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CLIMAN

EDUCATION, SCIENCE AND INDUSTRY ON THE PATH TO CLIMATE CHANGE PREVENTION, ADAPTATION AND MITIGATION

MONOGRAPH

English edition

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The collective monograph was prepared by researchers from partner universities of the international ERASMUS+ project "Synergy of educational, scientific, managerial and industrial components for climate management and climate change prevention / CLIMAN" 619119-EPP-1-2020 -1-NL-EPPKA2- CBHE-JP. The publication highlights the results of own research on the general issues and origins of global climate change, sectoral issues of sustainable development, the implementation of natural based solutions, the application of innovative approaches to energy support for the development of transport, agriculture and waste disposal.

The monograph is intended for a wide range of readers who are interested in the problems of global climate change, as well as ways of possible prevention, adaptation and mitigation of the climate change consequences.

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INTRODUCTION

Climate change caused by human activities is defined in modern conditions as one of the most significant challenges for the countries, governments, businesses and individuals, with large-scale consequences for the humanitarian system and the natural ecosystem. At the 21st session of the Conference of the UNO on Climate Change on 12.12.2015, the Paris Agreement was adopted, which is aimed at implementing of the resolution of the UN General Assembly "Transformation of our world: Agenda for Sustainable Development till 2030" and was aimed to support ecological integrity, renewable energy, green economy, transfer of high-performance technologies, climate change mitigation and adaptation to the changing climate. In response to this global trend, the initiatives are being developed and implemented to limit the concentration of greenhouse gas (GHG) in the atmosphere of Earth. Such initiatives rely on the assessment, monitoring, notification and verification of GHG emissions and / or elimination of emissions. Therefore, there is no doubt in relevance of the provision on the need to consolidate professionally oriented activities in the field of prevention, adaptation and mitigation of consequences, including training of highly qualified specialists in the field of climate control, climate initiatives and climate management.

To solve this task, the international Erasmus+ project "Synergy of educational, scientific, management and industrial components for climate management and climate change prevention / CLIMAN" 619119-EPP-1-2020-1-NL-EPPKA2-CBHE-JP was developed and is being implemented.

Project duration: 15.11.2020-14.11.2024

The aim of the project is to help the universities of Georgia and Ukraine to become centers for the development of research of climate management to accelerate integration into the global climate market and to meet global climate regulation requirements by acquiring best European practices in the field of climate change prevention, adaptation and mitigation.

The specific objectives of the project are as follows:

1. Update the existing master desgree programs by developing an interdisciplinary training module "Climate Management".

2. Establish consulting Climate Management Centers at partner universities and ensure their sustainable development.

3. Facilitate the development and strengthening of institutional capacity of partner universities aiming to develop recommendations for the industrial, transport, energy, tourism sectors and local authorities in the sphere of climate change prevention, adaptation and mitigation.

Activities:

- learning of the EU experience in scientific and practical activities on climate management;
- development of the Training Module "Climate Management" at Partner HEIs;
- establishment of the Climate Management Center;
- implementation of the updated Master Degree Program at Partner Universities;
- quality management;
- dissemination and sustainability;
- project management.

Expected results:

- Updated Master Degree Program by means of development and implementation of Training Module "Climate Management".
- Trained staff.
- Consulting Centers of Climate Management are established at partner universities.
- Developed "roadmap" of cooperation between the industrial, transport, agricultural and tourism sectors and local authorities on the implementation of climate management policy.
- Qualified climate managers.

Project Partners:

Project Coordinator: Netherlands Business Academy, Netherlands.

Project Co-Coordinator: KROK University.

- «HTW Berlin, University of Applied Sciences», Germany;
- Foggia University, Italy;
- Mykolas Romeris University, Lithuania;
- Turiba University, Latvia;
- Kharkiv National Automobile and Highway University, Ukraine;
- Lviv Polytechnic National University, Ukraine;
- Akaki Tsereteli State University Kutaisi, Georgia;
- Batumi Shota Rustaveli State University, Georgia;
- West Ukrainian National University, Ukraine.
- Hultgren Nachhaltigkeitsberatung UG, Germany.

Project web-site: https://climancoordinator.wixsite.com/climan

PART 1
CLIMATE CHANGE AND COUNTERMEASURES

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1.1. Global climate change

Weather and climate are related but distinct concepts that describe different aspects of atmospheric conditions.

Weather refers to the short-term state of the atmosphere at a specific location, typically measured over hours, days, or weeks. It describes the current conditions of temperature, humidity, precipitation, wind speed, cloud cover, and other atmospheric variables. Weather conditions can change rapidly and vary from day to day or even within the same day. Weather forecasts provide information about expected weather conditions for a specific period, usually up to a week in advance.

Climate refers to the long-term average weather patterns observed in a region over a more extended period, typically 30 years or more. It represents the statistical information about weather conditions, including average temperatures, rainfall patterns, and seasonal variations, for a particular area. Climate provides a description of the typical or expected weather conditions for a specific region over an extended period. It helps us understand the climate zones and the overall climate characteristics of different parts of the world.

Climate refers to an averaged condition of the lower layers of the atmosphere and the associated waters and the Earth's surface. Indicators that describe a climate include annual average temperature, average annual maximum and minimum temperature, annual precipitation, etc.

The World Meteorological Organization[1] advises to assess climate data using at least 30 years period. More frequently data of relatively longer periods (centuries, millennia, and more) are applied for analysis. Thus, climate describes the average weather conditions of a particular location over a long period of time.

Since the Industrial Revolution, there has been a clear warming trend in the Earth's average temperature. Multiple scientific studies and assessments, including those conducted by the Intergovernmental Panel on Climate Change (IPCC) and National Oceanic and Atmospheric Administration (NOAA), have confirmed this trend.

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[1] *https://public.wmo.int/en*

It should be noted that since the beginning of the 21st century, the temperature has been increasing in parallel with the concentration of carbon dioxide in the atmosphere. According to the IPCC data, from 2005 to the present, the average annual temperature increase was 0.87oC, which is higher than the average annual temperature increase during the entire 20th century (Fig. 1.1).

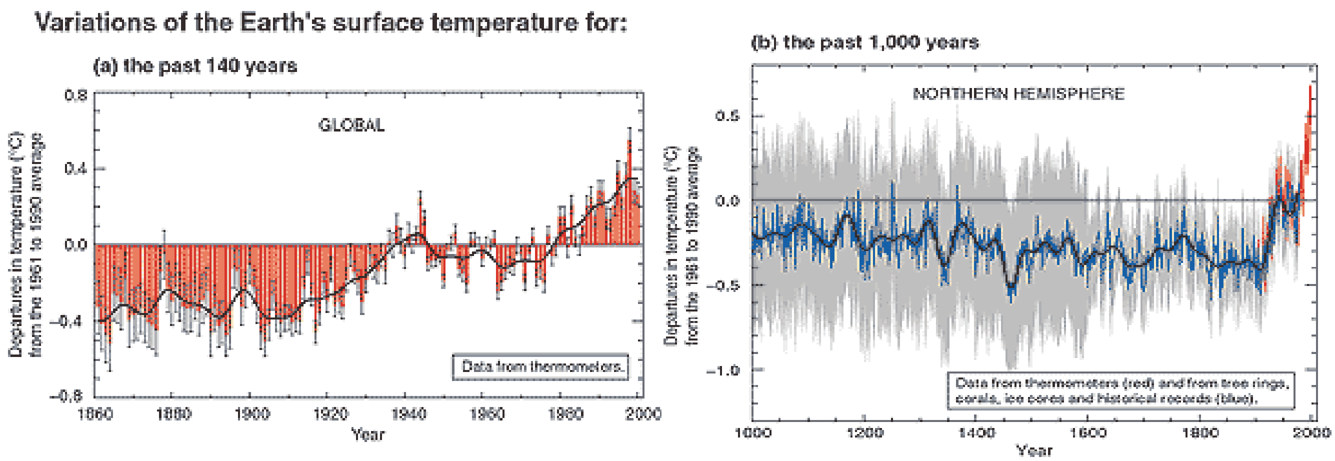

Fig. 1.1 Variations of the Earth`s surface temperature

The global warming trend is characterized by the following signs:

- Historical Warming: Over the past century, the Earth's average surface temperature has risen by approximately 1.1 degrees Celsius (2 degrees Fahrenheit) above pre-industrial levels (late 19th century). This increase has been observed across multiple continents and ocean regions;
- Acceleration in Warming: The rate of global warming has accelerated in recent decades. The period from the late 20th century to the present has witnessed a more rapid increase in temperature compared to earlier periods (Fig. 1.2).

Regional Variations: While the global average temperature is increasing, the warming is not evenly distributed across the planet. Some regions, such as the Arctic, have experienced significantly greater temperature increases compared to global averages. This has led to rapid melting of glaciers, reduction in sea ice extent, and changes in ecosystems (Fig. 1.3).

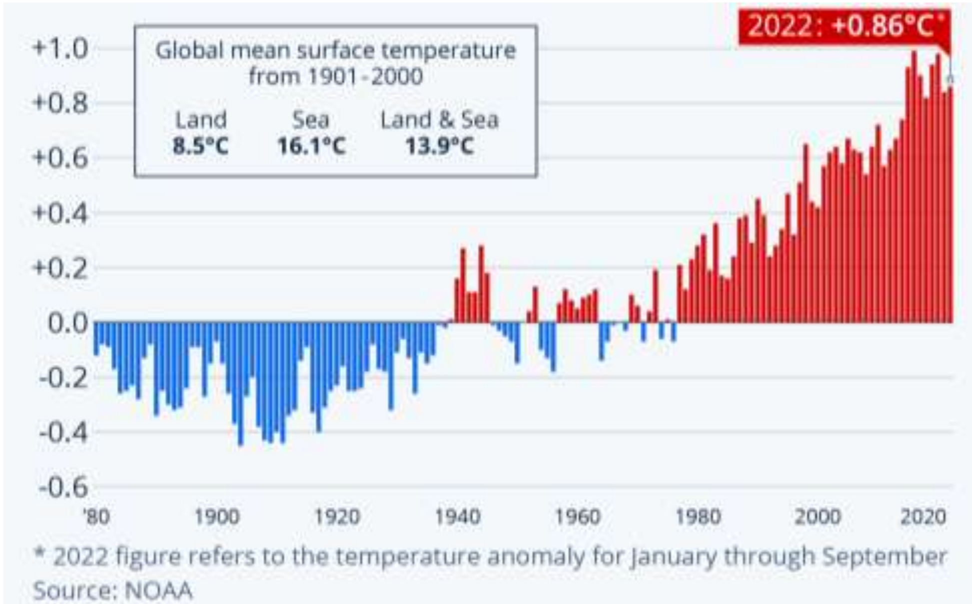

Fig. 1.2. Refers to the temperature anomaly for January through September

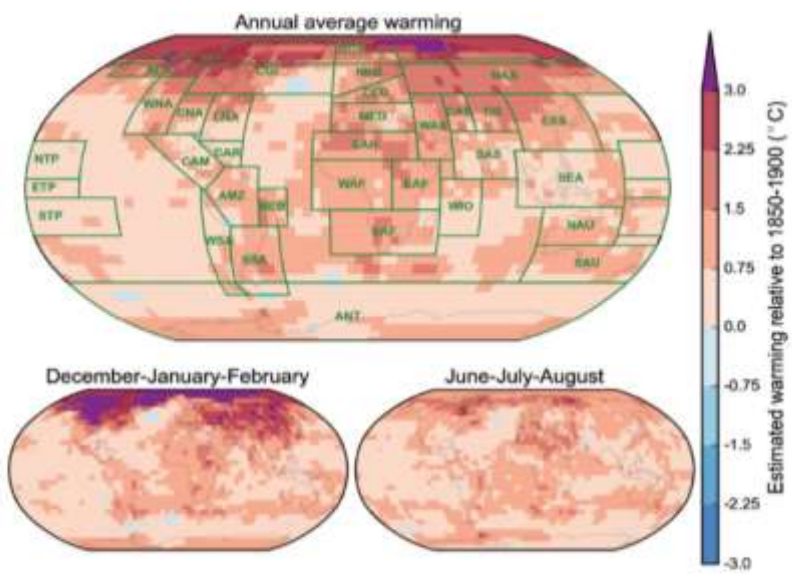

Fig. 1.3. Regional warming in 2006-2015, compared to the pre-industrial period (1850-1900)

Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January, and February (bottom left) and for June, July, and August (bottom right).

As the map shows, global warming does not mean that temperatures are rising at the same rate everywhere. In one region, the temperature may increase by 5 degrees, and in another, it may decrease by 2 degrees. For example, an exceptionally cold winter in one place may be balanced by an extremely warm winter in another part of the world. In general, warming is greater over land than over oceans because water absorbs and releases heat more slowly (thermal inertia). Warming can also vary substantially across specific land masses and ocean basins.The image below shows global temperature anomalies in 2022, which tied for the fifth warmest year on record (Fig. 1.4). The past nine years have been the warmest years since modern recordkeeping began in 1880.

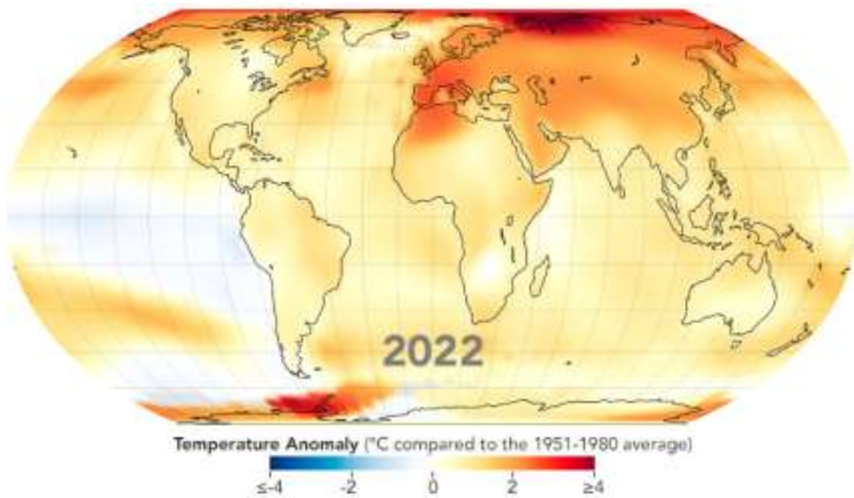

Fig.1.4. Temperature Anomaly

1.2. Ambient air composition and greenhouse effect

The atmosphere is a complex mixture of gases, suspended particles, and trace amounts of various compounds. The typical composition of Earth's atmosphere is as follows:

- Nitrogen (N_2) – It is the most abundant gas in the atmosphere, making up about 78 % of the total volume. Nitrogen is a non-reactive gas and plays a crucial role in various biological processes.
- Oxygen (O_2) – Oxygen constitutes approximately 21 % of the atmosphere. It is essential for the survival of many organisms, including humans, as it is involved in respiration and combustion processes.
- Argon (Ar) – Argon is an inert gas and makes up about 0.93 % of the atmosphere. It is primarily a byproduct of the radioactive decay of potassium in the Earth's crust.

• Carbon Dioxide (CO_2) – Carbon dioxide is a trace gas present in the atmosphere, accounting for around 0.04 %. It plays a crucial role in the Earth's climate system and is considered a greenhouse gas.

• Neon (Ne), Helium (He), Methane (CH_4), and Krypton (Kr) - These gases are present in very small quantities, collectively making up less than 0.02 % of the atmosphere (Fi. 1.5).

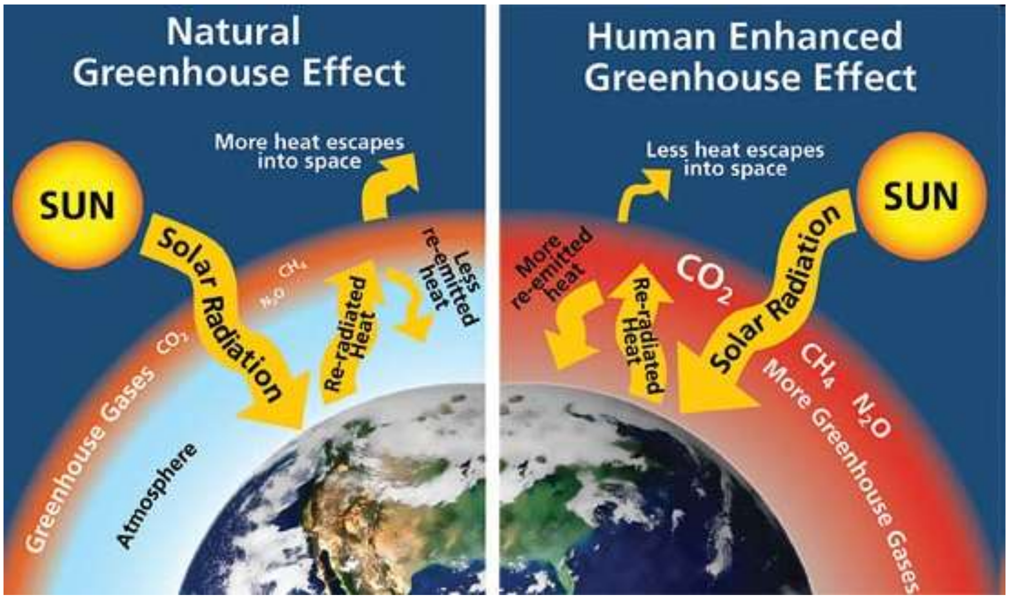

Fig. 1.5. Types of Greenhouse Effects

In addition to these gases, the atmosphere also contains varying amounts of water vapor (H_2O), which is the gaseous form of water. The concentration of water vapor can range from almost 0 % to about 4 % in humid conditions.

The greenhouse effect refers to the process by which certain gases in the Earth's atmosphere trap and re-emit heat, thus warming the planet. It plays a crucial role in maintaining the Earth's temperature at a level suitable for supporting life. Without the greenhouse effect, the Earth would be much colder, making it inhospitable for most forms of life.

The greenhouse effect works as a result of the following processes:

• Solar radiation from the Sun reaches the Earth's atmosphere, including visible light and a range of other wavelengths, such as ultraviolet (UV) and infrared (IR) radiation.

• The Earth's surface absorbs some of the incoming solar radiation, while the atmosphere absorbs a portion of the remaining radiation.

- Certain gases in the atmosphere, known as greenhouse gases, have the property of trapping some of the heat radiated by the Earth's surface. These greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and others.
- The absorbed energy by the Earth's surface is re-emitted as thermal radiation (infrared radiation). Greenhouse gases in the atmosphere absorb a significant portion of this thermal radiation and re-emit it in all directions, including back toward the Earth's surface.
- The re-emitted infrared radiation adds heat to the lower atmosphere, increasing its temperature. This process is similar to the way a greenhouse retains heat, hence the term "greenhouse effect."

Human activities, particularly the burning of fossil fuels (such as coal, oil, and natural gas) and deforestation, have significantly increased the concentration of greenhouse gases in the atmosphere. This increase in greenhouse gases, especially carbon dioxide, has enhanced the greenhouse effect, leading to a phenomenon known as anthropogenic or human-induced global warming. This amplified warming has various consequences, including rising global temperatures, shifts in weather patterns, sea-level rise, and changes in ecosystems. Mitigating and adapting to these impacts is a significant challenge facing humanity today.

The major greenhouse gases are:

- Carbon Dioxide (CO_2): Carbon dioxide is the most prominent greenhouse gas in terms of its overall contribution to global warming. It is primarily released through the burning of fossil fuels such as coal, oil, and natural gas, as well as deforestation and other land-use changes.
- Methane (CH_4): Methane is a potent greenhouse gas with a higher warming potential than carbon dioxide, although it exists in much lower concentrations. It is emitted from various sources, including natural processes such as wetland emissions, as well as human activities such as livestock farming, rice cultivation, landfills, and the extraction and transport of fossil fuels.
- Nitrous Oxide (N_2O): Nitrous oxide is a greenhouse gas that is emitted through natural processes like microbial activity in soils and oceans, as well as human activities such as agricultural and industrial activities, combustion of fossil fuels, and waste management. It has a higher warming potential than carbon dioxide.
- Fluorinated Gases: Fluorinated gases, including hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), are synthetic compounds used in various industrial applications such as refrigeration, air conditioning, and electronics. They are potent greenhouse gases with significantly higher warming potentials than carbon dioxide.

- Water Vapor: Although not directly emitted by human activities, water vapor is an important greenhouse gas. It is the most abundant greenhouse gas in the atmosphere, and its concentration is influenced by temperature changes. While human activities do not directly control water vapor levels, they can indirectly influence it through the emission of other greenhouse gases (Fig. 1.6).

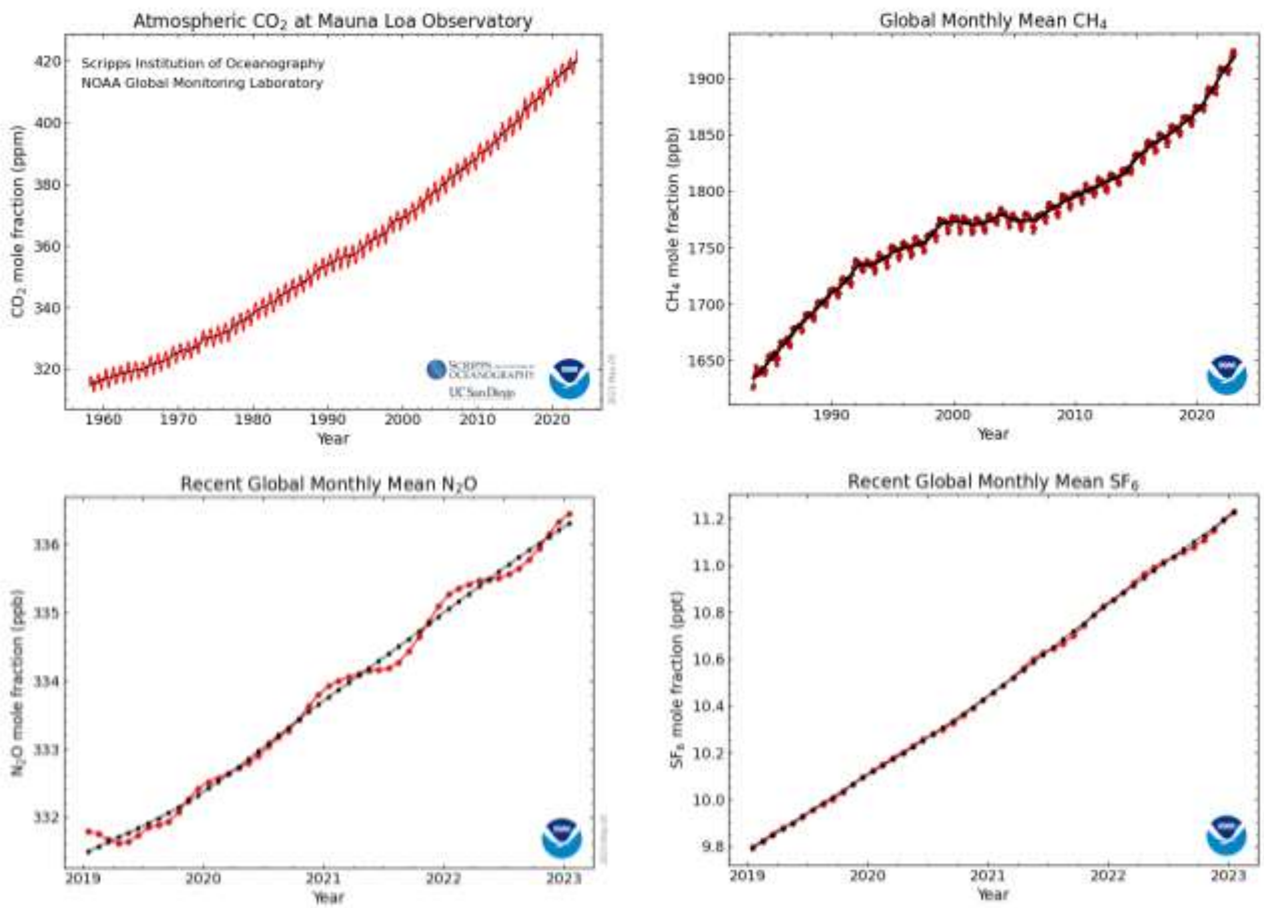

Fig. 1.6. Dynamics of changes in the concentration of main greenhouse gases in the atmosphere

The greenhouse gases concentrations and warming potentials vary, and their impact on the climate system depends on their emissions, atmospheric lifetime, and interactions with other components of the Earth's climate system.

Data that have been published since the 1980s indicate a direct link between increased CO_2 emissions and global climate change. In 1975, the first data were published by Killing and his colleagues (based on information of the Mauna Loa

Observatory and other sources) that show that CO_2 concentrations alone have increased by almost 42 percent since the pre-industrial period.

Studies have shown that the current concentration of atmospheric carbon dioxide is approximately 420 parts per million (ppm); it was 280 ppm in the early 18th century. The increase in CO_2 concentration consequently enhances the greenhouse effect. Data published by Mann and Jones supports this theory. Their data shows that the mean annual temperature increase over the last 200 years coincides with increases in the concentration of atmospheric CO_2.

Since the onset of the industrial era, carbon dioxide emissions have been constantly increasing. If 40-50 years ago emissions were increasing by 10 to 12 Gt per year, currently this figure is in a range of 35-38 Gt. This is largely due to global economic growth and the emergence of new economic powers (e.g., China, India, Brazil, etc.) that consequently, increases demand for resources.

According to climate models, without significant reductions in greenhouse gas emissions, global average temperatures will continue to rise throughout the 21st century. The magnitude of future warming depends on the trajectory of emissions and the effectiveness of mitigation efforts.

1.3. Consequences and future impacts of climate change

Rising temperatures have far-reaching implications. They contribute to changes in precipitation patterns, increased frequency and intensity of extreme weather events, sea-level rise, disruptions to ecosystems and biodiversity, and impacts on human health, agriculture, and water resources.

Climate change influences the frequency, intensity, and duration of extreme weather events such as heatwaves, droughts, heavy rainfall, hurricanes, and wildfires. These events can lead to significant economic and social impacts, including property damage, loss of life, disruptions to agriculture, and threats to infrastructure.

Climate change affects precipitation patterns, leading to changes in rainfall distribution and intensity. Some regions may experience increased rainfall and flooding, while others may face more frequent droughts and water scarcity. These changes can impact agriculture, water resources, ecosystems, and human livelihoods.

As global temperatures rise, glaciers and ice caps melt, contributing to sea-level rise. This poses risks to coastal communities, low-lying areas, and small island nations, leading to increased coastal erosion, saltwater intrusion into freshwater sources, and the potential for more frequent and severe coastal flooding during storms (Fig. 1.7).

Data and Statistics / Facts and Figures:

- Since 1880, global mean sea level has risen by 21–24 cm.
- In 2021, global sea level rise will set a new record of 97 mm, compared to 1993.
- The rate of global sea level rise is accelerating: 1.4 mm per year for most of the 20th century, and 3.6 mm per year in 2006–2015.
- From 1880 to 2012, average global temperature increased by 0.85 °C
- Oceans have warmed, the amounts of snow and ice have diminished and sea level has risen. From 1901 to 2010, the global average sea level rose by 19 cm as oceans expanded. The Arctic's sea ice extent has shrunk in every successive decade since 1979.
- Global emissions of carbon dioxide (CO_2) have increased by almost 50 per cent since 1990.
- Emissions grew more quickly between 2000 and 2010 than in each of the three previous decades.

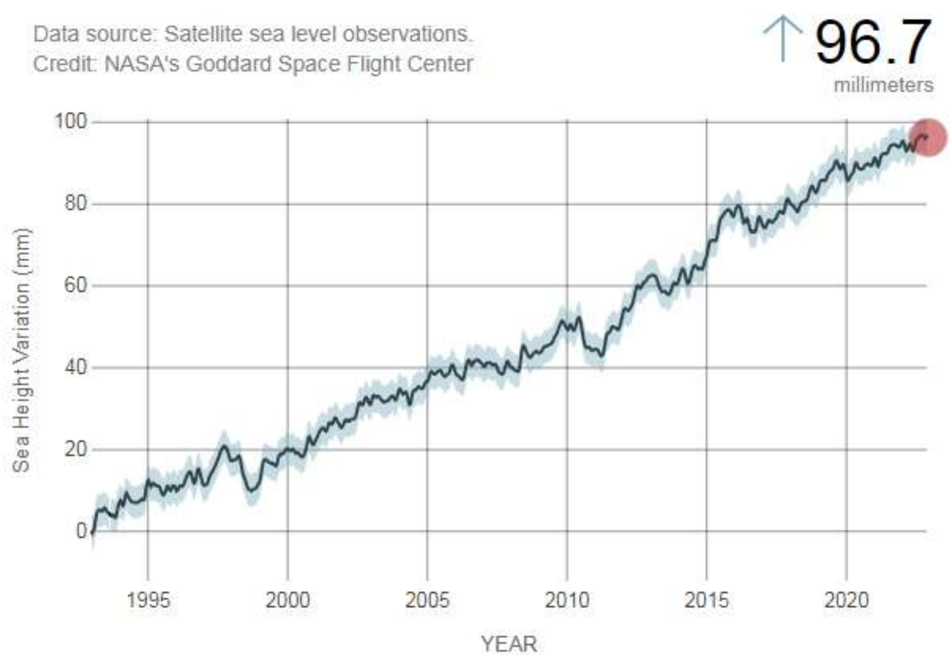

Fig. 1.7. Results of satellite observations of sea level changes

Climate change is increasing the frequency and intensity of extreme weather events such as heat waves, droughts, floods and tropical cyclones, aggravating water management problems, reducing agricultural production and food security, increasing health risks, damaging critical infrastructure and interrupting the provision of basic services such water and sanitation, education, energy and transport.

Targets linked to the environment:

- Target 13.1: Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.

• Target 13.2: Integrate climate change measures into national policies, strategies and planning.

• Target 13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.

• Target 13.a: Implement the commitment undertaken by developed-country parties to the United Nations Framework Convention on Climate Change to a goal of mobilizing jointly $100 billion annually by 2020 from all sources to address the needs of developing countries in the context of meaningful mitigation actions and transparency on implementation and fully operationalize the Green Climate Fund through its capitalization as soon as possible.

• Target 13.b: Promote mechanisms for raising capacity for effective climate change-related planning and management in least developed countries and small island developing States, including focusing on women, youth and local and marginalized communities (Fig. 1.8, 1.9).

