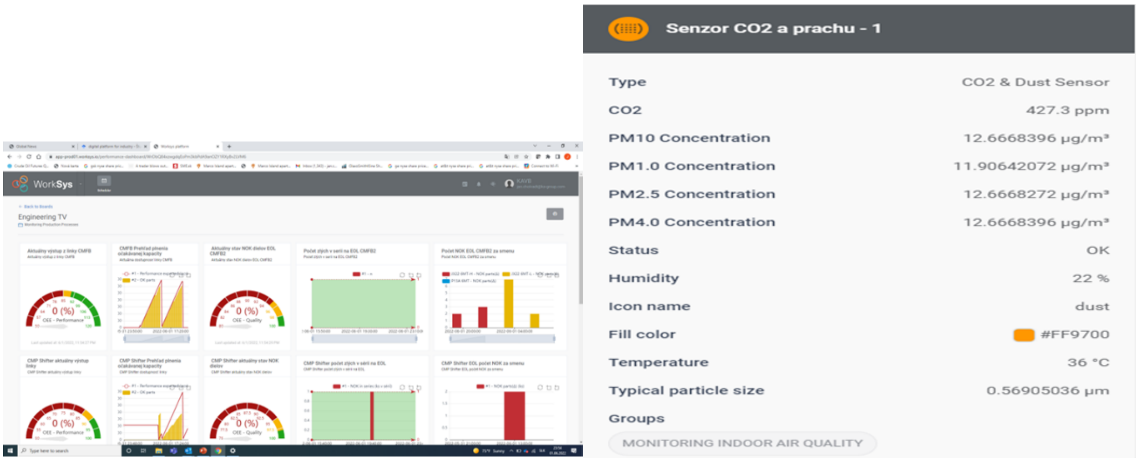


Fig. 6.3 Installation of sensors and integration into the IoT system, data collection and their visualisation in the Factory Dashboard on the Smart IoT platform

Fig. 6.4 Display of online data after setting up active control by the Smart platform – CO_2, dust, electricity consumption and others

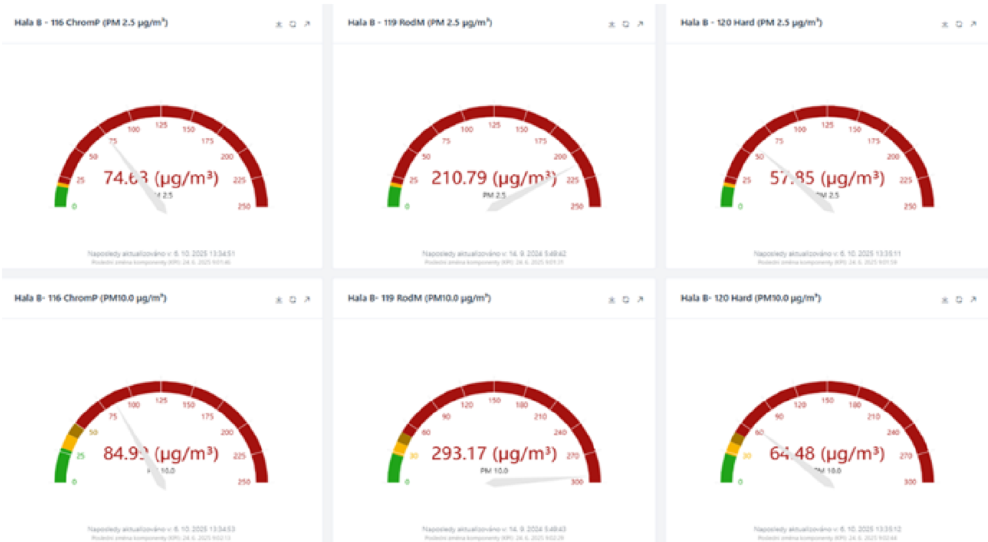
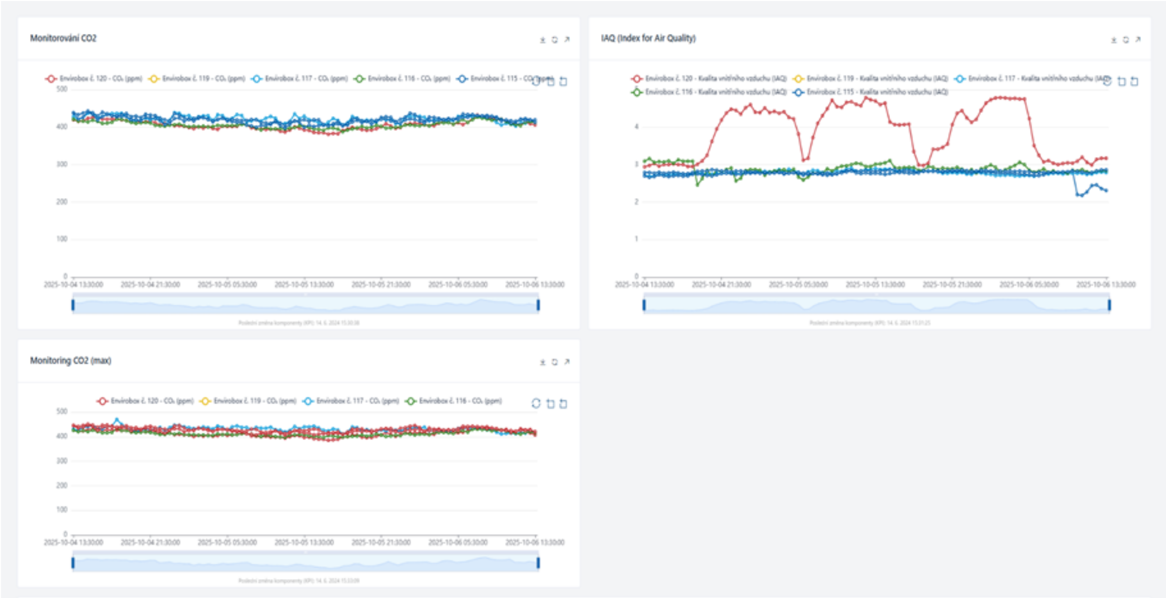


Fig. 6.5 Measurements and active control of the production environment according to the current development of measured parameters in production areas reduced the number of air exchanges by 62% compared to the standard settings of the older M&R based on the standard, while continuously ensuring healthy fresh air in all areas for employees and without the need to manually set M&R for different operating modes



Based on the measurements, a new air exchange process was set up, which extended the time between individual exchanges according to the need for CO_2 and dust monitoring in individual areas in combination with VOC, temperature and dust & humidity. The system directly controls the M&R air exchange technology via the Smart Industry platform. All values are recorded in the platform's cloud.

Costs: Installation of the described design of the Slovak platform Worksys.space, 1 hall, 6,000 m², 17 years.

Initial analysis – €0 (customer accepted the existing solution of the Worksys.space platform)

Hardware:

IoT Sensor Box Enviro – 4X – €780

EDGE + accessories – €2,480

Preparation of the environment in the platform – €3,200

Total: €6,460

The customer performed the installation of the sensors in the production hall with their own maintenance team.

The customer had received quotations for a SW-HW upgrade for new M&R – €79,400 (best price) – still without comprehensive environmental and energy active monitoring and without connection to the remaining M&R in other halls and parts of the plant.

Savings and waste elimination = calculation: 1 hall 6,000 m²

- Price for air exchange (37,000 m³) – €6.8 (single exchange) = 34 Kwh
- Number of necessary completed exchanges per week before installation of IoT technology – 168 times – according to STN EN 13779: 2007

- Number of completed exchanges per week after installation of IoT and digitisation – 35 times on average – while meeting the STN standard for air quality.
- Total savings per week (€6.8 x 133 exchanges): €904 (4,522 Kwh)
- Total savings per year (€904 x 48 weeks): **€43,392 (approximately 54.3 MWh)**
- CO_2 – in the calculation (gCO_2/kWh) 357.56 g (Slovak energy mix for 2023 published by OKTE SK), the impact on **CO_2 reduction is – approximately 19.4 tonnes/year**
- Smart technology eliminated the need for unnecessary reheating of intake air in the winter period (gas) – **optimal waste heat recovery**
- A lower number of operating hours of the air conditioning reduced the need for service interventions **by 75% (1x2 years from a half-year period)** and the creation of service waste for disposal (filters, parts, refrigerant, belts) **by 2.6 tonnes per year**.

6.3. Summary and conclusions

Summary of the benefits of the analytical functions of the Industrial IoT data and integration platform

The industrial IoT data and integration platform is more than just data collection – it is a tool for active management of performance, costs and operational sustainability. Thanks to integrated analytics, visualisations and predictive calculations, it allows:

- Evaluating operational efficiency (e.g. OEE, availability, performance)
- Monitoring consumption of resources and energy (electricity, water, gas, CO_2)
- Detecting deviations, losses and waste before they cause damage
- Predicting future development of load, consumption, failures and costs
- Generating clear reports and outputs for management, audit, ISO, ESG reporting

Thanks to the elasticity of the software platform, it is possible to implement the system gradually – and each of its parts brings measurable value.

General advice on how to start with sustainability in a company (e.g. in energy)

Start by measuring – what you don't measure, you don't manage.

→ Identify the main energy consumers and collect key operational data.

Energy efficiency begins with a thorough understanding of where and how energy or other company assets are consumed in your organisation. Without accurate data, any consumption management is just guesswork.

Perform a detailed analysis of energy flows in your company and identify the equipment, operations or technological units that are among the largest consumers. Set up regular measurement and monitoring of parameters such as electricity, gas, water or heat at these nodes.

The collected data will allow you to:

- detect energy losses and inefficient processes,
- set targeted measures to reduce consumption,
- compare consumption trends over time and evaluate the effectiveness of implemented changes,
- create documentation for reporting and meeting legislative requirements (e.g. according to the ISO 50001 standard).

It is recommended to deploy modern systems for automated data collection and visualisation, which will ensure measurement accuracy and an immediate overview of energy management. Thanks to them, it is possible to react quickly to deviations and make informed decisions about optimisation.

Practical examples of measurement:

- **Production lines:** monitoring the power input of motors and machines to identify consumption peaks.
- **Lighting:** monitoring consumption in different parts of buildings with the aim of optimising operating hours.
- **Compressed air:** checking for leaks and unnecessary operational losses.
- **Thermal management:** measuring temperature parameters and the efficiency of boilers, heat exchangers and cooling equipment.

Through regular measurement and continuous data evaluation, you will gain a solid foundation for implementing measures that can significantly reduce the company's energy consumption, and, consequently, its operating costs.

Choose one place for data consolidation → Centralisation of data in one platform (e.g. an industrial IoT data and integration platform) will prevent fragmentation and improve clarity.

One of the key steps to achieving higher energy efficiency is the **centralisation of all energy and operational data into one platform.** In practice, it often happens that data from measurements and individual systems (energy meters, production technology, BMS systems, Excel spreadsheets, etc.) are scattered across different applications and among different users. This fragmentation not only makes their evaluation difficult, but often causes valuable information to be lost or not reach the responsible persons at all.

Centralisation of data in one platform – for example, **in an industrial IoT data and integration platform** – provides the following benefits:

- **Complete overview:** All data are available in one place, which significantly improves clarity and facilitates decision-making.
- **Elimination of duplicates:** The need to transfer data between different systems or spreadsheets is eliminated, thereby reducing errors.
- **Possibility of automation:** A centralised system allows setting alarms, automatic reports and predictive consumption analyses.
- **Real-time data access:** Responsible persons have immediate access to current information from anywhere.
- **Security and audit trail:** A single data storage makes it easier to retrieve historical records and ensures a higher level of cybersecurity.

Through data consolidation into one platform, you will gain a comprehensive picture of the company's energy management, be able to better identify inefficient processes and propose effective measures to reduce consumption and costs.

Focus on 'quick wins'.
→ Monitor consumption outside working hours, outages, overloads or unnecessary machine operation.

After implementing measurement and data consolidation, it is important to identify and implement measures with an immediate and measurable benefit, so-called quick wins. These are changes that do not require large investment or complex operational interventions, but can bring significant energy and cost savings.

What to focus on:

- **Monitoring consumption outside working hours:** Consumption should be minimal during periods when operations are not active. If the values are too high, it may mean unnecessary operation of equipment.
- **Identification of outages and overloads:** Overloaded technologies consume more energy and may wear out faster. Conversely, unplanned outages can lead to inefficient restarting of processes.
- **Unnecessary operation of machines and equipment:** It often happens that machines or systems run even when they are not needed – for example, conveyors, ventilation, pumps or compressors.
- **Optimisation of settings:** Check time settings and controls (e.g. heating, air conditioning, lighting) to see if they correspond to the actual needs of the operation.
- **Repair of leaks:** Especially in compressed air or thermal management systems, leaks can represent significant energy losses.

Benefits of quick wins:

- **Rapid reduction of energy costs** without the need for extensive investment.
- **Visible results** that will help motivate employees and management to take further measures.
- **Creation of a basic 'cushion' of savings**, which can be used to finance more complex projects in the future.

Through detailed monitoring and central data evaluation, it is possible to detect these measures practically immediately. **An industrial IoT data and integration platform** and similar solutions can automatically alert you to anomalies, such as excessive consumption outside working hours, thereby minimising reaction time.

Visualise so that data are understandable.
→ Visual overviews motivate workers and management to actively improve.
Collected and consolidated data have a real benefit only if they are clearly and understandably presented to all stakeholders – from operational staff to company management.

Why visualise:

- **Employee motivation:** Clear charts and indicators immediately show the status of consumption, achieved savings or exceeded limits. Employees then better understand the importance of energy measures.
- **Management support:** Strategic decision-making is easier if management has clear and visually presented data on trends and savings available.

- **Faster reaction:** Charts and dashboards help to quickly identify deviations or anomalies (e.g. a sharp increase in consumption).
- **Clarifying complex data:** A large amount of numbers and tables is difficult to evaluate; visualization allows a better understanding of relationships and priorities.

How to do it:

- Use dashboards with key performance indicators (KPIs) – e.g. energy consumption per unit of production, year-on-year comparison or goal achievement.
- Create charts and consumption maps (e.g. for branches, production lines or technological units).
- Use colour indicators and alarms that immediately alert you when set limits are exceeded.
- Ensure that the visualisation is available online and in real time for all relevant employees.

An industrial IoT data and integration platform allows setting up clear visualisations that are automatically updated and can be shared across the organisation. This increases the engagement of both employees and management and supports an active approach to continuous improvement of energy efficiency.

Implement an alert system → Timely notification of deviations helps prevent losses and increases accountability.

Even with consistent monitoring of consumption and regular analyses, unexpected deviations can occur. To be able to react immediately and prevent financial losses or equipment damage, it is advisable to implement an automated alert (alarm) system.

Why an alert system is important:

- **Timely notification**: Anomalies in consumption, technical parameters or equipment operation are detected immediately – not just after the monthly billing.
- **Loss prevention**: Quick reaction to atypical phenomena (e.g. excessive consumption outside working hours, energy leaks or unplanned downtime) minimises financial and operational impacts.
- **Increased accountability**: Workers have clearly defined signals for when it is necessary to intervene, which improves their involvement in the energy efficiency management process.

How to set up an alert system:

- **Define threshold values for individual indicators** – e.g. maximum allowed consumption during weekends, temperature limits for cooling equipment or machine performance deviations.
- **Set different alert levels** (e.g. informative notification vs. critical alarm).
- **Ensure automatic distribution of alerts to relevant persons** via email, SMS or through an application.
- **Enable tracking and evaluation of alert history**, which will help reveal recurring problems and address them in a targeted manner.

Example of use:

- The system detects unusually high water consumption outside working hours and immediately informs maintenance – it could be a burst pipe or a leak.
- The alarm warns of compressor overload, which could lead to a breakdown and unplanned production downtime.

Modern platforms, such as the industrial IoT data and integration platform, allow not only setting up alerts but also connecting them with visualisations and overviews. This creates a comprehensive tool for managing and optimising energy efficiency in real time.

Evaluate and report regularly → Create monthly reporting, compare with the past, look for trends.

Data collection and visualisation only make sense if they are regularly evaluated and translated into concrete conclusions and measures.

One of the key tools is the introduction of systematic reporting, which provides management and operational-level staff with a clear overview of energy efficiency.

How to do effective evaluation and reporting:

- **Implement periodic reporting**: Regular evaluation of energy consumption (electricity, gas, water, heat, etc.) allows quick reaction to deviations and planning of measures.
- **Compare with the past**: Monitor year-on-year, month-on-month or week-on-week development. Look for deviations and anomalies that may indicate inefficiency or a malfunction.
- **Look for trends**: Identify areas with increasing consumption and analyse the causes. On the other hand, evaluate the success of measures that have produced savings.
- **Include key performance indicators (KPIs)**: e.g. energy consumption per unit of production, percentage of consumption outside working hours, energy costs per employee, etc.
- **Share results**: Reports should be available to management, operations managers and employees. Transparency motivates collective goal achievement.

Tips for efficiency:

- **Use time-automated report generation** – systems like WorkSys.Space can create regular overviews and send them directly to responsible persons via a web link.
- **Combine visual overviews (charts, dashboards) with a short commentary** that summarises the most important findings.
- **Monitor long-term trends, not just individual anomalies** – this will help set strategic savings goals and plan investment.

Through regular evaluation and reporting, you create a cycle of continuous improvement: Data → Evaluation → Measure → Result review.

This approach is the foundation for systematic energy efficiency management and long-term cost reduction.

Notes and additional information:

Dependence on data quality

Methodology note: validation, cleaning and data quality assurance

1) Validation (at input and during processing)

- **Schema & types:** each tag has a defined type, unit, frequency, obligation (required/optional).
- **Ranges & physics:** min–max, impossible values (e.g. negative kWh), unexpected jumps (derivation).
- **Monotonicity of counters:** counters do not decrease without a 'reset flag'.
- **Uniqueness:** deduplication by (source + time + sequence).
- **Time consistency:** same time zone/epoch, check for delays and order.
- **Validation in processing:** after transformation, the schema is verified again (contract tests).

2) Cleaning (controlled and auditable)

- **Standardisation:** units, rounding, time zones.
- **Data gaps:** interpolate short outages and mark ('interpolated' flag); leave long ones as NULL.
- **Outliers:** IQR/z-score → only **flag** as 'suspect', **do not delete** raw data.
- **Reconciliation:** checksums (e.g., sub-metering vs. main metering) within a defined tolerance.
- **Rule versioning:** every change of rule/transformation = new version + reason.

3) Quality assurance (management, metrics, security)

- **DQ-score:** display KPIs/dashboards only when DQ-score ≥ defined threshold (e.g. 90%).
- **Metrics (examples):**
  - Completeness ≥ 98% of expected records/day
  - Type/unit validity ≥ 99%
  - Uniqueness = 0% duplicate events
  - Timeliness ≥ 95% delivered within X minutes
- **Data contracts:** source identity, tag list, types, units, frequency, tolerances, SLA, owners (owner/steward).
- **Monitoring & SOP:** alerts for completeness drops, stream outages, tolerance violations; clear runbook (identification → workaround → fix → retrospective).
- **Audit & security:** RBAC (least privilege), encryption in transit/at rest, audit trail of all changes, regular access review.
- **Retention:** 'raw' layer immutable (immutable/WORM); derived layers with defined retention policy.