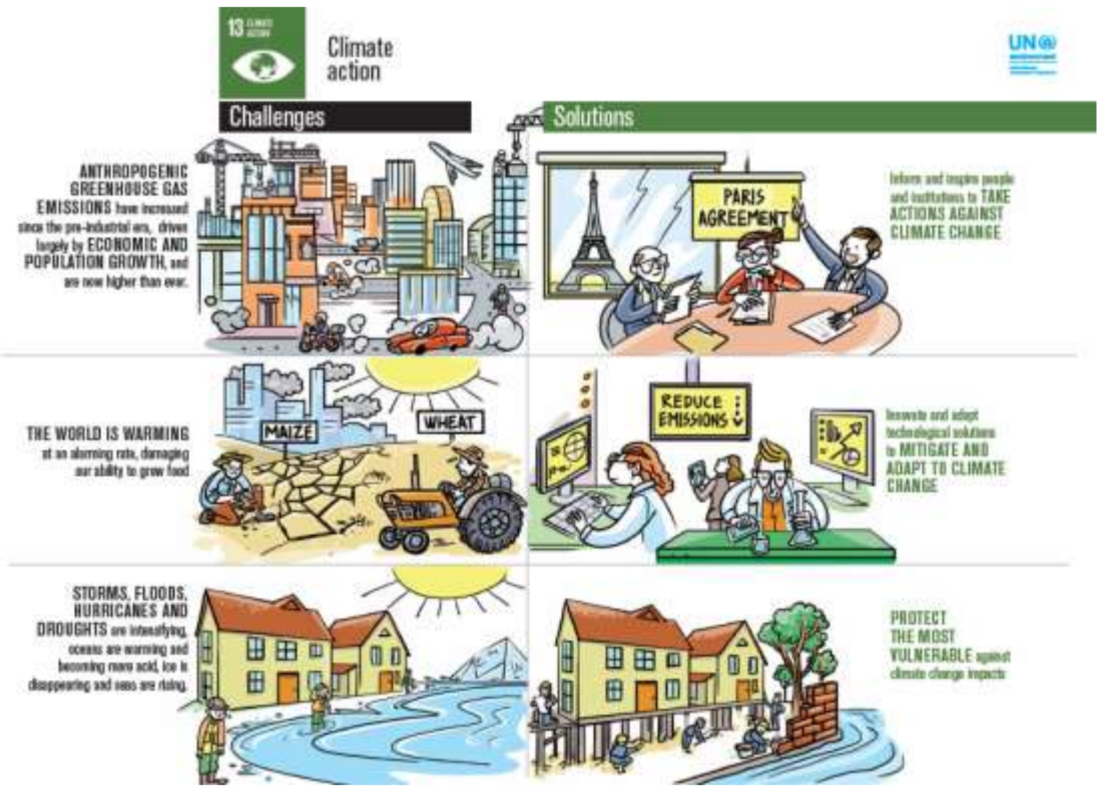

Fig. 1.8. Challenges and solutions in SDG 13 achieving

Climate change affects ecosystems and biodiversity. Species may face challenges in adapting to rapidly changing conditions, leading to shifts in their ranges or even extinction. Ecosystem services, such as pollination, water purification, and carbon storage, can be disrupted, impacting human well-being and ecological balance (Tab. 1.1).

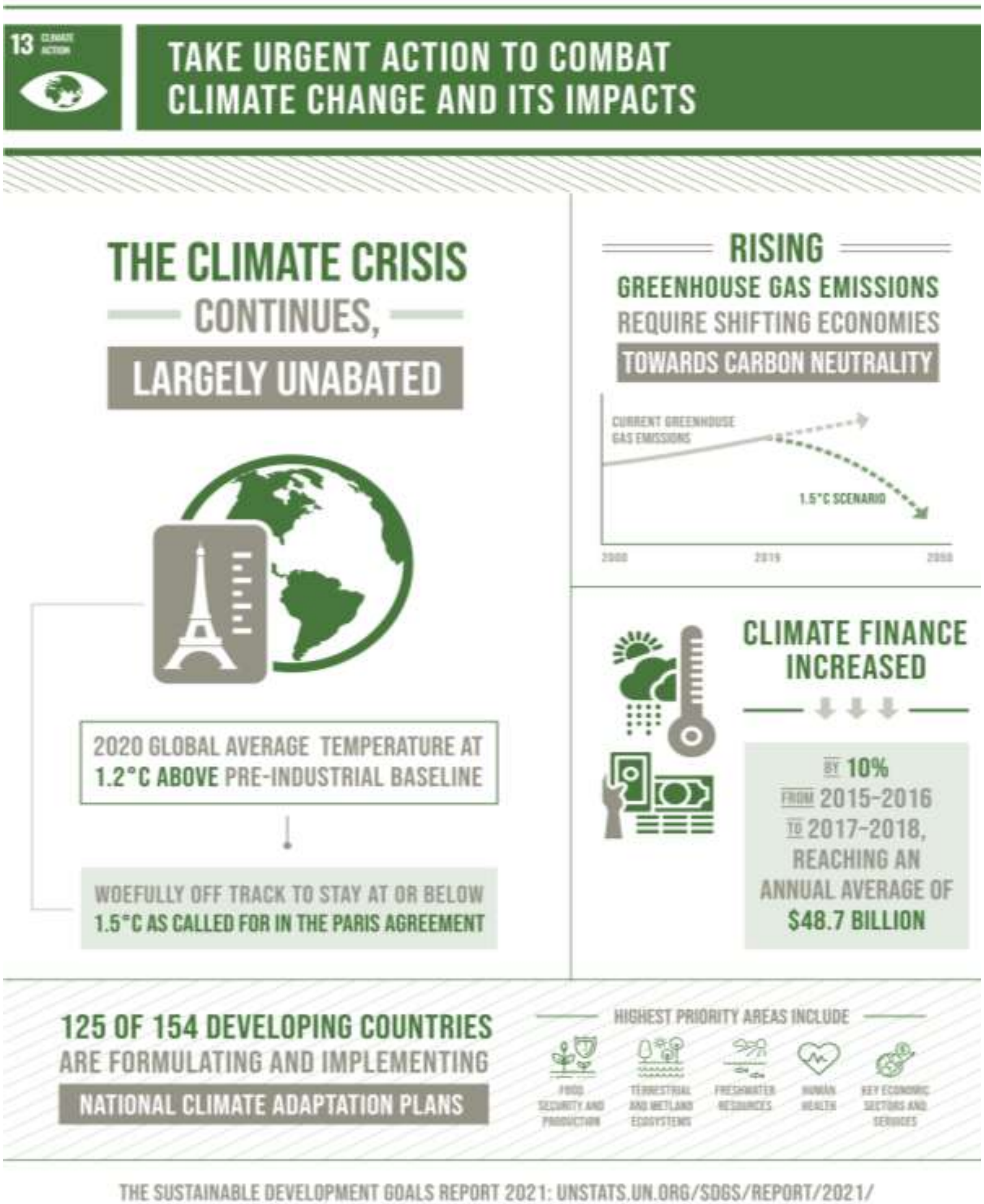

Fig. 1.9. Climate action trends

Table 1.1.

Comparison of climate change impacts with temperatures increases by 1.5 °C and by 2 °C

Climate change impacts on some environmental characteristics	1.5 °C limit	2 °C limit
Sea level rise	48 sm	56 sm
Arctic ice cover	Without ice, once in 100 years	Without ice, once in 100 years
Glacier melting's in the 21st century	76 mm	89 mm
Sea level rise by 2100	0.26 – 0.77 m	0.30 – 0.83 m
Increased number of hot days	16 %	25 %
Average period of drought	2 months	4 months
Population at risk in the coastal zones in case of sea-level rise	271 million	388 million
Increase in heat wave periods	31 – 69 million	32 – 80 million
Probably of -10/+10 % changes by 2100	17 days	35 days
Wheat yields	84 %	73 %
Rice yields	+6 %	+6 %
Species to lose 50 % habitats:		
Plants	8 %	16
Invertebrates	6 %	18 %
Vertebrates	4 %	8 %
Insects	6 %	18 %

1.4. Environmental impacts of climate change in Georgia[2]

The climate change processes have significantly intensified in Georgia, with a wide range of adverse impacts (MEPA, 2020). In particular:

- Between 1986 and 2015, as compared to 1956-1985, average annual air temperatures have increased almost throughout the country within the range of up to 1 °C with average increase of 0.5 °C.
- Between 1986 and 2015, as compared to 1956–1985, annual precipitation has increased in most parts of western Georgia, while it decreased in some areas of eastern Georgia. More specifically, 5 to 15 % increase in precipitation was recorded for a significant part of western Georgia. The upward trend in precipitation in western Georgia seems to be caused by the increase in rainfall.
- In contrast to western Georgia, precipitation has decreased by 5 to 15 % in most parts of eastern Georgia over the last 30 years. In the south and east of the country

[2] *This chapter is an excerpt from the document "2030 Climate Change Strategy of Georgia", 2021*

(especially in Kakheti and Mtskheta-Mtianeti), precipitation indices reflect a decrease in precipitation due to the increase in the duration of the dry periods.

- Relative humidity has increased throughout the country, with fluctuations between (-1 %) – (5 %). High humidity is observed in winter months in western Georgia and should be driven by extremely humid days (10-12 days/year), with decreasing trends most intensely observed in early summer-autumn.
- Average wind speed has decreased throughout the country during all seasons by about 1-2 m/s. It should be noted that observations show the most significant decline in the areas (Mount Sabueti, Poti), which are considered in the Wind Atlas as the most prospective sites for wind energy development. While average wind speed is decreasing, the number of days with strong winds is increasing in some areas, which should be attributed to the increasing frequency of such days over the last 15 years and is most frequently observed in River Mtkvari Valley (Gori, Tbilisi).

The expected adverse effects will amplify even more in the future. Without the development of climate-resilient practices, climate change mitigation measures, and the improvement of the country's preparedness and capabilities, the most climate-sensitive sectors will become more vulnerable, and other negative impacts of climate change will also increase, in particular:

- Increase of the frequency and intensity of extreme hydrometeorological events in the context of climate change, a trend already observed in Georgia;
- Increase of the scales and frequencies of landslide/gravity and mudflow processes, a trend already observed in Georgia;
- Intensive melting of glaciers, a trend already observed in Georgia;
- Accelerated processes of flooding and loss of coastal areas due to anthropogenic impacts. Sea level rise – the major adverse effect of global warming for coastal areas – makes Georgia's coastline particularly vulnerable;
- Soil erosion, one of the main causes of degradation of agricultural, forest and alpine lands.
- Temperature rise affects livestock farming and its productivity, as well as perennial and grain crops and biodiversity;
- Rising temperatures are contributing to the reduction of water resources, a trend already observed in Georgia;
- The adverse climate impact on forests is evident in terms of both the progression of existing pests and diseases, as well as the emergence of new harmful insects and diseases.

1.5. The international aspects of climate control activities

The international aspects of climate control activities involve the cooperation and coordination between countries to address the challenges of climate change on a global scale. Recognizing that climate change is a transboundary issue that requires collective action, countries have come together to develop frameworks, agreements, and institutions to mitigate greenhouse gas emissions, adapt to the impacts of climate change, and support sustainable development. Here are some key international aspects of climate control activities.

United Nations Framework Convention on Climate Change (UNFCCC).

The UNFCCC, established in 1992, is a global treaty that provides the overarching framework for international cooperation on climate change. It aims to stabilize greenhouse gas concentrations in the atmosphere and prevent dangerous human interference with the climate system. The treaty sets the stage for subsequent negotiations and agreements, including the Paris Agreement.

In 1992, the United Nations adopted the UN Framework Convention on Climate Change (UNFCCC), which aimed to stabilize GHG concentrations in the atmosphere. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change.

The UNFCCC has been signed and ratified by 196 countries and 1 regional organization. The UNFCCC is a framework convention that creates an overall regime for addressing climate change. Specific and legally binding targets are outlined in other complementary treaties – the 1997 Kyoto Protocol (entered into force in 2005) and the 2015 Paris Agreement (entered into force in 2016).

The UNFCCC requires Parties to the Convention, including Georgia, to collect information and report on the following gases:

- Carbon dioxide (CO_2);
- Methane (CH_4);
- Nitrous oxide (N_2O);
- Hydrofluorocarbons (HFC);
- Perfluorocarbon (PFC);
- Sulfur hexafluoride (SF_6).

The Convention is built on principles of equity and “common but differentiated responsibility”.

This means that the Convention offers different GHG emission regimes for individual countries. For example, it imposes a heavier burden on developed countries; they have to play a leading role in climate change action and reduce emissions to a greater extent than developing countries. These are referred to as ‘Annex I countries’ and include all developed countries as well as the Russian Federation, Turkey, the Czech Republic, Belarus and Ukraine.

The Kyoto Protocol required 37 industrialized countries and the European Union to reduce GHG emissions on an average 5 % below 1990 levels in the 2008-2012 period, whereas developing nations (including Georgia), that are part of ‘Annex II countries', were given the choice to comply voluntarily and to gradually prepare for reducing their emissions (Fig. 1.10).

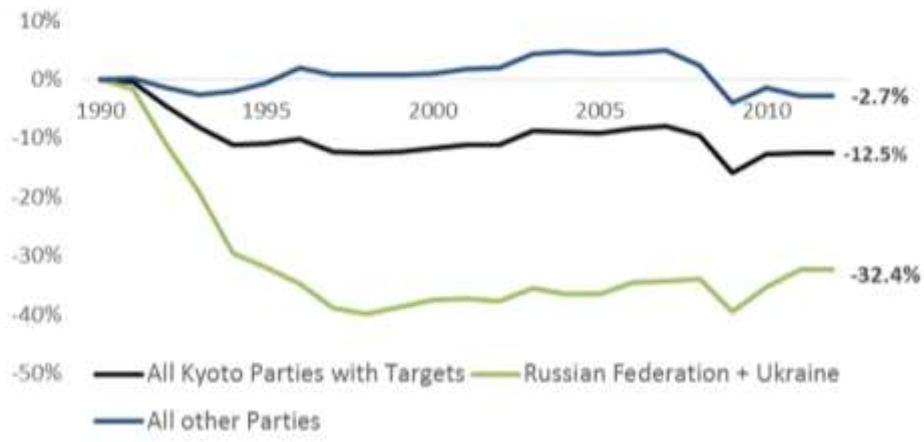

Fig. 1.10. Kyoto Protocol emissions, 1990-2012

Per the Protocol's requirements, developed countries were to cut greenhouse gas emissions by an average of 18 % by 2013-2020 compared with 1990 levels.

Joint implementation, defined by Article 17 of the Protocol, allowed developed countries who are unable to meet their targets to purchase emission credits from developing countries. This effectively allowed developed countries to buy their way around their commitments (Fig. 1.11).

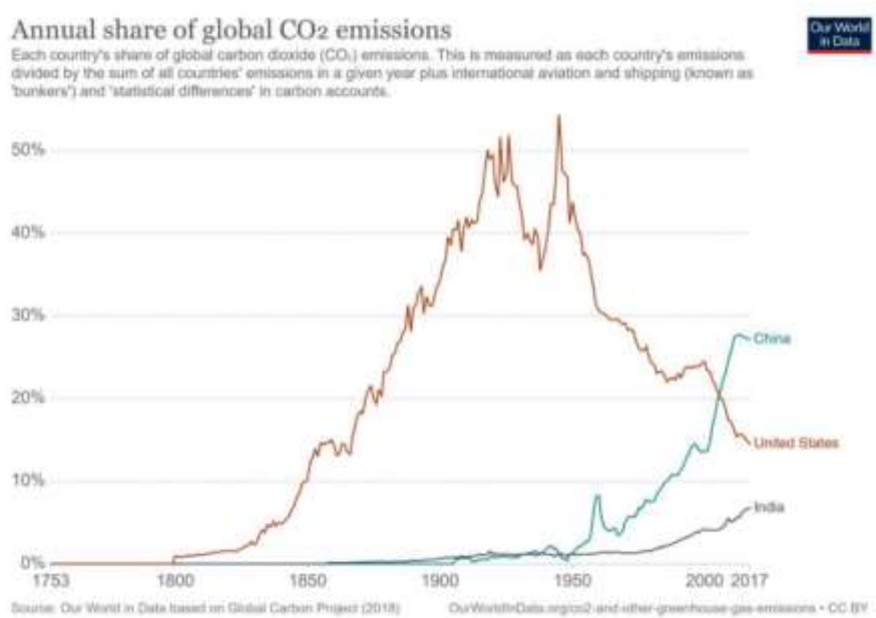

Fig. 1.11. Annual share of global CO_2 emissions

The initial idea was to direct finance toward the most cost-effective projects, while maintaining climate benefits. A 2015 report revealed that around 80 % of the projects under the Kyoto Protocol's emissions trading system were of low environmental quality. The joint implementation system actually increased emissions by roughly 600 million metric tons. Russian and Ukrainian companies were the main profiteers, having issued 90 % of the credits.

The Kyoto Protocol's deadline is 2020, so by definition it is not meant to be a long-term solution. The developed countries reduced their emissions by 20 % overall thanks to this agreement, which is both commendable, but insufficient.

How then to assess its effectiveness? Had it been a resounding success, fully achieving its potential, it would have curbed the US, China's and India's emissions by 20 %, along with other committed nations. Further, it only applied to industrialised countries, meaning it could not limit the growth of those in development which together, account for 75 % of global emissions (Fig. 1.12).

Fig. 1.12. The evolution of climate initiatives

Paris Agreement. The Paris Agreement, adopted in 2015 under the UNFCCC, is a landmark international agreement that aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5 degrees Celsius. It establishes a framework for countries to set their own nationally determined contributions (NDCs) to reduce greenhouse gas emissions, enhance climate resilience, and provide financial and technological support to developing countries. The agreement has been ratified by the majority of countries and represents a significant step in global climate cooperation.

Climatologists warn that countries' late 1990s-era commitments to GHG reduction as well as measures taken so far are not enough to prevent further increases in temperature. If countries are to continue with current trends of GHG emissions by 2100, the global average temperature might rise by 4.1 °C to 4.8 °C8. This would lead to irreversible changes in weather system, intensify glacier and ice sheet melting, increase extreme weather events, accelerate other negative climate change impacts.

It was increased call to prevent climate crisis that led to years long negotiations to draft a new course of action to combat climate change. In 2015 these efforts yielded result and international community came together to hammer out an agreement known as the Paris Agreement with a stricter set of targets. The Paris Agreement sets the target to limit global temperature rise to 2 °C and intends to pursue efforts to limit this increase to 1.5 °C. If target is achieved, the risks and impacts of climate change will be significantly reduced.

Reaching the target values of 2 °C and 1.5 °C would significantly reduce the risks and impacts of climate change compared to taking no action. As of January 2021, the Paris Agreement was signed by 197 Parties and ratified by 191 countries.

Other key commitments in the Paris Agreement include:

- Identifying Nationally Determined Contributions (NDC) to combat climate change;
- Developing and implementing long-term low-emission development strategies (LT-LEDS); and
- Creating a global carbon market system to move countries to a low-emission economy.

Climate change represents an urgent and potentially irreversible threat to human societies and the planet. In recognition of this, the overwhelming majority of countries around the world adopted the Paris Agreement in December 2015, the central aim of which includes pursuing efforts to limit global temperature rise to 1.5 °C. In doing so, these countries, through the United Nations Framework Convention on Climate Change (UNFCCC), also invited the IPCC to provide a Special Report on the impacts of global warming of 1.5 °C above preindustrial levels and related global greenhouse gas emissions pathways (Fig. 1.13).

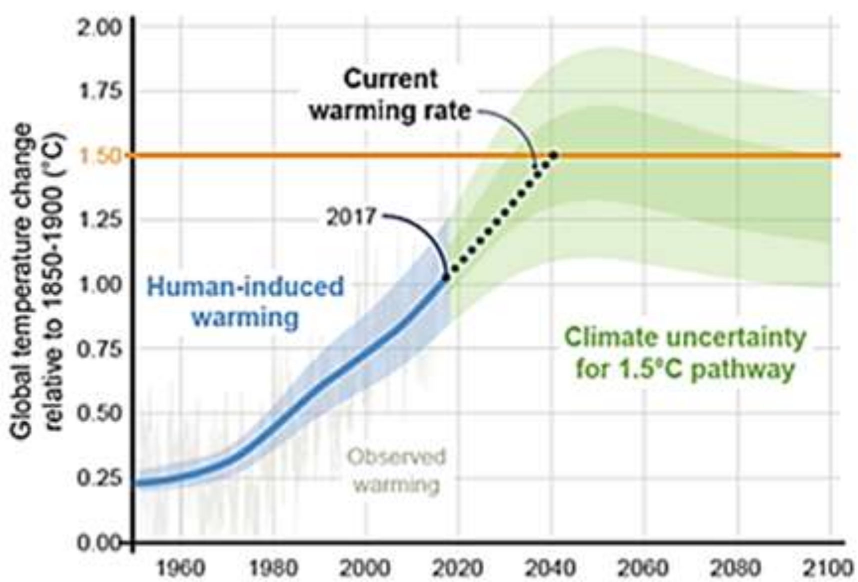

Fig. 1.13. Global temperature changes relative to 1850-1900 (ºC)

The IPCC study presents preliminary estimates of when a 1.5-fold increase in global temperatures is expected to be reached compared to pre-industrial times. If the world continues as usual in terms of greenhouse gas emissions, then a 1.5-fold increase will be observed in 2040.

Based on current forecasts, the annual average temperature is expected to increase by 2 to 5-6 °C by the end of the century, depending on whether emissions increase or decrease. If the CO_2 emissions stay the same, the worst scenario of events would be expected over the next 100 years, involving an increase of 3 to 5 °C in the annual average temperature. A decrease in emissions could limit the projected annual average temperature rise to approximately 1.5 °C. This scenario is enshrined in the Paris Agreement, which calls on UNFCCC Parties to reduce their GHG emissions (Fig. 1.14).

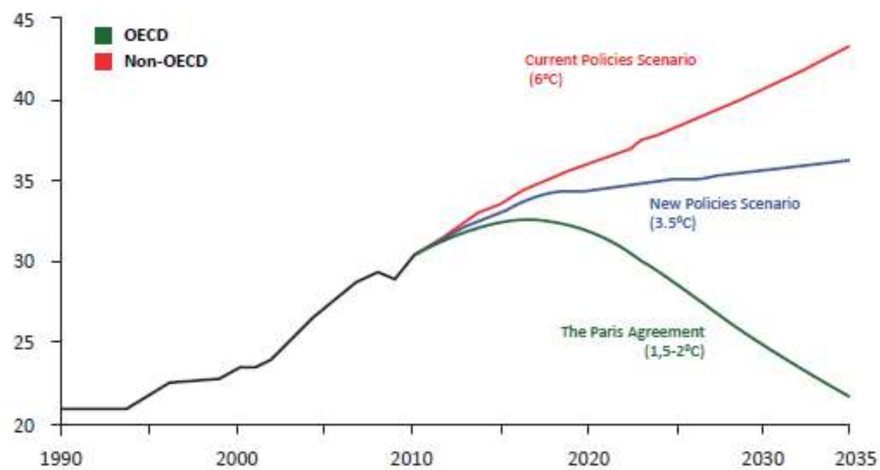

Fig. 1.14. Future Temperature Changes based on Projected Greenhouse Gas Emissions

The scenarios of annual average temperature increase depend on CO_2 emission rates: the current policy scenario leads (red line) to the worst outcomes, pushing up annual average temperature by 5-6 °C. The blue and green lines reflect new policy scenarios that involve measures to reduce CO_2 emissions, limiting the annual average temperature increase to 1.5 to 2 °C (Fig. 1.15).

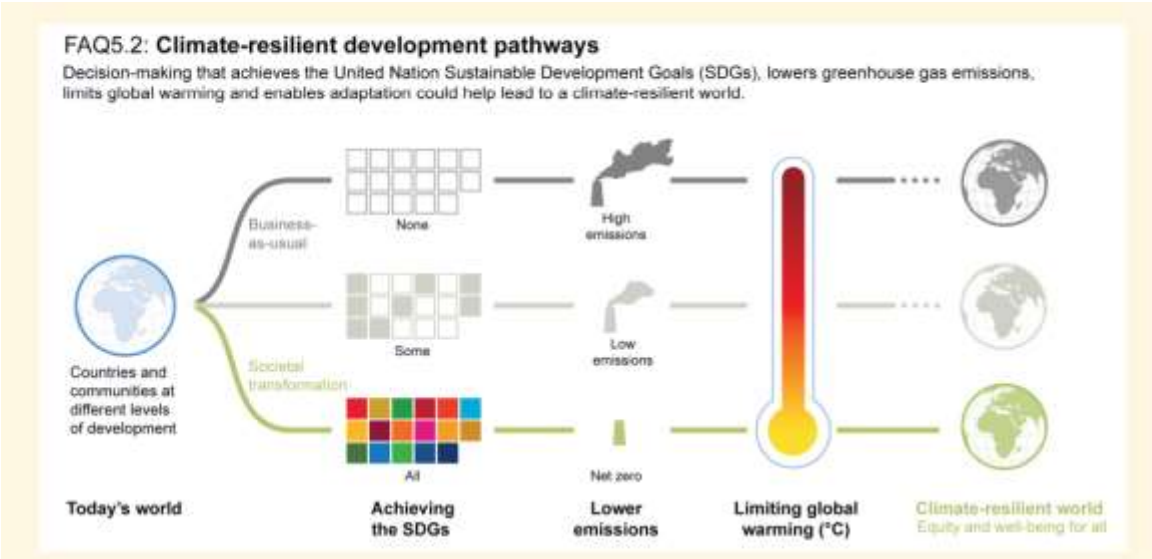

Fig. 1.15. Climate-resilient developments pathways

International aspects of climate control activities are essential to promote cooperation, promote equity and ensure coherence of global efforts to effectively tackle climate change. Continued international cooperation, enhanced ambition and effective implementation of climate policies are critical to achieving a sustainable and resilient future for all.

Nationally Determined Contributions (NDCs). Under the Paris Agreement, each participating country is required to submit its NDC, which outlines its self-determined goals and actions to address climate change. NDCs include emission reduction targets, adaptation plans, and strategies for sustainable development. Regular updates and revisions of NDCs are expected to reflect increasing ambition over time.

International Climate Funds. Various international climate funds have been established to support developing countries in their climate change mitigation and adaptation efforts. For example, the Green Climate Fund (GCF) provides financial resources to developing countries to assist with their climate projects and programs. Other funds include the Adaptation Fund, Global Environment Facility (GEF), and several bilateral and multilateral funds aimed at assisting vulnerable countries in their climate action.

Technology Transfer and Capacity Building. International cooperation involves the sharing of technological innovations, knowledge, and best practices among countries to accelerate climate action. Developed countries often support developing countries in technology transfer, capacity building, and access to climate finance, enabling them to implement mitigation and adaptation measures effectively.

Conferences of the Parties (COP). The COP is the supreme decision-making body of the UNFCCC. It convenes annually, bringing together representatives from member countries to assess progress, negotiate agreements, and make decisions on climate-related issues. The COP meetings provide a platform for countries to engage in negotiations, share experiences, and collaborate on addressing climate challenges.

1.6. Measures against climate change

Climate change response requires a comprehensive approach that mitigates the root causes of climate change (i.e. reduction of GHG emissions) and prevents or reduces its negative impacts. These two approaches are known as climate change mitigation and adaptation.

Climate change adaptation refers to the process of adjusting and preparing for the impacts of climate change in order to reduce vulnerability and increase resilience. It involves taking proactive measures to anticipate, cope with, and recover from the adverse effects of climate change on natural systems, human societies, and economies (Fig. 1.16).

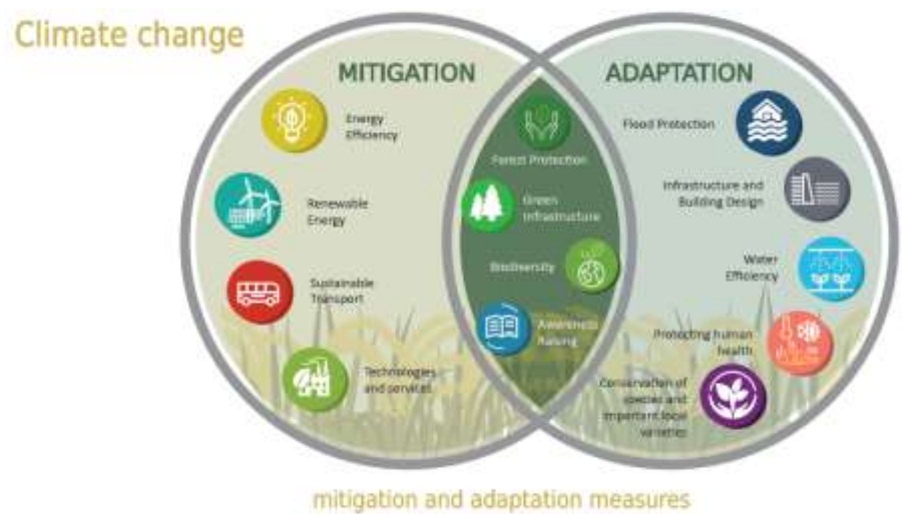

Fig. 1.16. Climate change mitigation and adaptation measures

Adaptation recognizes that some level of climate change is already occurring and is expected to continue in the future, even with mitigation efforts to reduce greenhouse gas emissions. It focuses on managing the risks and impacts associated with climate change, particularly in areas where it is not feasible to prevent or completely eliminate those impacts.

Several main aspects can be distinguished from climate change adaptation measures:

- Understanding Climate Risks - Assessing current and future climate risks specific to a region or sector is crucial. This involves understanding local climate patterns, projections, and the potential impacts on various systems, such as water resources, agriculture, infrastructure, ecosystems, and human health.

- Building Resilience - Developing strategies and actions to enhance resilience in the face of climate change impacts. This includes implementing measures that reduce vulnerability, strengthen adaptive capacity, and improve the ability to recover from extreme events.
- Infrastructure and Land Use Planning – Incorporating climate change considerations into infrastructure design, land use planning, and development policies. This includes designing buildings and infrastructure to withstand changing climate conditions, protecting critical infrastructure from sea-level rise or extreme weather events, and managing land use to avoid exposure to climate risks.
- Water Management- Adapting water resource management practices to changing precipitation patterns and increased water stress. This may involve improving water efficiency, enhancing water storage and conservation measures, and developing drought and flood management strategies.
- Agricultural Adaptation – Implementing climate-smart agriculture practices to enhance food security and resilience in the face of changing climate conditions. This may involve diversifying crops, improving water management, adopting sustainable farming techniques, and utilizing climate information for better decision-making.
- Ecosystem-Based Adaptation – Protecting and restoring natural ecosystems to enhance their ability to withstand climate change impacts. Preserving forests, wetlands, and coastal areas can help mitigate the impacts of flooding, erosion, and provide other ecosystem services that support human well-being.
- Health and Social Adaptation – Considering the impacts of climate change on human health, vulnerable populations, and social systems. This may involve developing public health strategies, improving disaster response capabilities, and addressing social inequalities exacerbated by climate change.
- Knowledge and Information Sharing – Promoting research, monitoring, and data collection to improve understanding of climate change impacts and adaptation strategies. Sharing knowledge, best practices, and experiences among stakeholders, including governments, communities, and organizations, can facilitate effective adaptation efforts.

Climate change adaptation is an ongoing process that requires collaboration and coordination among various stakeholders, including governments, communities, businesses, and non-governmental organizations. By proactively adapting to the changing climate, societies can minimize the adverse impacts, protect vulnerable populations, and build a more resilient future.

Mitigating climate change impacts requires collective efforts at both individual and societal levels. The following key measures are being considered in reducing greenhouse gas emissions and minimizing the impact of climate change:

- Transition to Renewable Energy – Shift from fossil fuel-based energy sources to renewable energy such as solar, wind, hydro, and geothermal power. Promote the development and adoption of clean energy technologies to reduce greenhouse gas emissions from electricity generation and transportation.
- Energy Efficiency - Improve energy efficiency in buildings, transportation, and industrial processes. This can be achieved through energy-efficient appliances, insulation, efficient transportation systems, and industrial practices that minimize energy waste.
- Sustainable Transportation – Encourage the use of public transportation, cycling, and walking. Promote the adoption of electric vehicles and develop infrastructure to support their charging. Reduce reliance on fossil fuel-powered vehicles and promote the use of low-carbon fuels.
- Forest Conservation and Reforestation – Protect and restore forests, as they act as carbon sinks by absorbing and storing carbon dioxide. Implement sustainable land management practices, reduce deforestation, and support reforestation efforts to enhance carbon sequestration.
- Sustainable Agriculture – Promote sustainable farming practices that reduce greenhouse gas emissions, such as organic farming, agroforestry, and precision agriculture. Minimize the use of synthetic fertilizers and promote sustainable livestock management.
- Waste Management – Implement effective waste management systems that prioritize recycling, composting, and waste-to-energy technologies. Reduce the generation of waste and promote circular economy principles to minimize greenhouse gas emissions from landfills.
- Green Building Practices – Encourage the construction of energy-efficient and environmentally friendly buildings. Promote the use of renewable materials, efficient insulation, energy-saving technologies, and sustainable design principles.
- Education and Awareness – Increase public awareness about climate change and its impacts. Promote education and communication campaigns to encourage sustainable behaviors, energy conservation, and responsible consumption.
- International Cooperation – Encourage global cooperation and collaboration to address climate change. Support international agreements and initiatives that aim to reduce greenhouse gas emissions, promote clean technologies, and provide financial assistance to developing countries for climate adaptation and mitigation.
- Policy and Regulation – Implement effective policies, regulations, and incentives to drive the transition to a low-carbon economy. Set emission reduction targets, establish carbon pricing mechanisms, and provide incentives for renewable energy adoption and energy efficiency improvements.

It's important to note that individual actions, along with collective efforts from governments, businesses, and communities, are necessary to effectively mitigate climate change impacts. By taking proactive measures to reduce greenhouse gas emissions and promote sustainable practices, we can help mitigate climate change and build a more resilient and sustainable future.

1.7. National legislative framework of Georgia in the field of climate change prevention, adaptation and mitigation of its consequences[3]

In April 2021, the Government of Georgia approved the updated Nationally Determined Contribution (NDC) and the 2030 Climate Strategy and Action Plan 2021-2023 (CSAP) as the NDC implementation tool.

Georgia plans to fulfill the contribution determined at the national level in the next decade. In particular, in the period from January 1, 2021 to December 31, 2030.

Long-term vision of the Climate Strategy and Action Plan involves reducing the total GHG emissions to 35 % below 1990 levels by 2030 for all the key sectors of the economy relevant to climate change mitigation.

In terms of mitigation, the updated NDC has increased its unconditional (35 %) and conditional (50-57 %) targets for reducing greenhouse gas emissions by 2030 compared to 1990; And in terms of adaptation, it commits to improving its adaptive capacity to climate change by mobilizing domestic and international resources for sectors that are particularly vulnerable to climate change.

In addition, the NDC includes sectoral mitigation targets, as well as provisions related to gender and climate change, to strengthen the role of women as agents of change through their participation in decision-making processes. It also plans to encourage gender analysis, capacity building and knowledge sharing in climate change related projects.

The purpose of the contribution determined at the national level of Georgia is to promote sustainable and balanced development of the country, within which climate, environmental and socio-economic challenges are considered equally. The contribution determined at the national level of Georgia is as follows:

- Georgia undertakes an unconditional commitment to reduce its national greenhouse gas emissions to 35 % below the 1990 level by 2030. This target does not include emissions from land-use, land-use change and forestry (LULUCF). This would imply that total national emissions, excluding LULUCF, should be limited to no more than 29.25 $MtCO_{2e}$ in 2030.

[3] *This chapter is compiled based on the document – Georgia's 2030 Climate Change Strategy, 2021*

•Georgia undertakes a conditional commitment to reduce its total national greenhouse gas emissions by 50-57 % compared to the 1990 level by 2030. In the case, if the world follows the scenario of limiting the average global temperature increase to 2 °C or 1.5 °C, respectively, with international support (Fig. 1.17).

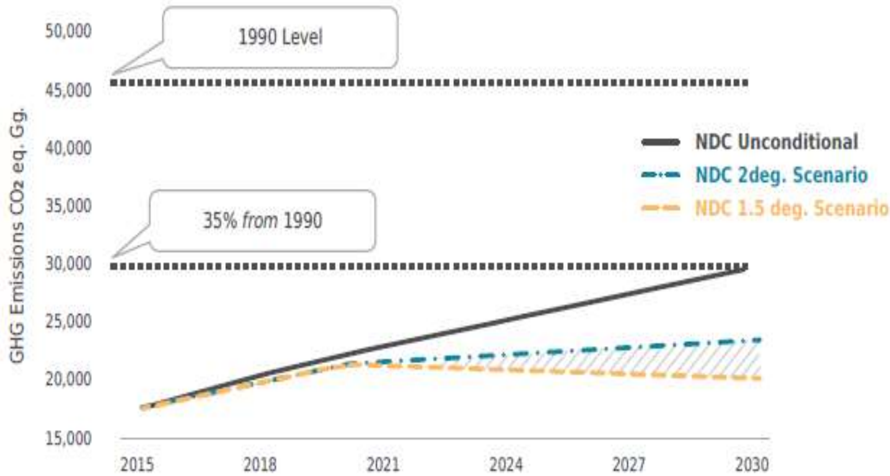

Fig. 1.17. Target indicators of the updated document of defined contribution 2021

According to 2015 data, the GHG emissions in Georgia amounted to 17.6 $MtCO_2e$. GHG emissions are generated in seven sectors: energy generation and transmission, transport, buildings, industry, agriculture, waste management, and the forest. Therefore, the Climate Strategy and Action Plan are divided in accordance with these sectors. This division slightly differs from the categorization of emission sources identified by the National Greenhouse Gas Inventory, which puts all energy-related emissions in one group. Under the Climate Strategy and Action Plan, the energy sector is divided into several key subcategories, as most of the Climate Action Plan measures are aimed at rational energy use and, consequently, the structure is formulated according to the energy production and consumption sectors.

Energy generation and transmission: GOAL 1 – Reduce greenhouse gas emissions in the energy generation and transmission sector to 15% below the reference scenario projections by 2030

Objectives:

1.1. Support renewable energy (wind, solar, hydro, biomass) generation

1.2. Improve average efficiency of thermal power plants

1.3. Strengthen the capac:ities of renewable energy integration in the transmission network of Georgia

1.4. Develop new policy documents and legislation for the energy sector

Other priority directions for the future:

- Further promotion of renewable energy (Hydro, Solar, Wind);
- Feasibility study for a biogas power station (Fig. 1.18, 1.19).

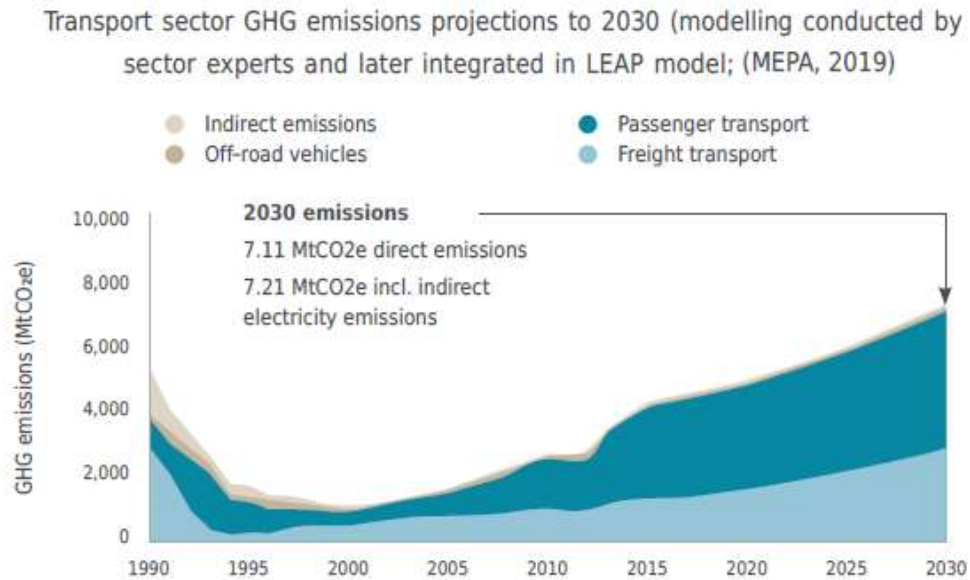

Fig. 1.18. 2030 GHG emission trajectory

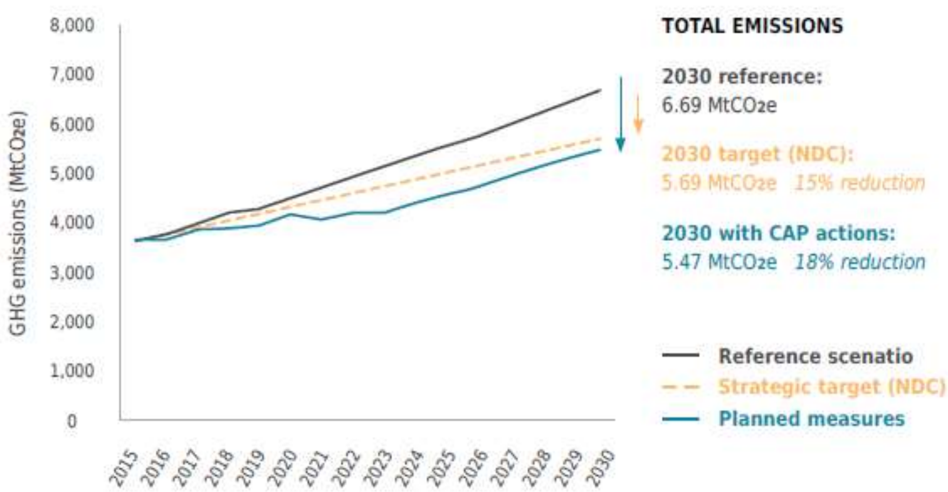

Fig. 1.19. Energy generation and transmission sector GHG emission reduction to 2030 under different scenarios

Energy consumption in transport: GOAL 2 – Reduce greenhouse gas emissions in the transport sector to 15 % below the reference scenario projections by 2030.

Objective:

2.1. Increase the share of low- and zero-emission and roadworthy private vehicles in the vehicle fleet

2.2. Encourage the reduced demand on fossil fuel and the use of biofuels
2.3. Promote non-motorized means of mobility and public transport
2.4. Implement innovative, evidence-based initiatives in the transport sector.

Other priority directions for the future:

- Replacing urban passenger transport with public and non-motorised transport;
- Replacing inter-city passenger transport with public trans;
- Improving energy efficiency of private light-duty vehicles;
- Shifting freight from road to rail tran (Fig. 1.20, 1.21).

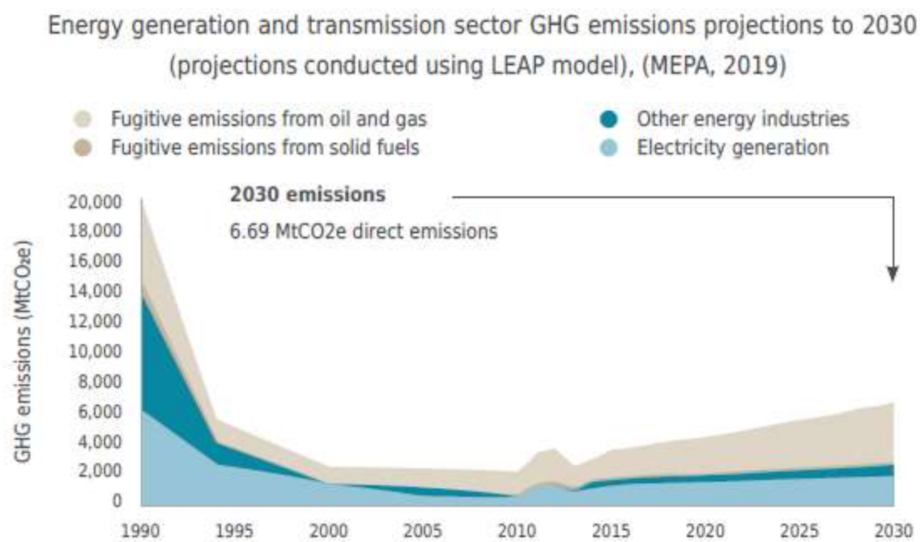

Fig 1.20. Energy generation and transmission sector GHG emission projects to 2030

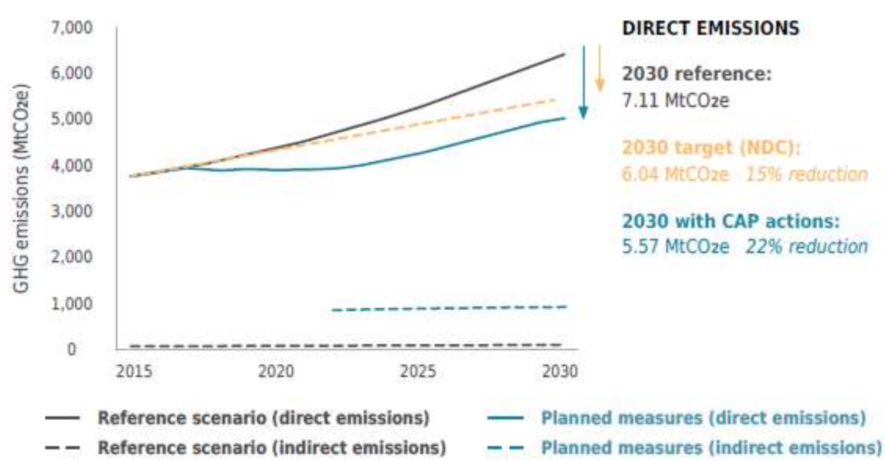

Fig. 1.21. Transport sector emission reduction to 2030 under different scenarios

Energy consumption in buildings: GOAL 3 – support development of low-carbon approaches in the buildings sector by promoting climate-smart and energy-efficient technologies and services.

Objective:

3.1. Develop a system for energy efficiency certification of buildings;

3.2. Raising consumer awareness about energy efficiency;

3.3. Encourage energy-efficient approaches and installation of energy-efficient lighting in residential, commercial and public buildings;

3.4. Support use of solar energy for water heating and use of energy-efficient stoves;

3.5. Train high professional standard personnel in energy efficiency.

Other priority directions for the future:

- Creating information system for energy efficiency of buildings;
- Improving energy efficiency of residential buildings;
- Heating supply in residential buildings;
- Updating climate-specific standards of construction;
- Introduction of energy-efficient approaches in the tourism sector (Fig. 1.22, 1.23).

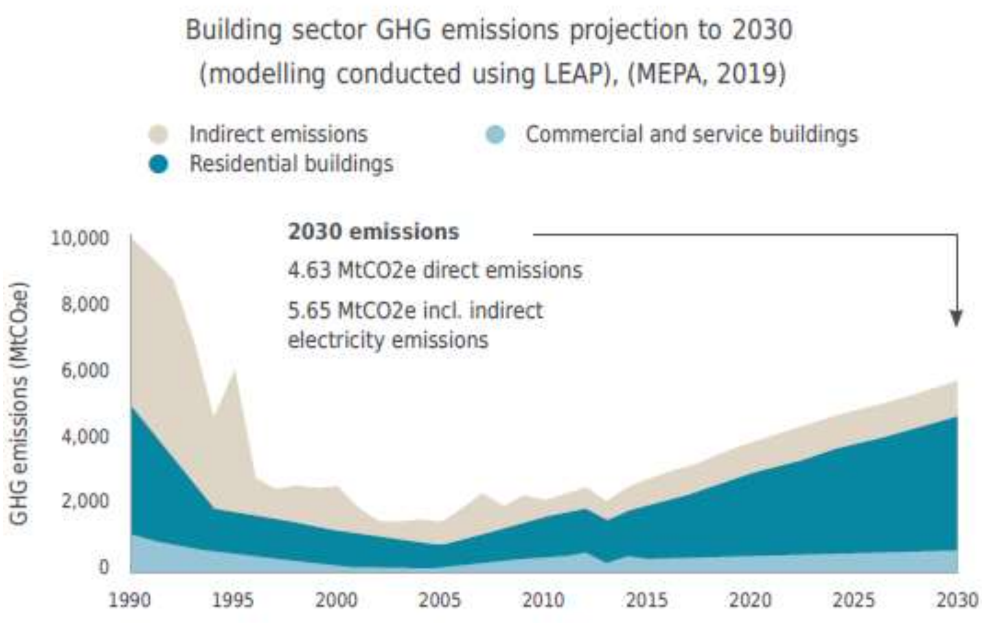

Fig. 1.22. Building sector GHG emission projection to 2030

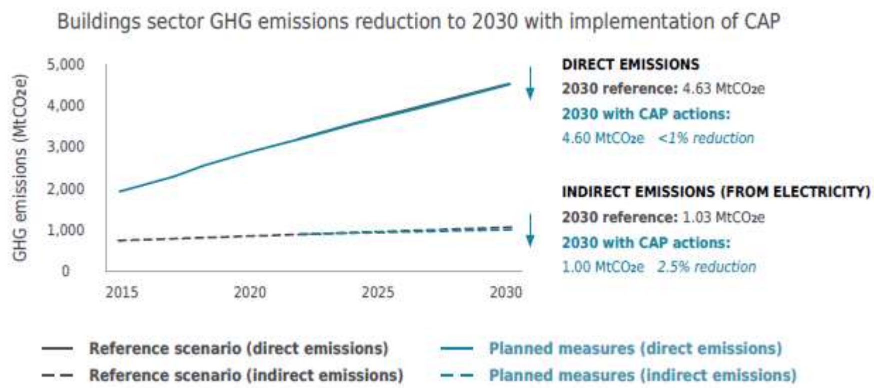

Fig. 1.23. Buildings sector GHG emissions reduction to 2030 with implementation of CAP

Energy consumption in industry and industrial processes: GOAL 4 – support development of the low-carbon approaches in the industry sector by promoting climate-smart and energy-efficient technologies and services to reduce greenhouse gas emissions to 5 % below the reference scenario projections by 2030.

Objectives:

4.1. Reduce the level of greenhouse gas emissions from industrial processes and from energy consumption of industrial facilities by introducing modern technologies;

4.2. Develop a system for studying the emission factors in the industry sector and for data management.

Other priority directions for the future:

- actions related to reducing emissions from steel production or supporting measures for the introduction of energy audits and certification schemes.
- shifting cement manufacturing industry towards the efficient use of waste (for heat production) (Fig. 1.24, 1.25).

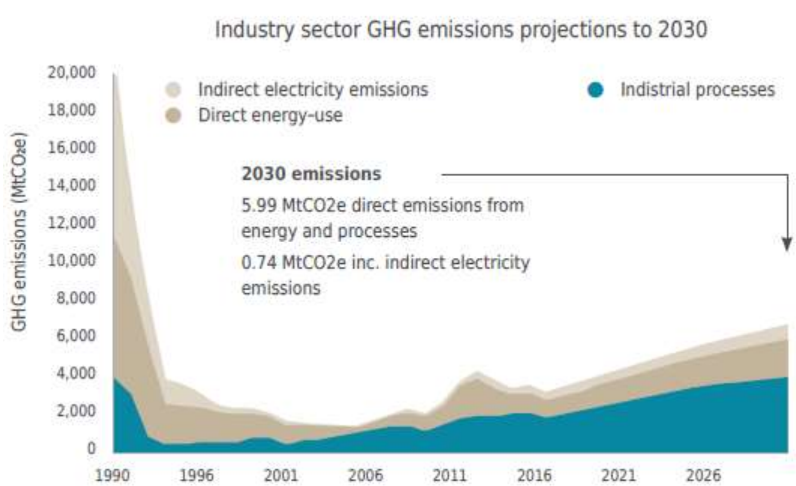

Fig. 1.24. 2030 GHG emission trajectory for industry

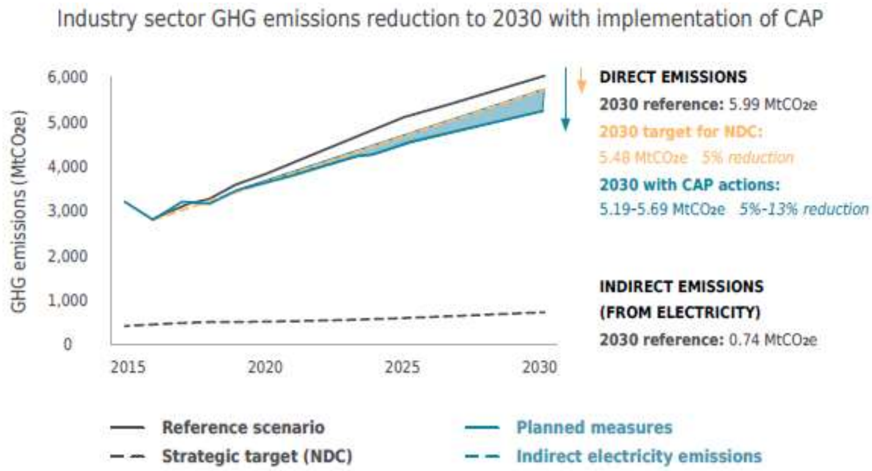

Fig. 1.25. Industry sector GHG emissions reduction to 2030 with implementation of CAP

Agriculture: GOAL 5 – support the low carbon development of the agriculture sector by encouraging the climate-smart and energy-efficient technologies and services.

Objectives:

5.1. Implement sustainable management of soil and pastures and support the introduction of sustainable domestic animal feeding practices;

5.2. Build capacities of generating scientific evidence for development of climate-smart approaches in the agriculture sector.

Other priority directions for the future:

- Improved data collection system;
- Regulating the burning practices and replanting the windbreaks;
- Regulating the irrigation practices;
- Regulating the overgrazing and the unsustainable use of soils;
- Agroforestry direction (Fig. 1.26, 1.27).

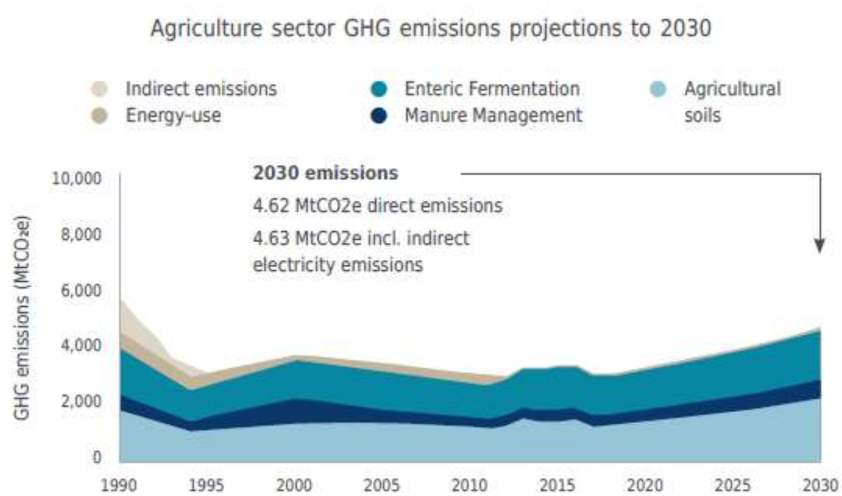

Fig. 1.26. 2030 GHG emission trajectory for agriculture

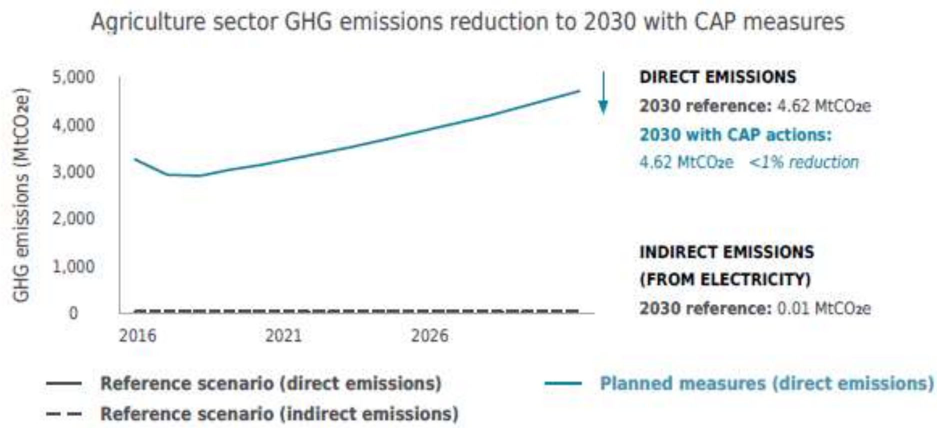

Fig. 1.27. Agriculture sector GHG emission reduction to 2030 with CAP measures

Waste management: GOAL 6 – support the low carbon development of the waste sector by promoting climate-smart and energy-efficient technologies and services.

Objectives:

6.1. Reduce GHG emissions from existing unauthorized dumpsites and non-hazardous landfills;

6.2. Support waste recycling;

6.3. Reduce greenhouse gas emissions from wastewater;

6.4. Develop a data-based waste management system.

Other priority directions for the future:

- Improved data collection system;
- Biodegradable waste management;
- Establishing Maximum Permissible Limits (MPL);
- Moving towards reducing and recycling (Fig. 128, 1.29).

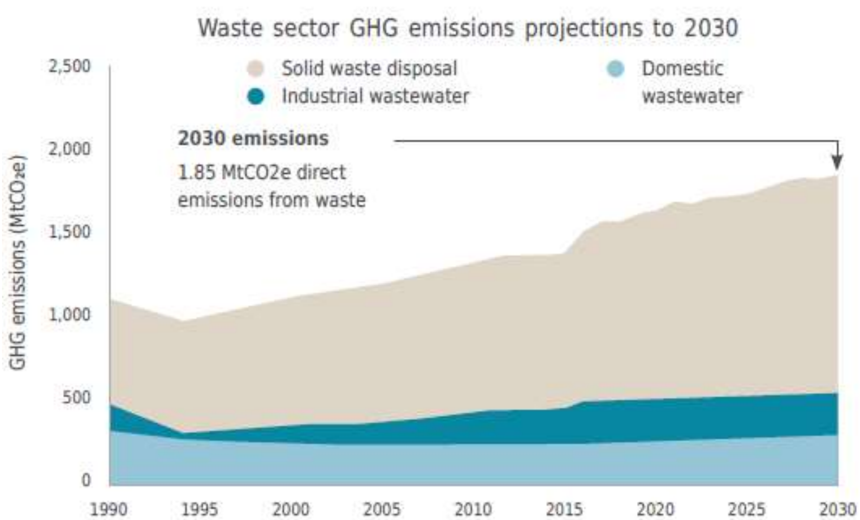

Fig. 1.28. 2030 GHG emission trajectory for waste management

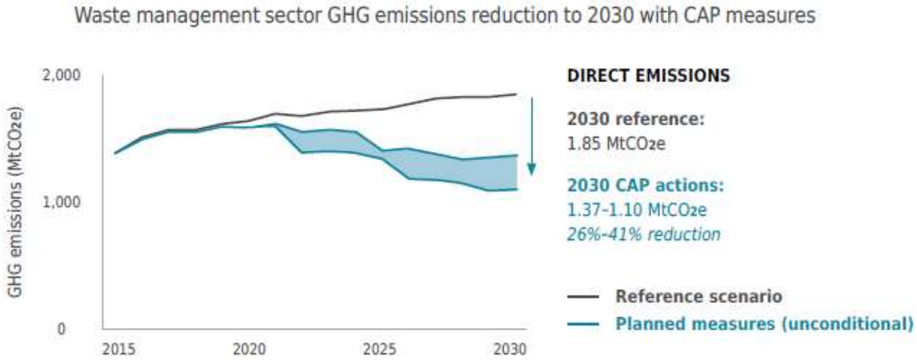

Fig. 1.29. Waste management sector GHG emission reduction to 2030 with CAP measures

Forestry: GOAL 7 – increase the carbon capturing capacity of the forestry sector by 10 % for 2030 compared to 2015.

Objectives:

7.1. Restore degraded forests;

7.2. Support sustainable forest management;

7.3. Develop a forest management system adequate to climate change challenges.

Other priority directions for the future:

- Improved data collection system;
- Reduce illegal logging;
- Access to alternative energy resources and technologies;
- Energy-efficient building envelopes;
- Forest fires (Fig. 1.30, 1.31).

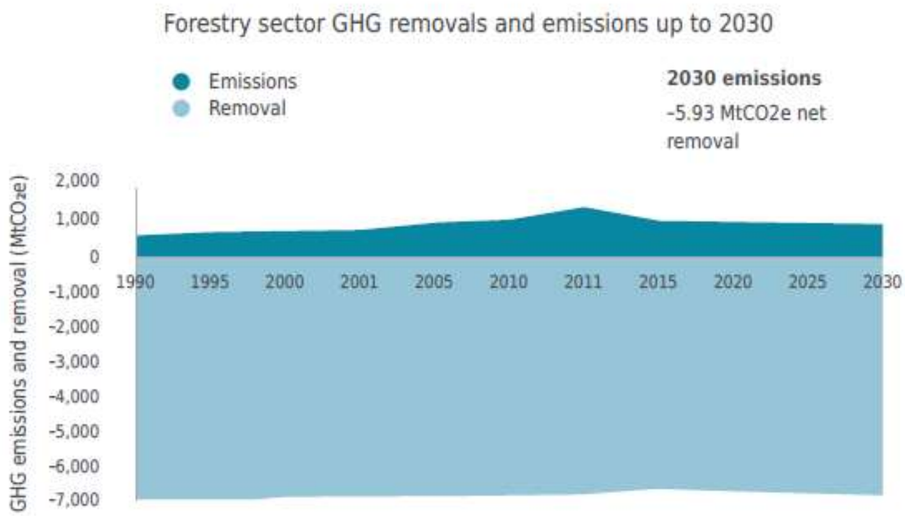

Fig. 1.30. 2030 GHG emission trajectory for forestry

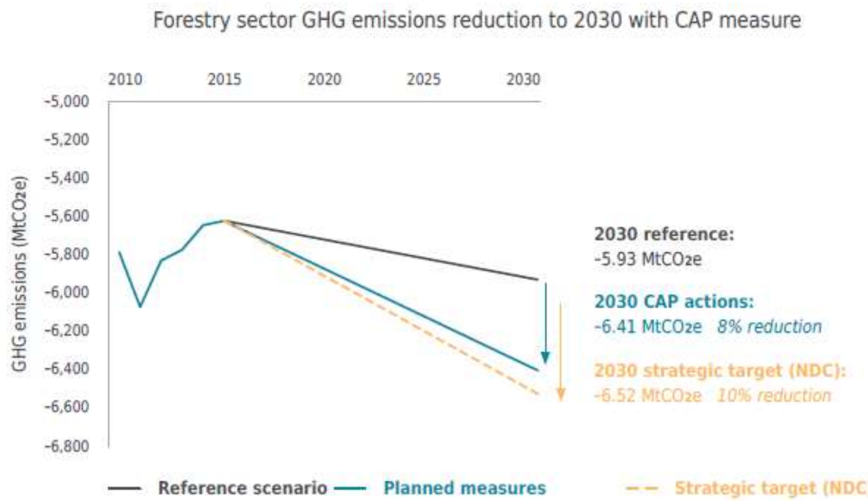

Fig. 1.31. Forestry sector GHG emission reduction to 2030 with CAP measures

The main goal of the nationally determined contribution of Georgia is to promote sustainable and balanced development of the country, in the process of which environmental and socio-economic challenges are considered equally.