Mini-checklist (at the end of the chapter)

1. Does every source have **a schema and data contract**?
2. Are **Gate 0** checks enabled (types, units, ranges, duplicates, monotonicity)?
3. Do we have a defined **gap policy** (interpolation vs. NULL) and **outlier flagging**?
4. Is a minimum DQ-score threshold set for KPIs?
5. Is **monitoring** with alerts running and is there an **SOP** for incidents?
6. Are **audit trail** and **RBAC working**?
7. Are there agreed **retention rules** for 'raw' and derived data?

Recommendations + specific examples and pitfalls

1) Strategy and scope (look at 'land & expand')

Recommendation: start with a narrow PoC (one line/cell, 4–6 workstations), with clear KPIs and DQ-score measurement.

Example: "Achieve, within 8 weeks, downtime reason coverage ≥ 85%, DQ-score ≥ 90%, reduce kWh/piece by 5%."

Pitfalls: overly ambitious scope → scattered attention, tired team, poor results.

Mitigation: timebox, specification of 'What is NOT in the PoC', executive-level sponsor.

2) People and change (employee resistance)

Recommendation: involve 'foremen' and operators from day 1; define the 'why' and what they get out of it.

Implementation example:

- 10-min kick-off in the hall (no 'powerpoints'): show 2 tiles (OEE, kWh/piece) and what will improve thanks to them (fewer ad-hoc night call-outs, simpler reporting).
- Choose a **line ambassador** (operator/foreman) who tests the kiosk/QR for downtime reasons and provides feedback.
- **Pitfalls:** feeling of 'control' and micromanagement, fear of evaluation.
- **Mitigation:** clearly communicate that the goal is to **remove obstacles** (material, mold, maintenance), not to evaluate individuals.

3) Data quality process and methodology

Recommendation: introduce three quality gates (Gate 0/1/2) and data contracts for every source.

Gate 0 – Validation at entry

Rule examples (pseudo-SQL):

```
-- Units and types
CHECK type = 'float' AND unit IN ('kWh','kW','pcs');

-- Ranges and physics
CHECK value BETWEEN 0 AND 2000;

-- Counter monotonicity
CHECK counter_value >= LAG(counter_value) OVER (PARTITION BY machine OR-
DER BY ts)
    OR reset_flag = TRUE;

 Event uniqueness
UNIQUE(machine_id, ts_bucket, seq_no);
```

Pitfalls: inconsistent clocks in PLCs, different time zones.

Mitigation: NTP for OT/IT, store everything in UTC, uniform granularity (e.g. 1s/5s).

Gate 1 – Cleaning and modelling
Rule examples:

- **Short gaps** (≤ 3 min) → linear interpolation + flag='interpolated'.
- **Long gaps** > 3 min → NULL + incident ticket.
- **Outliers**: ABS(value - median_1h) > 4 * MAD → flag='suspect', do not delete 'raw'.
- **Reconciliation**: ABS(sum(submeters) - main_meter) / main_meter ≤ 0.03.
  Pitfalls: overly aggressive 'cleaning' hides real problems.
  Mitigation: raw data immutable, all modifications only in the transformation layer with audit.

Gate 2 – Reporting & KPI
Logic example:

- KPI is displayed only if DQ_score >= 90% **and** coverage(downtime reasons) >= 85%.
- The KPI tile also displays a 'DQ-badge' thumbnail (e.g. 92%).

4) Technology and integration (automatic collection as default)
Recommendation: prefer **reading directly from PLC/interfaces** (OPC-UA/Modbus), manual inputs only for downtime/scrap reasons (via QR/kiosk).
Implementation examples:

- **Tag-mapping table** (CSV/JSON) with fields: source_id, tag, type, unit, freq_hz, min, max, is_counter, reset_tag.
- **Edge buffer**: local buffer memory for 24–48 h for network outages.
- **Idempotent ingest**: event hash(machine_id, ts, seq) → deduplication.

Pitfalls: 'shadow IT' integrations, firmware changes without notification, undocumented tags.
Mitigation: data contracts and **change-control**: every change = new version + validation test.

5) Cybersecurity (OT/IT)
Recommendation: principles of least privilege (RBAC), network segmentation, audit.
Implementation examples:

- **Segregation**: OT VLAN ↔ DMZ ↔ IT; no direct SMB/RDP from IT to OT.
- **Identity & access**: SSO/RBAC; service accounts with rotating keys; ban on 'shared accounts'.
- **Encryption**: e.g. TLS for transmission; encrypted disks for storage.
- **Immutable backups**: WORM/immutable bucket for 'raw'; recovery test
- **Incident runbook**: who calls whom, isolation, recovery, post-mortem.

Pitfalls: 'we'll open the ports and that's it', default passwords, unchecked vendor laptops.
Mitigation: communication whitelist, vulnerability scanners, onboarding for vendors (access standard).

6) Governance, roles and responsibilities
Recommendation: define **data owner** (business), **data steward** (quality), **tech curator** (integration).

RACI mini-matrix example:

- **Data contract definition** – R: steward, A: owner, C: IT/OT, I: quality
- **Tag/firmware changes** – R: IT/OT, A: owner, C: steward, I: production
- **Weekly DQ-report** – R: steward, A: owner, C: foremen, I: management

Pitfalls: 'IT is in charge of that', no one owns data quality.

Mitigation: clear RACI + quarterly DQ-review with management.

7) Reporting, visualization and 'behaviour design'

Recommendation: fewer panels, more action (watchers). Make visible **Top 5 downtimes**, **kWh/piece**, **Scrap** and show **DQ-badge** for every tile.

Implementation example:

- Early warning system – Watchers. For routine operation, send personalised warnings to specific people in the organisational structure.
- Effective dashboards e.g.
    - 'Top 5 downtimes' → clicking opens a form to add the reason (if missing).
    - 'kWh/piece' tile → link to checklist 'compressed air savings' (quick steps: leak detection, pressure optimisation, standby modes).

Pitfalls: 'dashboard fatigue', no one knows what to do. Mitigation: every chart has an owner and an action scenario ('if X, do Y within 24 h').

Summary

- Start with a small, measurable PoC, communicate **why** and involve key people.
- Implement **Gate 0/1/2**, **data contracts**, **DQ-score** and **incident runbook**.
- Keep security in mind (OT/IT segregation, RBAC, immutable backups).
- Every visualisation must lead to **action**.
- Continuously strengthen the data culture: retrospectives, sharing 'lessons learned', responsibility for data quality.

Yes, **harmonising data from multiple sources** into a unified data model is the right way. It enables comparable KPIs, simpler reporting, less technical debt and faster rollout. (Alternative – 'local specifics without harmonisation' – leads to fragmentation and hard-to-maintain exceptions.)

1) Principles

- **First-choice standards:** OPC UA/DA, Modbus TCP/RTU, MQTT, REST/CSV exports, SQL/ODBC.
- **Edge approach:** collection at gateway (buffer, store-and-forward, basic validation), secure transfer to central storage.
- **Harmonised model:** unified tag names, units (kWh, °C, bar), time in UTC, quality codes (OK/interpolated/suspect/missing).
- **Data contracts:** for every source define: tags, types, units, frequency, tolerances, SLA, version.

2) Typical limitations and solutions (reasonably brief)

A) Proprietary protocols / 'black box'

· **Limitation:** missing open interface; vendor changes formats.

· **Solution:** official OPC gateway/SDK (preferred) → scheduled exports (CSV/REST/MQTT) → last resort: adapter with custom parser.
· **Note:** agree on SLA and change-control; always run integration tests after update.
B) Older devices (legacy PLC, analogue, pulses)
· **Limitation:** RS-232/485 only RTU, 4–20 mA / 0–10 V, S0 pulses, no network.
· **Solution:** RS-485↔TCP gateways; ADC for analog; DI pulse reading as **counter**; or retrofit sensors.
· **Note:** calibration, galvanic isolation, shielding; min/max validations and noise derivations.
C) Non-standard/custom frames
· **Limitation:** custom binary/JSON frame, ambiguous timing.
· **Solution:** edge adapter → mapping to harmonised JSON/OPC, unified timestamping (UTC), payload versioning (v1, v1.1).
· **Note:** contract tests during deploy; fallback to local cache.
D) Integration via SCADA/Historian/ERP (secondary sources)
· **Limitation:** batch, delays, availability only via export.
· **Solution:** scheduled export (CSV/S3/REST), delta-pull by ts/id, idempotent ingest (hash deduplication).
· **Note:** healthcheck of exports; 'freeze window' during updates.
3) Operational minimum

- **Time:** NTP for OT/IT, storage in UTC; monotonicity of counters with reset_flag.
- **Reliability:** edge buffer 24–48 h, deduplication hash(source, ts, seq).
- **Security:** segmentation OT↔DMZ↔IT, RBAC, encryption, ban on 'shared accounts', immutable 'raw' backups.
- . 90%).

Security and GDPR

GDPR in industrial data is a question of the type of data collected on the SaaS platform:

- **GDPR does not apply** if it concerns pure machine telemetry data (pressures, temperatures, kWh) and process data without a link to a person
- **GDPR applies** immediately when a direct or indirect identifier of a person appears (operator login, RFID, text notes with names, photo/video, voice, combinations of tags).

Technical and organisational measures (selection)
1) Access management (RBAC & identity)

- **MFA + SSO** (if possible) and **least privilege** (you only need what you use).
- **Separate accounts** for people and services; ban on 'shared accounts'.
- **Regular access review** (quarterly), immediate revocation of access upon departure.

2) Audit trail and oversight

- **Audit trail**: who/when/what – logins, configuration changes, transformations, data quality rules.
- **Immutability of logs** (WORM/immutable bucket), retention periods (e.g. 12–24 months).

- **SIEM/monitoring**: event correlation (login from an atypical location, permission changes, DoS).

3) Network and architecture

- **Segmentation OT–DMZ–IT**, 'default deny' and **allowlist** of communications.
- **Edge-first**: local buffering (store-and-forward 24–48 h), encrypted transmission (TLS).
- **Hidden services**: no open management ports from the internet; bastion/jump host.

4) Encryption and secrets

- **In transit**: TLS 1.2+ with modern ciphers; **at rest**: encrypted disks/volumes.
- **Key management**: rotation of secrets (90 days), never in code; use of a vault (vault/key-store).

5) Backups and recovery (if not covered by a SaaS service)

- **3-2-1 principle**, **immutable backups** for 'raw' data.
- **RPO/RTO**: set (e.g. RPO ≤ 15 min, RTO ≤ 4 h) and **quarterly recovery tests**.

Runbook: priority map (what is restored first), contacts, procedures.

7. Analysis of Waste Volumes from the Automotive Industry

7.1. Introduction

The automotive industry is one of the key pillars of the modern global economy, and in the Slovak Republic, it is the dominant industrial sector. However, the growth in vehicle production is linked to an increase in the volume of waste, making the issue of effective waste management one of the key strategic priorities.

The Automotive Industry Association of the Slovak Republic (ZAP SR) views the issue of industrial waste processing as one of the key pillars of the sector's future competitiveness. This is a complex issue, as waste produced by the automotive industry includes a wide spectrum of materials with different properties, recovery possibilities and processing requirements.

ZAP SR is a partner of the UNIVNET association (University and Industrial Research and Educational Platform of the Recycling Society), which is recognized as a national platform for recycling and waste recovery with their application outputs into industrial sectors.

The primary objective of this study was to map waste generation in the Slovak automotive industry and analyse the processing capacity needs in the Slovak Republic. Members of ZAP SR were asked to provide waste generation reports for 2024, on the basis of which the study was then conducted.

The findings of the study, which map industry needs and processing capacity, provide a relevant perspective on the current state of automotive waste processing. The results of the study can serve as a basis for formulating systemic solutions in cooperation with all competent and interested entities. ZAP SR declares its readiness to continue professional dialogue and cooperation, particularly with representatives of the Ministry of Economy of the Slovak Republic, the Ministry of the Environment of the Slovak Republic, the Ministry of Education of the Slovak Republic and professional organisations.

7.2. Creation of a database

The data analysed in this study was collected through an official request for information on the types and quantities of waste generated, sent to manufacturing companies in the automotive industry The basis for this were reports on waste generation and management, prepared in accordance with Act No. 79/2015 Coll. on waste and in accordance with Decree No. 89/2024 Coll. of the Ministry of the Environment of the Slovak Republic on record-keeping and reporting obligations.

In terms of data structure, most reports were submitted in a machine-readable .xml format that complies with the electronic submission standards for the waste management information system. In the remaining cases, the data were extracted from .pdf files, which required subsequent manual conversion into the final database.

The latest data for 2024 are based on 84 reports submitted by 63 entities with unique IDs and contain a total of 2,452 records. In order to draw up the .xls table necessary to perform the analysis of data from the reports, we focused on the following sections in the report forms:

- Code and name of waste according to the current Waste Catalogue
- Waste category according to the Waste Catalogue
- Y-code
- Waste weight (the weight of waste with the same waste code was subsequently aggregated).

After completing the database, a unique identifier (ID code) was assigned to each entity. This step was taken to ensure that the results were strictly anonymised and to safeguard the internal data of the participating companies.

7.3. Waste generation

7.3.1. Companies

The total amount of waste from the automotive industry, as determined from data provided by the companies that submitted reports to us, was 2,483,270.49 tonnes in 2024. The largest waste producer among these companies is the company identified as ID_7187, accounting for as much as 29.19%. These are followed by companies identified as ID_4619, with a 15.42% share, and ID_6147, producing 14.14% of the waste.

Tab. 7.1
Largest waste producers in 2024

Company ID	**Weight (t)**
ID_7187	724,987.939
ID_4619	382,923.629
ID_6147	351,077.269
ID_8613	198,510.829
ID_6323	124,718.69
ID_3954	107,169.041
ID_8774	71,724.924
ID_6711	65,486.454
ID_5045	65,386.021
ID_4331	62,369.253

Based on these data, it can be concluded that the majority of waste generated within our sample is produced by a small group of companies with a dominant position, which can be considered key producers.

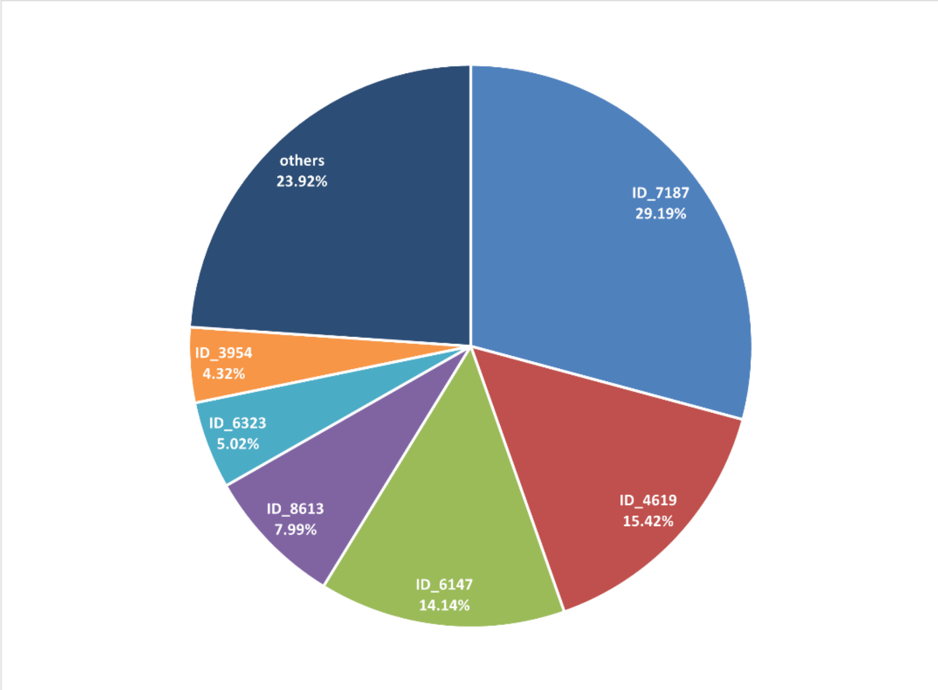


Fig. 7.1 Diagram of the largest waste producers in 2024

7.3.2. Types

In addition to the waste producers themselves, we believe it is important to examine the types of waste that are generated. Of the total of 230 different types of waste reported, the largest amount (in tonnes) consisted of ferrous metal dust and particles, accounting for 16.05% of the total waste generated. The second largest source of waste is waste from slag processing with a share of 10.87%. The most common type of waste was packaging containing residues of hazardous substances or contaminated with hazardous substances, which was reported in 125 cases but accounted for only 3.41% of the total weight of waste generated.

Tab. 7.2
Most common types of waste generated in 2024

Waste code	**Weight (t)**
12 01 02 – ferrous metal dust and particles	400,591.74
10 02 01 – wastes from the processing of slag	271,288.97
15 01 06 – mixed packaging	183,435.095
17 04 05 – iron and steel	173,498.609
15 01 01 – paper and cardboard packaging	117,036.575
19 08 14 – sludges from other treatment of industrial waste water other than those mentioned in 19 08 13	108,597.115

15 02 02 – absorbents, filter materials (including oil filters not otherwise specified), wiping cloths, protective clothing contaminated by hazardous substances	98,147.512
12 01 09 – machining emulsions and solutions free of halogens	92,898.995
20 01 36 – discarded electrical and electronic equipment other than those mentioned in 20 01 21, 20 01 23 and 20 01 35	91,781.299
15 01 10 – packaging containing residues of or contaminated by hazardous substances	85,010.813

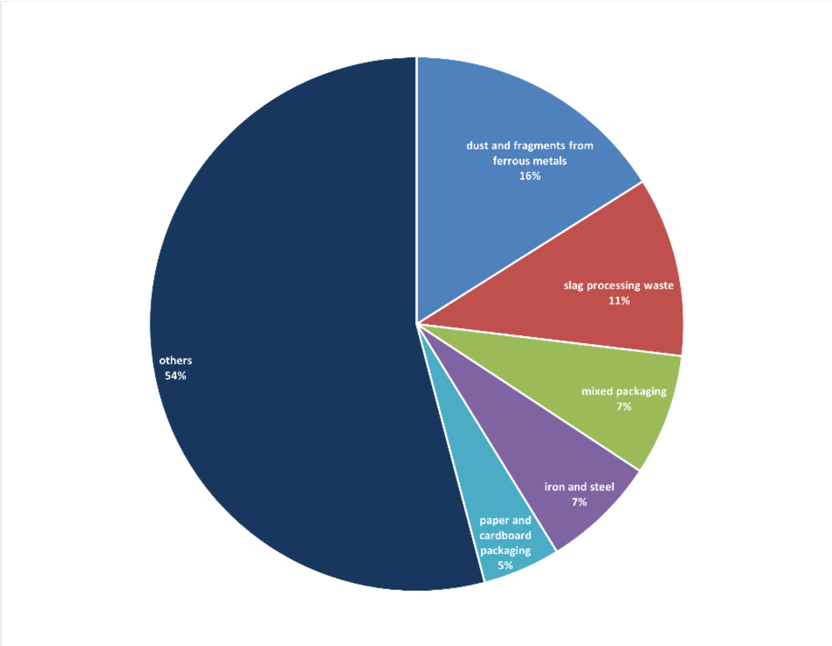


Fig. 7.2 Diagram of the most common types of waste generated in 2024

Of the total of 2,452 waste records analysed, other waste accounted for as much as 78.67% of the total weight. However, when compared to the relative frequency of reports, it appears that the ‘other waste‘ category only accounts for 55.71% of the total number of records. This significant disparity suggests that, although the frequency of hazardous waste generation is comparable to that of other types of waste, its weight is significantly lower.