It is important to note that climate change mitigation and adaptation measures create new opportunities in terms of economic growth, job creation and quality of life improvement - for example, production and installation of thermal insulation materials for houses, spreading of renewable energy resources, introduction of water-saving irrigation methods, etc. It will encourage economic growth and create new jobs.

1.8. Basic competencies of a specialist in the field of climate management

This guide is designed to support the implementation of the Climate Action Management (Climate Management) module.

The objective of the climate management module is to prepare a specialist, applying the following learning outcomes:

1. Discusses the manifestations of climate change and its consequences from a scientific point of view;

2. Reasonably presents his own opinions about climate change adaptation and mitigation measures for various sectors of the economy and public activities;

3. Evaluates climate management measures and technologies using various environmental indicators;

4. Can search for, analyze, generalize and evaluate news in the field;

5. Effectively presents materials and scientific information to a wide and professional audience;

6. Evaluates the peculiarities of his own learning process as a result of self-evaluation and self-criticism and can plan the learning process correctly, taking them into account.

The module was developed within the framework of the Erasmus+ international project "Development of an Innovative Master's Program in Climate Management".

The module provides engineering graduates with the knowledge, skills and motivation to develop, plan and implement climate change mitigation and adaptation technologies later in their careers.

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PART 2
CLIMATE CHANGE AND GEORGIA

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(Batumi Shota Rustaveli State University, Geotgia)

Climate change is a global problem that causes the formation of various natural, environmental problems and, in some cases, disasters. It is disasters that have a negative impact on disrupting the stable socio-economic life of countries and their population. The purpose of irrational actions carried out by man on the environment is the implementation of goals adapted to it and corresponding to their interests for their well-being, that is, therefore, there is a cause-and-effect relationship between nature, man and socio-economic development. Human action on this connection circle determines the scale of negative results, energy consumption, waste growth. The creation of new industrial technologies and improperly produced agriculture are accompanied by the release of various substances, including greenhouse gases, into the atmosphere, which is the main cause of global warming and changes in the global climate and climatic zones that have been formed over the years. At the turn of the 21st century, for the largest part of the planet's population, protection from natural disasters, safe operation of agricultural and engineering facilities, and ensuring a sustainable state of the environment became the most important socio-economic, political and ecological problem. Consequently, humanity is facing a lot of problems. The most important are the challenges that threaten the first human right and value - life. It is the growth and amplification of disasters in time and space.

Life is an inviolable human right and it is protected by law (Constitution of Georgia, Article 10). It is true that climate has changed throughout human history, but it has been a consistent and dynamic process. Uncontrolled human impact on the environment contributed to the acceleration of the climate change process. As a follow up, global warming was activated, which brought many negative consequences. As a result of global warming, the world's ice reserves, which represented 70 % of drinking water supplies, are melting at an unprecedented rate. Which in itself reduces the population's access to drinking water and, accordingly, leads to a significant decrease in the share of land on the Earth's surface.

Climate change results in nature and ecosystems change, the risk increase of diseases of mankind; it is significant that the intensity of the harmful effects of the "greenhouse effect" is increasing every year, which makes the need to solve the problem even more important. Obviously, Georgia is not an exception, and the adverse consequences caused by climate change will have a painful impact on our country as well.

On June 27, 2014, the "Georgia-EU Association Agreement" was signed. With this agreement, Georgia undertook to carry out reforms and ensure the progressive convergence of the country's legislation with up to 300 legal acts of the European Union (gradually, according to the agreed deadlines), including in the field of environmental protection and sustainable development. Enhanced environmental protection will benefit the citizens and business sector of Georgia and the European Union, by improving public health, preserving natural resources, increasing economic and environmental efficiency, the parties will develop and strengthen cooperation to overcome climate change; Cooperation will be carried out on the basis of equality and mutual benefit based on the interests of the parties, taking into account the interdependence between bilateral and multilateral obligations in this field.

Georgia, as a state party to the UN Framework Convention on Climate, the Kyoto Protocol and the Paris Agreement, is obliged to take into account the principles defined by the aforementioned international agreements and implement the obligations assumed at the national level. Deep changes in the components of the Earth's climate system are caused by the unhindered emission of greenhouse gases. Analysis of the results caused by global climate change shows that since the end of the last century, the increase in the average annual temperature and the change in the precipitation regime in Western Georgia have had a certain impact on the forest ecosystem. In eastern Georgia, the intensity of forest fires and the spread of pests have increased against the background of thermal changes and, especially, hot days. One of the most negative impacts of climate change is the increased frequency of droughts, depletion of water resources, and land degradation.

The main challenges of the climate change policy in Georgia are: reducing the emission of greenhouse gases that cause climate change and increasing the country's adaptation potential. Many high-budget projects are planned in Georgia with the support of donor organizations and countries to implement climate change mitigation goals. Climate change and environmental protection became even more relevant during the coronavirus pandemic, which clearly showed us that despite the development of technology, people are still unable to respond quickly to the challenges of nature and new diseases. Georgia experiences the consequences of climate change every day, and its impact on the country's economy and people's lives is worrying. Rapid melting of glaciers and activation of landslides can be observed in Georgia. The flood has already caused the famous tragic events in Tbilisi, on June 13, 2015, when 20 people lost their lives to the disaster caused by climate change. A recent landslide in the capital threatens several settlements and thousands of people. Forest fires have destroyed thousands of hectares of forest cover. In Tbilisi, where the concentration of CO_2 is particularly high, the problem of air pollution is acute.

Climate change and environmental protection issues are of the utmost importance in Georgia, as evidenced by the recent developments related to the construction of the Namakhvan Hydropower station. The mentioned issue is complex, because on the one hand the country needs energy independence and additional capacities of energy resources for development, and on the other hand, the unique potential of the Rioni valley requires a careful and research-based approach to environmental protection issues. In Georgia, the energy sector is responsible for 60 % of greenhouse gas emissions, and it takes the first place in terms of air pollution, which is mainly due to the excessive use of fossil fuels. According to the 2020-2030 energy strategy, Georgia has the opportunity to increase the share of renewable (e.g., water, wind and solar) energy in the energy sector, which will lead to a reduction in the use of thermal power plants and, accordingly, the harmful impact on the environment; In parallel with this process, the energy independence of Georgia will also increase. During the pandemic, on condition of the "lockdown" announced in many countries of the world, production and traffic were temporarily stopped, which, along with many negative consequences, gave the earth a chance to "breathe". We felt it in Georgia as well.

For example, the smog in Tbilisi dissipated and the sky became so clear that a glacier 180 km away appeared on the horizon. Such concrete and visible examples help us realize how we damage the natural environment where we live. Environmental experts warn that humanity has 10 years left before global warming exceeds 1.5 degrees Celsius, and climate change becomes an irreversible process. Even a slight change beyond this threshold would significantly increase the risk of natural disasters and extreme temperature changes, which in turn would put millions of people at risk of poverty. Despite the information available about climate change, the world's governments, the private sector and the population still do not understand how much this process poses a threat to humanity. In the pessimistic scenario, understanding the possible consequences of climate change may occur when the response is delayed and the damage caused will be virtually impossible to repair. The United Nations has developed a framework convention on climate change, according to which Georgia, as one of the organization's members, has undertaken relevant obligations.

Georgia is a signatory to all major international agreements and documents on climate change.

- In 1994, the country signed the United Nations Framework Convention on Climate Change.
- It joined the Kyoto Protocol in 1999, and the Paris Agreement in 2016.
- Within the framework of international obligations, Georgia submits a national report to the United Nations every 4 years on the current and future trends of climate change in the country and its consequences.

In April 2021, within the framework of recognized national obligations in the field of climate change, the Government of Georgia submitted to the Secretariat of the United Nations Framework Convention on Climate Change the Fourth National Communication of Georgia, which is one of the most versatile and comprehensive documents on climate change. The report reviews the steps taken by the country in the direction of fulfilling the terms of the convention, climate change and adaptation to it. The document also includes an updated greenhouse gas inventory report covering the period from 1990 to 2017. This year, Georgia undertook to reduce the total rate of greenhouse gas emissions by 35 % by 2030 compared to the rate recorded in 1990. The United Nations Development Program (UNDP) has been actively helping Georgia to build a climate-resilient society for more than 10 years. In mitigation of climate change and adaptation to its consequences. In the fulfillment of its international obligation in matters of environmental protection of the country and integration of environmental issues in all spheres of social and economic development of the country. Overcoming the consequences of climate change and reducing the risks caused by natural disasters is a priority activity of the Government of Georgia. This activity is carried out in cooperation with the Government of Georgia and international partners. However, it is clear that individual efforts of people are no less important for large-scale changes. Especially when, along with the sectors listed above, household activities are also responsible for releasing a large amount of carbon dioxide into the atmosphere. Therefore, it is important that every citizen of the world understands their own role in dealing with climate change.

The lecturers and students, of different directions, of Batumi Shota Rustaveli State University are actively involved in environmental activities. In 2020, at the faculty of Technology, with the grant project of the European Union Erasmus + program "Synergy of educational, scientific, management and industrial competences for climate management and climate change prevention", work on an agroecology program was commenced in the agrarian direction based on the experience of European partners. As a follow up a Climate Management Consulting Center was created.

Among the negative changes caused by climate changes, the most frequent are floods, waterfalls, droughts, winds, avalanches. Currently the condition of 35 % of agricultural fields is burdened by the problem of erosion, the areas of degraded land are likely to increase, the yield on such soils is reduced by 55-65 %, that is why it is necessary to train specialists in this field, agroecologists, who, in accordance with modern requirements, will be able to deal with the problems caused by climate change and be able to manage climate-smart agriculture.

Therefore, within the framework of the project, a Master's Program of Agroecology was developed, the curriculum of which includes global ecological problems and environmental protection in the following study courses: Meteorology, Climatology, Climate-smart Agriculture, Hydroecology, Economy of Nature Use, Agro-ecological Monitoring, Law; Moreover, causes of climate change, related problems, climate change and its impact on biological systems, ecological perspectives of global climate change, risks caused by climate change and features of their impact, impact of climate change on the productivity and quality indicators of different agricultural crops, global warming agains against the background of climate change, i.e. complex processes in the atmosphere and its consequences, are also considered. Students get acquainted with the modern problems of climate change, the regularities of the formation of global atmospheric processes and the consequences of climate change in Georgia.

At the initiative of the Climate Management Center, the training course "Negative Impact of Climate Change on Agriculture and Methods of Combating it" was held. The training was attended by representatives of the Ministry of Agriculture of Adjara, agricultural field extensionists, faculty professors and students. The following issues were discussed:

- Climate change, modern global eco-problems and Georgia;
- Basic principles of climate-smart agriculture;
- Organic agriculture on the example of climate-smart agriculture;
- Composting and pest control methods in climate-friendly agriculture (Fig. 2.1).

Fig. 2.1. Illustration of BSU activities

In June 2023, it is planned to hold the "Environmental Youth Summit", a joint event of BSU and the Student Scientific Society, the Climate Management Center and the Adjara Water Alliance, where school student teams from all five municipalities of the Autonomous Republic of Adjara will participate together with the university students. In the first phase, BSU academics held meetings in all schools. BSU Associate Professor Darejan Jashi conducted a lecture on "Climate Change and Water" in all five regions.

Meteorology Day has been systematically celebrated at the university for several years. This year a meeting was held on current issues of meteorology and climatology.

A quiz was held and the winning students were given souvenirs (March 23, 2023) (Fig. 2.2).

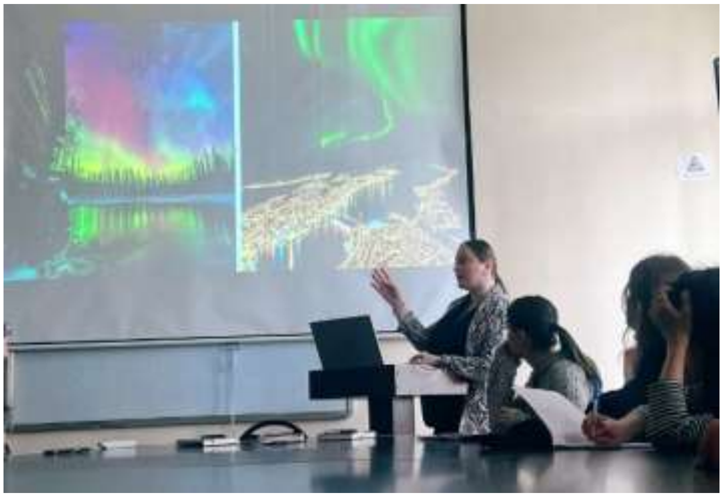

Fig. 2.2. Meteorology Day in BSU

In 2022, assistant professors Khatuna Chichileishvili and Tsira Kamadadze held a seminar for students on the topic: "Modern Climate Change".

In 2021, attention was focused on the scientific-practical importance of meteorology and the review of modern trends in the field. The graduate Koba Partenadze (who is currently working in the field of meteorology and presents weather forecast on Adjara TV) talked about issues related to weather forecasting (Fig. 2.3).

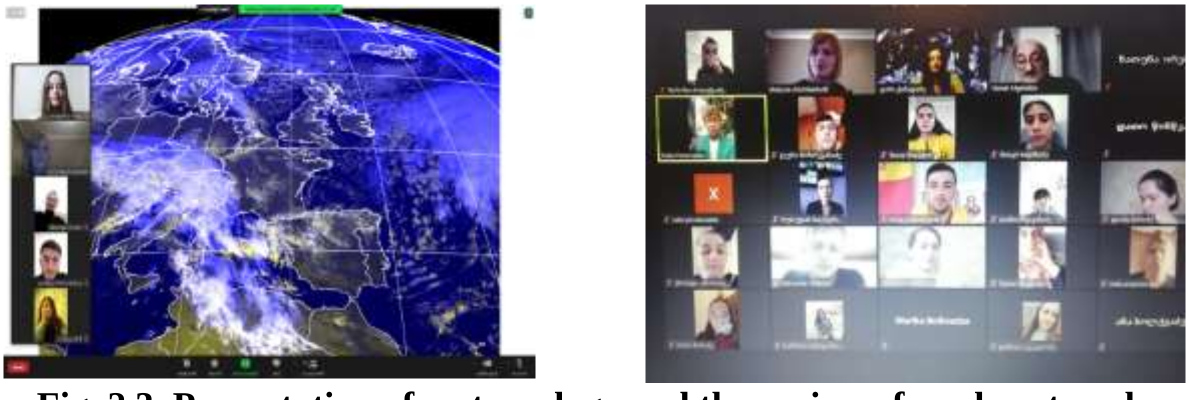

Fig. 2.3. Presentation of meteorology and the review of modern trends

In connection with the Day of Environmental Protection, an educational tour was organized in Mtirala National Park in 2022. The purpose of the event was to raise the awareness of young people and increase their active involvement in environmental issues (Fig. 2.4).

Fig. 2.4. Educational tour in Mtirala National Park

Kartlos Manvelidze, a student of the Master's Program in Geography, was awarded a 1500 GEL "Green Scholarship". The permanent representative of the United Nations Development Program (UNDP) in Georgia, Nick Beresford, and assistant professor Khatuna Chichileishvili, representative of BSU, gave certificates to the students.

The "Green Scholarship" program will help promote filling the gap in availability of professions in the field of the environment and encourage outstanding students. The "Green Scholarship" program is implemented by the Environmental Information and Education Center of the Ministry of Environment Protection and Agriculture, within the framework of the large-scale initiative of the United Nations Development Program (UNDP) "Reducing the risk of disasters caused by climate change in Georgia", the Green Climate Fund (GCF), With the support of the Georgian, Sweden and Swiss governments (Fig. 2.5).

The Department of Geography has signed a memorandum with the hydrometeorological service of the National Environmental Protection Agency, where, during their practice, students observe how data is collected and processed.

On the basis of field research, the student can (observe meteorological elements) determine the extent to which the climatic background changes depending on the region and evaluate it, describe the cataclysms caused by the current climate change in nature by means of various field methods and modern communication technologies (Fig. 2.6).

Fig. 2.5. Scholarship graduation

Fig. 2.6. Students meteorological events

GIS or geographic information systems are also taught at the Master's Program in Geography. The main goal of the study is for the student to gain broad knowledge about the collection, storage and analysis of GIS statistical data. GIS mapping and the practical importance of spatial data analysis systems.

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PART 3
NATURE CLIMATE SOLUTIONS IN URBAN AREAS AND THEIR BENEFITS FOR CARBON SEQUESTRATION, CLIMATE REGULATION AND FLOOD REGULATION

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Abstract

Climate change has a severe impact on ecosystems and human societies globally. Therefore, immediate action is required to combat the consequences of climate change. Implementing nature climate solutions (NCSs) that leverage the potential of natural ecosystems to address climate change challenges is a promising strategy for urban areas. NCSs sequestrate carbon and regulate urban climate by providing shadow, reflecting energy, and evapotranspiration effect of vegetation. Moreover, NCSs address other climate related urban issues like floods, water security, air quality, soil erosion, and landscape degradation. This paper aims to provide examples of implemented NCSs in Vilnius, Lithuania. Vilnius is the biggest and fastest growing city in Lithuania. It's a green city determined to become greener through afforestation, increased connectivity, unconventional meadow mowing, protection of existing parks and sustainable city growth. While NCSs can make a substantial contribution to the efforts of reducing the impact of climate change, it is crucial to recognize that comprehensive measures addressing climate change requires investment in conscious citizens and new technologies.

Keywords: Natural climate solutions, carbon sequestration, climate regulation, flood, Vilnius

3.1. Background

The phenomenon of climate change poses an enormous worldwide threat to the degradation of the environment. The primary drivers of global warming are anthropogenic activities like burning fossil fuel, industrial processes, agriculture and livestock practices, deforestation, and land use changes. The IPCC (2023) estimated a global surface temperature increase of 1.07 °C from 1850-1900 to 2010-2099, associated to human activity. The increase in temperature is already having an impact on global ecological security and human well-being all over the world. Though the impact is global on a global scale, it's not equally distributed. The top seven emitters are China, the EU27, India, Indonesia, Brazil, the Russian Federation, and the United States of America (UNEP, 2022). The least historically responsible for climate change less developed countries bear the highest impacts and are particularly more vulnerable to climate hazards.

Abnormally severe climatic conditions (e.g. heat waves, hurricanes, tropical cyclones, monsoons) are increasing in frequency and intensity which unequivocally leads to catastrophic events (e.g. extreme droughts, floods). Extreme heat events have a fatal impact on human health. In between 1998-2017 more than 166 000 people have died due to extreme temperature episodes (World health statistics, 2022). Increased temperature and humidity are facilitating the spread of vector-born diseases. Infections, pathogens, and outbreaks will be dispersed in previously non-endemic localities mainly through trade, migration, or travel (Rocklöv and Dubrow, 2020). Weak health from malnutrition is the result of negative impact of climate change on agricultural productivity. Over the past 50 years agricultural productivity has increased globally, but climate change has slowed this growth, with related negative effects primarily in mid- and low-latitude regions, and positive effects in some high-latitude regions (IPCC, 2023). Similarly, animal agriculture is impacted by climate through shortage of water, food supply, vector borne diseases, changing systems and livelihoods (Thornton et al., 2009). Livestock fertility, health, and milk yield are negatively affected by extreme high temperatures (Summer et al., 2019).

The impacts of climate change on the economy will be experienced by individuals, corporations, and countries, resulting in financial losses. The well-being, efficacy, output, personal assets, and real estate of individuals may be reduced or impaired. Industries sensitive to climatic exposure (e.g. agriculture, tourism) will have to deal with operational outbreaks, employees' inefficiency, properties deprivation. The climate index estimated that 48 % of countries constituting 90 of world economies may lose up to 18 % of their GDP if no actions are taken (Swish Re Institute, 2021). There are estimations stating that under baseline emission scenario the global annual monetary loss will reach 1628 billion by 2050, which is 0.79 % of the global annual GDP (Wang et al., 2020).

While climate change has not been the primary cause of biodiversity loss up till now, if global warming is not limited to less than 2 ^{o}C, and preferably 1.5 ^{o}C, it is likely to become the primary cause of biodiversity loss and the degradation of ecosystem services over the next few decades (WWF, 2022). According to Global Economic Forum biodiversity loss is in the 3rd place among the most severe risks on a global scale over the next 10 years (WEF, 2022; The global risks report, 2022). Species are shifting to higher latitudes and elevations altering local terrestrial, marine and freshwater ecosystems. It causes the mortality of in situ flora and fauna making the genetic pool less resilient and vulnerable to diseases and natural climate induced disasters. Displacement of species leaves them with less habitat, disconnecting them from dependent species and the new habitat might not be adaptable. The Living Population Index (LPI) shows an average rate of decline in population size of 68 % between 1970 and 2016 and this trend is likely to continue without drastic change in global temperature mitigation actions (WWF, 2020).

Combating climate change requires international cooperation. Currently are implemented numerous efforts in legal and technological field to eliminate the greenhouse gases emission. The Paris Agreement and The Kyoto Protocol facilitate the development of climate friendly policies globally. Following the United Nations framework and recommendations many countries deployed regulatory and economic resources in place which led to several Gt of $CO_{2\text{-eq}}$ less per year (IPCC, 2023). Low emission technologies are becoming more affordable. Since 2010 the unit cost of solar energy, wind energy, and lithium-ion batteries has decreased (85 %, 55 %, and 85 % respectively), and their use has become wider. Digital technologies like internet of things, sensors, robotics, artificial intelligence are improving energy efficiency usage in all sectors, but the reduced emission can be counterbalanced by increased consumption of goods due to digital devices (IPCC, 2022). Despite all collective achievements in mitigating climate change there is a substantial emission gap. IPCC (2023) report on emission gap showed that there is a significant difference between the emissions reductions promised and the emissions reductions needed to reach the climate goals of Paris Agreements by 2030 (UNEP, 2022).

3.2. Natural climate solutions in urban areas

Climate change is a major phenomenon jeopardizing urban sustainable development. Rising sea level, extreme weather events and spread of diseases are negatively affecting the city's infrastructure, services, and human health. Ironically cities are major contributors to climate change trough greenhouse emissions from urban transportation, electricity consumption, residential and commercial buildings and in some area's trough industrial activities. An effective and cost-wise practice to tackle climate related urban issues is to implement nature-based solutions (NBSs). The European Commission defines NBS as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions (European Commission, 2020). A more specific term under NBSs umbrella focused on solving climate change related issues is natural climate solutions (NCSs) (Griscom et al., 2017).

NCSs can serve as an effective solution to address urban climate related challenges like floods, water security, urban heat island, health and air pollution. Floods increasing in frequency are a disturbing and challenging natural hazard. Traditionally more acceptable and used was gray infrastructure yet NCSs are becoming more recognized as an effective mechanism to manage urban floods. An increase in blue-green areas in the form of vegetated facades, rain gardens, grassed swales, wetlands can reduce the urban runoff (Irvine et al., 2023; Singh et al., 2020). The capacity retention of storm water depends on plants type, air temperature, substrate moisture and properties, precipitation, weather, and climate (Xie et al., 2022).

NCSs also can reduce water pressure by treating it up to standards that is fit for its purpose of reuse. The water purification level depends on species, roots, size and soil. Despite that NCSs provide a certain amount of water filtration when it comes to safe drinking water natural filters cannot remove pathogens and can't fit in microbiological limits of the EU water standards (Tsatsou et al., 2023). Though the NBSs are capable to contribute to urban food security. Urban agriculture serves as biodiversity habitat, provide employment, provisioning service and can reduce GHG emission (Kafle et al., 2023; Kasprzyk et al., 2022).

Climate change is exacerbating the urban heat (UHI) island effect. Urbanization implies the increase of asphalt and concrete for roads, buildings and other infrastructure. Impervious surfaces absorb the sun's energy which leads to higher temperatures in urban areas. NCSs in contrast reflect the light. A row of trees can reduce air temperatures by 1 °C and a rain garden on a cloudy day can show up to 7 °C lower surface temperature than the surrounding pavements, and on sunny days this difference is up to 20 °C (Beaudoin and Gosselin, 2016; Kasprzyk et al., 2022*)*. While climate change adds temperature pressure to urban areas, UHI reversely increase the energy demand for buildings' cooling and heating (Ghiasi et al., 2021).

Cities are hot spots of air pollution. According to World Health Organization (WHO) nearly 99 % of global population is exposed to dangerously high concentrations of fine particulate matter (PM) and nitrogen dioxide. Ambient and household air pollution has been attributed to several health conditions such as: stroke, heart disease, lung cancer, lower respiratory infections and chronic obstructive pulmonary disease. Air pollution caused approximately 7 million fatalities worldwide in 2016. The most exposed to air pollutants low and middle-income countries (World health statistics, 2022). In some regions like Europe in primary PM, black carbon (BC), nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), methane (CH_4), and non-methane volatile organic compounds (NMVOCs) have decreased in the last decade, improving air quality (EEA, 2016). However, the WHO and Europen Union (EU) air quality standarts are not met in the many EU countries (Targa et al. 2023). Air quality is weather-dependent therefore sensitive to climate change. Climate change will worsen the air quality by increasing the amount of ground level ozone and particular matters. More frequent wildfires caused by climate change will contribute to air contamination. Smoke exposure increases acuteness of respiratory health mainly due to high consentration of $PM_{2.5}$ (Reid and Maestas, 2019). Additionally, warming climate is already prolonging the seasonality and concentration of allergens (Anderegg et al., 2021). The increasing concentration of CO_2, which is the principal carbon source for plant photosynthesis, can increase the allergenicity of some plants (e.g. oak pollen) (Kim et al., 2018)

Nature climate solutions have abilities to tackle the above stated urban air contamination issues. Implementation of green urban areas can improve the air quality, for example Rafael et al. (2018) found that vegetation in urban settings can decrease air pollution value up to 16 % mainly because of higher ventilation and dispersion capacity of the street canyon. Though in the same study it was stated that green roofs in some areas can increase air pollutants concentration due to vertical air flow reduction. However, numerous studies are giving credits to urban trees air purification. The amount of captured PM may depend on species and season. On average higher performance in terms of PM reduction demonstrate deciduous broadleaves trees and lower for evergreen broadleaves (Marando et al., 2016). In Fig. 3.1, there are shown different types of NCS.

Lawns

Forest

Urban gardens

Lake

Fig. 3.1. Different Nature Based Solutions that can be observed in an urban area

3.3. Examples of NCS important for ES in different cities

Carbon sequestration. GA are valuable urban carbon sinks. Many cities around the world are recognizing the importance of maintaining, restoring or expending GA for their multiply benefits including carbon storage (Chen, 2015; Misni et al., 2015). One of the most explored planted sinks are trees. Trees support cities' ecological health by storing carbon underground and above-ground woody biomass (Fares et al., 2017). Individual trees can store a substantial amount of carbon. For instance, Misni et al. (2015) found that some mature urban trees can store about 4.507 kg of carbon per tree per year. Similarly, other researchers estimated that trees depending on species type, variety, diameter, accumulated biomass, and density can absorb a relative amount CO_2 (Ferrari et al., 2017; Oviantari et al., 2018; Lahoti et al., 2020). The more mature trees are more carbon they store. Therefore, the long-life span should be guaranteed (Ariluoma et al., 2021). Numerous studies quantify the monetary value of accumulated carbon by trees, urban parks, and other NCS. (Jo et al., 2023; Shadman et al., 2022; Stoffberg et al., 2010). Residential yards are a vital component of urban green, and a growing number of studies emphasize the significance of private residential vegetation for providing urban ecosystem regulating services (Haase et al 2019; Contosta et al., 2020). Almost without attention are left urban cemeteries still they are a part of the green infrastructure system. A study conducted in Turkey gauged that a 14.02 ha cemetery can sequestrate 54.35 tons of carbon per year (Eyileten and Selim, 2023).

There are very limited studies focused on carbon sequestration in Vilnius. Though the capacity of the city can be considered significant. As Vilnius is recognized as one of the greenest cities in Europe (Pinto et al., 2022). Green space covers more than 11,000 ha of the city (27.5 %) and 13,700 ha is covered with urban forest. Notable is the fact that 17.3 % of the city consists of protected land, including one regional park, four state reserves, nine municipal reserves, and 44 natural heritage locations. The largest protected territories are Pavilniai and Verkiai Regional Park located within the municipal limits of Vilnius and are state protected area. In total 61 % of the city is urban green blue infrastructure (UGBI) such as: forest areas, herbaceous vegetation areas, sports areas, water and wetland areas (Priess et al., 2021). Vilnius has a lot of UGA and the city is determined to grow sustainably and greener. However, despite of synergistic benefits of UGA, its carbon sequestration capacities are sometimes overclaimed. An illustrative case is the study made in Prato municipality, that calculated that it would need to forest an area at least 30 times larger than the official plan to compensate for current emissions. And even under decreased emission the mitigation provided by different afforestation plans would not be enough to reach C-neutrality in 2030 (Brilli et al., 2022).

Climate regulation. Air temperature and Land Surface Temperature (LST) rises in urban areas as a result of climate change due to variables such rising temperatures, direct exposure of concrete surfaces to sunlight, and the retention of heat by these surfaces. This rise in LST has a severe effect on human health and urban environment. As a result, many studies are being done in different cities exploring the effect of green spaces on climate regulation. Zhou et al. (2023) examined the effect of urban greenery from 2013 to 2019 in Tongzhou District (Beijing), he found that when the vegetation coverage in the Tongzhou was increased by 10 %, the temperature fell by 0.58 0.68 °C. In Singapore, Lai at al. (2020) detected that the presence of turf and tree shade had a significant impact on urban surface temperatures, with the effect being greatest when both were present. The presence of turf reduced surface temperatures by as much as 10 °C, while tree shade reduced temperatures by 12 °C. A study across seven United States cities similarly found that tree cover has an average cooling effect of − 0.089 K per % cover, which is about four times stronger than the average grass cover cooling of −0.021 K per % cover (Smith et al., 2023).