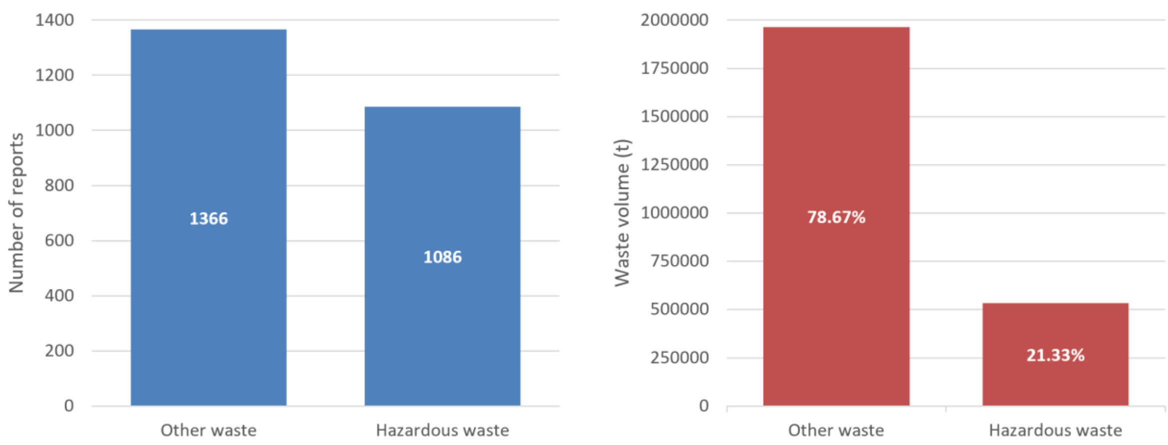


Fig. 7.3 Graphical comparison of the number and weight of waste by category

7.3.3. Groups

Waste producers were assigned to individual reference groups in accordance with the methodology (Šooš, 2022). It should be emphasised that this classification is independent of the official ISOH Waste Catalogue. The defined groups include:

a) Car plants
b) Rubber / Metal
c) Smelter / Casting
d) Pressing
e) Group assembly
f) Tools
g) Metalworking
h) Foams
i) Plastics / Press
j) Surface treatments
k) Glass
l) Lighting Fixtures
m) Textile
n) Forgings
o) Other

The selection of sample, reference producers for the given group of producers based on the activity, and production portfolio was carried out after the analysis of data about the waste categories gained after the first contact with ZAP SR member plants.

The largest number of submitted reports came from the metalworking and group assembly groups. On the other hand, we did not record a single report for the textile and forgings groups in 2024.

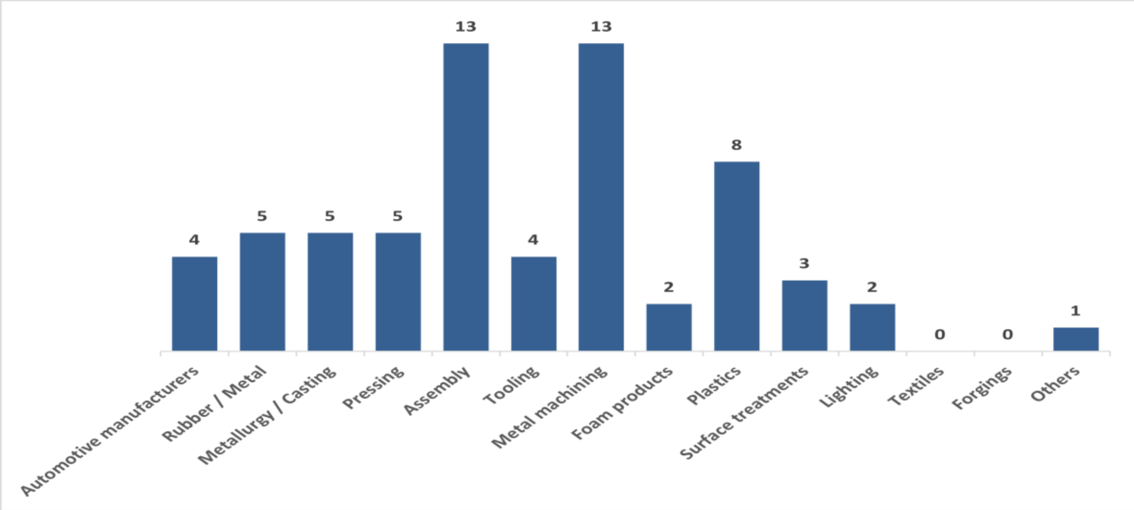


Fig. 7.4 Histogram of the number of companies in each group

When comparing the individual groups, companies in the smelter/casting group – 33.83% – and the metalworking group –32.83%. – by far generate the most waste.

Tab. 7.3
Waste generation by group in 2024

Group	**Waste weight (t)**
Car plants	157,975.143
Rubber / Metal	360,180.105
Smelter / Casting	840,156.876
Pressing	59,285.774
Group assembly	46,270.289
Tools	74,800.886
Metalworking	815,327.293
Foams	12,708.897
Plastics	99,210.379
Surface treat-ments	1,170.162
Lighting fixtures	4,411.440
Other	11.773.246

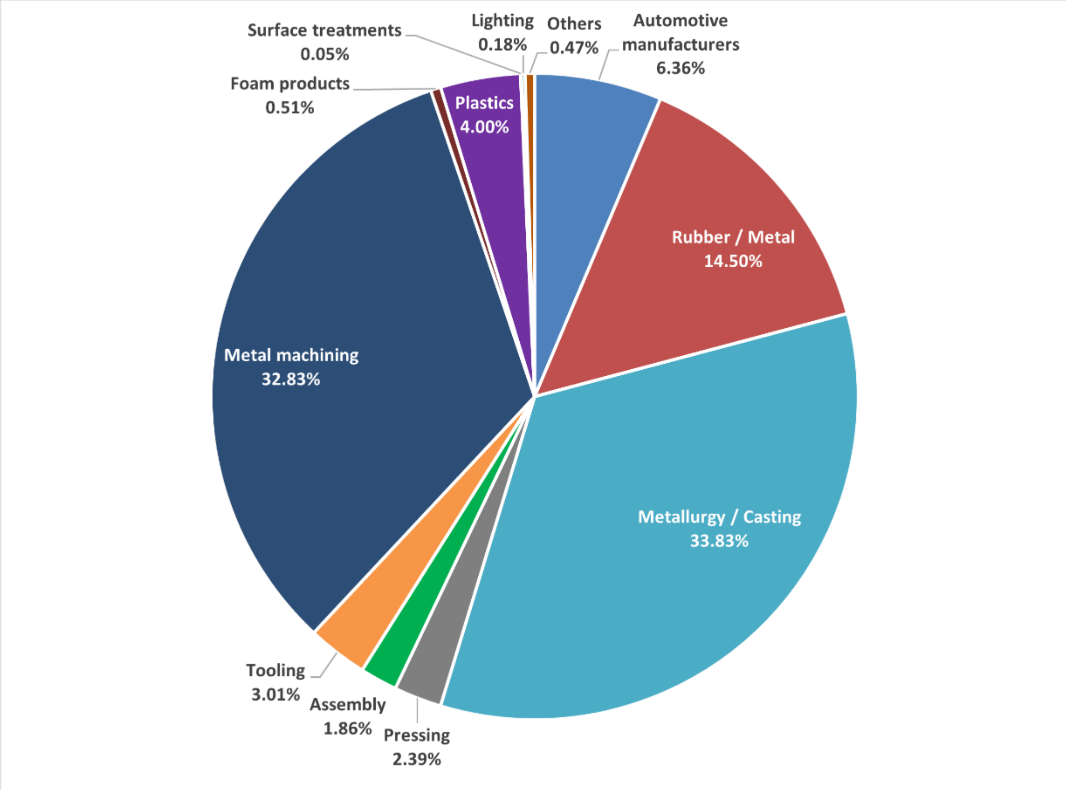


Fig. 7.5 Diagram of waste generation by group in 2024

At this point, it is important to emphasise that although entities from the metalworking group produce almost one-third of the total volume of waste recorded in our database, it is also the most numerous group. To gain a more relevant perspective, it is therefore essential to analyze additional metrics that provide a broader context for this data.

The first of these metrics is the average weight of waste per company in a given group. The comparison shows that, although the metalworking group remains among the major producers, its relative share has declined significantly compared to the smelter / casting group. Despite a similar volume of total production in both groups, the average company from the smelter / sasting segment shows the highest rate of waste generation among all monitored groups.

The second metric is the average waste generation per employee. For this purpose, data on the number of employees at all companies that submitted reports on waste generation were processed. This data was obtained from publicly available financial statements for 2024 via the Financial Statements Register portal (www.registeruz.sk). When compared using this metric, the Rubber / Metal group produces the most waste per employee. In addition to the Smelter / Casting and metalworking groups, we can also observe a high amount of waste per employee in the pressing group.

Based on a comparison of the metrics, it can be concluded that the average company in the metalworking and Rrubber / Metal groups generates a high total volume of waste while also reporting a high level of production per employee. However, the Car Plants and Pressing groups, as well as the tools group, are special. Although the average car plant generates a significant total volume of waste, this value is low when calculated per employee. On the other hand, the average company from the Pressing or Tools group does not show high total generation, but its average volume of waste per employee is relatively high compared to the other monitored groups.

Table 7.4
Waste generation by group, including average waste weight and average waste per employee

Group	**Waste weight (t)**	**Number of companies**	**Number of employees**	**Average waste weight**	**Average waste per employee**
Car plants	157,975.143	4	24,147	39,493.786	6,542
Rubber / Metal	360,180.105	5	2,806	72,036.021	128.361
Smelter / Casting	840,156.876	5	8,152	168,031,375	103.061
Pressing	59,285.774	5	705	11,857.155	84.093
Group assembly	46,270.289	13	11,292	3,559.253	4.098
Tools	74,800.886	4	1,028	18,700.222	72.764
Metalworking	815,327.293	13	10,578	62,717.484	77.078
Foams	12,708.897	2	714	6,354.449	17.800
Plastics	99,210.379	8	3,513	12,401.297	28.241
Surface treatments	1,170.162	3	262	390.054	4.466
Lighting fixtures	4,411.440	2	5.813	2,205.720	0.759

It is important to note that the use of arithmetic averages with a limited sample size is highly sensitive to the presence of outliers. These are entities characterised by extreme values (whether in terms of the number of employees or the volume of waste generated), which may ultimately distort the overall interpretation of the results for the given group.

7.4. Post-calculation

Based on the data collected, it is possible to estimate or calculate the volume of waste generated by entities that did not submit reports. In accordance with the methodology (Šooš et al., 2022), this estimate can be calculated in two ways.

The first method involves a calculation based on the ratio of the total number of employees in a given group (GTNE) to the number of employees at selected facilities (SFNE) for which waste volume data is available. This ratio is defined as 'coefficient 1'. By applying this coefficient to all entities belonging to a given group, it is possible to estimate the total waste generation for the entire sector, or waste generation by specific waste codes.

We can illustrate this process using the lighting fixtures group as an example. Companies identified as ID_3109 and ID_8628 employ a total of 5,813 workers and generate 4,411.44 tonnes of waste. If we expand this group to include a hypothetical company with 500 employees, the total estimated volume would be calculated as follows:

$$Koeficient\ 1 = \frac{CPZS}{PZVP} = \frac{6313}{5813} = 1{,}086$$

$$Objem\ odpadu\ v\ skupine = objem\ odpadu\ vybraných\ prevádzok\ \times koeficient\ 1$$

$$Objem\ odpadu\ v\ skupine = 4\ 411{,}44\ \times 1{,}086 = 4\ 790{,}824$$

In the example we have chosen, the total volume of waste for the lighting fixtures group would be 4,790.824 tonnes.

Tab. 7.5
Example of post-calculation using coefficient 1

Lighting fixtures	**Number of employees**	**Number of employees at selected facilities**	**Coefficient 1**	**Volume of waste (t)**
ID_3109	3,267	3,267		362.286
ID_8628	2,546	2,546		4,049.154
Hypothetical company	500		1,086	
total	**6,313**	**5,813**		**4,790.824**

The second method of calculation involves using the average volume of waste per employee, which is defined in the methodology as ‘coefficient 2’. Unlike the previous approach, this coefficient is not calculated as the ratio of the total volume of waste to the total number of employees in the group. Instead, generated volume per employee is calculated individually for each company, and the arithmetic average is then determined from these partial values.

The advantage of this approach is that it is more representative of a typical company in a given segment, as it eliminates the extreme influence of the largest entities. On the other hand, using the weighted average mentioned above provides a more accurate picture of the group as a whole, which is particularly crucial when estimating the overall environmental burden of a region or sector.

$$Koeficient\ 2 = \frac{\emptyset\ odpad\ na\ zamestnanca_1 + \emptyset\ odpad\ na\ zamestnanca_2}{počet\ \emptyset}$$

$$Koeficient\ 2 = \frac{0{,}111 + 1{,}590}{2} = 0{,}851$$

$$Objem\ odpadu\ firmy = počet\ zamestnancov\ \times koeficient\ 2$$

$$Objem\ odpadu\ firmu = 500\ \times 0{,}851 = 425{,}500$$

The estimated waste generation for the hypothetical company mentioned above, with 500 employees, calculated using coefficient 2, will be 425.5 tonnes, and the total volume for the Lighting Group will be 4,836.94 tonnes.

Tab. 7.6
Example of post-calculation using coefficient 2

Lighting fixtures	**Number of employees**	**Waste per employee**	**Coefficient 2**	**Volume of waste (t)**
ID_3109	3,267	0.111		362.286
ID_8628	2,546	1.590		4,049.154
Hypothetical company	500		0.851	425.500
total	**6,313**			**4,836.940**

The value of coefficient 2 was calculated in the same way for the other defined groups.

Tab. 7.7
Comparison of coefficient 2 values for different groups

Group	**Coefficient 2**
Car plants	8.635
Rubber / Metal	110.277
Smelter / Casting	41.209
Pressing	185.177
Group assembly	3.790
Tools	167.535
Metalworking	171.867
Foams	9.1509
Plastics	106.282
Surface treatments	4.0273
Lighting fixtures	0.851

It is important to emphasise that applying both of these methods will only provide approximate estimates of waste generation for the relevant group. In the model example we have chosen, both approaches show a high degree of agreement, with a difference of only 0.96%, however, for other groups, these differences may be more significant. The lack of actual data for verification remains a limiting factor, making it impossible to accurately determine the degree of reliability of these estimates.

When working with coefficient 2 (the arithmetic average of individual values), one alternative is the weighted average mentioned earlier. Compared to the traditional average, this average underestimates large producers to a lesser extent, thereby better reflecting the group as a whole in terms of total waste volume.

The second alternative is to use the median, which would represent a ‘typical’ company in the group more accurately than the arithmetic average, since it is not influenced by extreme values. In our case, when some groups contain only a limited number of reports, the median would be less stable, and its informative value would decrease with a low number of observations.

7.5. Alternative calculation method

Given that previous post-calculation methods are limited by the assumption of a direct proportional relationship between the number of employees and the volume of waste, we decided to explore an alternative approach using OLS (ordinary least squares) regression analysis.

Within this model, we worked with three basic variables:

1. Waste volume (in tonnes)
2. Number of employees
3. Sectoral categorisation of the company (according to SK NACE classification)

For the purposes of the regression model, we adopted a different categorisation of companies. The primary motivation for this change was to increase the number of entities in each group, thereby enhancing the statistical robustness of the model. Companies were grouped into five categories based on SK NACE codes:

a. Metal production
b. Accessories
c. Processing of plastics and rubber
d. Mechanical and electrical engineering
e. Heavy industry
f. Manufacture of motor vehicles

An analysis of the data structure itself confirms that both the volume of waste and the number of employees show a similar trend in the histograms. Both variables are characterised by significant right-skewness.

When it comes to waste generation, most companies generate relatively small volumes, ranging from a few to several thousand tonnes. At the same time, however, the histogram reveals a small group of entities with extreme generation levels, which, in the context of the entire dataset, represent significant outliers.

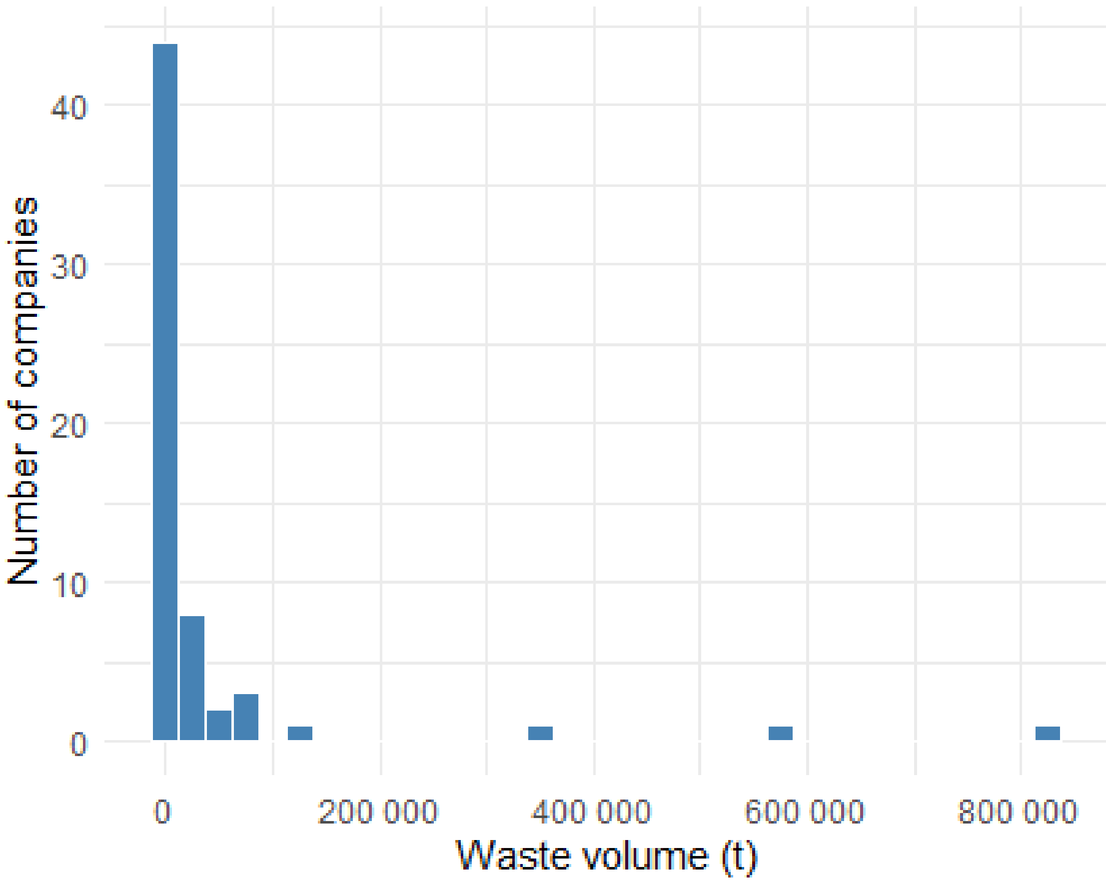


Fig. 7.6 Histogram of the number of companies by waste generation

The number of employees variable also shows a similar distribution, with the highest concentration of companies located on the left side of the histogram, which represents the segment of smaller employers. Unlike the distribution of waste, however, we also observe clusters of medium-sized companies with between 3,000 and 5,000 employees. Here, too, we can observe several dominant employers whose size represents outliers and deviates significantly from the overall average of the sample.

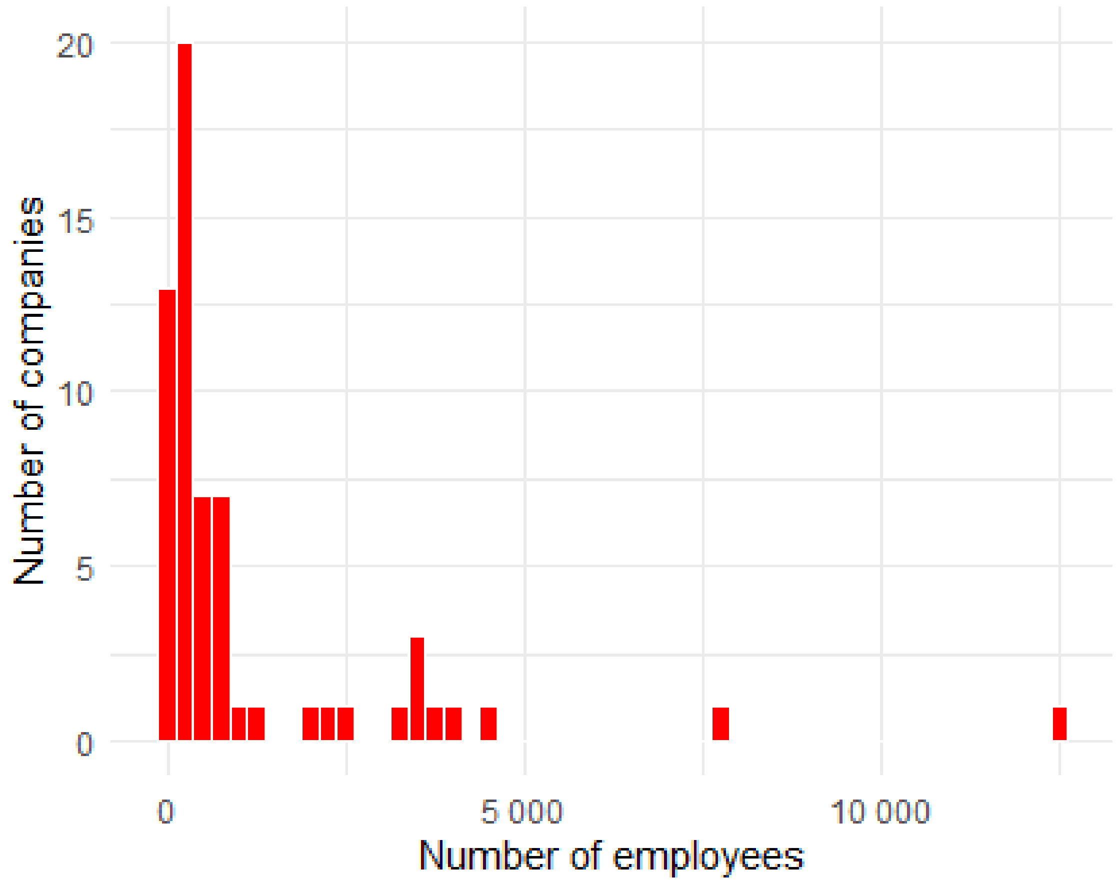


Fig. 7.7 Histogram of the number of companies by waste generation

Given the significant right-skewness of both variables, we applied a logarithmic transformation to them when constructing the regression model. The primary purpose of this procedure is to eliminate the influence of extreme outliers and bring the data distribution closer to a normal distribution. This adjustment ensures greater statistical stability of the model and allows the resulting coefficients to be interpreted as the elasticity of the relationship being studied.

7.5.1. Interpretation of results

The results of the regression analysis show that the elasticity coefficient of waste generation with respect to the number of employees is 1.087. Our interpretation of this value is that a 1% increase in the number of employees is expected to result in a 1.087% increase in waste generation%. Since the coefficient is greater than 1, this indicates an elastic relationship, suggesting that the volume of waste generated is growing at a faster rate than the size of the company.

The coefficients assigned to individual industry categories represent the rate of waste generation relative to the reference metal production group. Compared to this group, all other groups being studied generate less waste. The greatest differences can be observed in the mechanical and electrical engineering and accessories groups, which have the lowest generation level compared to the other groups.

	Waste Production Elasticity
Intercept - Metal manufacturing	2.887 *
	(1.313)
log (Number of employees)	1.087 ***
	(0.233)
Accessories	-2.139 *
	(0.814)
Plastics and rubber processing	-0.743
	(1.059)
Mechanical engineering and electrical engineering	-2.647 *
	(1.034)
Heavy industry	-1.690
	(1.313)
Motor vehicle manufacturing	-1.760
	(1.537)
R^2	0.357
Adj. R^2	0.285
Num. obs.	61

*** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$

Fig. 7.8 Regression model results

Using these coefficients, we can also demonstrate what the actual calculation would look like for a hypothetical company with 1,000 employees from our reference metal production group:

$$\mathbf{ln}(\boldsymbol{objem\ odpadu}) = \boldsymbol{\beta_0} + \boldsymbol{\beta_1} \times \mathbf{ln}(\boldsymbol{po\check{c}et\ zamestnancov})$$

$$\ln(objem\ odpadu) = 2{,}887 + 1{,}087 \times \ln(1000) = 10{,}396$$

$$objem\ odpadu = 32\,728{,}18\ ton$$

For a company that does not fall into the metal production category, the calculation method would be different, since the automotive industry serves as the reference category in our model. If, for example, we were to estimate projected production for a company in the accessories category, the regression equation would also include the coefficient corresponding to that group. In that case, the calculation would be performed as follows:

$$\ln(objem\ odpadu) = \beta_0 + \beta_1 \times \ln(po\check{c}et\ zamestnancov) + \beta_2$$

$$\ln(objem\ odpadu) = 2{,}887 + 1{,}087 \times \ln(1000) - 2{,}139 = 8{,}257$$
$$objem\ odpadu = 3\,854{,}54\ ton$$

It is important to emphasise that the predictive power of this model is largely limited by the quality and scope of the available data, particularly the small number of observations in some groups. For the processing of plastics and rubber, Heavy industry and Manufacture of motor vehicles categories, it was not possible to statistically demonstrate their direct impact on the amount of waste. In practice, this means that for these two groups, we cannot confirm with certainty whether their generation is actually different from that of the others.

Our model can explain approximately 35.7% of the variation in the amount of waste generated using data on the number of employees and the company category. However, the remaining 64.3% of the variation remain unexplained. This result suggests that other important factors – which were not included in our model – also affect waste generation in companies, or that these may be random errors and variations in the data. These findings highlight the complexity of the issue and open the door to more detailed research in the future.

7.5.2. Application of the post-calculation

Despite these shortcomings, the main advantage of this approach lies in the ability to compare the values predicted by the model with actual data and to accurately evaluate its performance.

As with the previous methods, it is important to emphasise that this model is primarily intended to estimate aggregate generation for larger groups of companies, not to forecast the individual generation of specific companies. This limit is evidenced by the high average percentage error, which reaches as high as 438.39%. However, this extreme value is primarily due to variations among small waste generators, where even a minimal nominal deviation results in a huge percentage change.

A more relevant indicator in this context is the median error, which is significantly lower, although it still reaches a high level of 95.74%.

After aggregating the actual data and model estimates, the total deviation is –82.51%. This result suggests that the model tends to systematically underestimate waste generation and fails to adequately capture the extent of waste generation, particularly among the largest entities.

However, if we focus on the model's ability to predict production for the middle 50% of companies (the so-called interquartile range), the total deviation drops to a level of 38.25%. This value is a good indicator of the fact that the model is better able to estimate total waste generation for typical companies, but loses accuracy when extreme values occur.

7.6. Comparison with 2019 and 2020

Compared to the period between 2019 and 2020, when the previous analysis was conducted, the number of reports collected has nearly doubled.

We have also recorded a significant increase in the total volume of waste generated, which is as much as 16 times higher than in 2020. However, this figure must be interpreted with caution, as it is primarily influenced by the size and nature of the companies that submitted reports this year. A similar conclusion can be drawn when comparing the composition of the most commonly generated waste types with the industrial sectors that generate the most waste.

Tab. 7.8
Comparison of basic characteristics between 2019/20 and 2024

	2019	2020	2024
Number of reports (companies)	34	35	63
Volume of waste (t)	120,235	157,221	2,483,270
Types	181		417
Most generated types of waste	Paper and cardboard packaging; waste plastic; absorbents, filter materials including oil filters, rags, clothing contaminated with hazardous substances (HS)		Dust and fragments of ferrous metals; waste from slag processing; mixed packaging
Groups with the highest waste generation	Car plants; pressing; group assembly		Smelters / Casting; Metalworking; Rubber / Metal

The relative representation of individual groups is relatively stable between the monitored periods. The most significant increase in numbers is recorded in the Metalworking and Group assembly categories.

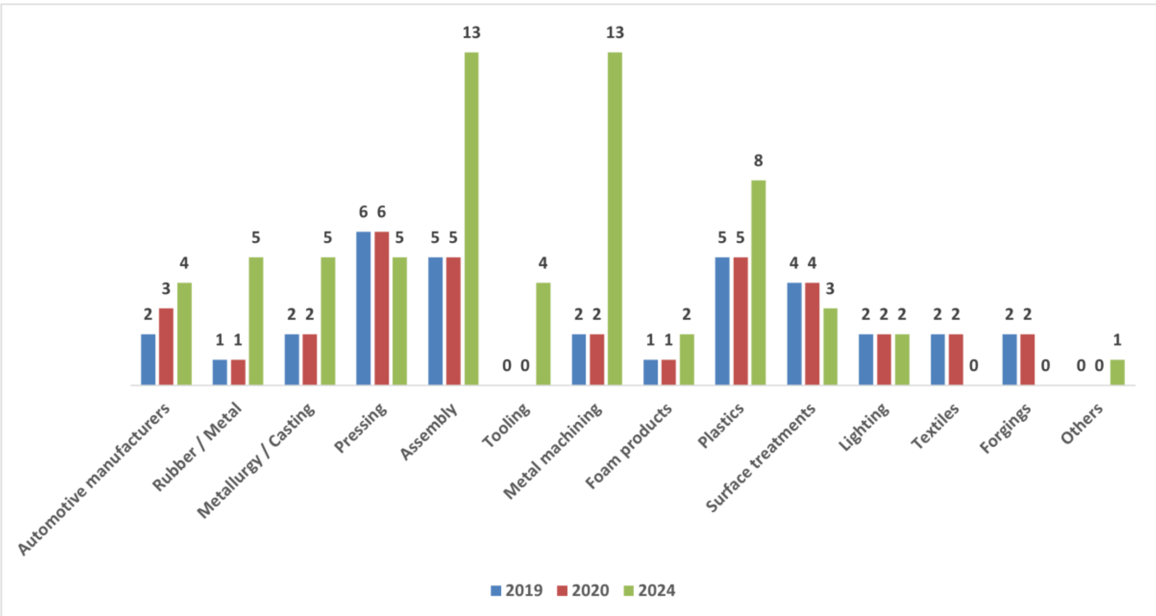


Fig. 7.9 Graphical comparison of the number of reports in individual groups

7.7. Conclusion

This analysis provides a comprehensive overview of the volume and composition of waste generated by the Slovak automotive industry, based on data collected for 2024. The compiled database, which includes 84 reports from 63 companies, made it possible to identify the main sources of waste generation, the predominant types of waste and the differences between individual production segments. The results show that waste generation is heavily concentrated in a relatively small group of large companies and that companies involved in metalworking and metallurgical processes account for the largest share of the total volume.

Another important part of the work involved testing various methodological approaches to estimating waste generation at entities that did not provide data. In addition to simpler calculations based on coefficients derived from the number of employees, a regression model using a logarithmic transformation of the variables was also analysed. Although this model was able to explain part of the variability in waste generation, its accuracy is limited by the scope and structure of the available data, particularly the presence of outliers and the low number of observations in some categories. These findings also open the door to further research on this issue.

The results of the study provide a relevant analytical basis for further discussions on the development of processing capacity and more efficient management of industrial waste in Slovakia. In the future, it would be advisable to expand the database to include a larger number of companies, add additional explanatory variables, and systematically continue data collection in order to model waste generation in the automotive industry more accurately and identify opportunities for waste reduction and material recovery.

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8. Electric Vehicle Sales Scenarios in EU Countries and Economic Impacts of the Transition to Electric Vehicle Production on the Slovak Economy

8.1. Introduction

Europe's environmentally and politically motivated shift towards electromobility and efforts to regulate the automotive market are encountering reduced acceptance of new electric vehicles by players in the automotive market. Whether in individual EU countries, groups of countries or the EU as a whole. This is due to the effects of deglobalization trends, the pandemic, the energy crisis and, more recently, the military and security crisis, which are affecting not only sales of new electric vehicles but also global value chains for electric vehicle production. These factors threaten the achievement of ambitious quantitative targets as well as the deadlines for the transition to the sale of new so-called 'zero-emission' vehicles across the entire EU. But especially in the converging – or even diverging – EU countries. Our research aims to contribute to the discussion on the alternative scenarios for the development of demand and sales of electric vehicles (ECVs) in EU countries – depending on alternative scenarios regarding the impact of those factors that, based on current knowledge, will influence new sales and demand for ECVs in EU countries. The article focuses particularly on developments in Slovakia and Sweden.

Current changes in the structure and trends of market-driven vehicle sales by powertrain type are at odds not only with the quantitative targets set in EU directives for electric vehicle sales, but also with the planned timelines for Europe's transition to the sale of new so-called 'zero-emission' vehicles. And not only in the EU. This is particularly true in the converging – or even diverging – EU countries, where the share of electric vehicle sales is several times lower and far from meeting the EU's quantitative targets. Achieving carbon neutrality in Europe by 2050 and reducing net GHG emissions by 55% by 2030 is possible only if there is a sharp departure from current trends. Such a turnaround assumes that EU countries will successfully and quickly absorb the impacts of the pandemic and the energy crisis in the coming years, whose effects contributed to halting the reduction in net GHG for the EU-27 countries in 2020–2022.

According to ACEA5, the European automotive industry is one of the most strictly regulated sectors. The EU's ambitious, supply-and-demand-driven plan for the transition to electric mobility and for Europe's transition to a carbon-neutral continent has recently faced new challenges and even threats. The consequences of deglobalization trends, the protection of the U.S. domestic market, the expansion of production of lower-cost BEV models in China, trade wars, the energy crisis and, more recently, the military-security crisis, as well as Europe's dependence on imports of rare earth minerals for the production of electric vehicles and their components,

[5] Automotive Regulatory Guide 2023, ACEA 2023. https://www.acea.auto/files/ACEA-Regulatory-Guide-2023.pdf

are having a significant impact on the competitiveness of European manufacturers. And also on consumer behaviour on the demand side for cars and electric vehicles.

Developments in the global motor vehicle market and the transition to electric mobility will increasingly influence the automotive sector in Slovakia. Regardless of the demand for electric vehicles in Slovakia, the production of motor vehicles intended for export (more than 90%) will have to adapt to global trends. The second part of this study therefore examines scenarios for the impact of this transition on the Slovak economy. We model two scenarios corresponding to a successful and an unsuccessful transition to electric vehicle production, with an unsuccessful transition resulting in significant losses in terms of value-added and employment. The transition to electric vehicle production in Slovakia depends on many external factors and the decisions of the car manufacturers themselves, and also requires significant investment to upgrade production lines. Investments in battery facilities and their operation will also have a strong impact.

In the first part, we examine the adoption of electric vehicles in selected EU countries. In the second part, we examine the economic impacts of the transition to electric vehicle production on the Slovak economy. The conclusion summarises the main findings and identifies open questions for further research.

8.2. Forecast scenarios for electric vehicle sales in selected EU countries

The first challenge facing economic research is to realistically anticipate and understand, in the context of these changing conditions, shifts in the behaviour of consumers and car manufacturers (including their suppliers) regarding demand for different types of vehicles and fleet renewal – whether in estimating the consequences of the direct economic impacts on households, businesses and producers, or as a result of broader contexts and changes in global value chains. In addition to the factors already mentioned – such as deglobalization trends and trade wars among economic powers – they include climate pollution caused by emissions in the global economy, against a backdrop of increased military build-up and armed conflicts. And also the power-driven shift of zero- and low-emission transit flows of energy carriers worldwide towards more energy-intensive and emission-intensive modes of transport.

The second challenge is the call for a more open scientific debate, based on new and often conflicting findings, regarding the overall environmental impact of electric vehicles throughout their life cycle. In other words, it is not just about the zero carbon footprint of electric vehicles, but also about understanding the overall greenhouse gas emissions throughout their life cycle – from the production of electric vehicles and their components, through their operation, to the recycling of electric vehicles at the end of their useful life.

Given that this is a complex and interdisciplinary issue – primarily one for scientific research – the aim of this work is to contribute to the discussion by helping to clarify the factors driving demand for electric vehicles in EU countries and to outline the current sales scenarios for ECVs in selected EU countries.

To this end, the first part of the study provides some theoretical background and research findings relevant to current developments in the global and EU automotive markets. This part of the work summarises relevant findings from the science literature, which – viewed through the lens of regulatory theory and other theories, combined with the results of empirical studies – form the knowledge base for explaining: (a) the key determinants and correlations of ex post ECV sales in EU countries, (b) differences among individual EU countries, and (c) the construction of a predictive model for ECV sales in the medium term across EU countries.