Vilnius is one of the leaders in Eastern Europe in terms of climate endeavors. It has many areas that are properly managed and serve as NCSs for the city. It has joined the The Green City Accord, whose long-term goal is to attain climate neutrality by 2050[4]. Vilnius also, has been selected by the European Commission as one of 100 EU cities to partake in its mission to become a climate-neutral and smart city by 2030. Moreover, it signed the "Climate Campaigners EU" recently[5]. General Plan (GP) of Vilnius that was sign in 2021 aims to increase connectivity between green areas and construct a network of green spaces in the highly built-up metropolitan regions, ensuring their availability within 200 to 300 m of housing and major urban parks no more than 2000 m away.[6] Vilnius municipality planned to plant more than 100,000 trees, 10 million bushes and 300,000 climbing vines in the frame of "The Green Wave" project[7]. Likewise, the municipality promotes sustainable meadows care. The places farer from residential areas such as: highways, steep slopes of streets and rivers, roundabouts and reservations, non-walking zones are not traditionally short and neat mowed. The presence of wild growing plants, grass, bushes, and trees contribute to UHI reduction, water retention and habitat for biodiversity. Naturalistic planting design requires less input resources for maintenance and management than conventional mowed GA (Alizadeh and Hitchmough, 2019). Regardless all the stated climate actions, Depellegrin et al. (2016) in a study assessing ES potential in Lithuania noted that regulating ES have a very low potential in urban areas, especially in growing cities like Vilnius.

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[4] *https://environment.ec.europa.eu/topics/urban-environment/green-city-accord_en*
[5] *https://environment.ec.europa.eu/news/green-city-accord-focus-vilnius-2022-12-07_en*
[6] *https://vilnius.lt/en/2021/06/04/vilnius-is-entering-a-new-stage-the-general-city-plan-has-been-approved/*
[7] *https://vilnius.lt/en/2021/10/01/the-green-wave-is-rising-in-vilnius-with-hundreds-of-thousands-of-trees-millions-of-shrubs-and-vines/*

Flood regulation. Urbanization raises mean and heavy precipitation over cities resulting in severer runoff (IPCC, 2023). Non-structural measures have demonstrated efficacy and cost-effectiveness in mitigating the escalating problem of urban flooding (Biasin et al., 2023). Vilnius has extensive flood-control nature-based areas. Pereira et al. (2022) developed a quantitative and validated framework to map and assess flood supply and demand in Vilnius (Fig. 3.2).

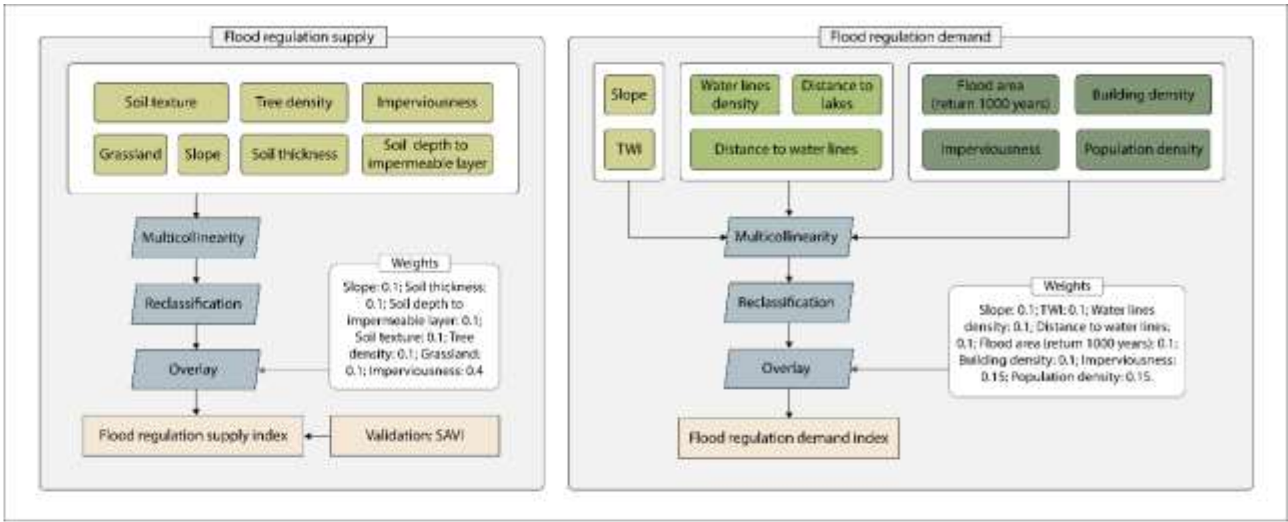

Fig. 3.2. Framework to assess flood regulation supply and demand
(Pereira et al., 2022)

Soil-vegetation adjusted index (SAVI) was used to validate the flood regulation supply index and the flood regulation demand index was validated by comparing the historical flood points with the model results. The flood regulation supply index was 0.490, and the flood regulation demand index was 0.475. The standard deviation showed low results: 0.085 for the flood regulation supply index and 0.069 for the flood regulation demand index. The northeast and south parts of Vilnius showed the highest flood regulation supply index. These urban zones have relatively high forest, parks, and trees coverage. This result supports the other research on NBSs for flood mitigation. Likewise, Medina Camarena et al. (2022) estimated that a single tree has the capacity to retain urban runoff that corresponds to the volume of a cup of coffee per second (0.139 ± 0.133 L/s). Similarly, another study found that areas covered with trees have a higher water supply depth of 9 mm on forested areas and 4 mm over green areas (Wübbelmann et al., 2022). Contrarywise, the flood regulation demand index had the highest values in the city center, and few districts in the north, east and southeast Vilnius. Those areas can be characterized as having a high percentage of impervious surface and low saturated conductivity. SAVI index explained 43 % of the flood regulation supply. The flood regulation supply depends on multiple variables like soil properties or topography. There was observed a mismatch between the regulation supply and demand indexes can be explained by land use. The areas with reduced greenery cover and high population density have a higher flood regulation demand than less urbanized areas with low population density (Baró et al., 2015; Chen et al., 2019) (Fig. 3.3).

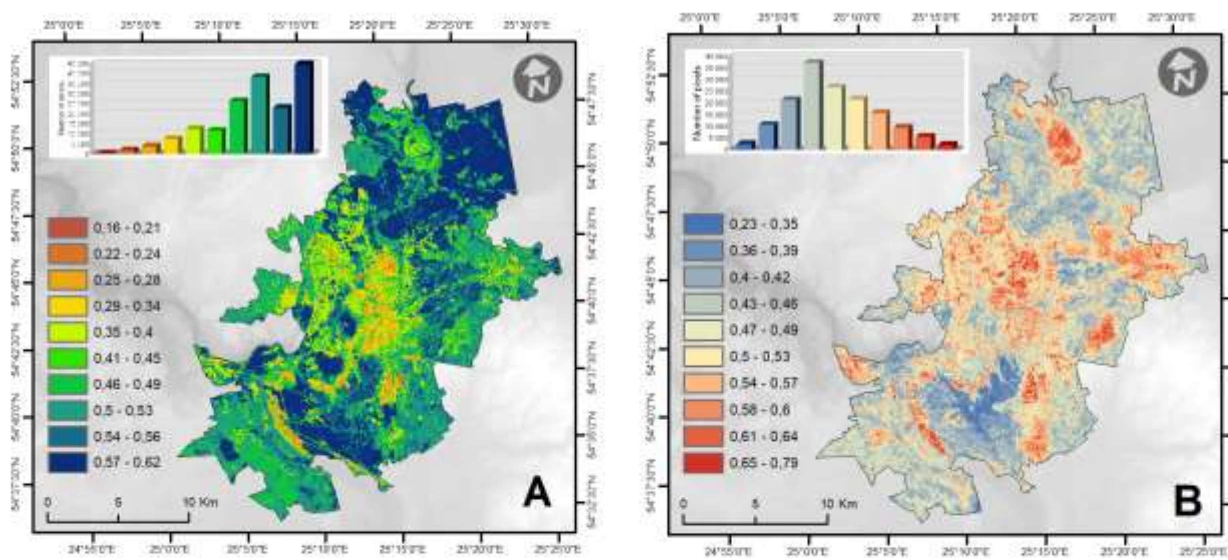

Fig. 3.3. Flood supply index and (B) flood demand index
(Pereira et al., 2022)

Ecosystem management to improve NCS. As landscapes become more urbanized, ecosystems are being threatened not only by changing climate and land use changes but also by ineffective management (Elmqvist et al. 2016). Landscape management in Vilnius is improving, the management practices are becoming more sustainable, albeit nonviable green areas management still have place to be. Figure 4 is an illustration of detrimental management practice. The areas showing low Normalized Difference Vegetation Index (NDVI) value (an indicator of vegetation greenness) are close to sidewalks and more often mowed than areas with high NDVI value. The intensive mowing of lawns with heavy machinery and dispersed unmanaged walking paths lead to vegetation, soil, and habitat degradation. The implementation of unconventional grass management has the potential to mitigate carbon emissions, augment soil organic matter, and improve pollinator habitats, specifically those conducive to bee populations (Lerman et al., 2018; Del Toro and Ribbons, 2020) (Fig. 3.4).

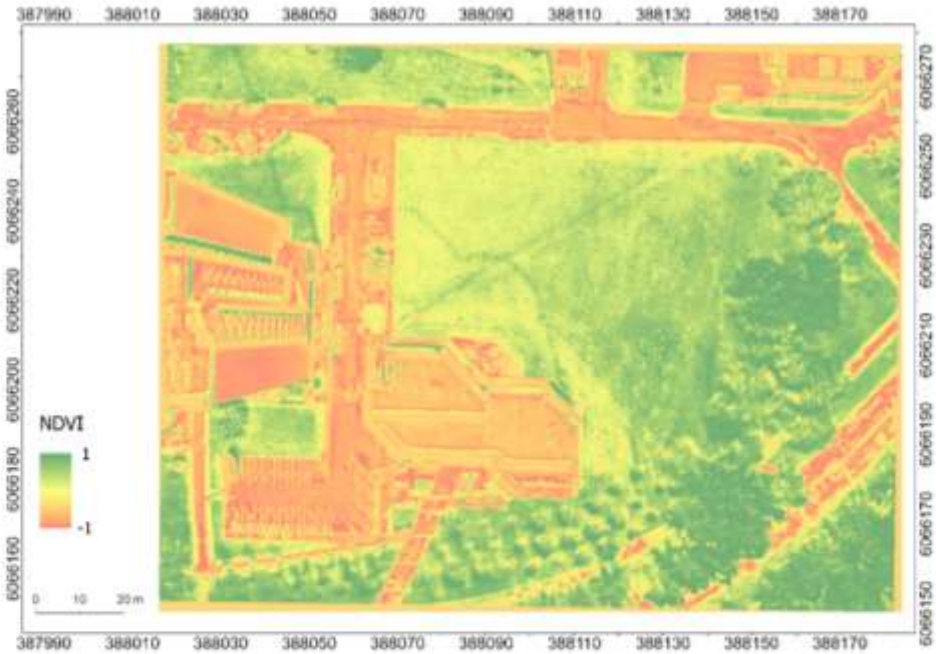

Fig. 3.4. NDVI index map in an urban area

3.4. Final remarks

NCS's are essential to make the urban areas more liveable. They increase the cities vulnerability to extreme events such as floods or heatwaves. They are important also for increasing carbon sequestration and mitigate the human impacts on climate change. Although this was not discussed, it is important to highlight that NBS and NCS, supply many other services key for urban areas such as air and water purification, pollination, food, biomass, landscape aesthetics or recreation. Therefore, it is key to consider them when we plan NBS or NCS. This work showed that they give important benefits for the ES studied. Therefore, NBS and NCS are key to be established in urban cities and contribute to a society wellbeing.

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PART 4
FEATURES OF ADAPTATION TO CLIMATE CHANGE IN AGRICULTURE

4.1. Interconnection between low-carbon agriculture, transport and energy: strengthening resilience of European and national climate security

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To ensure climate management and circular use of natural resources, the biomass is considered as a source for obtaining "green" heat and electrical energy, as well as biofuels (solid biofuels: pellets; biogas; solid biofuels: bioethanol, biodiesel), that form the basis for the development of "green" energy, environmentally friendly transport. The introduction of innovations in business processes with environmental and economic benefits is of particular importance at the level of energy and transport enterprises [1-3].

In turn, the implementation of the European climate-neutral economic development principles should be comprehensive, while also possessing a capacity to predict consideration of the regional specifics of sectoral development. Considering this, to identify effective ways to strengthen the climate component in the ecological and energy security of the economic development of the region, it is advisable to define the ecological "footprint" of the place and to integrate climate policy into regional development programs. In this context, among low-carbon related approaches at the regional level, that are among numerous incentives for the development of "green" energy based on diversification and circular use of renewable energy sources, such novelties as the greening of transport (in particular, the transition to electric vehicles), the energy modernization of buildings (transition to "smart houses") are considered. [4].

«Specifically, monitoring the climate change trend determines the importance of observing environmental values. In conditions of the development of artificial intelligence and virtual enterprises and the possibility of remote employment, it is relevant to affirm such an urban trend as the migration of labor force from megacities to small cities. As a result, a new orientation of environmental values is formed, such as the use of vehicles with minimization of emissions of pollutants into the atmosphere in cross-border regions» [5], which, in turn, creates the basis for the development of sustainable "smart" cities, as well as the implementation of such a strategic priority of the European Union as sustainable urban mobility.

In scientific works, "sustainable transportation" is interpreted as "transportation that meets current transport needs without hindering the future satisfaction of their own needs. Criteria for sustainable transportation are degree of satisfaction of transport demand, technical and commercial feasibility of transport technology, etc. (economic goals); production and regeneration functions (environmental objectives); cultural wealth, institutional factors, social justice, etc. (social goals)» [6].

Now in this context, the concept of "Smart Sustainable Cities", which was developed in the European Union, should be thoroughly clarified. This concept combines urban sustainability and mobility, emphasizing that both aspects should be considered simultaneously. The emergence of this concept can be defined as a response to criticism of such smart urban solutions that contradict sustainability and as an attempt to meet the needs of cities that are now digitized highly and more fully than the traditional concept of sustainability can imply [7]. «Smart Sustainable City» is seen as «an innovative city that uses information and communication technologies and other means to improve the quality of life, efficiency of functioning and services in cities, as well as ensure the competitiveness, needs of current and future generations regarding economic, social, environmental and cultural aspects» [8].

To determine the features of integration of climate-neutral and energy-efficient vectors into the strategic development of transport infrastructure based on sustainable mobility «analysis of the level of carbon dioxide emissions into the air by vehicles in the total structure of stationary sources of pollution by type of economic activity (percent to the total) for the period of 2017-2020 was carried out (Fig. 4.1).

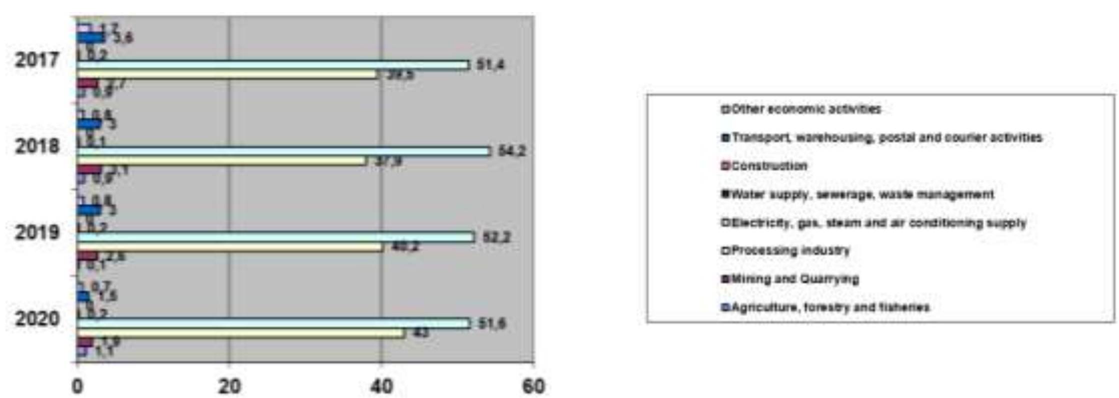

Fig. 4.1. Level of carbon dioxide emissions into the air by vehicles in the total structure of stationary sources of pollution by types of economic activity (percent to total) [10]

In particular, the positive dynamics of reducing emissions by vehicles was tracked from 3.6 % in 2017 down to 1.5 % in 2020. Meanwhile, in the context of the subject of our study, we consider it necessary to pay attention to tracking the tendency of increasing levels of carbon dioxide emissions into the air through the supply of electricity, gas, steam, and air conditioning from 51, 4 % in 2017 up to 51.6 % in 2020. This indicates a threat of increasing emissions of harmful substances into the atmosphere, which can be resulted in climate change» [9].

«In terms of data during 2016-2020 (Tab. 4.1, 4.2), a decrease in the number of gas stations in the western regions compared to the Kyiv region was tracked. However, there is also a continuing trend toward the use of traditional fuels in the transport sector of Ukraine (motor gasoline, fuel oil) detected during this period. More than that, the overall usage of natural gas in 2020 decreased by 7.7 billion cubic meters compared to 2016. At the same time, there are tracked tendencies towards a decrease in the use of fuel briquettes and granules made of wood and other natural raw materials in 2020 by 0.8 thousand tons compared to 2016» [7].

Table 4.1.

Number of gas stations in certain regions of Ukraine in 2016-2020 (at the end of the year, units) [10]

Region Name	Ternopil	Lviv	Khmelnytskyi	Vinnytsya	Ivano-Frankivsk	Kyiv
2016	189	377	234	303	183	492
2017	191	371	216	281	180	487
2018	186	372	240	306	174	463
2019	184	369	206	281	169	449
2020	176	351	204	294	173	491
The deviation between 2020 and 2016	-13	-26	-30	-9	-10	-1

«In general, the results of numerous analytical studies have shed light on an established positive trend regarding the growth of demand among the population of Ukraine for vehicles that are safe for the environment. Instead, a correlation between the demand for eco-transport and the need to open specialized refueling stations for users of eco-transport in communities have been identified.

Such obtained analytical data indicate the relevance of the issue of developing measures to promote environmentally safe transport through the development of sustainable transport infrastructure» [7] «(installation of charging power stations), primarily in cities, improving the infrastructure for powering batteries for electric cars (particularly for taxis)» [12].

«In this context, it is worth noting the active ecologically oriented political activity in the European Union, where one of the directions is the development of economic and scientific partnerships with the southern and eastern neighboring countries by financing the relevant programs. Notably, one of the programs worth mentioning is the EU4Energy Program (2016-2020), which is aimed at improving the quality of data and statistics in the field of energy, forming regional discussions in the field of political decision-making, strengthening the legislative and regulatory framework and improving access to information in partner countries.

Table 4.2.

Share of usage of certain fuels in transport, warehousing, postal and courier activities in Ukraine in 2016-2020 [10]

Name of the Fuel	Fuel briquettes and granules from wood and other natural materials, ths. tons	Motor gasoline, ths. tons	Liquefied propane and butane, ths. tons	Heavy fuel oils, ths. tons	Natural gas, billion m3
2016	2.4	2.5	1.9	4.4	11.1
2017	2.6	2.8	2.0	4.4	7.4
2018	2.0	3.1	1.8	6.0	6.6
2019	1.9	3.4	1.7	16.6	3.7
2020	1.6	2.6	1.5	10.2	3.4
The deviation between 2020 and 2016	-0.8	+0.1	-0.4	+5.8	-7.7

Another relevant program is EU4Climate (2018-2022), which supports the development and implementation of climate policy by the Eastern Partnership countries, which contributes to low emissions, prevention of climate change, and the fulfillment of obligations under the 2015 Paris Agreement on climate change» [5, 7, 9].

«As a result, the increased attention to the integral solution of the issue of global climate change determines the allocation of such a strategic vector of sustainable development of cross-border regions of the European Union and Ukraine as the reform of urban transport infrastructure based on environmental studies as well as the introduction of "smart" technologies to reduce the level of carbon dioxide emissions into the atmosphere» [5]. Particularly, «The European Union proposed a reduction in greenhouse gas emissions by 2020, which officially supported the Copenhagen Agreement on climate change and where it presented its commitments to emission reduction goals. These approvals consist of a unilateral commitment to reduce total emissions in the

European Union by 20 % from 1990 levels and a conditional proposal to increase this reduction to 30 %, provided that other major sides agree to take a fair share of global efforts to increase amounts of reduction» [6].

«In turn, we track the positive trend of implementing international experience in the sustainable development of the transport sector based on electrification of transport in the regulatory framework of Ukraine, which is among the countries participating in the European Neighborhood Policy, which has been in force since 2004. For example, there are plenty of measures within the framework of the Association Agreement with the European Union, that are contributing to such main goals as reducing the energy intensity of the economy, diversifying sources and ways of supplying energy resources, and increasing domestic production based on sustainable development» [13]. The Energy Strategy of Ukraine for the period up to 2035 ("Security, Energy Efficiency, Competitiveness") provides for "intensive involvement of investments in the renewable energy sector, development of distributed generation, in particular, elaboration and realization of the plan for the implementation of "smart" energy networks (Smart Grids) and the creation of an extensive infrastructure for the electric transport development» [14]. «It is noted that in the field of transport, a progressive withdrawal from exploitation of internal combustion engines of hydrocarbons and the replacement of a significant part of such vehicles with rolling stock using emission-free electric engines and environmentally friendly hydrogen engines were heavily expected» [13, 14].

«Energy Strategy of Ukraine until 2050», approved by the Cabinet of Ministers of Ukraine on April 21, 2023 by order No. 373-r [15], is focused on achieving carbon neutrality in Ukraine. This goal is planned to be achieved by diversifying renewable energy sources, producing bioethanol and hydrogen, modernizing and automating energy networks, and gradually reducing gas consumption (starting from 2035) due to the transition to electricity consumption.

«Moreover, the Ministry of Energy and Environmental Protection of Ukraine supported the "European Green Agreement" and developed the Concept of the "Green" energy transition of Ukraine, which should be implemented up until 2050. According to the Concept of decarbonization and greening of transport, certain measures are to be provided. These measures are aimed at the following tasks:

- upgrading the fleet of vehicles with internal combustion engines to electric, hydrogen, and fuel cell vehicles or others that meet the criteria for sustainability and environmental friendliness;
- optimization of the structure of passenger and freight traffic by increasing the share of public and railway transport, respectively;
- improving the transport network planning and public transport routes; developing the use of ecological transport and micro mobility in cities;
- introduction of intermodal freight transport technology;
- modernization and increase in the number of water and river ports;

- introduction of energy saving at all levels of technological chain» [13].

In general, in terms of developing measures to implement the goals of integrating renewable energy sources into the central heating system, we note the tendency to convert boiler houses to use biomass and solid biofuels, along with the construction of thermal power plants using biomass, and usage of biofuels in transport. In the Law of Ukraine "On Alternative Fuels" [16], the concept of "biomass" is interpreted as "a biologically renewable substance of organic origin that undergoes biological decomposition (waste from agriculture (crop and livestock), forestry and certain technologically related industries), as well as an organic part of industrial and household waste» [16].

One of the alternative sources of "green" electricity and heat is biogas. Accordingly, it is important to create a favorable market environment for the functioning of such enterprises that use biogas to produce electricity and heat.

This transitivity of socio-economic development leads to a change in the approach to the positioning of "green" energy as a climate-neutral commodity in the market, which is namely a combination of resource-saving and climate-neutral approaches. This demonstrates the importance of measures, that are needed to introduce climate-neutral innovations as critical energy-efficient and climate-neutral technologies in energetics. And this introduction can be possible by diversifying renewable energy sources based on a closed cycle of energy resources usage, decarbonizing the energy supply chain, and developing "green" local energy networks on the basis of smart management and cross-sectoral cooperation.

In addition, one of the imperatives of improving the energy efficiency of the economy is the development and optimization of technologies for growing energy (photosynthetic) crops, which are specially used as biofuels or energy production. Biomass is a carbon-neutral fuel, which means that its' exploitation does not increase the global greenhouse effect. Today, the main suppliers of biomass used for biofuels are agriculture, forestry, energy transplants, and the microbiological industry.

The advantage of switching to energy crops as prime biomass for the production of solid biofuels is their availability and simplicity of production. And this, in turn, is an alternative replacement for forest biomass (wood/timber), the cost of which is constantly growing. In addition, «the cultivation of energy crops can occur on degraded lands and contribute to the prevention of soil erosion» [17].

«Since 2013 the member countries of the EU follow the integrated environmental policy, which obliges farmers who own more than 15 hectares of arable land to allocate at least 5 % of the corresponding area for environmental and energy demands. Since 2017, such a share of land for relevant demands has increased up to 7 %. According to the European Commission, about 10 % of all agricultural terrains should be used for energy crops. In addition, farmers are obliged to grow energy crops without using pesticides and mineral fertilizers» [18, 19]. «In the European Union, 13.2 million hectares of land are available for growing energy crops. Until 2025 this number can grow to 20.5 million hectares, and by 2030 – up to 26.2 million hectares» [19, 20].

«In Ukraine, there are about 3.5 million hectares of land that were withdrawn from sowing plans due to their low fertility, tendency to erosion, etc. Cultivation of fast-growing high-yielding energy crops on these lands, including artichoke, can save soils from erosion, increase the power of the humus layer and generally improve the ecological and energy state of the country» [19]. «According to 2016 data, the economically justified energy potential of existing biomass waste reaches 25 million tons of conventional fuel, and the energy potential of biomass that can be grown on unused agricultural land of more than 4 million hectares is about 13 million tons of conventional fuel. With this potential, it is possible to cover up to 18 % of the total consumption of primary energy carriers in Ukraine» [19, 21].

However, the transition to the production of energy crops as an alternative resource for replacing gas for energy production in Ukraine provides for regulatory improvement, which can be reached thanks to «consideration and approval by the Verkhovna Rada of Ukraine (Supreme Council of Ukraine) of draft laws 5227 and 5228 of 12.03.2021 and definition of the term "energy plants", increasing the term of the land lease agreement for growing energy crops up to 20 years (nowadays it is only 7 years), simplification of the process of leasing unproductive land for growing energy crops without land tenders, limiting the maximum amount of rent for unproductive and degraded land on which energy plants are grown to 5 % of the normative monetary value (now it is up to 12 %). Such changes will lay the foundations for the development of the energy crops sector in Ukraine (Tab. 4.3) with the potential to replace natural gas up to 8.9 billion m^3/year (while growing them on 2 million hectares of land), reduce greenhouse gas emissions to 18 million tons of CO_2/year and with a significant positive impact on the macroeconomic indicators of the Ukrainian economy» [22].

Table 4.3.

Income from various alternatives to agricultural land usage [22]

Ways of land utilization	**The average yield, tons/hectare**	**Average Domestic Sales Price, Euro/tones**	**Incomes, Euro/hectares**
Cultivation of wheat	4.65	160	744
Cultivation of corn for grains	6	160	960
Cultivation of corn silage for biomethane production	24.3	40	972
Cultivation of energy crops (willow, poplar)	18	60	1080

The use of biomass of plants for bioenergy production to ensure the competitiveness of rural areas and agrarian formations «requires taking into account certain fundamental conditions: biogenic sources of this type of industrial raw material must be well adapted to specific soil and climatic conditions of cultivation, provide a high and stable amount of production of commercial products and its high yield from a unit of sowing area; production and processing of plant products should be regionally connected, which excludes unjustified costs for transportation and storage of such products; growing plant raw materials should be provided with a reliable seed production system; the system of production and processing of plant raw materials should be suitable for its multi-purpose industrial use and utilization of commercially valuable co-products, which ensures the zero-waste nature of this process and resources» [23].

At the same time, the climate and economic challenge to ensure sustainable development of the agrarian sector through the laying of energy transplants (energy poplar and willow, paulownia, switchgrass, miscanthus, eucalyptus, hemp, reed, cane, etc.) is defining individual hydrometeorological characteristics of energy crops by the indicator of multipath (avoidance of annual plowing contributes to the preservation of soil moisture), an indicator of the time of harvest, as well as an indicator of moisture resistance. Accordingly, the main tasks of effective management of business processes in the organizational sphere at renewable energy enterprises (bioenergy) and clean transport enterprises are: «designing the structure of business processes (allocation of responsibility centers and formation of a model of their interaction), consolidation of departments in order to control the time for the implementation of integrations in the business process management system, selection and adaptation of software and hardware tools for effective management of business processes» [24].

At the same time, on [25] attention is drawn to the close correlation between the number of biofuel producers and the number of products they manufacture. This shows that instead of establishing a tendency to enlarge production, there is a constant renewal of producers (mainly due to the cycle of small producers, some of which are frequently shutting down, while others are constantly emerging). Among the reasons for this phenomenon are «unadjusted supplies of raw materials (agricultural raw materials), improper location of production relative to the raw material base (agricultural enterprises), and lack of access to European markets. In addition, determining the introduction of effective production and consumption of biofuels is to obtain a complete set of effects: economic, social, environmental and energy» [26]. As a result, a compromise management decision may be the use of a cross-sectoral approach to the creation of climate energy clusters with the participation of agrarian, bio-processing, energy, and transport enterprises in the chain of production of "green" energy, which can optimize the planning of the creation of energy crops plantations with the adaptation to climatic factors (seasonal amount and frequency of precipitation, change in temperature regimes and others) in different regions of Ukraine.

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4.2. Development of agriculture in the Ternopil region of Ukraine in the context of climate change

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The urgency of optimising and adapting modern farming systems in the face of climate change is extremely important. The development of agriculture is a process of its adaptation to climate and weather [4].

Current climate change, caused mainly by anthropogenic factors, began in the 70s of the last century [2].

At the end of the second half of the 20th century, the study of the Earth's climate became especially important. This is connected with the the anticipated increase in the greenhouse effect and, consequently, the rise in global air temperature. Scientists have reached a global consensus that the climate has changed over the past 150 years, mainly due to human activity. Global temperatures are rising, rainfall patterns are becoming more unpredictable, and sea levels are rising. These trends are expected to continue for decades to come [7].

According to the World Meteorological Organization (WMO), since the 80s of the last century, each decade has been warmer than the previous one, and this trend will continue in the future. The annual global temperature in 2019 was 1.1 °C higher than the 1850-1900 average) [9].

In recent decades, changes in the modern climate are caused by changes in large-scale atmospheric circulation, position of the centers of mass action in the troposphere, which are consequence of global climate warming [2].

The consequences of rapid climate change process represent a wide range of multi-directional and multi-scale phenomena [1]. Climate change, which observed on a global scale, were also reflected in the territory of Ukraine (Fig. 4.2). These changes occur synchronously, especially this is manifested in anomalous phenomena and temperature regimes, which tend to increase [5].

Analysis of Fig. 1 shows that in the period from 1850 to the beginning of the 2000s, the average annual air temperatures were mostly lower than in the base period of 1971-2000, with only a few years being warmer. The beginning of the 21st century was marked by steady warming, and during this period there are no years in which the temperature was colder than in 1971-2000.