The second part – which focuses on methodology – presents the hypotheses, which are then transformed into econometric panel regression models, as well as the data used and their sources. In the following part, the paper evaluates the empirical results of the model estimates, the predictive accuracy of the most appropriate model, and alternative scenarios for ECV sales across the EU-27 countries.

8.2.1. Economic and other determinants of demand for electric vehicles from the perspective of theory and empirical studies

Price theory has several implications for empirical research on developments in the electric vehicle market. A historical overview of the development of price theory by Ozer–Phillips (2012), Weyl (2014), Weyl (2019) and others provides several useful insights for understanding the modern market forces that shape the supply and demand for electric vehicles in individual markets. The essence of price theory is to explain economic activity in terms of the creation and transfer of value, which includes the exchange of goods and services among various economic agents. While in the past, price theories explained why water is so cheap and diamonds are so expensive, even though water is essential for survival and diamonds are not, Adam Smith (1776) later distinguished between two different meanings of value for two different goods: first, the usefulness of a particular object, and second, the ability to purchase other goods that ownership of that object entails – 'value in use'; the second is 'value in exchange' (p. 31). He derived value, and consequently price, using the example of a diamond, based on its relative rarity and the amount of labour required to obtain it. He thus regarded labour intensity as the basic unit of the value in exchange of goods (or 'items'), which therefore determines their 'real prices'.

Later, Menger (1871) and other authors pointed out that the value of given goods is intrinsically linked to their marginal utility. Walras (1874/77) linked price to the value of goods in a barter economy by positing that the market price of goods tends to rise as long as there is positive excess demand. On the other hand, it tends to fall when there is a positive excess supply. The related process of adjustment is generally referred to as Walrasian trial-and-error, and Walras is widely recognised as the father of general equilibrium theory.

Economic factors of electric vehicle sales

In accordance with free-market theory, the dominant economic factor influencing the supply and demand for electric vehicles is the generally accepted purchase price of electric vehicles and their substitutes, externalities and the level of consumer income. Prices of electric vehicles are on average much higher than their petrol equivalents, around €35,000 (EURACTIVE, 2023), and in many non-European countries these prices are 2- to 2.5-times higher than comparable conventionally powered vehicles (Sriram, et. al. 2022).

For many drivers, electric vehicles are beyond their financial means, despite the substantial fiscal and other incentives aimed at narrowing the price gap between purchasing an electric car and a conventional vehicle. Although, according to (Paoli–Gul, 2022), fiscal demand incentives are becoming increasingly effective in persuading consumers to purchase electric vehicles, these incentives still appear insufficient today for purely economic reasons.

The current dynamics is mainly driven by sales in economically developed countries and higher incomes of the population. Convincing empirical evidence is provided, for example, by

(Rokicki et al. 2022), which used the Lorenz concentration curve to find that among the leaders in the development of electric mobility are countries in Western Europe, the most economically developed ones. This finding has held true since 2011, and in 2020, the top five countries in the EU with the highest share of electric vehicles were Germany, the United Kingdom, France, the Netherlands and Sweden. The top ten countries accounted for a total of 92% of such cars, and this group consisted exclusively of Western European countries. And this is despite the fact that there is a gradual shift in the Lorenz curve, i.e. a reduction in the concentration of sales in the leading countries.

In addition, a country's income level also determines the age structure of its vehicle fleets, which in turn influences the development of services and technologies related to vehicle maintenance and end-of-life management. According to ACEA, cars in the EU are currently 12 years old on average. The oldest vehicle fleets are in Greece and Estonia, with vehicles nearly 17 years old. The newest passenger cars are in the Luxembourg vehicle fleet (7.6 years).

According to (Rokicki et al. 2022), it is not only the purchase price but also concerns about the total cost of owning an EV, including unknown or unpredictable maintenance and operating costs, as well as the cost of the EV battery and its lifespan, that are either a motivation or a barrier for consumers when purchasing an EV. Some consumers are considering purchasing an electric vehicle once it reaches the same price as vehicles with internal combustion engines (ICE), or are not considering a purchase at this time because they expect the price to fall in the future. The study confirmed the findings in (Noel et al. 2020) that a key factor for consumers when making a purchase is knowledge of the price of the electric vehicle and its battery.

Over the past decade, policymakers have introduced many financial and non-financial incentives aimed at increasing the use of electric vehicles. Financial incentive policies address both the supply and demand sides (Melton et al., 2020; Liu et al., 2021). On the supply side, financial incentives in the form of tax breaks for zero-emission vehicles, special loans, research and development (R&D) grants and income tax reductions have stimulated widespread use of light-duty vehicles (LDVs) and supported the scale of electric vehicle and battery production (IEA, 2023b; ACEA, 2021b). On the demand side, financial incentives in the form of direct purchase subsidies, registration tax discounts and tax breaks through exemptions (Yao et al., 2020) are being implemented to make the price of electric vehicles comparable to that of ICEVs. Our study focuses on demand-side financial incentives.

Demand-side financial incentives have existed in Europe for more than a decade. In 2010, 16 European countries provided financial incentives for consumers buying electric vehicles, and another seven countries provided their consumers with implicit tax incentives (Münzel et al., 2019). By 2022, out of the 27 member countries of the European Union, only Estonia had not introduced any financial incentive policies. Financial incentive policies require significant investment from governments (Lu et al., 2022). In Europe, between 2019 and 2021, government investment per electric vehicle ranged between USD 5,000 and 6,000 (IEA, 2021). Financial incentives are also used in other parts of the world. For example, in 2020, the U.S. government made a federal tax credit of up to USD 7,500 available for the purchase of an electric vehicle (IEA, 2021), and in 2021, the Canadian government announced an investment of USD 1.3 billion to extend the incentive program for zero-emission vehicles (ZEV) until March 2025 (Government of Canada, 2023).

Given the importance of electric vehicles for sustainable transport and the costs associated with incentives, a vast body of literature has emerged examining the impacts of financial incentive policies on electric vehicle adoption. The results are contradictory. For example, studies conducted in Europe (Yan, 2018, Münzel et al., 2019), the USA (Wee et al., 2018), and globally (Wang et al., 2019a) have shown that policies positively contribute to the expansion of electric vehicle adoption. However, some studies have found inconclusive results regarding the relationship between these policies and electric vehicle adoption (Plötz et al., 2016, Jenn et al., 2018).

Furthermore, there are important gaps in research that make it difficult to understand the impact of these policies in individual countries. Firstly, most studies focus on impacts in the USA or globally. For example, in a literature review conducted by Münzel et al. (2019), out of eighteen identified articles, only three examined the impact of policies in Europe.

A similar result was found in a review by Austmann (2021). Given this context and the spread of financial incentive policies for electric vehicle purchases in most major European markets (IEA, 2022), we focus on Europe to conduct a more specific analysis of the effects of policies related to electric vehicles.

A second limitation of the literature is that studies using fixed-effects regressions (Jenn et al., 2018, Wee et al., 2018, Azarafshar and Vermeulen, 2020) are not able to provide a dynamic analysis of the effect of policy implementation over time, but rather an estimate of the average impact of an intervention in one period. This can lead to estimates that hide interesting patterns of electric vehicle adoption in different countries. Thirdly, studies conducted in Europe (Yan, 2018, Münzel et al., 2019) and even globally (Chandra, 2022, Xue et al., 2021) suggest that policies positively contribute to the expansion of the electric vehicle market. However, countries in the samples are heterogeneous because they have different levels of economic development, geographical location (Zheng et al., 2022) and cultural factors. These differences have not been fully explored.

Finally, many studies evaluating the impact of financial incentive policies on electric vehicle adoption do not distinguish between BEVs and PHEVs (Hardman et al., 2017). However, given the different characteristics of these vehicles in terms of their energy source, range, performance, emissions and environmental impact (Rezvani et al., 2015), the policy implications for each vehicle type may be different, as these characteristics can influence consumer perception and choice (Hardman et al., 2017, Wee et al., 2018). In our study, we made estimates for a combined sample of BEVs and PHEVs (ECVs), as these vehicles depend on the development of the charging network and offer the greatest potential for reducing CO_2 emissions in passenger transportation.

Factors influencing the adoption of electric vehicles (EVs) have been the subject of research by many authors. In this regard, fiscal incentives, if substantial enough to offset the price difference between EVs and conventional cars, are considered the most important reason for purchasing an EV (Bjerkan et al., 2016).

The level and design of incentives vary greatly from country to country. Incentives are significantly influenced by broader policy considerations aimed, for example, at mitigating climate change, improving air quality, ensuring energy security or enhancing industrial competitiveness.

As Lévay et al. (2017) note, EV market shares vary considerably and do not appear to correlate strongly with GDP per capita levels, which motivates an examination of differences in EV sales across countries and their relationship to fiscal incentives and other costs associated with EV ownership. Then they conducted pairwise comparisons of EVs with internal combustion engine (ICE) vehicles, which are not subject to such incentives, to qualitatively assess the effects of fiscal incentives on EV market penetration in eight European countries.

They concluded that fiscal incentives (i.e. tax exemptions or subsidies) for battery electric vehicles (BEVs) are necessary, while their descriptive analysis indicated a link between fiscal incentives and the electric vehicle market share. Martins et al. (2024) reveal that purchase incentive policies are associated with increased registrations of battery electric vehicles and plug-in hybrid electric vehicles (PHEVs), and that the effect persists over time. However, the size and duration of these effects are more important for battery electric vehicles. Breetz and Salon (2018) concluded that government incentives are necessary for BEVs to be competitive because of their higher purchase price and rapid depreciation, which outweigh fuel savings.

The effect of fiscal incentives may depend on demand elasticity. Segmented price elasticities of vehicles were examined, for example, by Berry et al. (1996); Coibion and Einav (2006); Eftec (2008). They suggest that elasticity is lower in the larger car segments and higher in the smaller ones.

One controversial issue regarding fiscal incentives for electrically powered cars is whether they are actually necessary, and if so, what the optimal level would be. Li and Wang (2023) stated that subsidies are necessary, while price parity with ICE vehicles is not sufficient due to consumers' concerns about electric vehicle range and battery life. The authors also stated that the optimal level of subsidies for BEVs to maximize social welfare would be based on money spent on subsidies relative to consumer welfare and producer profit, as well as the overall environmental benefits for society.

Wittich (2021) concluded that very generous purchase subsidies of up to EUR 9,000 led to an increase in electric vehicle sales in 2020 of more than 200%, although other factors may also exist. Subsidies were found to have a statistically significant positive impact on the number of new EV registrations in the USA (Wee et al. 2018), and a USD 1,000 subsidy can increase BEV sales by 5–11%. However, by calculating the total cost of ownership for three different car sizes in the United Kingdom, Santos and Rembalski (2021) found that some electric cars were approaching price parity with ICE cars, and that government intervention may not be necessary, and is needed only if the goal is to accelerate the transition, while PHEVs should not be subsidised at all due to their high actual emissions and the fact that BEVs are close in price.

Similarly, Ribeiro and Silveira (2024) assess the impact of financial incentives on the total cost of ownership of electric light commercial vehicles in the European Union and their role in achieving cost competitiveness of electric vehicles. Their analysis confirms that financial incentives have a major impact on the total cost of ownership and are, in most cases, necessary to achieve cost competitiveness of electric vehicles.

In specific cases, however, financial incentives may no longer be necessary, because the cost of owning electric vehicles would be lower than that of diesel vehicles even without them. They demonstrate that it is important to adjust government incentives to avoid unnecessary allocation of funds while also supporting the decarbonization of light commercial vehicles, especially because the number of incentives does not directly correlate with electric vehicle adoption. Some authors also argued that subsidies are not economically efficient due to high costs and the low monetary equivalent of saved CO_2, which results from the environmental policy of CO_2 pricing applied by most governments.

For example, the most important finding of Jurlina's (2023) research is that in the 31 European countries examined, the incentives are not well designed. For every 1 tonne of CO_2 saved by company plug-in hybrid electric sport utility vehicles, tax incentives amounted to EUR 3,400, compared with just EUR 106 for small battery-powered electric vehicles, with significant variations among countries. Active tax incentives had a relatively low impact on the share of BEVs in total passenger car sales across 31 European countries in 2021 and 2022, while the difference in the price of electricity compared to petrol, combined with the proportion of residents living in urban and suburban areas, can be a fairly strong incentive for purchasing BEVs.

However, the factor that had the greatest impact on the share of battery electric vehicles in total sales was national wealth across countries, as measured by relative final consumption expenditure per capita. The study suggests that fiscal incentives for electrically powered vehicles in Europe were too large and were not well designed or targeted at less wealthy households.

The results of the presented research are consistent with the findings of Transport & Environment (2022), which concluded that there is a weak positive correlation between the tax difference for BEVs and their sales. In a multi-country analysis, Yao et al. (2020) evaluated the impact of financial and non-financial incentives on the use of electric vehicles and concluded that the importance of subsidies is very limited and that public policies should focus on affordable public charging networks. Based on a survey analysis across the EU, Gezelius and Mortazavi (2022) concluded that there is a significantly positive correlation between solar panels and BEV purchase thanks to the possibility of charging at lower cost.

Psychological and other factors

A review by Liao et al. (2017) found that, in addition to financial incentives and technical attributes, socio-psychological factors such as social influence and experience also significantly affect the use of battery electric vehicles (BEVs). This claim was also confirmed by Yang and Chen (2021), who examined the effect of socio-psychological factors such as knowledge, personality and social influence on consumer preferences regarding BEV attributes and willingness to pay in two different Chinese cities.

These factors were integrated with an object-case best-worst scaling experiment through a hybrid choice model. The findings show that these factors influence consumer preferences and willingness to pay differently across the cities studied. Knowledge and environmental concerns have a weaker impact on preferences compared to social influence and innovativeness. The results suggest that in smaller cities, it is necessary to clarify policy in order to deepen citizens' knowledge about BEVs and subsidies. In large cities, social influence and innovativeness can complement each other and increase the use of BEVs.

Although the number of ECV-type electric vehicles6 is growing in many countries, they still do not reach a market share that would allow a significant reduction in emissions from road transport, despite the removal of most financial and technological barriers to their adoption. According to researchers from the University of Geneva (Herberz et al., 2022), the barriers to ECV adoption lie mainly in cognitive biases. They examined psychological barriers and found that car owners systematically underestimate the range of ECVs relative to their mobility requirements. This is related to increased demand for long battery ranges and reduced willingness to adopt electric vehicles. They also demonstrated how important it is for car owners to have access to relevant information tailored to their specific needs in order to reduce their concerns and increase their willingness to accept an electric vehicle.

Range anxiety (RA) is a complex phenomenon that involves many factors, such as driver psychological characteristics, algorithms, interface features, technical aspects of ECVs, parking configurations, policies and management. As a psychological factor, RA affects BEV adoption by reducing perceived ease of use, driving pleasure and safety. These negative feelings, in turn, increase aversion to the price of BEVs, which is perceived as excessive compared to their benefits, and negatively affect the overall perception of the vehicle's value. Rainieri et al. (2023) offer a systematic review of 17 analysed articles concerning range anxiety (RA). RA is addressed from psychological, human, and sociotechnical perspectives and is measured using various tools, such as the PASA questionnaire, scenarios and behavioral analysis. The review shows that the best solution to reduce range anxiety may be to design improvements that minimise disruption to lifestyle and behaviour compared to a traditional vehicle.

Bounded rationality is a frequently mentioned issue when making decisions about purchasing electric vehicles. Since electric vehicles have a higher net price than ICE vehicles, consumers face large costs at the time of purchase, while benefits accumulate over the period of ownership. Consumers do not always have enough information about potential fuel savings, maintenance, etc., which can lead to suboptimal decisions.

Another relevant cognitive factor is social norms, as suggested, for example, by Barth et al. (2016). They emphasised that social validation plays an important role in purchasing decisions in the early stages of the spread of new technologies. They argued that targeted educational and experiential programmes could effectively complement economic or technological interventions. In addition to psychological considerations, range anxiety can also prevent customers from buying an EV. In their cross-country regression analysis, Sierzchula et al. (2014) found that the share of EVs in the national market is well explained by the number of charging stations. This is in line with the results of Lieven (2015).

[6] ECV electrically chargeable vehicles, i.e. BEV plus plug-in hybrid (PHEV).

Regulation of the EU car market through the lens of regulation theory

In the past, pragmatic reasons and the need for economic regulation of markets were almost exclusively associated with antitrust policy, which aimed to regulate specific industries exhibiting the characteristics of a natural monopoly. Theory and research in this area concentrated on the functioning of new regulatory agencies, on their powers to intervene in prices, restrict certain inputs and further control what products and quantities are produced, how they affect markets, their efficiency and the distribution of income – including the incomes of national economies (Joskow, Noll, 1981).

The regulation theory related to the public interest, associated with Pigou (1938)[7], is based on the assumption that unregulated markets often fail due to monopoly problems on the part of certain producers or industries, or due to the externalities they impose on third parties. At the same time, this theory assumes that governments are capable of correcting these market failures precisely through regulation (Shleifer, 2005).

In line with this understanding, the theory of the public interest and regulation 'have become the cornerstone of modern public economics, as well as the socialist bible of left-leaning politicians', and for justifying the growth of public ownership and regulation in the 20th century. The regulation theory was used to explain and recommend what governments should do in a situation of market failure in democratic market economies.

It was mainly about proposals on how to control prices so that natural monopolies would not overcharge, how to introduce safety and environmental standards to prevent accidents, environmental disasters, fires, mass poisonings, health problems, and, in the present day, the marginalisation of certain groups of the population, etc.

The public interest regulation theory faced extensive criticism, especially from representatives of the Chicago School of Law and Economics. This criticism and its more detailed arguments concerned the thesis that markets and private orders can take care of correcting most market failures without any government intervention. Further, that even in cases of imperfect market functioning, lawsuits can resolve any conflicts between market participants. As a third argument, concerns are cited that even in cases where markets and courts cannot solve problems without state intervention, the interventions of government regulators can further worsen the situation in markets, if they are incompetent, corrupt or biased.

The New Chicago School (Lawrence, 1998)8identifies new alternatives as additional tools for more effective regulatory activism and expresses hope that the state and its regulation can do more. Especially if one fully grasps the question and the answer, such as what would happen without intervention, with a proper understanding of the significance of the intervention.

According to Schleifer (2005), at a theoretical level, the Chicago School's trust in private ordering without regulation and trust in courts is appealing, but in real life, it is exaggerated. Although private ordering works extremely well in some situations, in others it degenerates into the anarchy of private enforcement: the strong determine the rules of behaviour, corruption, and costly and delayed enforcement of rules. Market participants can use their economic,

[7] A. C Pigou, "The Economics of Welfare," 4th Edition, Macmillan and Co., London, 1938.
[8] Lessig, Lawrence. "The New Chicago School." *The Journal of Legal Studies* 27, no. S2 (1998): 661–91. https://doi.org/10.1086/468039.

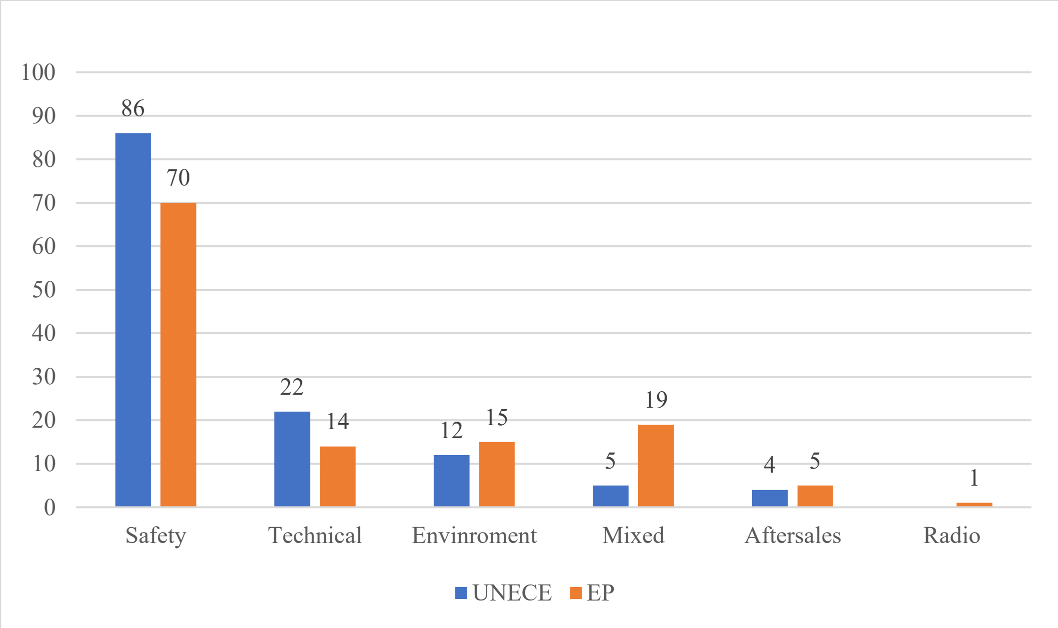
political or social resources and position to harm their rivals through predation, monopoly pricing and even social exclusion.

In line with the seminal paper by Posner (1974), some generally accepted theories have been developed to explain the reasons for and patterns of government regulation in the economy. These included, in particular, the 'public interest (regulation)' theory and several versions of the 'interest group' or 'capture' theory. One of the main recommendations of the paper was that the most promising regulation theory is a version of the interest group theory. Hertog (2010) adds that economic public interest regulation theories assume that regulatory bodies have sufficient information and enforcement powers to effectively enforce the public interest. Their basis and subject of interest are market failures and effective government. According to these theories, in such cases, regulation increases social welfare.

Other economic studies of regulation are based on the assumptions that regulatory bodies lack sufficient information about costs, demand, quality and company behaviour. Moreover, it is generally true that all economic entities pursue their own self-interest before the public interest. Under these assumptions, regulation itself may not necessarily support the true public interest. Economic theories that rely on these assumptions are therefore often called 'private interest regulation theories'. Regulation is then explained as the result of interest group behaviour, assuming transfers of wealth, costs and economic power to interest groups – companies, consumers or consumer groups, regulators or their employees, legislators, unions, etc.

According to ACEA (2023), in 2023, the European automotive industry was subject to 129 regulatory measures from the United Nations Economic Commission for Europe (UNECE) and 124 regulations and directives from the European Parliament (EP). These were subsequently individually applied in the national legislation of EU countries. On the car supply side, the sector is bound by compliance with vehicle specifications regarding safety, the environment, telecommunications equipment, technical requirements for vehicles and their components, and their post-sale use[9].

[9] Detailed in the ACEA annual reports, Automotive regulatory guide, www.acea.auto.



Source: Own work based on ACEA.

Fig. 8.1 Number of regulations by type and authority

Specific directives for the European automotive market are focused on compliance with quantified targets for the gradual transition towards the sale and purchase of zero-emission vehicles. The EU has defined a CO_2 emission target for the entire fleet of cars and vans; from 2035, it is 0 g CO_2/km. On one hand, this target is supported by the regulation of the supply and production of car types and parameters on the EU market. With the aim of affecting demand through regulation, zero-emission car sales targets in the EU are supported by various national policies and financial incentives aimed at increasing consumer demand for zero-emission cars in the EU.

There are three categories of EU country support for the purchase and operation of zero-emission vehicles: tax relief (for acquisition, ownership and support of company vehicle fleets). And two categories of incentives (purchase stimulation and infrastructure support).

In light of Bluff (2018), which examined some of the advantages and challenges of five theories of economic regulation, European regulatory efforts and regulatory targets regarding the sale of zero-emission vehicles have evolved, gradually incorporating elements of the first three theoretical approaches in particular. In the first, the regulator (EC and national legislatures) uses systematic prioritisation of regulatory activities and resource deployment based on environmental risk assessment for the targets it has set.

In the second approach, regulatory bodies systematically analyse and address specific damage, threats and risk concentrations through tailored interventions or solutions. In the third, the regulator seeks to achieve the targets of the regulatory strategy in an escalating (pyramidal) manner. In addition to gradual deterrence, it also applies a ‘support pyramid for progressively building regulatory capacities and supporting strengths’. Simultaneously, it applies more punitive sanctions or reforms regulation in the event of failures to meet regulatory targets (fines for manufacturers for non-compliance with zero-emission vehicle sales targets).

The pandemic, but especially the energy crisis, combined with the global repercussions of the war in Ukraine, has affected sales, the scope of support measures, consumer preferences when purchasing cars and the pressure to change regulatory frameworks for the automotive sector in the EU. From the perspective of interest group theory, these developments have intensified the conflict between the previously dominant environmental interests of regulators (the European Parliament, national parliaments, and governments) on the one hand, and the economic pragmatism of market actors in the EU automotive sector on the other. As this work demonstrates in the following parts based on current facts, car manufacturers in the EU, in particular, have come under pressure from regulators and competitors and are facing the consequences of an economically, socially and psychologically driven decline in consumer interest in low- and zero-emission vehicles in most EU countries.

The life cycle of electric vehicles and the environment.

Electric vehicle batteries require the extraction of natural resources, their processing and battery production, which is energy-intensive – 3 times more energy-intensive than batteries in internal combustion engine vehicles. Further, when a battery reaches the end of its life cycle, it is usually disposed of as electronic waste in landfills, which can lead to the leaching of hazardous compounds into the soil and cause large fires that are extremely difficult to control due to the large amount of flammable waste it is mixed with. Governments are promoting battery recycling, but it is expensive because there is no standardisation in battery design and they are difficult to disassemble. Like many aspects of the government-imposed green transition, it seems that much of the foresight that typically accompanies market-driven revolutions is, in fact, hindsight, with consumers having to bear the burden of ill-conceived decisions and regulations.

BEVs have zero tailpipe emissions, but they are not without environmental impact. Elsewhere in the global supply chain, greenhouse gas emissions are released mainly during material production and battery manufacturing. Mining and refining of materials, cell manufacturing processes and battery assembly processes account for 10–30 % of total life-cycle emissions of BEVs (3). These negative externalities could potentially offset the absolute benefit. However, for BEVs to be needed, electricity would need to be generated with a very high greenhouse gas intensity (almost entirely from coal), as they have higher life-cycle emissions than ICEVs. Efforts to reduce energy-use intensity in terms of greenhouse gas emissions, especially in electricity generation, could further reduce emissions from BEVs in the future. Emissions associated with the production of BEVs (including batteries) will account for the majority of their life-cycle emissions; emissions during the use phase are reduced thanks to charging with low-GHG electricity. The objective of the study was to quantify selected environmental impacts (i.e. primary energy use and greenhouse gas emissions) of battery production within the global value chain and their change over time until 2050, taking into account country-specific electricity generation mixes in various geographic regions. And throughout the battery supply chain.

The battery recycling model developed in this study uses data from the EverBatt 2020 model developed by Argonne National Laboratory. Collected material recovery fractions. Recycling inventory data are applied to projected recycling scenarios in Europe, China, the United

States, Germany and the United Kingdom (using current and future electricity grid mixes). This sensitivity analysis shows what happens if recycling takes place in a country where electricity is not so decarbonized, for example China, which dominates current global recycling capacity; or in Europe, where Germany, with its grid still heavily dependent on coal, and the United Kingdom, where the grid is less CO_2-intensive compared with the EU average.

The study assumes two closed-loop recycling scenarios – the European battery scenario and the circular battery scenario – and assumes that the selected countries adopt these scenarios. These scenarios do not predict what will happen, but they attempt to put into context how recycling could reduce impacts in the future. Secondary materials will never meet the growing demand for batteries, which means that while recycling provides useful supplementary resources, it can only meet a tiny fraction of the total demand.

A sustainable low-carbon transition through electric vehicles will require a comprehensive understanding of the environmental impacts of the global lithium-ion battery supply chain. Here it is necessary to analyse energy consumption from cradle to future nickel-manganese-cobalt and lithium-iron-phosphate battery technologies. If we take into account existing battery supply chains, future prospects for decarbonizing the electricity grid are extremely important for countries involved in material mining and battery manufacturing.

In 2021, Bieker published an extensive study on greenhouse gas emissions over the life cycle of passenger cars in China, Europe, India and the United States. The study found that, over their lifetime, BEVs result in 66 to 69% lower emissions than petrol-powered cars in Europe and a 60% to 69% reduction in the United States, 37% to 45% in China and 19% to 34% in India (Bieker, 2021). With the continued decarbonization of the electricity grid over the coming decades, the climate benefit of BEVs will be even greater. For PHEVs, however, the advantage in terms of life-cycle greenhouse gas emissions compared to vehicles with internal combustion engines is limited due to the low proportion of electric propulsion during real-world use.

Bieker (2021) found that greenhouse gas emissions from battery production account for a small share of total BEV life-cycle emissions. For an average BEV sold in Europe or the United States in 2021, the battery accounts for 12% to 17% of life-cycle greenhouse gas emissions. The contribution of manufacturing the rest of the vehicle is approximately twice as high, at the level of 20–32%. The largest contributor to BEV life-cycle greenhouse gas emissions electricity consumption, which accounts for 47–64%. In China or India, where emissions from electricity consumption are higher, battery production accounts for only 5–8% of total BEV life-cycle GHG emissions.

Updating and standardising regulations on the transport and handling of end-of-life products from electric vehicle batteries could also reduce costs and support growth. Availability of end-of-life batteries is low, but it is expected to rise significantly. It is estimated that 1.2 million batteries from light and heavy BEVs and PHEVs will reach their end of life globally in 2030, rising to 14 million in 2040 and 50 million in 2050, which is a critical time to create a supportive policy environment for the reuse and recycling of these batteries. Reusing 50% of depleted vehicle batteries for energy storage could offer a capacity of 96 GWh in 2030, 3,000 GWh in 2040 and 12,000 GWh by 2050. Effective recycling of scrap vehicle batteries, in some cases after their long-term use in second-life applications, could reduce the combined annual demand for new mining of lithium, cobalt, nickel and manganese by 3% in 2030, 11% in 2040 and 28% in 2050.

LIB applications are often referred to as 'zero emissions'. However, this ignores supply chain emissions generated during the procurement and manufacturing phase. LIBs are one of the main contributors to greenhouse gas (GHG) emissions during EV production. Although the LIB recycling process will produce carbon emissions, recycled materials can be used directly for battery production, thereby avoiding carbon emissions caused by the mining and refining of raw materials. Therefore, engineers estimate the extent to which LIBs reduce greenhouse gas emissions compared to conventional batteries.

The automotive industry is currently on the verge of a transition to electricity, and the environmental performance of electric vehicles (EVs) is raising major concerns. In order to scientifically and accurately assess the environmental characteristics of EVs, we examined the environmental impacts of EVs throughout their life cycle and compared them with those of internal combustion engine vehicles (ICEVs). Given that the battery is the main component of electric vehicles, we further summarise the environmental impacts of battery production, use, secondary use, recycling and refurbishment. The results showed that the environmental impact of EVs in the production phase is higher than that of ICEVs due to battery production.

EVs scored better overall during the use phase than ICEVs, although this depended to a large extent on the share of clean energy in the power grid. In the recycling phase, the reworking and refurbishment of scrap batteries is helpful in improving the environmental benefits of electric vehicles. Throughout their life cycle, electric vehicles have the potential to reduce greenhouse gas emissions and fossil energy consumption; however, they have a higher impact than ICEVs in terms of metal and mineral consumption and potential toxicity to humans. In short, optimising the energy structure, upgrading battery technology and improving recycling efficiency are of great importance for the large-scale promotion of electric vehicles, closed-loop battery production and the sustainable development of resources, the environment and the economy.

8.2.2. Methodological foundations, data and hypothesis formulation

Based on a review of studies on electric vehicle sales in the EU, it can be concluded that there is an overlap among three main (non-price and non-behavioural) determinants that influence differences in EU countries' adoption of electric mobility: economic development, charging station network density and government incentives. In addition, environmental awareness appears to be a significant factor that is influenced not only by economic development but also by a country's traditions regarding the types of renewable energy sources it has been developing over the long term.

GDP per capita (nominal) in PPS is a measure of economic performance that takes into account differences in the cost of living among countries. Purchasing Power Standards (PPS) are a unit of a common currency used to compare the actual purchasing power of different economies, which means they eliminate differences in price levels to allow for a meaningful comparison of the volume of goods and services per person. The 'nominal' part of the term can be misleading in this context, because PPS inherently takes into account differences in price levels, which nominal GDP does not. GDP per capita in PPS is therefore a measure of actual economic performance per person, adjusted for price differences, and is best used for comparing economic prosperity between countries, rather than over time.

As for network density, the number of charging stations per capita will be used as the key comparative indicator, which may influence a consumer's decision to purchase an electric vehicle due to shorter travel distances or increase level of adoption of electric vehicles in these economies.

We will summarise government support measures using the government electric mobility support intensity index, which is based on an overview and data from ACEA. The index is conceived as an expert assessment of the level of e-mobility support in a country for 3 sub-indicators(SI) of taxation (tax benefits TB type) and one of purchase incentives type:

- *SI_1 acquisition (TB type),*
- *SI_2 ownership (TB type),*
- *SI_3 company cars (TB type),*
- *SI_4 purchase incentiveness (PI type).*

Using the multi-criteria evaluation method for variants (for country j), each co-author (s) calculated an FIS index, which is the weighted sum of the country's score based on the level of individual support (criteria):

$$FIS_{s,j} = \sum_{s=1}^{4} SI_{s,i,j}, v_i \tag{1}$$

The weights vI were determined by the authors of this part of the report and the scientific article through expert assignment of weights with values v1 = 0.141, v2 = 0.154, v3 = 0.205, v4 = 0.5, with the authors agreeing to assign the same weight of 0.5 to both sales support and cumulative tax support instruments. The level of support for sub-indicators SIs,i,j is determined by a holistic expert method, where each co-author s evaluates each sub-indicator i for country j with a value SIi,j,s in the 1–100 interval.

The arithmetic average of the value of IIGs,j indexes was used to determine the value of the e-mobility support indicator in country j as:

$$SIG_j = \left(\sum_{s=1}^{4} IIG_{s,j} \right)/4 \tag{2}$$

In addition, environmental awareness appears to be a significant factor that is influenced not only by economic development but also by a country's traditions regarding the types of renewable energy sources it has been developing over the long term. For this consideration, we formulated the hypothesis that the share of renewable energy sources is the appropriate proxy indicator that captures environmental awareness in a country.

The first step of the research was to examine how the market share of electric vehicles (ECVs) according to ACEA in EU countries depended on nominal GDP at purchasing power parity per capita (GDPpcPPS) according to Eurostat, as well as on the density of the charging station network (CHP_ECV_inhabitants) as reported by ACEA, the index of e-mobility support measures (FIS=SIG) developed by the authors, and the share of renewable energy sources in total energy consumption (RES).

Results of the model estimation and its ex ante verification

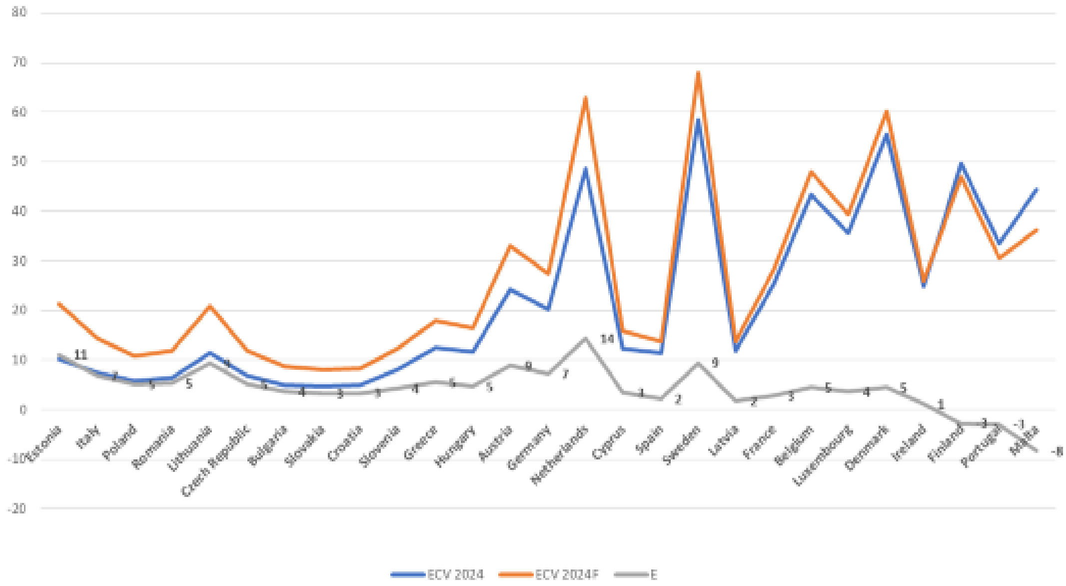
The model's results and the test of its predictive capabilities are based on data from EU countries for 2019 to 2023 The following tables show:

a. Results of the panel regression model estimation for 27 EU countries from data for 2019 to 2023.
b. Ex ante test of the model's predictive accuracy for 2024, where the model prediction of ECVs for 2024 using the values of exogenous variables for 2024 is compared with the actual ECV sales values for 2024.
c. Evaluation of test results.
d. Modelled sales predictions for ECVs in 2030 and 2035 for Sweden and Slovakia, which represent two 'opposites' in terms of the share of ECV sales in Europe. The prediction is based on a trend scenario for the development of the explanatory variables for each variable.
e. Evaluation of model prediction results.