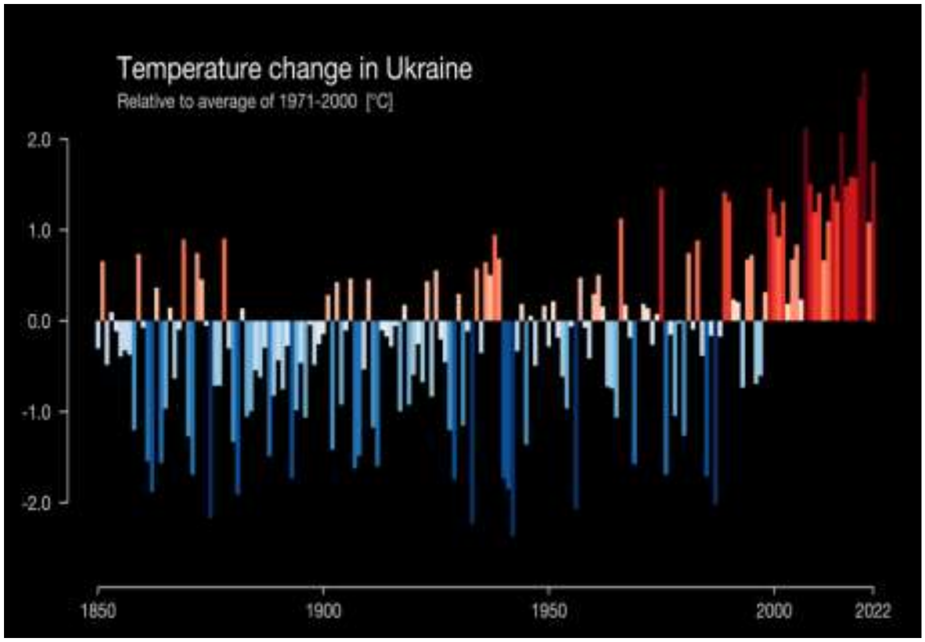

Fig.4.2. Temperature changes in Ukraine compared to the period 1971-2000 [3]

The analysis of dynamics of temperature regime of the Ternopil region in the period 1881-2020 and its comparison with the global dynamics showed a similar trend in temperature growth compared to the control period 1951-1980.

On a global scale, temperature increases have been observed since 1977 and continue to this day. Within Ternopil region, the mentioned climatic changes began in 1988 and continue to this day (with the exception of 1996).

It should be noted that the amplitude of temperature fluctuations within the planet is much smaller compared to the regional scale. Since then, the average annual air temperature has been gradually increasing, which before the changes was 7.2 °C, and during the following years it increased, and in the period from 2011 to 2020 it was at the level of 9.0 °C.

Similar changes occurred in the warm and cold periods of the year. Thus, with the average long-term norm for April-October of 13.5 °C, the temperature rose to the level of 15.6 °C. The cold season (November-March) was also accompanied by an increase in the temperature regime to -0.2°C, while the average long-term indicators were – 1.6 °C.

One of the main characteristics of the thermal regime is the average monthly air temperature. It has a clearly defined annual course. On average for the period 1881–2020, this indicator was lowest in January (-4.3 °C), and highest (18.7 °C) in July. Analyzing the dynamics of air temperature by months and years of observation, it should be noted that from 1881 to 1960 it was 7.2 °C, which is within the long-term norm (7.2 °C).

The following period, 1961-1980, was marked by a slight decrease in the average annual air temperature by 0.2 °C. Starting from the 80s of the last century, there has been a first gradual (by 0.2 °C in 1981-1990), and then a sharp increase in the average annual air temperature. In 2011-2020, it was 9.0 °C, which is 1.8 °C higher than the average long-term norm.

The development of agricultural production in the world in general and in Ukraine in particular, from the end of the 20th to the beginning of the 21st century, takes place in the conditions of climatic changes, which are accompanied by global warming and are characterized by such signs as an increase in the frequency of temperature extremes, an increase in the number of hot days, a decrease in the amount of precipitation and their uneven distribution [4, 6, 10].

The increase in the temperature regime of the Ternopil region caused by climatic changes in the XIX-XX and early XXI centuries had a significant impact on the development of agriculture in the region, radically changing the approaches to agricultural production compared to the previous period, (Fig. 4.3).

A characteristic feature of this process is that there was a coincidence in the time of the onset of climate changes and economic and economic prerequisites for the development of agricultural production. Thus, as evidenced by the data of meteorological observations, the beginning of global climate changes, which were reflected in the territory of the Ternopil region, dates back to the 90s of the 20th century and manifested itself in:

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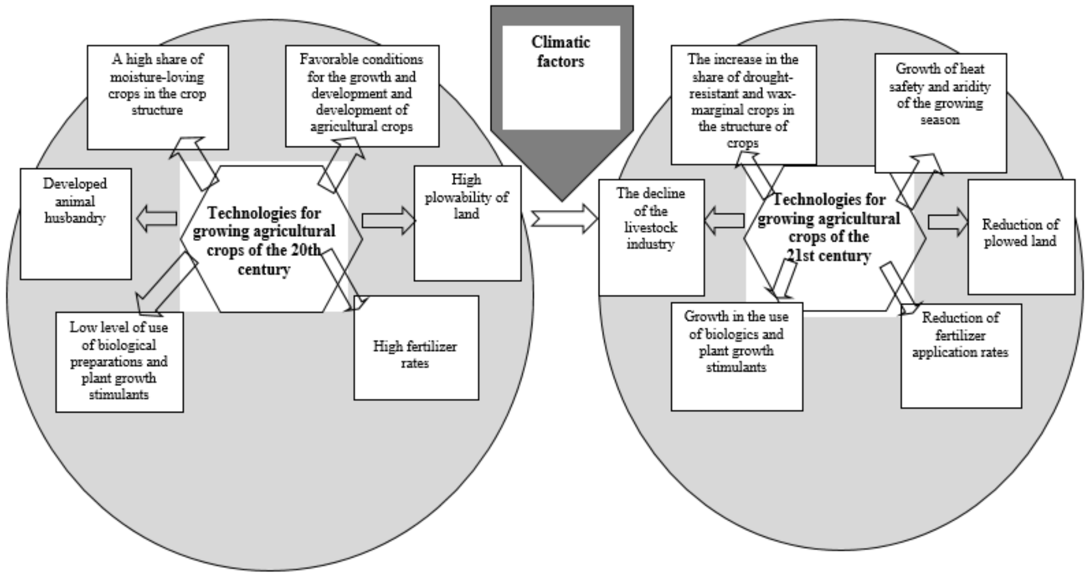

Fig. 4.2. Features of growing crops in the Ternopil region

- increase in average monthly and average annual air temperatures;
- deterioration of moisture supply during the growing season;
- shifts in the timing of the last spring and first autumn frosts;
- reduction or complete absence of the rest period in winter crops and perennial grasses;
- extension of the vegetation period of agricultural crops;
- growth of the sum of active and effective temperatures;
- increase in the number of dry and acutely dry years.

It was during this period (the beginning of the 90s of the last century) that changes also took place in all spheres of the economy, including in the agricultural sector, which were manifested in the fact that:

- the sown areas of export-oriented and high-margin crops such as sunflower, soy, rapeseed and corn have increased and the sown areas of peas, typical forage and fodder crops have decreased;
- the number of farm animals, in particular cattle, decreased, and a trend towards the increase in the number of pigs and poultry;
- rates of application of mineral and organic fertilizers decreased.
- the use of growth stimulants and anti-stressors has increased, as one of the effective mechanisms for obtaining high yields of agricultural crops in adverse climatic conditions; the use of bacterial preparations has increased, mainly in technologies for growing legumes;
- in the structure of crops, the share of areas sown with seeds of foreign origin has increased significantly, and the use of seed material of domestic selection has sharply decreased;

- the development of agricultural production was reoriented to energy saving due to the use of new agricultural machinery with better operational characteristics.

In connection with this, radical changes took place in the technologies of growing agricultural crops, which were aimed at their maximum adaptability to new climatic and economic conditions.

The importance of this issue is also due to the fact that global climate changes coincided with population growth during the last century, leading to a significant increase in the demand for food. The United Nations predicts that the world's population will reach 9.7 billion by 2050, to 2080 – 10.8 billion and 2100 – 11.2 billion. While these projections actually suggest a slowdown in overall global population growth, Africa and South Asia are expected to see significant and sustained increases: by 2100, these two regions may well be home to a combined population of 9 billion of the planet's projected 11 billion people. Driven by these important demographic forces, product demand is expected to grow significantly, particularly in Africa and South Asia [8].

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PART 5

ENVIRONMENTAL SUSTAINABILITY ASPECTS IN THE DEMAND AND SUPPLY OF LATVIAN CATERING COMPANIES

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Annotation

Environmental sustainability has today become as important as ever. Moreover, it has reached a time when, in addition to speaking in public, more and more green practices are being introduced into the business, including the catering business. Customers are the ones that primarily create demand for environmental sustainability practices, but catering companies offer it, including them both in cooking and service and in the management of the business. The demand study shows that it is particularly important for customers that catering companies primarily introduce green practices that can directly affect the health of each customer. Important customers also point out what are widely communicated practices, such as sorting waste. On the other hand, only green practices that are either regulated by law or financially beneficial to the company are primarily introduced in catering companies.

Key words: environmental sustainability, green practice, catering enterprises.

5.1. Introduction

Sustainability remains an actively discussed subject across a broad range of academic and practical areas. Although sustainability and its concepts were first discussed by academia and the general public a long time ago, it gained its true prominence this century. While everyone can have a different understanding of the need for sustainability, it generally involves responding to the needs of society while not compromising the ability of future generations to meet their needs and their ability to develop and prosper (WCED, 1987). The more the public is aware that its rapid development may also harm the lives of future generations, the more its demand for sustainable practices and activities increases.

Catering services are one of the industries which have a significant impact on the environment, since food production consumes a large amount of energy and water, and generates waste and carbon dioxide emissions (Filimonau, Lemmer, Marshall, & Bejjani, 2017; Gössling & Hall, 2013). Many earlier restaurant studies, while extremely valuable, have documented sustainable practices on environmental issues without basing them on the opinion of catering companies themselves (Kim, Hall, 2020). This study looks at the views of both stakeholders – customers and managers of catering companies, researching the importance of various "green" practices for customers and evaluating the extent of their implementation by Latvian restaurants.

5.2. Literature review

Despite numerous definitions in both scientific literature and policy documents, it should be acknowledged that the term sustainability is still understood in various manners. Several authors have pointed out in their articles (Hawkins, 2006; Stabler, Papatheodorou, Sinclair, 2010) that there are as many explanations of sustainability as there are stakeholders. Therefore, any definition of sustainability can be understood and interpreted in various ways. It should be noted that "sustainable" originally meant 'capable of being borne or endured'. Only later it became 'capable of being upheld or defended' (Hawkins, 2006). The initial clarification option is closer to those interested in the environmental and social aspects and related not only to preventive but also to proactive activities, whilst business tends towards the newest. Looking at the definitions by several authors, one of the most comprehensive definitions, in the author's view, has been proposed by Stabler, Papatheodorou, Sinclair (2010), where they consider sustainability as the management of resources and their products to ensure economic development and growth while maintaining the quality of human and natural capital stocks for the current generation, as well as transferring to future the opportunity and means to maintain the same economic, environmental and quality of life benefits to future generations. Consequently, sustainability can be said to be driven by the economic and social needs of society, while at the same time maintaining and restoring the resources available at that moment. Since this study aims to understand the importance of the environmental sustainability aspects and its current application practices, it is environmental sustainability that is characterized in greater detail. These aspects are particularly important due to the development of globalisation, where several challenges arise, along with many positive aspects. Scientists point to climate change, rising sea levels, water, air and soil pollution, including those from non-biodegradable waste, and degradation of wild biotopes as the main environmental challenges (Stabler, et. al., 2010).

Environmental practices have been identified as a key motivator for the development of sustainability in organizations. The term "green business" has emerged in recent years referring to environmental sustainability practices for companies implementing them. It describes organizations that are committed to ecological sustainability, make an effort to use renewable resources and reduce any negative environmental effects brought on by their operations (Čekanavičius, Bazytė & Dičmonaitė, 2014). Overall, it can be argued that “green” organizations should engage in one of the "4Rs": reduction, reuse, recycling, or recovery. Each of these "Rs" can be accomplished via the use of a variety of strategies and practices, some of which may serve the goal of more than one of these "Rs”. Such green practices can include eco-cleaning, the reduction of power waste, green packaging, waste sorting, decreased printing, etc. (Čekanavičius, Bazytė & Dičmonaitė, 2014).

According to studies, being “green” in a business is not only good in the eyes of the public, but can also be financially beneficial. Comprehensive implementation of green practices can lead to greater achievements and benefits for businesses are generally manifested in two ways: revenue rising and/or cost savings. Going green can have a positive effect on a company's revenue by, inter alia, differentiating its products and brand image, improving customer communication, adding value, and increasing productivity. By going green, a company can improve its future networking opportunities with other environmentally conscious companies. This can be an important benefit of opting for green practices. Waste utilization and resource-saving are the primary contributors to cost saving. Some examples of such practices include producing heat via the burning of garbage, reducing paper usage in favour of electronic communication, and shutting off electrical equipment when it is not in use (Čekanavičius, Bazytė & Dičmonaitė, 2014).

As mentioned above, one of the sectors affecting the environment most of all is the catering sector. Increasing awareness of the importance of environmental sustainability increases the number of catering companies introducing individual “green” practices. Although there is no universally accepted definition, sustainable restaurants are often regarded as ‘green’ restaurants that operate in an environmentally friendly manner (Green Restaurant Association, 2019; Iamkovaia et al., 2019).

Scientists have studied the environmental impact of various practices that are more commonly used in the catering industry to come up with suggestions for the industry. According to literature (Dutta, Umashankar, Choi & Parsa, 2008; Schubert, Kandampully, Solnet & Kralj, 2010; Mahabubul, 2021), there are several green practices that restaurants can adopt. For recycling and reuse, catering companies can use reusable containers, cutlery, and plates instead of disposable ones. Businesses can also provide recycling bins in the kitchen and dining area to collect recyclable materials. The use of recyclable cutlery and paper bags for delivery services is recommended. Another group of practices includes the usage of energy-efficient equipment - refrigeration, food preparation and cooking, cooling, heating, ventilation, lighting, etc. Restaurants' high energy expenditures are mostly attributable to inefficient food cooking, holding, and storage equipment (US Environmental Protection Agency, 2006). Replacement of old, inefficient equipment with energy-efficient models, such as LED lighting, and occupancy sensors, putting in place starting and shutdown plans for equipment operations, switching off equipment when not in use and constant cleaning and upkeep of equipment should be common green practices for saving energy. It is recommended the reduction and composting of food waste is accomplished by setting up a composting system to recycle food waste and utilize the compost that results in nourishing a garden or farm. Excess food can be donated to local charities or food banks to prevent food waste. Some food waste reduction strategies include monitoring inventory, using compostable packaging, and donating excess food to food banks or shelters. Sourcing local and organic produce is important for cutting transportation emissions and supporting local communities. Sustainable purchasing is highly dependent on eco supply chain availability and plays a major role in environmental sustainability. Due to the global shortage of drinking water, it is important to minimize water use by installing low-flow faucets and toilets and swiftly repairing leaks and teaching employees how to utilize water wisely. Water-saving suggestions include using a low-flow pre-rinse spray valve, keeping water-using equipment in excellent working order by fixing any component failure, water bodies on-site being treated and reused, and installing water sense toilets and faucets (US Environmental Protection Agency, 2012). Employment of non-toxic, biodegradable cleaning products that are safe for the environment and personnel is another important practice recommended (Dutta, Umashankar, Choi & Parsa, 2008; Schubert, Kandampully, Solnet & Kralj, 2010; Mahabubul, 2021). Given these possible green practices, it can be said that the green restaurant is environmentally friendly in all aspects of food production and sales, including menu design, ingredient selection, preparation methods, and the use of materials such as table settings, clothes, napkins, decoration, energy, cleaning products, and packaging materials. The concept of being "green" also necessitates more responsible water and energy use, waste management, reuse, and recycling, and more efficient delivery methods, as well as a preference for locally and domestically produced goods (IGI Global, 2019).

To investigate the degree of significance of environmental aspects when choosing a catering enterprise, the quantitative method was used. Therefore, the demand for environmental sustainability-related activities was analysed. In turn, interviews explained the environmental sustainability aspects of catering business practices. The results of the qualitative study provide a sufficient basis for an assessment of the activities offered by catering undertakings in this respect.

The assessment of the demand was carried out using quantitative data. A total of 314 European tourists were surveyed who were in Latvia at the time of the survey. The survey was conducted in the city of Riga. The survey was aimed at clarifying the views of potential foreign customers, particularly tourists from the Nordic countries, on the importance of environmental sustainability aspects when choosing catering services. The questionnaire covered environmental sustainability aspects only that can be assessed by the customer –waste sorting, using disposable containers, etc. Their opinion on importance was assessed by respondents on the six-point Likert scale, where 1 – is not significant at all and 6 – is very significant. The six-point scale was selected to avoid a neutral average score. The data have been analysed using descriptive statistical methods. The views of tourists have been assessed together for the whole sample and separately for Nordic tourists. The Nordic tourists have been selected as a distributable sample on the basis that, compared to other European countries, these countries much more focus on sustainability aspects and their importance at all stages of education (Seikkula-Leino, Jónsdóttir, Håkansson - Lindqvist, Westerberg, Eriksson - Bergström 2021). Therefore, further studies will make it possible to compare and draw conclusions on the impacts of education on people's decision-making.

The qualitative part of the study conducted semi-structured interviews with catering company executives. Interviews aimed to assess the introduction of the following three green practices in catering companies – waste management practices, energy efficiency and water saving practices, and product purchase and supply practices. The information obtained in the interviews was coded and grouped according to the predefined aspects. In addition, managers of companies were asked to self-assess the defined green practices in the company on a five-point scale where 1 – very bad and 5 – excellent. Seven catering companies that have identified themselves as sustainable providers of catering services in the public space were selected for the research. The companies included in the study were coded.

5.3. Research and analyses

To ascertain the importance of environmental sustainability aspects in choosing a catering company for tourists, a survey was conducted. Overall, tourists from 14 European countries, travelling in Latvia at the time of the study, participated in the research. Of all respondents, 44 % were tourists from the Nordic countries.

In the beginning, it was essential to clarify respondents' common habits of eating outside the house on a holiday. This makes it possible to understand if the environmental sustainability of catering activities is important for respondents at all. The results showed that there was a strong demand for catering services. Only 3 respondents noted that they haven't eaten outside in the course of the past three months. In addition, 56 % of respondents indicated that they had eaten outside at least four times over the past three months.

The findings reveal that for respondents the most important aspects of environmental sustainability involve the commitment of companies to recycling and sorting of waste. 89 % of tourists (Fig. 5.1) identified this as an important aspect (more important than irrelevant, important, very important). Moreover, there is no difference in this regard between the views of Nordic tourists and other European tourists. This aspect also has the highest overall average score of 4.61 and a low standard deviation of 0.99. This can be explained by the common position of the European Union to ensure that at least 65 % of all waste is sorted and recycled by 2035, which is also being actively communicated and explained in public. The fact that the company supplies takeaway food in customers' containers only is significantly less important to respondents (57 % of respondents indicated this as important). In part, this may be because not all customers choose to take food with them and therefore this aspect is irrelevant to them.

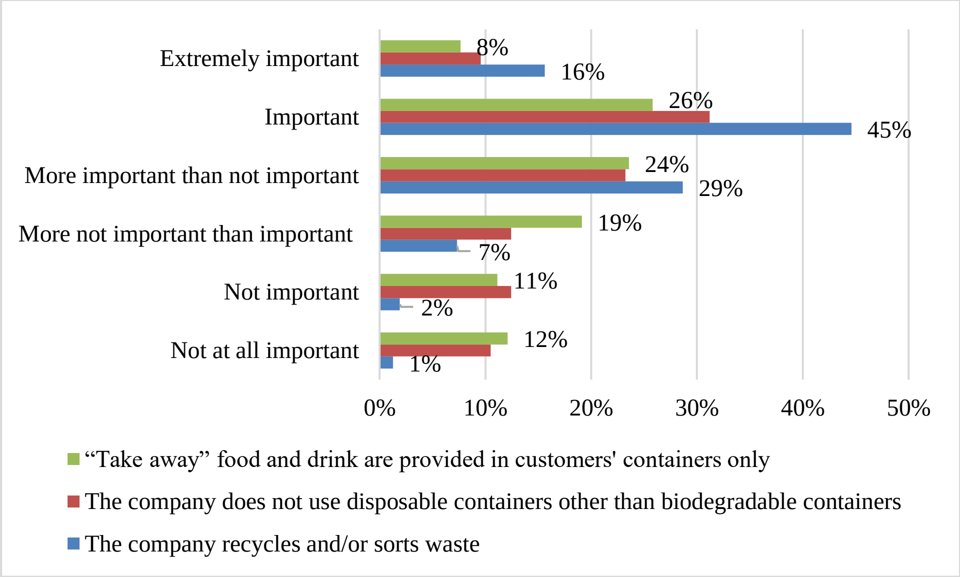

Fig. 5.1. Tourists' views on the importance of the activities of businesses related to environmental sustainability

Analysing the importance of environmental sustainability aspects that can directly affect the health of the customer (Fig. 5.2), it can be concluded that the most important aspect to potential customers is that a catering company's menu includes dishes prepared from local products. 68 % of tourists have identified these aspects as important. It should be noted that this aspect is more important to Nordic tourists, where 73 % of respondents, respectively, identified it as essential. The respondents also attach great importance to the fact that the company does not use semi-hydrogenated fats, food additives as taste enhancers, glutamate, sodium nitrates, paints, etc. 66 % of respondents identified it as an important factor. Moreover, this factor was the most important to the respondents aged 45 and older and 100 % of this age group noted it as important.

61.5 % of the respondents think that it is important that a catering company promotes some of its dishes as healthy, where, for example, less salt or oil is used.

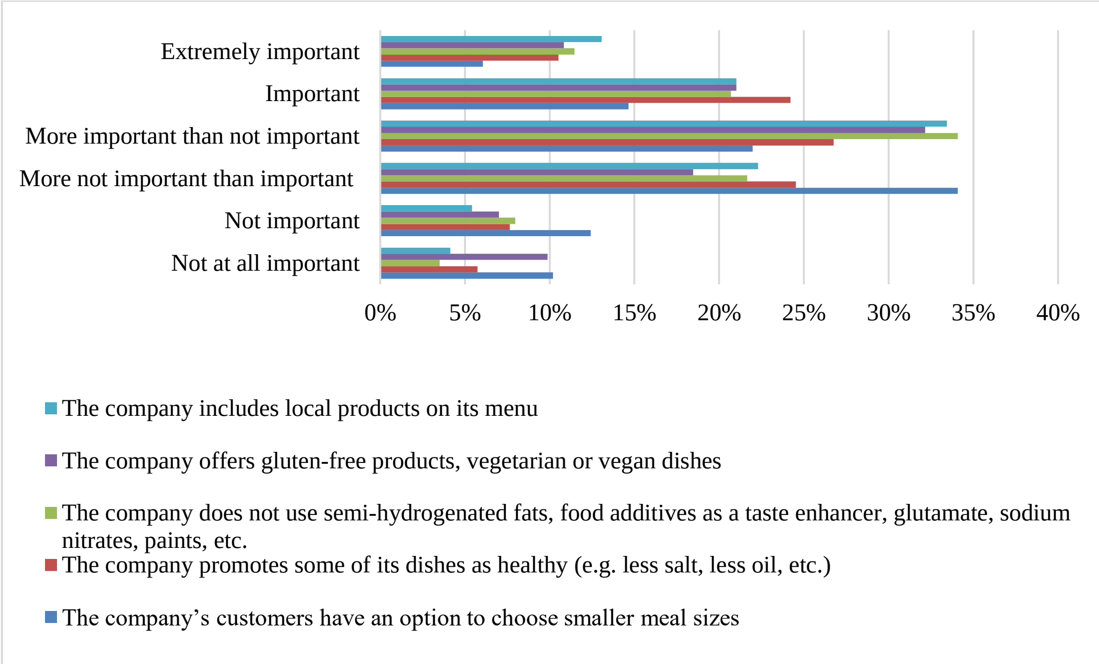

Fig. 5.2. The importance of the environmental sustainability factors related to human health for tourists

The possibility of purchasing a smaller size meal, thus allowing for the reduction of food waste was not considered as important – 56 % of the respondents described it as very unimportant. According to the respondents, sizes of meals may be equal to the amount needed per meal and this aspect is not relevant for the respondents.

In general, the use of local products appears to be the most important thing for the respondents. This is demonstrated by the highest average of 4.02 with a standard deviation of 1.22, which indicates a relatively small distribution. The smallest average (3.37) is for the optional factor of smaller-sized meals (standard deviation – 1.33).

In the closing question of the survey, the respondents were asked to assess how well were they informed about the sustainability practice at the catering company they visited most recently. Of all the tourists, 14 % noted that there was no information available at all on the aspects of the company's sustainable practices. On a positive note, it should be noted that 13 respondents indicated that information was available from various sources (home pages, menus, information posters, etc.). These respondents also valued each aspect of sustainability more significantly.

A qualitative study was carried out to assess the practices of catering companies in promoting environmental sustainability. In the analysis of interviews with seven catering companies, all of the company practices they had mentioned were compiled and grouped into three pre-defined environmental sustainability groups.

Information compiled from interviews in the “waste management practice” group, leads to the conclusion that the most common use is the sorting of waste, which is applied in all the companies analysed. Other practices such as the rational ordering of products, thereby reducing waste generation, as well as nature-friendly packaging, are on the agenda of the five catering companies analysed.

In terms of energy efficiency and water saving, the introduction of energy-efficient lighting was often mentioned − five companies have installed energy-efficient lighting. In the introduction of other activities, company leaders mentioned different practices. A more in-depth analysis of interviews revealed that managers understand energy efficiency differently and their practices were not directly comparable. For example, during periods of lower customer turnout two companies use their equipment only in part. Mechanically reducing electricity and water consumption in cases where it was not necessary to use them in full also was mentioned by several company executives. Although positive activities, they cannot be assessed as practices indicate a systemic approach to addressing this aspect.

In terms of product delivery practices, it can be concluded that all companies purchase also local products for their menus. Therefore, it is clear that not only local producers of products are supported, but also that transport and emissions from the product supply chain are significantly reduced. To draw a clear comparison of the proportion of local products in the common menu, an additional in-depth study is needed, since none of the company's executives could say how proportionally the products purchased were of local origin.

Overall, one can conclude that all the companies have implemented individual environmental sustainability practices, however, definite actions are on the agenda of only one of the companies. The CEO of this company stressed that the company introduced such specific practices as the use of unconsumed food for feeding animals, the development of a demand-based menu, decreased use of paper towels as well as utilization of energy-efficient kitchen equipment and lowering of water pressure in the production process. No other company has introduced such or similar practices in their daily work.

Processing of information acquired at all of the interviews one can conclude that the aspects of environmental sustainability are being practised at the catering companies only in part. This is evidenced by both the number of practices mentioned in the interviews and the self-assessment where none of the managers assessed their overall environmental sustainability practices as excellent (Tab. 5.1).

The analysis of the self-assessment survey of managers of the catering companies by specific environmental sustainability groups reveals that the lowest ratings are related to energy efficiency and water-saving practices where the self-assessment index is 2.86 and standard deviation – 0.38. This shows a homogeneous low self-assessment of company managers. According to the managers, the highest-rated company performance is related to their product purchase and supply practices The average self-assessment index in this category is 3.86. The self-assessment results lead to the conclusion that company managers, despite having not implemented comprehensive positive practices of environmental sustainability, understand their importance and necessity.

Table 5.1.

The self-assessment of catering company managers of the main environmental sustainability criteria

Company	Waste management practices	Energy efficiency and water-saving practices	Practices for the purchase and supply of products	Total sustainability (self-assessment)	Total sustainability (calculated average)
A	3	3	5	5	4
B	4	3	4	5	4
C	4	3	4	3	3.5
D	3	3	4	4	3.5
E	4	2	4	3	3.25
F	4	3	3	4	3.5
G	3	3	3	3	3

5.4. Conclusions and dissuasions

The significance of environmental sustainability or green practice is increasing in society. This means that there is a necessity for increased activities of businesses, including catering services, to develop their businesses sustainably.

Overall, assessing the significance of environmental sustainability factors in the demand for catering services one can conclude that potential clients hold in high regard such aspects, which have been communicated publicly most of all, as the sorting of waste, refusal to utilise plastic packages, etc. With the rising understanding of the impacts of the environment on human health, clients also attach great importance to the aspects affecting human health and well-being. In this respect, clients specifically point to the practice whereas companies do not use semi-hydrogenated fats, food additives as taste enhancers, glutamate, sodium nitrates, paints, etc. Clients, including tourists, pay significantly less attention to the aspects which do not affect the particular client directly but rather affect environmental sustainability in general. The opportunity for collecting “take-away” food and drink in customers’ containers only is valued as an important aspect by only 57 % of the respondents, while the practice of companies abandoning disposable containers in favour of biodegradable ones – by 64 %.

With the assessment of the green practices adopted by catering companies and the awareness of managers of their importance, one must conclude that the companies are implementing the basic practices, like sorting waste or introducing energy-efficient lightning while not rushing into the implementation of other additional measures. To understand the reasons for companies failing to implement many other possible practices affecting environmental sustainability, it is necessary to continue the research, including by broadening its scope. This kind of in-depth study would also provide for developing a national or municipal programme of support to businesses in the implementation activities.

To summarize, it can be concluded that there is a demand for green practices by potential clients. However, the client demand has been focused on those aspects, which either affect a particular person directly or have already been well-established among the general public. Clients still do not demand that businesses implement a broader range of green practices leading to the development of sustainable businesses and a greener environment in general. The activities of business can be characterised as being at their early stages and companies predominantly implement practices creating cost-saving effects or are mandatory by the current regulatory acts. This means that businesses still have broad opportunities for adopting and implementing additional measures, but this would, inter alia, require greater customer demand.

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PART 6

THE ROLE OF HYDROGEN IN A FUTURE CARBON-FREE ENERGY ECONOMY – AN OVERVIEW WITH A SPECIAL FOCUS ON THE MOBILITY/TRANSPORTATION SECTOR

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6.1. Introduction

On the way to a secure and climate-neutral energy supply, hydrogen can play an important role as the energy carrier of the future. The EU faces a major challenge here, as its energy production and consumption is still dominated by fossil fuels and these fuels are responsible for a large proportion of anthropogenic greenhouse gas emissions. In addition, many European countries are heavily dependent on energy imports in the form of coal, oil, and natural gas. Hydrogen is a flexible, easily storable, and transportable energy carrier. In July 2020, the European Commission proposed a hydrogen strategy for a climate-neutral Europe. Hydrogen is a key priority to achieve the European Green Deal and Europe's clean energy transition because it can be used as a feedstock, fuel, or an energy carrier and storage, and has many possible applications across industry, transport, power, and buildings sectors (EC 2020, A hydrogen strategy for a climate-neutral Europe).

The following chapter will focus on the opportunities of producing hydrogen in a sustainable and climate-friendly manner, thus replacing the fossil fuels that are predominantly used used in the transport sector. The transport sector is responsible for more than 20 % of anthropogenic CO_2 emissions [1]. In the future hydrogen has a huge potential to replace such fossil fuels and to ensure renewable, sustainable, and climate-friendly transport.

6.2. Hydrogen as an energy carrier

Hydrogen (named after the Greek words hydro for "water" and genes for "forming") is a chemical element with the symbol H and atomic number 1 in the periodic system of elements and was discovered by the English physicist Henry Cavendish in

1766. Under standard conditions (0 °C & 1.013 bar) it is a non-toxic, colorless and odorless gas and exists as a diatomic molecule with the chemical formula H_2.