The model test demonstrated good predictive power of the model as a whole and also for individual countries. Furthermore, the model overestimated the prediction – the prediction for 2024F was higher than the actual trend in the share of ECV sales in 2024 across 24 countries with a positive prediction deviation (E): the Netherlands (+14%), Romania (12%), Estonia (+11%) and Sweden along with Lithuania (+9%). Only three countries achieved higher real ECV market shares in 2024 than the 2024F model prediction – Finland and Portugal (with E=-3), and Malta (with E=-8%). New factors have emerged that are slowing the growth of ECVs' market share in 2024 and leading to changes in consumer preferences.

Results of the panel regression model estimation for 27 EU countries from data for 2019 to 2023:

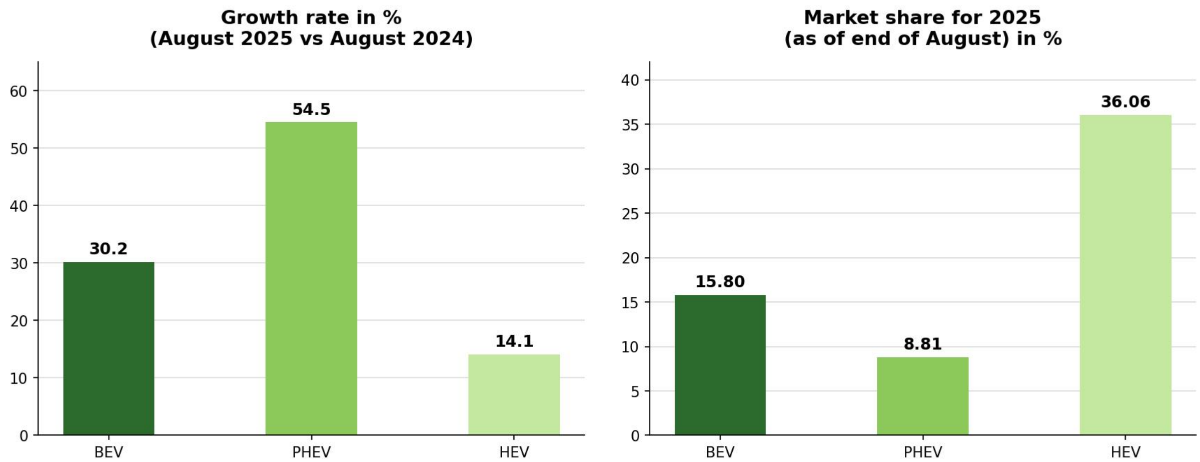
```
Model 12: Fixed-effects, using 135 observations
Included 27 cross-sectional units
Time-series length = 5
Dependent variable: ECV
Standard errors clustered by unit
                         coefficient     std. error     t-ratio     p-value
--------------------------------------------------------------------------------
const                    -53.7289       10.1199        -5.309      1.49e-05  ***
FIS                        0.102534      0.0493416      2.078      0.0477   **
CHP_ECV_inhabita~          3.72040       1.51158        2.461      0.0208   **
GDPpcPPS                   0.000707624   0.000107264    6.597      5.37e-07 ***
RES                        1.39687       0.403146       3.465      0.0019   ***

Mean dependent var        12.64963      S.D. dependent var     13.26799
Sum squared resid       2329.517        S.E. of regression       4.732780
LSDV R-squared            0.901247      Within R-squared         0.749756
Log-likelihood         -383.8063        Akaike criterion       829.6125
Schwarz criterion       919.6760        Hannan-Quinn           866.2118
rho                        0.193112     Durbin-Watson            1.044088

Joint test on named regressors -
  Test statistic: F(4, 26) = 44.9071
  with p-value = P(F(4, 26) > 44.9071) = 2.60891e-11

Robust test for differing group intercepts -
  Null hypothesis: The groups have a common intercept
  Test statistic: Welch F(26, 38.7) = 9.77331
  with p-value = P(F(26, 38.7) > 9.77331) = 3.34076e-10
```



Source: Own calculations.

Fig. 8.2 Ex-ante test of model accuracy for 2024

The model test demonstrated good predictive power of the model as a whole and also for individual countries. Furthermore, the model overestimated the prediction – the prediction for 2024F was higher than the actual trend in the share of ECV sales in 2024 across 24 countries with a positive prediction deviation (E): the Netherlands (+14%), Romania (12%), Estonia (+11%) and Sweden along with Lithuania (+9%). Only three countries achieved higher real ECV market shares in 2024 than the 2024F model prediction – Finland and Portugal (with E=-3), and Malta (with E=-8%). New factors have emerged that are slowing the growth of ECVs' market share in 2024 and leading to changes in consumer preferences.



Source: ACEA.

Fig. 8.3 Growth rate in % (Left Panel) and market share in % (Right Panel)

The prediction of the share of ECV sales for 2030 and 2035 is based on the results and estimates of the panel regression model, as well as on the trend of the exogenous variables

GDPpcPPS, CHP_ECV_inhabitants) according to ACEA, the e-mobility support measures index (FIS), and the trend in the share of renewable energy sources (RES) in total consumption.

The estimated value of the level constant parameter for Slovakia is -41.19208 and -86.72162 for Sweden.

Tab. 8.1

Parameters for Slovakia and Sweden, 2030F and 2035F

Slovakia	2019	2020	2021	2022	2023	2024	2030F	2035F	Parameters
ECV F							16.61351	25.73413	
Fis	11.44	13.13	13.13	14.44	13.92	15.72	21.5	28	0.103
CHP	0.1	0.2	0.3	0.5	0.4	0.6	1.19	1.62	3.7024
GDP	22100	22600	24500	25700	28100	29900	38000	47500	0.0007
RES	16.9	17.3	17.4	17.5	17	17.2	17.4	17.5	1.39687
Sweden									
ECV F							80.31	99.18	
Fis	39.48	49.47	47.83	52.76	51.93	53.98	57	59	0.103
CHP	0.9	1	2.4	2.4	3.5	5.1	7	9	3.70
GDP	37100	36700	40000	41400	43400	44700	51000	61000	0.0007
RES	55.8	60.1	62.5	66.3	66.4	70	71	74	1.397

Source: Own calculations.

The conclusions or findings of the research results and model tests provide arguments for the following conclusions. The worsening consequences of the war in Ukraine, trade wars, the economic strength of EU countries and their households, as well as shifts in public spending and restrictions on fiscal stimulus, have affected the automotive markets in EU countries, creating new priorities and uncertainty:

a. For consumers:

- Regarding the extent of stimulus measures amid rising defense spending, a slowdown in economic growth in some countries, and an increase in public debt as a percentage of GDP in most EU and EA countries in the first half of the year
- Regarding the consequences of trade barriers on the prices of EVs and components
- Regarding the marketability of used EVs, range anxiety and a shortage of service specialists
- Rhere is a shift towards less dependent – diversified – PHEV-type powertrains

b. For companies in the EU automotive sector, which are facing:

- Weak demand for EVs
- American tariffs
- Strong competition from China, which dominates the electric vehicle segment

- Costs for emission allowances across the entire value chain, which reduces their competitiveness
- Dependence on the import of components and rare raw materials from territories outside the EU

Based on the above predictions, supported by a relatively high degree of model accuracy, it follows that:

a. Even the most optimistic model scenario for ECV market share across all EU countries falls far short of the market's willingness to only accept the purchase of BEVs and PHEVs by 2035.
b. Sweden, the country with the highest ECV market share in 2024, could, according to the prediction, reach an ECV market share of 80.31% in 2030 and 99.18% in 2035%. Thus, even the Swedish automotive market would not naturally reach a 100% share of BEV + PHEV.
c. Slovakia, as a country representing converging countries with lower EV acceptance, could reach an ECV sales market share of 16.61% in 2030 and 25.73% in 2035%.

Model results on updated data

Based on updated data for 2019 to 2024, the fixed-effects model was again estimated as the best model for the EU 27 countries. There have been slight adjustments to the parameter values to reflect changes in actual conditions for 2024.

```
Model 2: Fixed-effects, using 135 observations
Included 27 cross-sectional units
Time-series length = 5
Dependent variable: ECV_upt
Standard errors clustered by unit

                        coefficient     std. error     t-ratio     p-value
--------------------------------------------------------------------------------
const                   -54,1311       10,0409        -5,391      1,20e-05  ***
FIS                       0,109727      0,0486836      2,254      0,0329   **
CHP_ECV_inhabita~         3,72870       1,52961        2,438      0,0211   **
GDPpcPPS                  0,000707136   0,000105406    6,709      4,06e-07 ***
RES                       1,40484       0,402787       3,488      0,0017   ***

Mean dependent var       12,68222      S.D. dependent var     13,27912
Sum squared resid      2284,486        S.E. of regression      4,686812
LSDV R-squared            0,903318     Within R-squared        0,756191
Log-likelihood         -382,4886       Akaike criterion       826,9773
Schwarz criterion       917,0408       Hannan-Quinn           863,5766
rho                       0,192784     Durbin-Watson            1,044387

Joint test on named regressors -
  Test statistic: F(4, 26) = 46,299
  with p-value = P(F(4, 26) > 46,299) = 1,8499e-11

Robust test for differing group intercepts -
  Null hypothesis: The groups have a common intercept
  Test statistic: Welch F(26, 38,6) = 10,1564
  with p-value = P(F(26, 38,6) > 10,1564) = 1,86035e-10
```

The level (numerical value) of the constant for individual countries (per unit constant) is shown in the following table.

Tab. 8.2
Level constants for individual countries

Country	Per unit constant	Country	Per unit constant
Austria	–78.43673	Italy	–49.69569
Belgium	–37.17265	Latvia	–73.12336
Bulgaria	–43.11879	Lithuania	–58.61056
Croatia	–58.2868	Luxembourg	–71.96412
Cyprus	–47.09983	Malta	–25.23334
Czech Republic	–46.17606	Netherlands	–47.42181
Denmark	–66.27654	Poland	–39.90866
Estonia	–68.22692	Portugal	–53.41123
Finland	–69.75196	Romania	–49.06538
France	–47.54661	Slovakia	–41.49864
Germany	–46.23593	Slovenia	–54.26023
Greece	–44.23118	Spain	–54.15252
Hungary	–40.10611	Sweden	–87.52236
Ireland	–63.00518		

Source: Own calculations.

At this stage of the EUBA team's project, the team is preparing, refining and evaluating possible scenarios for ECV sales in European countries until 2030.

In a pessimistic scenario until 2030, we project, for individual countries:

- maintaining fiscal support from national governments at the current level (constant value of the exogenous variable *FIS)*,
- trend development of charging infrastructure *(CHP_ECV_inhabitants)*, based on the most appropriate trend function,
- nominal GDP in purchasing power parity per capita (*GDPpcPPS*) until 2027 based on the EC's autumn 2025 GDP and inflation forecast, and then the trend until 2030 based on the most suitable trend function,
- development of the share of renewable energy sources in total consumption *(RES)* until 2030 based on the most suitable trend function.

In a optimistic scenario until 2030, we project, for individual countries:

- achieving fiscal support from national governments at the current level of the highest support from Austria for 2025 in every country from 2028 at the level of the best country in 2025 – for 2026 and 2027 - FIS = 88.61)
- trend development of charging infrastructure *(CHP_ECV_inhabitants)*, based on the average growth to date across all EU countries,
- nominal GDP in purchasing power parity per capita (*GDPpcPPS*) until 2027 based on the EC's autumn 2025 GDP and inflation forecast, and then the trend until 2030 based on the most suitable trend function,
- development of the share of renewable energy sources in total consumption *(RES)* until 2030 as a growth trend of the share of renewable sources for all countries – max 100.

The results of the forecast scenarios – again for Slovakia and Sweden confirm that:

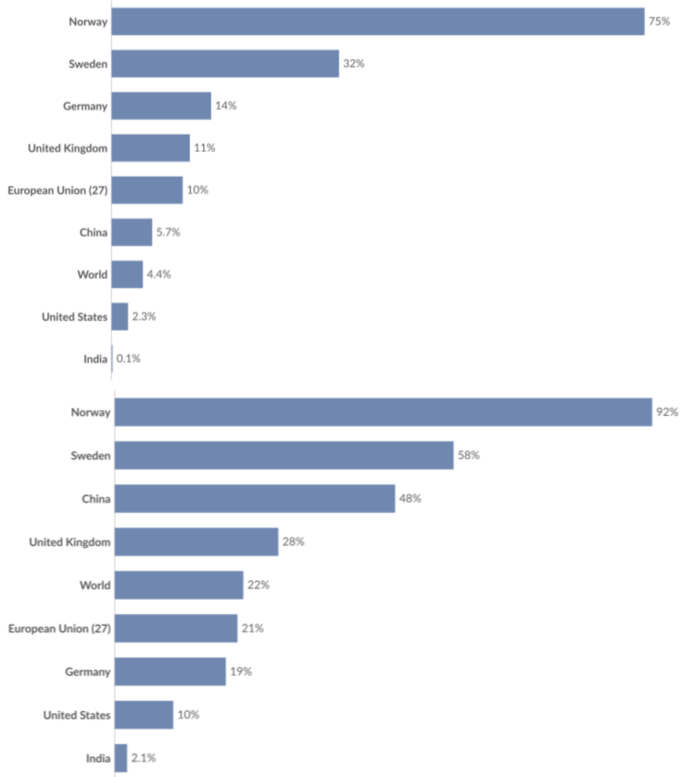
- Based on updated data and the model described above, Sweden is capable of achieving a 100%, share of ECV sales by 2030 under both pessimistic and optimistic scenarios.
- Based on updated data and the model described above, Slovakia is capable of achieving a 18.55%, share of ECV sales by 2030 under the pessimistic scenario.
- In Slovakia, based on updated data and the model described above, there is a chance, even under the optimistic scenario, that the share of ECV sales will approach approximately 60%. by 2030.

8.3. Economic impact of the transition to electric vehicle production in Slovakia

This part examines the socioeconomic impact of various scenarios on the transition to electric vehicle production in Slovakia. A multi-regional input-output model with an employment extension is used for modelling the impact. Scenarios and exogenous development changes are formulated based on expert estimates of stakeholders and international studies in this area. The difference between the positive and pessimistic scenarios represents a significant loss of added value and employment in the event of a failed transition to electric vehicle production, regardless of the rate at which electric vehicles are purchased in Slovakia. First, we examine the broader context of global trends in the electric vehicle market. Then we point out the importance of the automotive industry for the Slovak economy. This is followed by an explanation of the methodology used and presentation of the results of modelling scenarios for the transition to electric vehicle production, as well as the investment requirements for this transition.

8.3.1. Broader context – the global electric vehicle market

Figure 8.4 shows the shares of electric vehicle (EV) sales, including plug-in hybrids (PHEV), in total new motor vehicle sales in selected countries, the EU-27, and globally in 2020 (Panel A) and 2024 (Panel B). During this short four-year period, there have been significant changes in the demand for electric vehicles (EVs and PHEVs). In 2020, their share of total global sales was 4.4%, in 2024 22 %. During this period, their sales share also doubled in the EU-27, from 10% in 2020 to 21% in 2024. Global sales growth was driven primarily by new electric vehicle sales in China, where their share grew from 5.7% to 48% in 2024. Almost every second car sold in China in 2024 was either a purely electric vehicle or a plug-in hybrid. Among European countries, the highest sales shares were achieved in Sweden (58% in 2024) and Norway (92% in 2024), where nearly all vehicles sold were new electric vehicles.



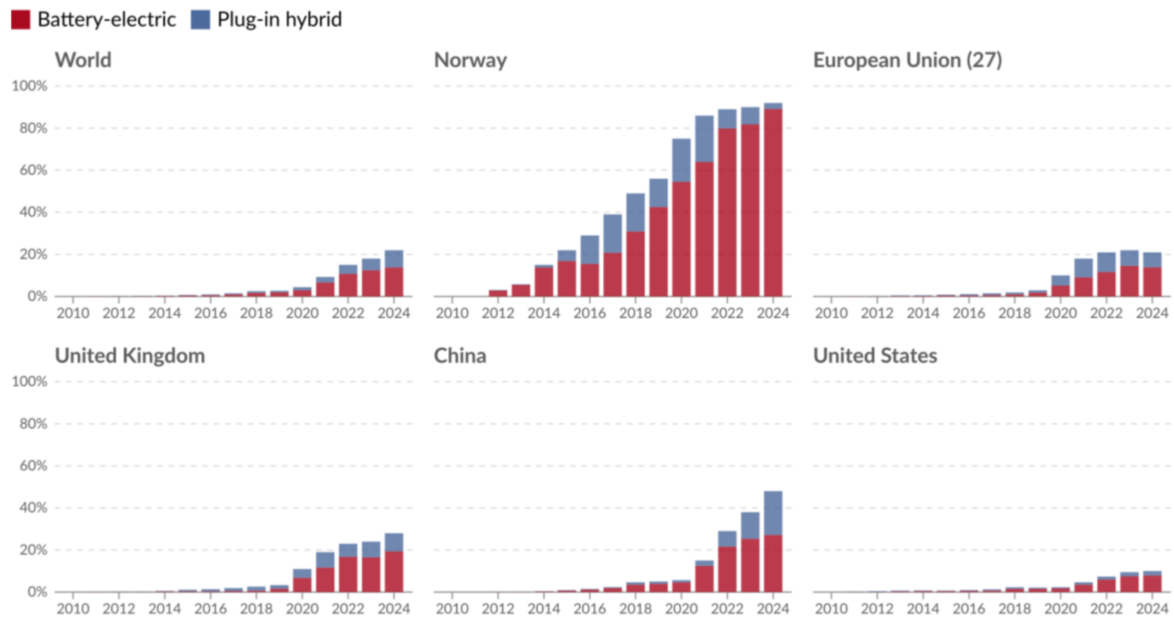
Panel A: 2020

Panel B: 2024

Source: Hannah Ritchie (2024) – "Tracking global data on electric vehicles" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/electric-car-sales' [Online Resource]

Fig. 8.4 Share of new electric car sales, Panel A 2020, Panel B 2024 (EV + PHEV)

The next figure documents the development of electric motor vehicle sales separately for purely electric vehicles (EVs) and plug-in hybrids (PHEVs). The majority of global sales consist of purely electric vehicles, about two-thirds. The European Union is in a similar position, but with an even higher share of purely electric vehicles. Since 2021, there has been no growth in the share of electric motor vehicles sales there (still around 20%), but internally, sales have shifted from PHEVs to EVs. In China, on the other hand, PHEV sales have grown faster than EV sales over the last three years. Electric vehicle sales in the USA are at a significantly lower level than in China, the EU or the global average, with a very small share of PHEV sales.

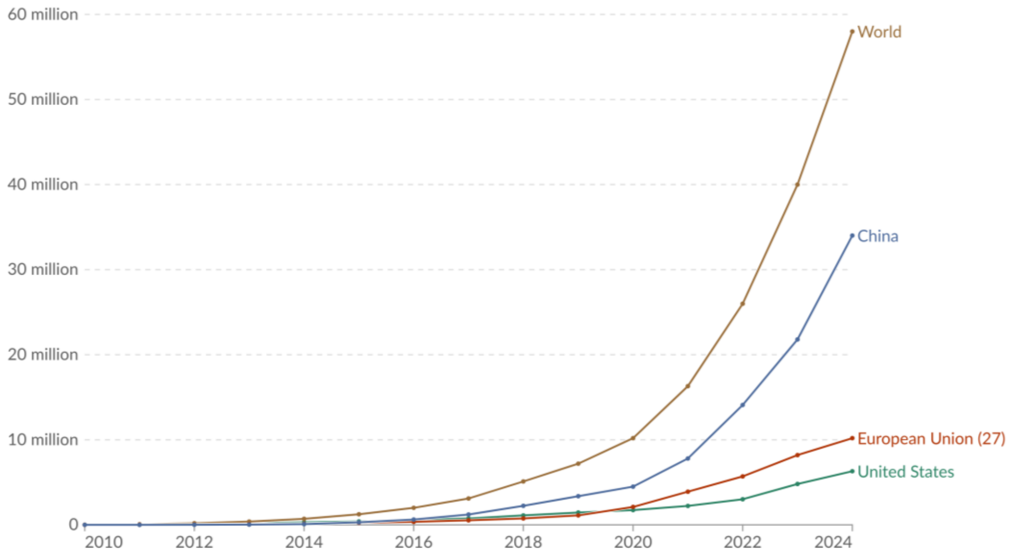


Source: Hannah Ritchie (2024) – "Tracking global data on electric vehicles" Published online at OurWorldinData.org. Retrieved from: 'https://ourworldindata.org/electric-car-sales' [Online Resource]

Fig. 8.5 Share of new EV and PHEV cars sold, 2010–2024

The global market for new motor vehicle sales experienced its highest sales between 2016 and 2018, when about 80 million new vehicles were sold annually. These sales then fell to below 70 million annually between 2019 and 2022, and only in the last monitored year (2024) did they return to just under 80 million. However, these new sales have increased electric vehicle sales significantly. Sales of internal combustion engine cars have fallen to just over 60 million annually, with the remainder consisting of EV and PHEV sales. In the EU-27, approximately 17 million new cars were sold annually until 2019; in 2024, that figure was just over 14 million, driven once again by growing demand for electric vehicles (based on data from the IEA, Global EV Outlook 2025).

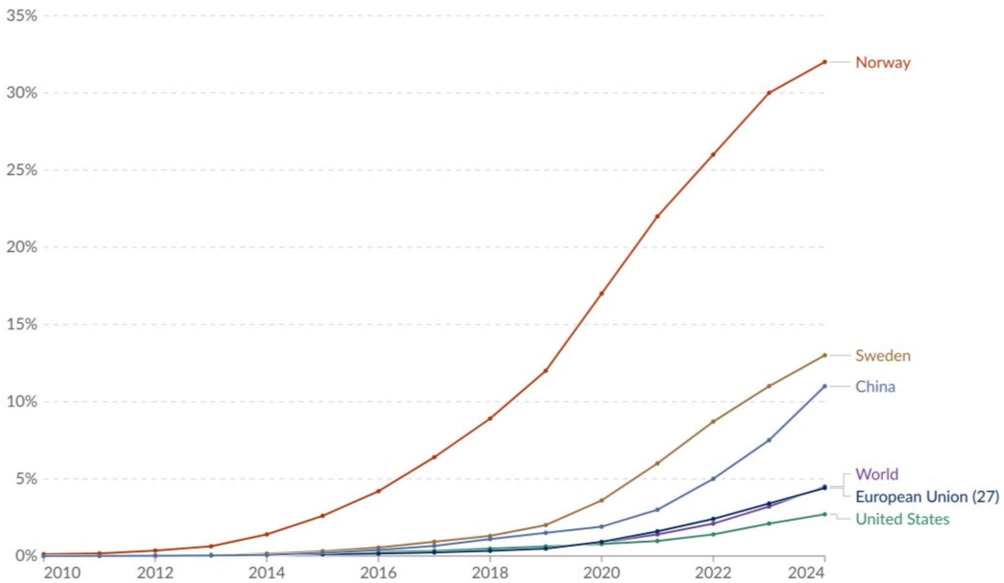
The next figure shows the development of the total fleet of electric vehicles since 2010. The total global fleet in 2024 came to just under 60 million motor vehicles (EVs and PHEVs), of which approximately 35 million were in China. Approximately 10 million electric vehicles were on the roads in the EU-27.



Source: International Energy Agency. Global EV Outlook 2025. Retrieved from: ‘https://ourworldindata.org/energy [Online Resource]

Fig. 8.6 Electric motor vehicle fleet, 2010–2024 (EV + PHEV)

Figure 8.7 shows the trend in the share of electric vehicle fleet in the total vehicle fleet in selected countries and worldwide. While this share is approximately 5% of the total car fleet globally and in the EU-27, it is significantly above 10% in China and Sweden, and at a level of more than 30%. in Norway. This means that one in every three cars in Norway is electric.



Source: International Energy Agency. Global EV Outlook 2025. Retrieved from: ‘https://ourworldindata.org/energy [Online Resource]

Fig. 8.7 Share of electric motor vehicles in the total fleet on the roads, 2010–2024

Documented global trends in new motor vehicle sales will determine the production of new motor vehicles in Slovakia. The Slovak automotive industry thus faces the challenge of successfully transitioning to the production of electric vehicles.

8.3.2. The importance of the automotive industry for the Slovak economy

A successful transition to electric vehicle production in Slovakia is key to maintaining employment and generating added value in the manufacturing industry. Its importance lies not only in the jobs it directly creates at car manufacturers, but especially in the entire production chain located in Slovakia. In 2024, the automotive industry directly and indirectly generated approximately 200,000 jobs (own calculations based on data from the Statistical Office of the Slovak Republic, Automotive Industry Association of the Slovak Republic and FIGARO 2025ed). The share of industry (excluding construction) in Slovakia's GDP in 2024 was 23.4%. The automotive sector (car manufacturers and TIER1 – TIER3 suppliers) created more than 51% of total industrial production. The share of the automotive sector in the export of goods and services from Slovakia was 42.6%. The export of motor vehicles directly and indirectly generated more than 10 billion euros in value-added, which in 2024 represented 8.8% of the total value-added of the Slovak Republic (own calculations based on data from the Statistical Office of the Slovak Republic, Automotive Industry Association of the Slovak Republic and FIGARO 2025ed). These statistics demonstrate the significance of a successful transition to electric vehicle production, which is linked both to the introduction of new models of motor vehicles manufactured in Slovakia and to substantial investment requirements. In this work, we model transition scenarios, investment requirements and their economic impact using a multi-regional input-output model, which will be explained in the following subsection.

8.3.3. Multi-regional input-output model

This part describes the application of a multi-regional input-output (MRIO) model to estimate the impact of changes in final demand for cars on production, value-added and employment. The model is based on the standard open static Leontief model and assumes fixed technical coefficients, linear relationships between inputs and outputs, as well as fixed prices and the absence of capacity constraints.

The model is based on the intermediate consumption matrix Z, which captures production flows between industries and regions, the gross production vector x and the final demand vector y. Technical coefficients are calculated as $A = Z * x^{-1}$, where each element of matrix A expresses the amount of input from a given industry and region required to produce one unit of production in another industry and region.

The equilibrium condition of the model is given by $x = A x + y$, which means that total prodction equals the sum of intermediate consumption and final demand. After adjustment, we obtain the basic Leontief relationship $x = (I - A)^{(-1)} y$, where $(I - A)^{-1}$ represents the Leontief inverse matrix.

This matrix captures the total (both direct and indirect) effects on production caused by a unit change in final demand.

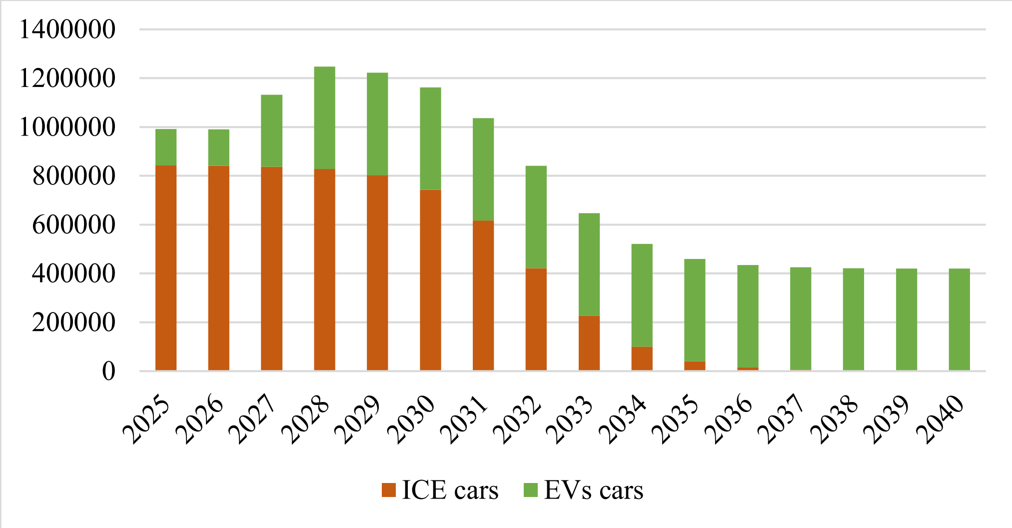
The change in final demand for cars is represented by the vector Δy, which is non-zero only in items corresponding to the automotive industry. The total impact on production is then calculated as $\Delta x = (I - A)^{-1} \Delta y$. This result includes both the direct impact on the automotive industry and indirect effects in supplier sectors such as metal, plastics and electronics production, energy and transport services.

When converting effects to value-added, value-added coefficients, defined as the ratio of value added to production, are used. By multiplying the diagonal matrix of these coefficients by the vector Δx, we obtain the change in value-added: $\Delta VA = \hat{g}\ \Delta x$. Analogously, we can calculate the effects on employment through employment coefficients. Direct effects are changes in production within the automotive industry itself as a result of increased final demand, while indirect effects occur in the sectors involved in the supply chain.

When analysing the effects of investment requirements for the transition to e-mobility, we start from the gross fixed capital formation vector. The structure of this vector corresponds to the structure of investments in Slovakia in the input-output table used. We model the volume of investment based on publicly available information.

8.3.4. Scenarios for the transition to electric vehicle production, the investment requirements for this transition and their economic impact

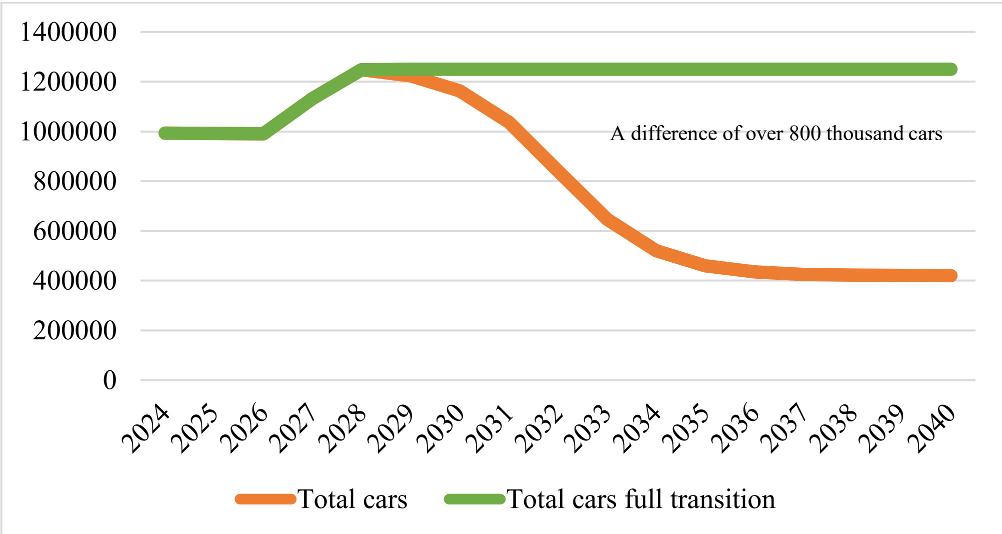
When modeling the scenarios for the transition to electric vehicle production, we were inspired by the Cambridge Econometrics (2022) study. However, the modelled scenarios are adjusted to include the latest available data on actual electric vehicle production in Slovakia. In the Cambridge Econometrics (2022) study, the difference between the best and worst-case scenarios was at the level of 10% of Slovakia's GDP and 4% of net employment. The optimistic scenario projected an annual production level of 1 million motor vehicles, with the share of electric vehicles rising from less than 10% in 2020 to more than 90% in 2035, and 100% of production consisting of electric vehicles by 2040. In the worst-case scenario, by 2040, the production of motor vehicles with internal combustion engines had ceased and had not been replaced by the production of electric vehicles, which therefore remained at a level below 100,000 cars per year. Given the car manufacturer' current plans, the upgrade of production lines and Volvo's expected launch of electric vehicle production, we consider this worst-case scenario to be overly pessimistic. In Slovakia, capacity for the production of more than 400,000 electric vehicles per year is already being built. This production also represents the most pessimistic scenario for the development of automotive industry production until 2040.



Source: Own calculations using the MIOM model and Figaro 2024

Fig. 8.8 Scenario of an unsuccessful transition to EV production with a decline in ICE vehicle production

The next figure compares the pessimistic scenario (400,000 vehicles per year) with the optimistic scenario (growth of car production to 1.2 million per year by 2028 and maintaining this production until 2040). This scenario is based, among other things, on the successful launch of Volvo electric motor vehicle production at a level of 250,000 per year.



Source: Own work.

Fig. 8.9 Comparison of the optimistic and pessimistic scenarios until 2040

Table 8.3 compares the effects of a successful transition to electric vehicle production with a partial transition to electric vehicle production and a gradual decline in the production of internal combustion engine vehicles. In the last column, we present the difference in the effects of these two scenarios. We present the effects on exports, employment and value-added. We estimate the percentage effect on GDP, jobs at risk and public-sector revenues.

Tab. 8.3
Effects of scenarios for the transition to EV production and their impact on exports, employment, value-added and public sector revenues

	Successful transition to EV produc-tion*	**Partial transi-tion to EV production**	**Difference**
Export value in mil. EUR (2024 prices)	38,234	12,846	**25,388**
Directly and indirectly generated employment, number of jobs	205,307	68,980	**136,328**
Directly and indirectly generated value-added, in mil. EUR	8,563.2	2,877.1	**5,686.1**
Effects on GDP in % of total GDP	8.47%	2.85%	**5.62%**
Employment at risk in %	–	–	**5.6%**
Effects on public sector revenues in % of total GDP**			**2.42%**

Source: Own calculations using the MIOM model and Figaro 2024
Note: * without modelling battery production, ** based on public sector revenues for 2023 of 43%.

With a successful transition to electric vehicle production and an annual production of 1.2 million vehicles, the estimated export volume is at the level of EUR 38 billion (in 2024 prices). With an unsuccessful transition, exports would fall to just under EUR 13 billion. The difference in generated (direct and indirect) employment between the optimistic and pessimistic scenarios is 136,000 jobs, which represents 5.6% of employment at risk. Depending on behavioural reactions and structural changes in the economy, some of these workers would find employment in other sectors, while others would end up unemployed. The importance of the automotive sector would fall below 3% of GDP under the pessimistic scenario, and this decline would cause a decrease in public sector revenues of 2.4%.

A successful scenario of transition to EV production requires substantial investment. Based on a study by Cambridge Econometrics (2022), the conversion of the production line in Zwickau with a capacity of 330,000 vehicles per year required an investment of EUR 1.2 billion. billion. After calculating the difference between current and expected capacities under the optimistic scenario, a successful transition in Slovakia will require approximately EUR 3 billion in investment by the car manufacturers themselves, for which they must compete with other production plants. Using the multi-regional input-output model, we estimate the national economic effects of this investment at 0.22% of GDP annually and the creation of 6,000 jobs.

In the previous scenarios, we did not consider changes in the input structure. However, how the need for EV batteries will be covered plays an important role. What are the investment requirements for battery production to fully cover EV production under the optimistic scenario? According to a study by Cambridge Econometrics (2022), 1 GWh of annual battery production requires a total investment of EUR 85 million. billion. According to publicly available information about investment in the battery plant in Šurany, with a planned capacity of 20 GWh, its value is EUR 1.2 billion, which would amount to EUR 60 million per 1 GWh of annual production. With an average battery capacity of 70 kWh and an annual production of 1.2 million electric vehicles, full coverage would require battery production with a capacity of 84 GWh per year. Additional investment in battery plants would thus be EUR 3.8 billion, i.e. approximately EUR 640 million annually over six years. We estimate the national economic effects of this investment at 0.28% of GDP annually with the creation of approximately 7,600 jobs.

8.4. Conclusion

The conflicting views and findings of expert studies call for caution regarding the reckless push to ban the sale of emission-producing passenger cars in Europe. Both in terms of vehicle operation and their entire life cycle. This EU strategy is being met with resistance not only from EU car manufacturers, but also from consumers, who are reluctant to comply with the regulatory pressure exerted by some European policymakers when purchasing BEVs. Especially in less developed European countries, where, among other reasons, consumers perceive ECVs as being beyond their means.

It is becoming clear that even the fiscal incentives provided are unable to overcome this resistance, and the stubborn pursuit of a path to carbon neutrality through e-mobility, without a primary focus on the transition to low-emission energy sources and energy carrier transmission, is more likely to lead to a decline in the competitiveness of manufacturers in the European automotive sector. The results of our research independently support this as well.

Model projections of ECV sales (/BEV+PHEV) suggest that, in a sales-driven market, only a country like Sweden (currently the European leader) can, by 2035, or even as early as 2030, come close to consumer preferences for purchasing exclusively electric vehicles (including ECVs). Forecast scenarios for ECV sales in Slovakia confirm that the country, which currently ranks among the countries lagging behind in ECV sales, could reach a 60%. share of ECV sales by 2030 if there were a dramatic increase in fiscal support and growth in renewable energy sources. Without substantial fiscal support and without a higher share of renewable energy sources in total energy consumption, Slovakia could reach a maximum share of ECSs in total vehicle sales of 18.6% by 2030 and, by 2035, exceed a one-quarter share of ECVs in total car sales.

The difference between a successful and an unsuccessful transition to electric vehicle production in Slovakia has significant economic implications. If we assume that this difference amounts to 800,000 cars produced annually, then from a national economic perspective, a failed transition would result in a loss of exports worth over EUR 25 billion, a threat to the jobs of 5.6% of workers in Slovakia, a decline in the automotive sector's share of GDP to below 3% and a shortfall in public revenue of 2.4% of GDP. Restoring the competitiveness of the automotive industry and, in a broader context, the entire manufacturing industry should be one of the priorities of economic policy.

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