It's the most common element in the universe, estimated to account for 90 % (73 % of the mass of all matter in the visible universe) of all atoms. Although hydrogen is the most abundant element in the universe it makes up only about 0.14 % of Earth's crust by weight and in its pure molecular form (H_2) rare on Earth [2]. It is present on Earth combined with other elements, forming e.g., water and organic materials such as Biomass and fossil fuels (all hydrocarbon fuels are chemical compounds of carbon and hydrogen). Hydrogen in itself is not an energy source, but it is a clean and versatile energy carrier that can be produced from a variety of sources, including renewable energy sources. It's a carbon-free energy carrier, which means that no CO_2 emissions are released into the atmosphere when hydrogen is burned or converted. Hydrogen can be used directly via fuel cells or in gas turbines for electricity generation, and as feedstock to produce synthetic fuels such as methane, methanol, Fischer-Tropsch diesel and gasoline fuels, sustainable aviation fuels such as synthetic kerosene, and a multitude of chemical raw materials such as ammonia.

Hydrogen is a very promising energy carrier, caused by the high energy content stored in the molecule. On a mass basis, hydrogen has an energy content of 143 MJ/kg (gross caloric value GVV) and thus the highest energy density of all chemical fuels (Tab. 6.1). Even though hydrogen has the highest gravimetric energy density, its low density poses a challenge for storing and transporting large quantities of hydrogen.

Table 6.1.

Comparsion of caloric value and density of some common chemical fuels [3, 4]

Fuel	**GCV* (MJ/kg)**	**NCV (MJ/kg)**	**Density (kg/m^3) at 0 °C and 1 bar**
Hydrogen	141.7	120.0	0.090
Methane	55.5	50	0.716
Gasoline	42.7 – 44.2	40.1 – 41.8	0.720 – 0.775
Hard coal $_{(wf)}$	27 – 32	26 – 31	1.3
Woody biomass $_{(wf)}$	19 – 21	18 – 20	0.5 – 0.7

*****GCV: gross caloric value. NCV: net caloric value.

With a density of about 0.090 g/L (1 bar, 0℃) , gaseous hydrogen is about 8 times lighter than methane, and compression or liquefaction is required for economic use of hydrogen as an energy carrier (Fig. 6.1).

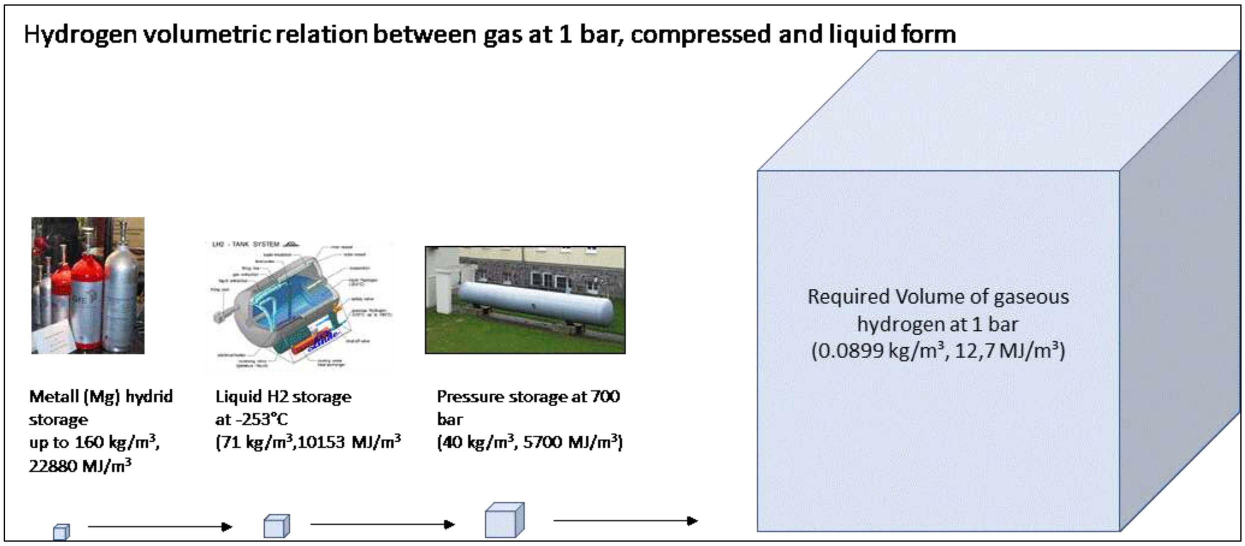

Fig. 6.1. Volume/energy density relation of hydrogen at various conditions

Since hydrogen is not available in nature in pure elemental form, it must be produced from a hydrogen-containing molecule (water or hydrocarbons) using a conversion technology that requires energy input. Hydrogen can be produced from fossil fuels (hydrogen-carbon molecules) or biomass resources (hydrogen-oxygen-carbon molecules) or be produced from water (hydrogen-oxygen molecules).

6.3. Production of hydrogen

Hydrogen is a carbon-free energy carrier, which means that no CO_2 emissions are released into the atmosphere when hydrogen is burned or converted, but this does not mean that hydrogen is produced without CO_2 emissions throughout its life cycle. Since hydrogen does not exist in pure molecular form in nature on Earth it must be produced from a hydrogen-containing molecule (water or hydrocarbons) using a conversion technology that requires energy input. The largest proportion of terrestrial hydrogen occurs in the compound water. In this form, it covers more than two-thirds of the earth's surface. Besides this, natural gas (essentially methane), petroleum, coal, and biomass are important to further hydrogen-containing compounds on Earth. Colors are defined to help to differentiate between the types of hydrogen depending on the production process. The most known color is green hydrogen, which indicates that the hydrogen is produced from renewable energy sources. Green hydrogen is defined as hydrogen created from renewable energy sources such as solar, wind, hydropower, biomass, biogas, or municipal waste. Green hydrogen can be produced via the electrolysis of water using renewable power or through the decomposition of biomass using biological processes (biogas/dark fermentation processes) or thermochemical processes, such as biomass gasification. Grey, brown or black hydrogen, is usually obtained from fossil sources and the production process will release huge amounts of CO_2 which is the most important greenhouse gas. Further used colors are purple or pink for hydrogen produced via electrolysis using nuclear power (theoretically CO_2 neutral), yellow hydrogen produced by electrolysis using grid electricity from various sources and those often not carbon-free, and turquoise hydrogen, produced by splitting methane into hydrogen and solid carbon (theoretically CO_2 neutral). White hydrogen is a further rare and widely unknown natural resource that scientists have found as a free gas in layers of the continental crust, deep in the oceanic crust, in volcanic gases, or hydrothermal systems.

More than 95 % of current global hydrogen production (approx. 120 Mt per year) is “grey”, “brown” or “black” hydrogen [5] shown in Fig. 6.2.

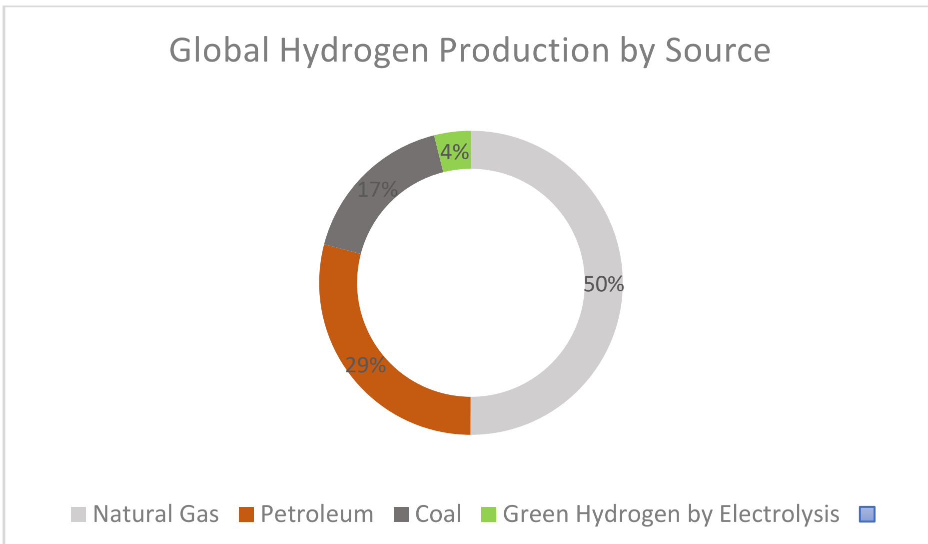

Fig. 6.2. Share of manufacturing processes in global hydrogen production

Hydrogen production from fossil fuels is neither climate-friendly nor sustainable. Even the theoretically CO_2-neutral production of pink or turquoise hydrogen cannot be considered sustainable production. In the case of purple or pink hydrogen, the risks associated with the operation of nuclear power plants for electricity production, and above all the unresolved problem of dealing with nuclear residues, must also be considered, and in the case of turquoise hydrogen, the methane leaks associated with the production of natural gas led to high greenhouse gas emissions to the atmosphere. In addition, purple/pink and turquoise hydrogen production has not yet taken place to any significant extent. Sustainable and climate-friendly hydrogen production must therefore be green hydrogen, whereby the possibilities of production from the water via electrolysis (exclusively with renewable electricity) as well as biomass-based processes can be used.

Green Hydrogen Production via Electrolysis.

Hydrogen production via electrolysis is a process that involves the splitting of water molecules into hydrogen and oxygen using an electric current.

Basic principle:

Decomposition of water into hydrogen and oxygen by using electric current in a volume ratio of 2:1.

Reaction Formula:

$$H_2O_{(liquid)} + energy \longrightarrow H_{2\,(gaseous)} + O_{2(gaseous)},\ \Delta H_R = 242\ kJ/mol$$

The energy demand for the decomposition of water is defined by the standard enthalpy of the formation of water (ΔH_R= -242 kJ/mol) and the efficiency of the electrolyzer. Typical system efficiencies of commercial electrolyzers are in the range of 75 %, meaning approx. 75 % of the electrical energy used for the decomposition is chemically stored in the hydrogen. Larger pressurized electrolyzers have a specific energy consumption between 4.5 and 5.0 kWh/Nm³, leading to system efficiencies of up to 78 %. Electrolysis using renewable electricity offers a sustainable and environmentally friendly way to generate hydrogen and store energy chemically and it does not rely on fossil fuels and produces only water vapor as a byproduct.

Like fuel cells, electrolyzers consist of an anode and a cathode separated by an electrolyte (Fig. 6.3).

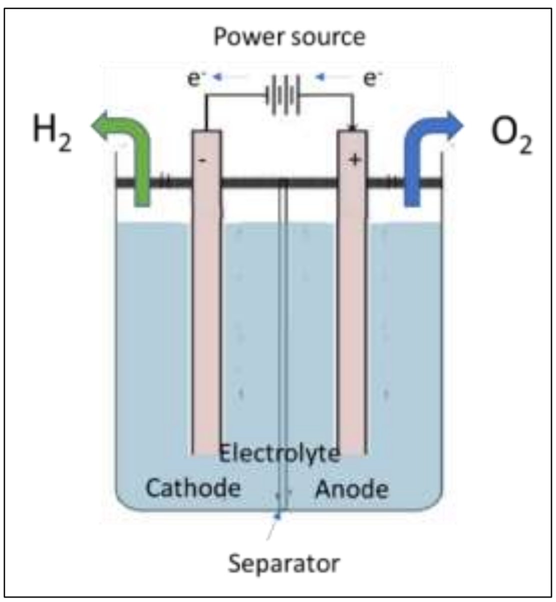

Fig. 6.3. Basic principle of electrolysis

Different types of electrolyzers are available on the market. The most common types are:

- Alkaline Electrolysers (AEL);
- Polymer Electrolyte Membrane Electrolysers (PEMEL);
- Solid Oxide Electrolysers (SOEL) (Tab. 6.2).

Table 6.2.

Cell reactions and temperature ranges of the three most common types of electrolyzers

Type of electrolyzer	Temperature range (°C)	Cathode reaction (HER)	Anode reaction (OER)	Charge carriers
AEL	40 – 90	$2H_2O + 2e^- \longrightarrow H_2 + 2OH^-$	$2OH^- \longrightarrow 1/2O_2 + H_2O + 2e^-$	OH^-
PEMEL	20 – 100	$2H^+ + 2e^- \longrightarrow H_2$	$H_2O \longrightarrow 1/2O_2 + 2H^+ + 2e^-$	H^+
SOEL	700 – 1000	$H_2O + 2e^- \longrightarrow H_2 + O^{2-}$	$O^{2-} \longrightarrow 1/2O_2 + 2e^-$	O^{2-}

In alkaline electrolysis (AE), the electrolyte used is typically a solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH). This type of electrolysis has been widely used for many years and is known for its high efficiency and durability.

PEM electrolysis employs a solid polymer electrolyte membrane, which allows for higher operating pressures and faster response times. This type of electrolysis is more suitable for smaller-scale applications and has gained popularity in recent years due to its compact size and flexibility.

Solid oxide electrolyzers (SOE) have only recently started to receive greater interest. The Solid oxide electrolysis uses a solid ceramic material as the electrolyte, that selectively conducts negatively charged oxygen ions (O^{2-}) at elevated temperatures and generates hydrogen in a slightly different way. Steam at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions then pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit.

Solid oxide electrolyzers operate at temperatures around 700 – 1000 °C [6], compared to PEM electrolyzers, which operate at 20 – 100 °C, and commercial alkaline electrolyzers, which typically operate at less than 40 – 90 °C).

Hydrogen production through electrolysis offers synergy effects, especially concerning the fluctuating energy production from volatile renewable energies such as wind and solar energy. In combination with the dynamic and intermittent power generation characteristics of wind power and PV installation systems, electrolyzers can be operated when these renewable energies are in abundance and prices are low. The combined generation of hydrogen and electricity in wind farms then increases the flexibility of the systems, since the energy can be used continuously in times when the wind farms are otherwise curtailed caused by excess electricity in the grids. Furthermore, the produced hydrogen represents a storage option for the excess energy. With the current standard efficiency of the electrolyzers, 75 to 78 % of the (renewable) electrical energy generated in wind farms and PV applications can be stored chemically in hydrogen and used in other applications and sectors of the energy economy.

6.4. Utilization opportunities for hydrogen

Around 120 Mt tons of hydrogen are currently produced worldwide each year, of which two-thirds is pure hydrogen and one-third is in a mixture with other gases [7]. This represents 17.1 exajoules (EJ) or about 3% of today's global primary energy consumption (595 EJ in 2021). This hydrogen is mainly used in oil refining and for the production of chemical fertilizers (70 Mt/year) and in other applications such as metallurgy or Methanol production and other utilization options (45 Mt/year) (Fig. 6.3).

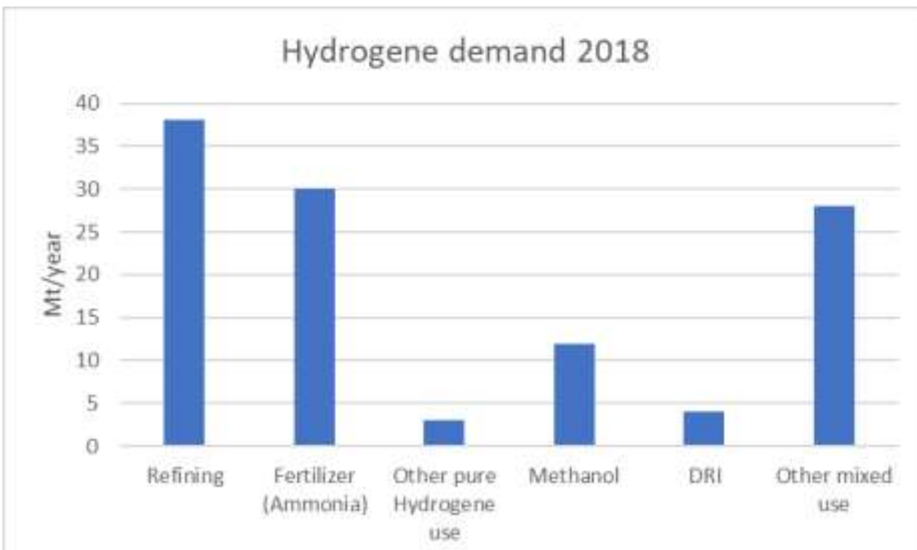

Fig. 6.3. Global annual demand for hydrogen 2019[1]

Since the current production of hydrogen is based on fossil fuels more than 900 Mt of CO_2 emissions are released by the hydrogen production processes. For this reason, the switch of hydrogen production from fossil fuel-based production to low-emission hydrogen (green hydrogen) has the highest priority.

In the near future, Hydrogen and its derivatives should be predominantly used in the decarbonization of those sectors, where emissions are hard to abate and alternative

[1] *https://www.statista.com/*

solutions are either unavailable or difficult to implement, such as heavy industry and transportation (especially in shipping, aviation, and heavy-duty transport).

Green hydrogen and green hydrogen-based fuels are important tools for the decarbonization of heavy industry and the energy economy in general. Projections indicate that the market for green hydrogen will grow strongly in the coming years. While fossil-produced hydrogen has dominated so far, production capacities of up to 600 Mt/year of green hydrogen (five times more than the current fossil fuel-based Hydrogen generation) are expected to be built up by 2050. Especially in the transport sector, particularly in applications where other clean energy alternatives, such as direct electrification, present technical challenges or cannot be implemented, green hydrogen can play a significant role in the future. Other promising options include converting the hydrogen into biomethane, for example, which can then be fed into natural gas grids as a substitute for fossil natural gas and made available for a wide range of applications in the industrial, heating, and mobility sectors. Hydrogen can be well integrated into existing energy infrastructures. It can be transported as a gas by pipelines or in liquid form by ships, much like liquefied natural gas (LNG). It can be transformed into electricity and methane to power homes and feed industry, and into fuels for cars, trucks, ships, and planes.

Future opportunities for Hydrogen in the mobility and transportation sector

The transportation sector is responsible for releasing huge amounts of GHG emissions into the atmosphere each year. In the European Union, about 23 % of all GHG emissions are caused by the transport sector (including international aviation) (Fig. 6.4).

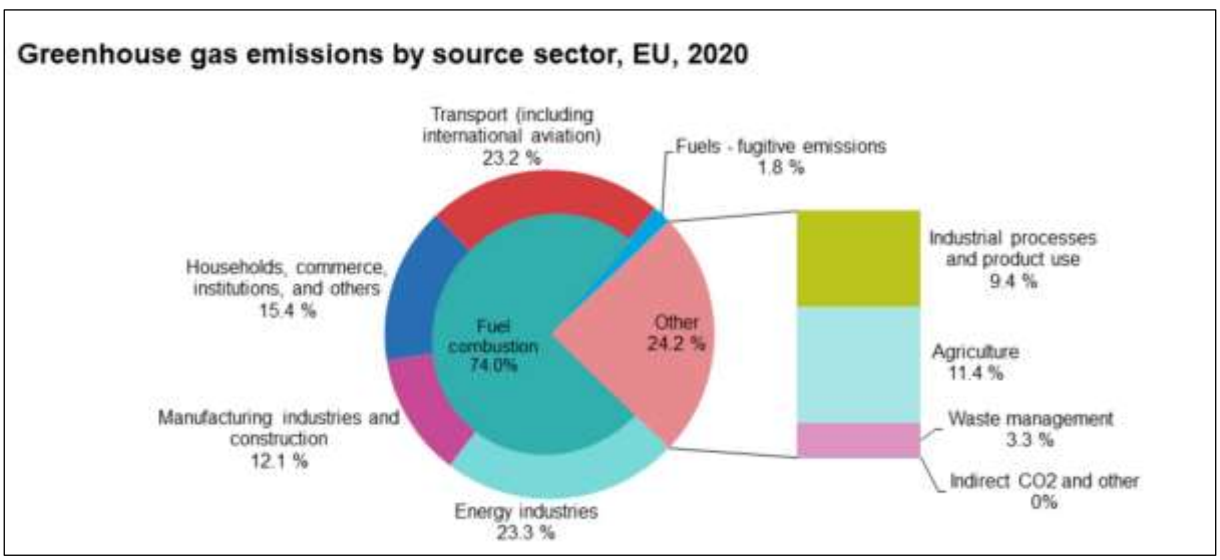

Fig. 6.4. GHG emissions by sector, EU, 2020 [2]

[2] *Source: EEA*

The highest share is related to Road transportation (70 % of the total GHG emissions in the transport sector), counting about 700 Mt CO_2/year whereby passenger cars are the biggest single contributor, emitting nearly 500 Mt CO_2/year, and heavy-duty vehicles emitting nearly 200 Mt CO_2/year. Aviation and maritime transport are counting each with 14 % and Railway and Others are counting only 1 % each to the total GHG emissions in transportation (Fig. 6.5).

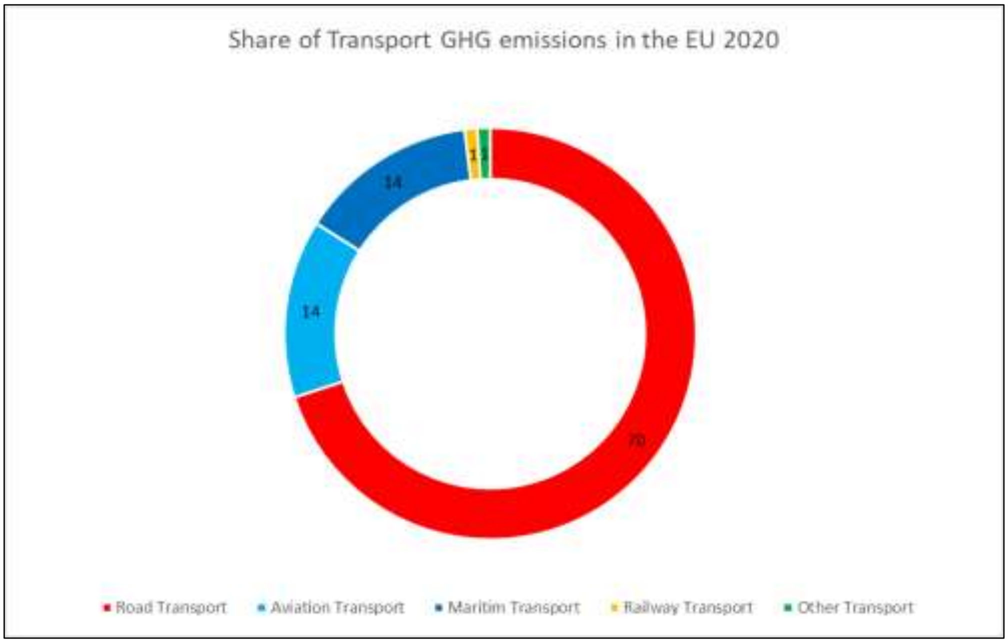

Fig. 6.5. Share of transport GHG emissions in the EU 2020

In principle, hydrogen can be used in all the above-shown segments of the transport sector and contribute to its decarbonization.

6.5. Direct use of hydrogen in fuel cell electric vehicles (FCEV)

For road transportation, the direct use of Hydrogen is possible in fuel cell electric vehicles (FCEVs) which are available as passenger cars and as heavy-duty vehicles. Like all-electric vehicles, FCEVs use electricity to power an electric motor (Fig. 6.6).

In the fuel cell as the key component of a FCEV, the hydrogen reacts electrochemically to produce electricity which is transferred to a battery required to power the car. The fuel cell is composed of an anode, cathode, and an electrolyte membrane, similar to the electrolysis system but working in the opposite principle.

Fuel cell cars can carry enough hydrogen fuel for a 500-600 kilometer of range and their tanks can be refilled as quickly as that of a standard car's gas tank [9]. Due to the low volumetric energy density of hydrogen, the tank has to be pressurized with a pressure of up to 700 bar to achieve sufficiently large vehicle ranges.

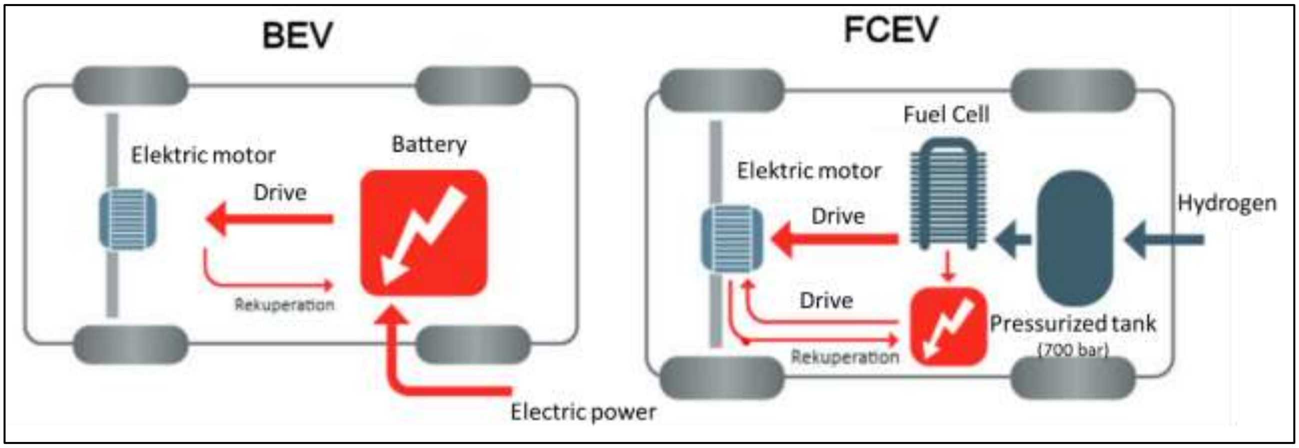

Fig. 6.6. Basic principle of BEV and FCEV [8]

Fuel cell vehicles have only just entered the market because they are very expensive (twice as expensive as comparable vehicles with internal combustion engines) and a comprehensive hydrogen infrastructure must first be built up.

Fuel cell electric vehicles from the manufacturers Toyota and Hyunday (Toyota Mirai and Hyundai Nexo) are currently the dominant models on the European market. Even if these models are available as series vehicles, they will probably only be used to a limited extent in passenger transport. It is expected that battery electric vehicles (BEVs) in particular will make a significant contribution to decarbonization in this area. In the heavy-duty traffic segment, in which other framework conditions prevail simply because of the enormous weight of the required battery systems and the longer charging times of the batteries, fuel cell vehicles can make an interesting contribution to reducing the GHG emissions from this segment, as the charging options and range of hydrogen fuel cell heavy trucks make it more suited for long-distance travels. Nonetheless, with an estimated market for only 45,000 heavy trucks with fuel cell systems in Europe in 2030 (there are more than 6.2 million trucks in circulation throughout the EU) alternative decarbonization options have to be implemented as soon as possible [10].

6.6. Use of hydrogen to produce synthetic (Bio-)fuels

Since electrification (directly through BEVs and indirectly through FCEVs) cannot be deployed in all segments of the transport sector in the short term, existing internal combustion engines will continue to dominate e.g., the road, aviation, and maritime transport for decades, which means that sustainable renewable fuels are needed to power these transport segments as well to achieve the global climate protection goals. Sustainable solutions such as renewable diesel, gasoline, kerosene, and synthetic natural gas that can be used as a direct replacement to fossil fuels in combustion engines, will help significantly to cut emissions with the urgency that is required. Processes for the production of synthetic (climate-neutral fuels) use carbon-containing gases such as

CO or CO_2 to produce fuels such as petrol, diesel, kerosene, or synthetic natural gas through a chemical reaction with hydrogen. However, the prerequisite for the fuel produced to be climate-neutral is, that not only the hydrogen used but also the carbon source is not fossil, but renewable, i.e., from biomass using the Biomass-to-Liquid (BtL) pathway to substitute the fossil fuels. Almost any type of biomass can be used for biofuel production. However, considering sustainability criteria, the biomass use path should not impact the food or feed use sector and for this reason, especially agricultural and forestry residues and biowastes are promising raw materials for biofuel production. Synthetic Biofuels are fully compatible with the already existing, conventional fuels and can be used as a drop-in into the existing fuel infrastructure, but also used as stand-alone products.

Production of Synthetic Biofuels via Biomass Gasification.

Gasification is a key process for the thermochemical conversion of biomass to produce synthetic biofuels. In the presence of an oxygen-containing gasification agent (air, oxygen, water vapor, or carbon dioxide), the biomass is converted into a gaseous mixture at high temperatures of over 800°C, which mainly consists of CO, H_2, CO_2, CH_4, and other components such as H_2O, H_2S, NH_3, tar, and other trace substances. The gas produced (called synthesis gas when used for chemical synthesis) needs to be cleaned and can be converted into various carbonaceous fuels depending on the synthesis process chosen. Various synthesis processes are available to convert product gases from biomass gasification into synthetic biofuels. What all processes have in common is that a disproportionately high amount of hydrogen is required from the carbon monoxide contained in the syngas, but when biomass is gasified, the product gas is hydrogen deficient and has a low H_2/CO ratio (usually less than one). Depending on the selected production pathway for synthetic biofuels additional (green) hydrogen is required for the chemical reactions (Fig. 6.7).

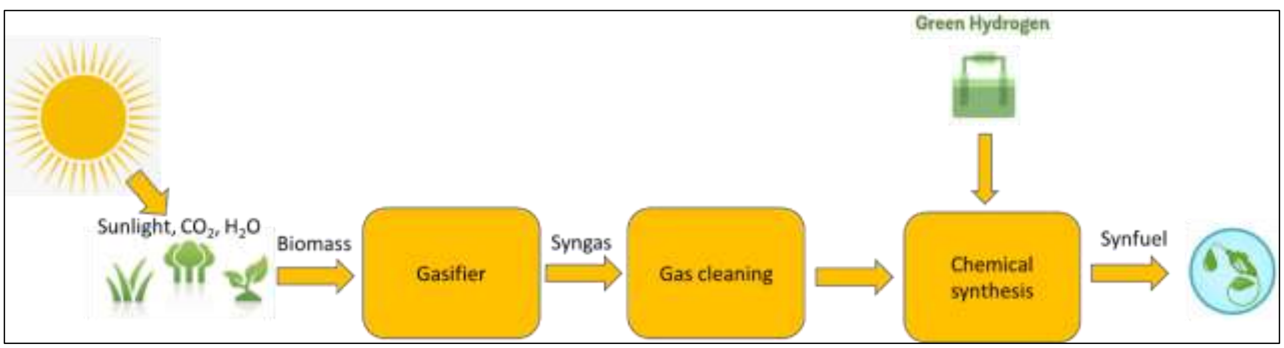

Fig. 6.7. Production pathway for synthetic biofuels

The most common synthetic biofuels include:

Fischer-Tropsch fuels (FTS-fuels) = Fuels for diesel and gasoline engines (also named BtL or "Biomass to Liquid" fuels).

The Fischer-Tropsch synthesis (also known as the Fischer-Tropsch process) is an industrial-scale process developed by Franz Fischer and Hans Tropsch in 1925 for the conversion of carbon monoxide-hydrogen mixtures into liquid hydrocarbons. It is a heterogeneously catalyzed reaction of CO and H_2 (main components of the so-called synthesis gas) to hydrocarbons. Metals, above all iron, cobalt, nickel, and ruthenium, are used as catalysts. The main reaction equation of the Fischer-Tropsch synthesis is:

$$nCO + 2nH_2 \rightarrow (-CH_2-)_n + nH_2O \qquad \Delta H_R = -165 \text{ kJ/mol.}$$

The conversion of the H_2 and CO into the final product is a multi-step reaction with several intermediate compounds and consists of a multitude of formed hydrocarbon compounds. The reaction can be carried out either as a high-temperature synthesis at 300-350℃ and 20−40 bar or as a low-temperature synthesis at 200-220 ℃ and 20 bar. Due to the exothermicity of the reaction, the reactors have to be cooled to prevent overheating and thus a shift in the reaction equilibrium and a thermal deactivation of the catalysts. The temperature also affects the adsorption and desorption processes on the catalyst surfaces. Thus, high-temperature synthesis leads to an increased formation of short-chain hydrocarbons that can be converted into gasoline fuels, and low-temperature synthesis to an increased formation of long-chain hydrocarbon compounds that can be used to produce diesel fuels. In any case, due to the product range that is being formed, further processing is necessary to be able to produce fuels that comply with the standards for transportation fuels.

SNG (synthetic natural gas) – synthesis produced by thermochemical synthesis of CO and H_2 to produce CH_4 which can be used in CNG vehicles and for all applications using natural gas.

Synthetic natural gas (SNG) describes a variety of natural gas alternatives and can be derived from coal, biomass, or other carbonaceous fuels using hydrogen and CO/CO_2 as carbon carriers.

Using Syngas from biomass gasification the main reaction of methanation is the highly exothermic conversion of carbon monoxide and hydrogen into methane.

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad \Delta H_R = -206 \text{ kJ/mol} \qquad (6.1)$$

Due to the need to reorganize the energy industry ecologically and economically, the methanation reaction using carbon dioxide as a carbon carrier, which was discovered in 1902 by the French chemist Paul Sabatier and was rather insignificant at the time, has attained new high relevance today. The methanation of hydrogen with CO_2 takes place in two main steps:

- 1st step: Reversed Water Gas Shift Reaction (RWGS)

$$CO_2 + H_2 \rightarrow CO + H_2O \qquad \Delta H_R = 41 \text{ kJ/mol}$$

- 2nd step: CO Hydrogenation

$$CO + 3H_2 \rightarrow CH_4 + H_2O \qquad \Delta HR = -206 \text{ kJ/mol}$$

- Overall reaction: CO_2 methanation = Sabatier reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \qquad \Delta H_R = -165 \text{ kJ/mol}$$

Like the Fischer Tropsch reaction, the methanation reaction is highly exothermic and the methanation reactors have to be cooled to prevent overheating and a shift in the reaction equilibrium, and a thermal deactivation of the catalysts. The world's first industrial-scale plant that generates feed-in synthetic natural gas from CO_2 and hydrogen from renewable electricity was built in Werlte (Germany) in 2013. The used CO_2 is provided from a Biogas-upgrade (removal of the carbon dioxide contained in the raw biogas) plant which is already producing biomethane for the injection into the gas grid. Further just newly implemented demonstration plants for methanation are using CO_2 from the ethanol production process as carbon carriers for the methanation.

Methanol synthesis and further conversion to DME to produce a liquid fuel for compression-ignition engines.

BASF chemists had been working on the high-pressure hydrogenation of carbon monoxide since 1913, and Mittasch and his colleagues discovered the formation of oxygen-containing compounds - including methanol - through the reaction of hydrogen and carbon monoxide on iron catalyst surfaces. In 1923 the chemist Matthias Pier succeeded for the first time in the large-scale production of methanol from synthesis gas in the high-pressure process over zinc oxide-chromium oxide catalysts and developed a process that produced pure methanol at pressures of 200 to 300 bar and temperatures of 350 – 400 °C. Modern methanol synthesis can be performed with both carbon monoxide and carbon dioxide using the following basic equations:

$$CO + 2H_2 \rightarrow CH_3OH \qquad \Delta H_{R(300\,°C)} = -91 \text{ kJ/mol} \qquad (6.2)$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \qquad \Delta H_{R(300\,°C)} = -50 \text{ kJ/mol} \qquad (6.3)$$

High-pressure synthesis processes (p = 250-350 bar, T = 320-400 °C) can be performed using ZnO/Cr_2O_3 catalysts or low-pressure synthesis methods (p = 50 − 100 bar, T= 200 – 300 °C) can be performed using more active and more selective Cu/ZnO catalysts. Due to the milder reaction conditions, low-pressure synthesis is now preferably used for large-scale methanol production.

The further conversion of methanol into dimethylether (DME) is of special interest to the transport sector. The advantage is that DME (dimethyl ether, C_2H_6O) can be used in conventional diesel engines without modifying the engine technology and is, therefore, suitable as a fuel in long-distance transport (truck fleets). DME is a gas that can be liquefied at a pressure of five bar. The lower energy content of DME (28.4 MJ/kg), which is just over half that of conventional diesel fuel (42.5 MJ/kg), can be simply equalized by the installation of larger tanks [11].

For example, DME (C_2H_6O) can be obtained by acid-catalyzed condensation of 2 molecules of methanol (with the elimination of water). The reaction equation is:

$$2CH_3OH \rightarrow CH_3\text{-}O\text{-}CH_3 + H_2O$$

The synthesis is a two-stage process in which methanol is first produced with the help of appropriate catalysts (usually $CuO/ZnO/Al_2O_3$) at temperatures of 270 °C and a pressure of 5 to 10 MPa (conventional methanol synthesis), which is dehydrogenated in a second step in the presence of an acid catalyst (usually aluminum) within the same process. If conventional fossil diesel fuel were to be replaced by bio-DME, the CO_2 emissions could be reduced by around 95 percent. Bio-DME thus has great potential to replace the consumption of fossil diesel fuel, especially in heavy and long-distance traffic.

6.6. Summary

Hydrogen is not a primary energy carrier, but an energy carrier that can be provided from renewable energy. Green hydrogen generated by using renewable energy will play an important role in the future energy supply system to reduce greenhouse gas emissions and ensure energy security based on non-fossil renewable resources. Generation and use of energy can be separated in terms of time and space, and its function as a chemical storage device can positively influence the power grids concerning the availability of volatile renewable electricity within the framework of sector coupling.

The transport sector is one of the main causes of greenhouse gas emissions (in the EU around more than 23 % of the total GHG emissions). At present, fossil fuels are used almost entirely in the transport sector, which means that the transport sector releases large amounts of greenhouse gases. In future transport, hydrogen can be used directly, e.g., in fuel cell electric vehicles, or as a secondary energy source for the production of synthetic biofuels in transport segments where battery electric drives are not suitable (e. g. aviation, maritime transport, or heavy and long-distance transport). Hydrogen will not be the most suitable energy carrier in all segments of the transport sector. Especially in the area of individual mobility with passenger cars, battery-powered vehicles have clear advantages compared to hydrogen or synthetic fuels. On the one hand, it is easier to set up a charging infrastructure for BEVs than a hydrogen infrastructure for FCEVs, and the efficiency of energy use is also significantly higher because there are no conversion losses for hydrogen production and use. But in aviation, maritime transport, or heavy and long-distance transport vehicles the use of hydrogen in its pure form or converted into synthetic biofuels is a promising opportunity for the near future.

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The contents presented in this chapter is part of the activities to support the partner Universities to become centers for the development of research of climate management to accelerate integration into the global climate market and to meet global climate regulation requirements by acquiring best European practices in the field of climate change prevention, adaptation, and mitigation.

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PART 7

CLIMATE-ORIENTED TECHNOLOGIES IN ROAD TRANSPORT: UNCONVENTIONAL AND ALTERNATIVE MOTOR FUELS

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7.1. Introduction

Today, motor fuels form the basis of the transport industry in the majority of countries of the world, and also make up the majority of oil refining products, simultaneously with the production of a significant load on all components of the environment at all stages of the life cycle. That is why careful attention should be paid to the study of the peculiarities of their application, as well as the development of alternative and environmentally friendly types of motor fuel.

In today's conditions, internal combustion engines of various types use appropriate motor fuels: automotive and aviation gasoline, diesel fuel for high-speed diesel engines, jet and rocket fuels, gas turbine fuels, heavy motor and marine fuels for slow-speed diesel engines, as well as compressed (compressed) natural gas and liquefied natural and petroleum gases. Liquid hydrogen is used as rocket fuel for powerful rocket carriers of some types; tests are being conducted regarding its application on automotive and aviation equipment.

The future of motor vehicles is mainly seen in non-traditional, including alternative, motor fuels, which provide a reduction in the consumption of petroleum fuels and minimize the carcinogenic and mutagenic danger of cars [1, 2].

Alternative motor fuels include: natural gas, as the most efficient energy carrier for the transition period; synthetic motor fuels (SMF), primarily alcohol, as well as dimethyl ether (DME) for diesel engines; biofuel; hydrogen, which can be used as a highly effective additive to combustible mixtures and as a necessary component in the production of SMP, as well as the main energy carrier. It should be noted that these alternatives, including composite, motor fuels have increased detonation resistance. Their octane numbers (OCD): methane – 120, propane – 112, butane – 94, methanol –

106, hydrogen – 130. At the same time, the indicators of composite fuel (petrol A-80 + 10% hydrogen by mass) are as follows:

- OCD – 98; $Q_н^p = 54$ MJ/kg;
- $ά_{lim.}$ = 0,7-2,0; prise ≤ 45 \$/GJ.

Some important physico-chemical and operational indicators of both petroleum and non-traditional motor fuels, including hydrogen, are presented in the table. 7.1 [3].

Table 7.1.

Physico-chemical properties of hydrocarbon motor fuels and hydrogen

Motor fuels	ρ, kg/m³	$Q_н^p$, MJ/kg	L_0, kg/kg	T_{max}, K	$ά_{lim.}$	Compocition, % mass		З, \$/ПО
						H/C	O	
Gasoline A-98	710-760	44	15	2350	0,7-1,1	17,6	–	≥ 45
Diesel	820-870	43	14,2	2370	0,9-5	16,3	–	≥ 40
Methanol	795	20	6,5	2175	0,7-1,4	33,3	50	≥ 30*
Propane-butane	542	46	15,2	2149	0,7-1,2	19,0	–	≥ 30
Methane	0,8 (416)	49-50	17	2065	0,8-1,7	33,3	–	≥ 20
Hydrogen	0,09 (71)	120,1	34,5	2470	0,2-5	100	–	≥ 90**

Notes. ρ – density (liquid methane and hydrogen); $Q_н^p$ – estimated lower heat of combustion; T_{max} – maximum temperature during fuel combustion in air; $α_{lim.}$ – the limit of sustainable burning of fuel according to the coefficient of excess air; P – price (market energy cost); * – methanol produced from coal (at the price of coal ~ 60 \$/t); ** – electrolytic hydrogen (at the cost of electricity ~ 0.25 hryvnias/kWh).

7.2. Natural gas

Natural gas, which has the highest hydrogen and anti-detonation indicators (among hydrocarbon motor fuels), is the most effective substitute for petroleum fuels for city vehicles with internal combustion engines. High heat-technical and anti-detonation indicators of natural gas (methane), a wide range of changes in concentration limits of ignition of gas-air combustible mixtures allow to significantly increase the degree of compression in internal combustion engines with forced, including fore-chamber-flare ignition, to realize energetically and environmentally highly efficient combustion of depleted gas-air mixtures (limit ignition of a lean mixture is characterized by $α_{max}$ = 1.7 and remains unchanged for all compression ratio values $ε ≤ 16$).

When it is used in diesel engines, emissions of supertoxicants (CO, NO_x, PM) are significantly reduced, and carbon dioxide (CO_2) emissions are also reduced (~ by 20 %). Therefore, the use of natural gas in city vehicles allows to ensure a significant economic effect as a result of reducing fuel costs and compensation for environmental damage, as well as reducing atmospheric pollution in cities [4].

In 60 countries of the world, more than 11 million cars run on natural gas, the mileage at one gas station reaches 400 km. The world leader is Argentina (more than 1 million cars running on natural gas). In accordance with the plans of the UN Economic Commission for Europe, by 2020 ~ 30 million cars or about a tenth of the European car park will run on natural gas, mainly city buses, minibuses, passenger cars, which are in individual use. The annual consumption of natural gas with such a number of machines will amount to more than 50 billion m^3. In Germany, the transition of cars to the use of natural gas is one of the priority areas of energy development and environmental safety. In France, a ban has been introduced on the use of hydrocarbon fuels (except natural gas) on municipal buses and garbage collection vehicles. Italy has introduced a ban on the construction of gas stations without a natural gas filling station.

Further improvement of the economic, ecological and dynamic characteristics of gas engines is achieved due to the additional use of synthesis gas (H_2 + CO), which is prepared by converting part of natural gas in a compact catalytic reactor directly on board the gas vehicle using a microprocessor control system. Thus, a sharp improvement in the quality of natural gas combustion due to the introduction of synthesis gas initiator additives leads to the possibility of working on leaner combustible mixtures, fuel economy and a further significant reduction in the levels of supertoxicants emissions.

According to the data of a number of motor transport enterprises of the city of Kharkiv, the minimum costs for fuel components are ensured when operating even traditional cars with modernization of gasoline internal combustion engines to run on natural gas. A route minibus-taxi with a gasoline engine when operating around the city consumes ~ 16 tons of gasoline per year (at a cost of ~ 20,000 dollars). A minibus-taxi with a modern highly economical gas engine (with the same mileage in city conditions) will approximately consume no more than 17,000 m^3 of natural gas, worth ~ 6,000 dollars. (At the price of compressed gas ~ $0.35/$m^3$). Annual savings on fuel alone will be at least 10,000 dollars, taking into account the difference in the cost of cars (~ 4,000 dollars) and without taking into account the significant reduction in environmental damage from the harmful effects of GHG when operating cars with a gas engine. The results of the car with a diesel engine also confirmed the high efficiency of using natural gas. Thus, the use of compressed natural gas in the gas-diesel process with an ignition dose of diesel fuel ~ 15 % by mass. made it possible to reduce fuel costs by ~ 20 %, and environmental damage costs by ~ 24 %.

Effective use of natural gas in city vehicles is possible if the following conditions are met:

- a significant reduction in the cost and operation of gas filling compressor stations, as well as their location within the city;
- reduction of mass and cost of gas cylinder equipment;
- creation or acquisition of the world's best models of cars with gas engines with increased (at least 20 %) operating fuel efficiency.

The program to convert a part of urban road transport to natural gas should be economically justified for a specific region, carried out both at the state (which is very important) and regional (which is more realistic) levels, as well as on the basis of international cooperation [5].

In perspective, it should be noted that huge amounts of methane (at least 104 quadrillion m^3) are stored in methane hydrates that lie in the sediments of the World Ocean. Melting 1 m3 of methane hydrate granules yields up to 200 m^3 of methane and 0.87 m^3 of fresh water. In the Black Sea, methane hydrates lie at a depth of 200–400 m.

7.3. Alcohol and benzo-alcohol fuels

It should be noted that alcohol fuels (ethanol, methanol) with a high hydrogen index and high anti-detonation qualities can be used most effectively, as confirmed by the experience of many countries of the world, in internal combustion engines with forced ignition of lean combustible mixtures as benzo-alcohol fuel, the main fuel or hydrogen energy carriers.

It should be noted that as early as 1921 (also during the oil crisis), the German engineer Friedrich Bergius patented the technology for the production of alcohol fuels, including synthetic gasoline, from lignite, launched a number of plants, and was awarded the Nobel Prize for solving the most important in that period of the fuel and energy problem.

Large-scale production of synthetic energy carriers, including methanol, has begun in the world. The most likely raw materials for such production of synthetic hydrocarbon fuels in the near future are coal and shale. In the world reserves of fossil energy resources, they account for more than 80 % of the total energy content, and at current levels of production, their reserves will last for approximately 300-400 years. In 2006, the ASFF alliance was created, which unites producers and consumers of synthetic fuels (Shell, Shevron-SASOL, Daimler, Renault and Volkswagen). The goal of this alliance is to create highly economical and environmentally safer cars that run on synthetic and combined fuels. At the first stage, synthetic fuels are used together with traditional motor fuels, which ensures a decrease in the consumption levels of petroleum fuels. Thus, the addition of methanol in the amount of ~ 15 % to gasoline with an octane number of 72 increases the octane number to 82 and allows the effective use of such a benzomethanol mixture in series-used engines with forced ignition of combustible mixtures when it is depleted. This significantly increases the environmental performance of vehicles, since sulfur and aromatic hydrocarbons are practically absent in synthetic fuels. The latter is very important from the point of view of reducing the pollution of the environment by carcinogenic and mutagenic ingredients emitted from the exhaust gases of vehicles.

The use of methanol (or other alcohol fuel) as the main hydrogen carrier is also one of the promising ways to improve the environmental and energy efficiency of automotive technology. This is primarily due to the fact that the conversion gas (congas) produced as a result of methanol conversion contains 67 % (vol.) of hydrogen and 33 % (vol.) of carbon monoxide, which are environmentally friendly fuel components and allow for significant fuel depletion -air mixture, which in turn helps to increase engine efficiency, as well as to reduce the levels of emissions of toxic and carcinogenic ingredients from the exhaust gases (EG) of cars. The second important factor that increases the cost-effectiveness of such a power plant is the utilization of the internal energy of EG by partial selection of it in the methanol decomposition reactor. At 100 % conversion, the increase in the energy intensity of congas is approximately 10 % compared to methanol, and its return to the cycle allows to increase the indicator efficiency of the engine by 3-4 %. It should also be taken into account the convenience of on-board storage of methanol (ethanol), which is practically no different from the storage of gasoline. The schematic diagram of a reciprocating diesel engine with catalytic conversion of methanol is shown in Fig. 7.1 [5, 6].

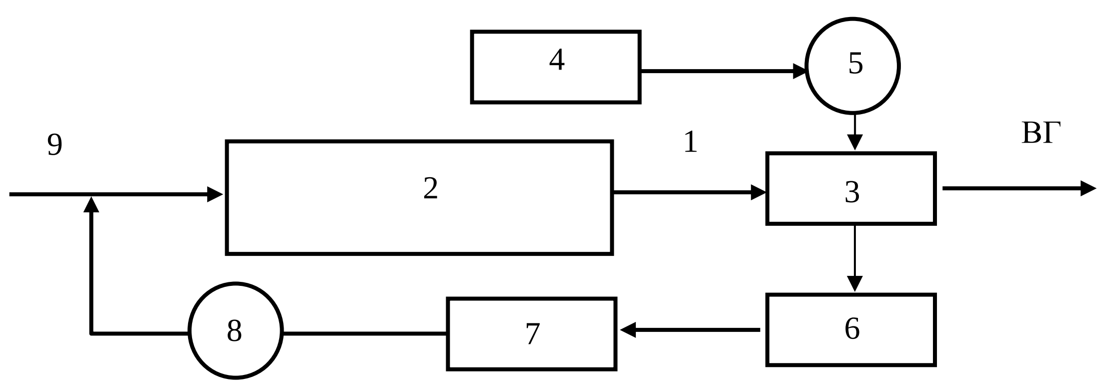


Fig. 7.1. Scheme of operation of an internal combustion engine with catalytic conversion of methanol

A catalytic reactor 3 for methanol conversion is installed in the exhaust pipe 1 of engine 2. Two bundles of heat exchange tubes are placed in the hermetic reactor housing, one of which forms an evaporation chamber, and the other, filled with a catalyst, forms a reaction chamber. Liquid methanol from the fuel tank 4 is fed into the reactor by the fuel pump 5. Methanol conversion products through the cooler 6, the reducer 7 and the gas supply regulator 8 are fed to the intake air receiver 9 of the engine. Experimental studies conducted on the ZMZ-402 engine when operating on A-76 gasoline, evaporated methanol, and with a methanol conversion reactor (3M3 -1 catalyst, conversion rate ~ 60 %) showed that at an engine crankshaft rotation frequency of 2500 min–1 and at 30 % load, the engine efficiency was: 28, 33, and 36 %, respectively, with a total excess air ratio of 0.95; 1.5 and 2.1; and the levels of NO_x concentrations corresponded to: 3200, 1200 and 250 million 1. When using conversion gas, there were no carcinogenic hydrocarbons in the HG of the engine. Such a scheme for the conversion of alcohol fuels is particularly promising for cars of the future with electrochemical fuel cells. Model samples of such cars, as well as cars with hybrid power plants, are being tested by the world's leading automobile companies (Honda, Toyota, General Motors, SAAB, etc.). On the other hand, a campaign has been launched in the USA to replace every fifth liter of gasoline with biofuel (BiF). In 2005, approximately 19 billion liters of ethanol were produced from corn in the United States. At this rate of growth of BiF consumption, by 2015, more than half of the corn grown in the USA will be needed for its production. As the vice president of the Dupon concern for biotechnology stated: "Economics and national security have created a unique convergence of interests for the expansion of biofuel production." And this is not only an American trend. Western Europe plans to replace every 20 liters of gasoline with BiF by 2015. At present, ~ 2 million tons of rape seed oil are already produced in Europe.

Benzoethanol fuel is a huge potential for Ukraine to reduce the consumption of light petroleum products, protect the environment, increase agricultural production and create jobs. The experience of countries developing the production and consumption of benzoethanol fuel shows the profitability of investments invested in the production of bioethanol, the increase in the profits of agricultural producers, the growth of tax revenues to the budget. Under favorable conditions in Ukraine, in a short period of time it is possible to establish the production of experimental batches of benzoethanol fuel with different ethanol content, to conduct engine tests for their adaptation, to determine the optimal ratio of gasoline to ethanol, from the point of view of economy and toxicity, normative expenditure characteristics, to develop recommendations for the operation of engines vehicles on benzoethanol fuel.

In the Tab/ 7.2 shows the properties of ethanol and benzoethanol mixtures in comparison with gasoline. As can be seen from the Tab.7.2 the densities of gasoline and ethanol differ slightly, therefore, the mass of the mixed fuel stock on the car practically does not increase. In terms of calorific value, ethanol is inferior to gasoline by 40 %, but the calorific value of benzoethanol mixtures (up to 10 % by volume of ethanol) is only 4.5 % lower than that of gasoline. Therefore, it is possible to predict an increase in the relative volume consumption of fuel to perform the same work by 4-5 % [7].

Table 7.2.

Basic properties of gasoline, ethanol and benzoethanol mixtures

Properties	**Measurement units.**	**Gasoline**	**Ethanol**	**Benzo-ethanol (5 % vol.)**	**Benzo-ethanol (10 % vol.)**
Density at 20 °C	kg/m^3	740	810	743.5	747
Lower calorific value	kJ/kg	43920	25900	42938	41967
Caloric content. mixture	kJ/m^3	3536	3453	3532	3528
Heat of vaporization	kJ/kg	330	850	358	386
Stoichiometric air-fuel ratio	kg/kg	14,9	9	14.6	14.3
Ignition limits of a mixture with air, α	–	0.5–1.16	0.4–1.7	0.5–1.19	0.5–1.22
OR according to the motor method	– –	76-84 92-100	94 108	81 –	86 95
OR according to the research method	m/s	37-43	–	–	–
The maximum speed of flame propagation	К	2335-2470	2235	–	–
Flame temperature	–	1	1,.7	1.023	1.047

Due to the change in the octane number and the stoichiometric air-fuel ratio for 10 % benzoethanol, when the engine is running on such fuel, it is necessary to slightly adjust the ignition advance angle and slightly change the cross-sections of the fuel jets of the carburetor. However, you should not expect a significant improvement in the efficiency of the engine running on benzoethanol without making structural changes. In fig. 8.16 shows the dependence of the increase in the OR of the original gasoline on the volume content of ethanol in it.

From Fig. 7.2 [4] it can be seen that the higher the OR of the original gasoline, the more it is necessary to increase the ethanol content to increase the OR of the mixture. Therefore, a 10% addition of ethanol to the original low-octane gasoline A-76 (benzoethanol-10) will allow to increase the OR of benzoethanol to 86 units, which is similar to gasoline A-95, and this, in turn, will allow the use of benzoethanol-10 for engines with higher degrees of compression. In addition, the depletion limit of the mixture increases from α = 1.16 on the original gasoline to α = 1.22 on benzoethanol-10. Therefore, it can be expected that the operation of the engine on benzoethanol will allow to increase its effective indicators and reduce the toxicity of EG. The disadvantages of ethanol, in addition to lower calorific values, include a higher heat of vaporization than gasoline, which causes difficulties in starting the engine at temperatures below 10 °C.

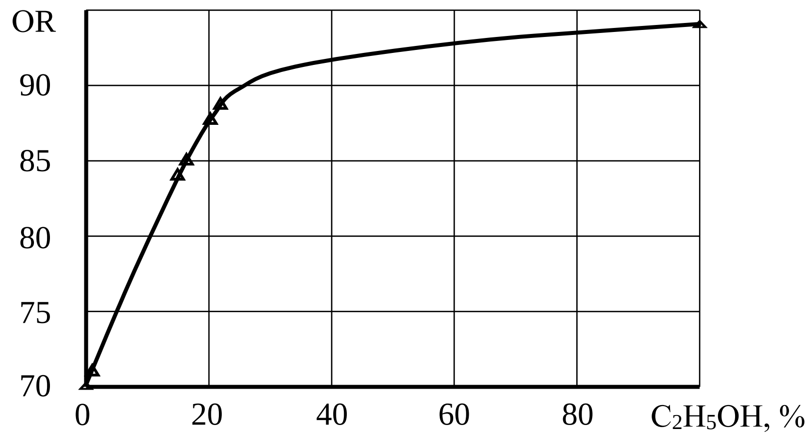


Fig. 7.2. The dependence of the increase in the octane number of the original gasoline on the content of ethanol in it

In the USA, Sweden and a number of other countries, the content of bioethanol (BE) in motor fuel has been increased to 85 % (Ethanol E85). Thanks to the state subsidy, its price is 1.5-2 times lower than the cost of gasoline. The Ford company sold more than 15,000 cars adapted to such fuel in Sweden. Sweden plans to completely abandon oil imports by 2050 due to the use of ethanol. In the USA and Brazil, gasohol fuel with 10 and 20 % ethanol content has been used for more than 20 years, and the Volkswagen concern has produced more than 2 million cars with internal combustion engines adapted to gasoline fuel.

In Ukraine, bioethanol or ethyl alcohol dehydrated from biologically renewable raw materials is produced from grain crops, potatoes, fruits, technical crops and is almost entirely exported. Bioethanol fuel could be a huge potential for Ukraine to reduce the consumption of petroleum fuels, protect the natural resources from natural disasters, increase agricultural production and create jobs. At the same time, Ukraine objectively has all the prerequisites for stimulating the production of benzo-alcohol fuels at domestic oil refining enterprises that have all stages of the technological process of their production.

However, biological material also has its limits and, according to a number of international experts, the actual volume of replacement of petroleum motor fuels with biofuels may not exceed 10 % by 2025. In addition, every twelfth person in the world suffers from malnutrition (in the UN report on food consumption, Jean Ziegler noted that mortality from malnutrition accounted for 58 % of the total mortality in 2006), and the inhabitants of "civilized" countries burn food that is valuable for life eating in their cars.

7.4. Hydrogen and gasoline-hydrogen fuels

One of the alternative long-term motor fuels for motor vehicles can be considered hydrogen. In automotive internal combustion engines, hydrogen can be used both as the main fuel and as an additive to traditional motor fuel. Hydrogen as a fuel has a number of significant advantages over traditional petroleum motor fuels:

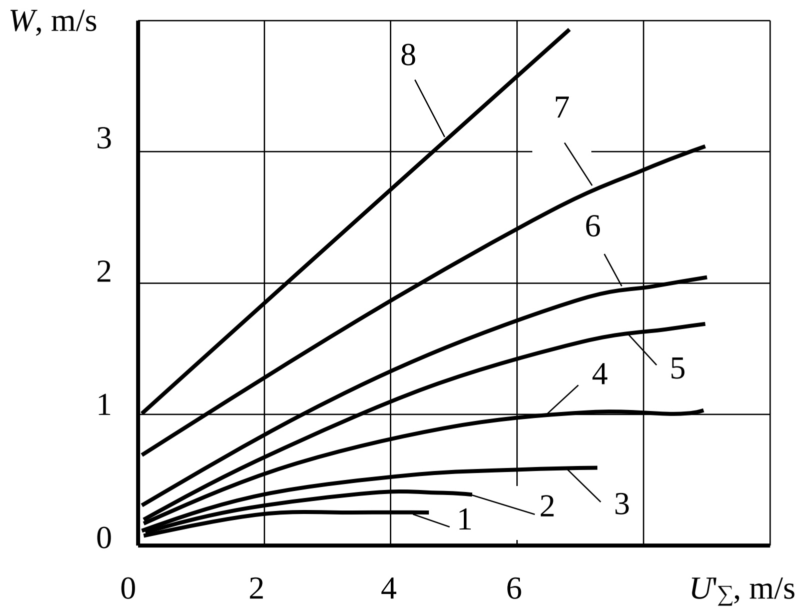
- high specific heat of combustion and low ignition energy;
- good flammability of the hydrogen-air mixture in a wide range of coefficients of excess air and temperatures, which ensures easy starting of the engine at almost any possible temperature of the fuel;
- high anti-detonation resistance, which allows operation at a compression ratio of up to 14 and higher;
- high speed and completeness of combustion, which makes it possible to bring the real cycle of the internal combustion engine with spark ignition closer to the ideal one with the addition of heat to the mixture at a constant volume, that is, to increase the efficiency of the cycle.

The flammability of hydrogen in a mixture with air in a wide range of compositions makes it possible to regulate the mixture formation in the engine by changing the amount of supplied hydrogen and practically abandon throttling of the air flow at the intake, that is, to organize a qualitative regulation of the internal combustion engine work process, thus increasing the thermal efficiency of the engine at partial load modes.

Wide concentration limits of ignition in air, high combustion speed, low ignition energy, high values of diffusion coefficients make hydrogen an ideal additive to conventional hydrocarbon fuels. The addition of hydrogen to the gasoline-air mixture reduces the stoichiometric ratio L_0, and this indicator of the combustible mixture is related to such important parameters of the work process as the limits of effective and maximum depletion of the fuel-air mixture ($\alpha_{\eta_i\ (max.)}$ i $\alpha_{(max.)}$), as well as the value of the inductive period combustion, which characterizes the stability and uniformity of the work process from cycle to cycle.

It is important, as shown by numerous studies conducted at the Anatolii Pidhornyi Institute of Mechanical Engineering Problems of the National Academy of Sciences of Ukraine, there is also the fact that mass additions of hydrogen (Δg_{H_2}) during the combustion of depleted gasoline-hydrogen-air mixtures significantly increase the completeness of fuel combustion (η_r), reduce the levels of NO_x formation, and inhibit the processes of formation of PM.

It was also established that hydrogen additives in depleted hydrocarbon-hydrogen combustible mixtures (HHCM) initiate the process of their combustion (Fig. 7.3), significantly expand the range of stable ignition and burning [7, 8].



1 – 0; **2** – 0,005; **3** – 0,011; **4** – 0,029; **5** – 0,063; **6** – 0,0152; **7** – 0,287; **8** – 1,0

Fig. 7.3. Dependence of the turbulent combustion speed of air mixtures of propane with hydrogen on the pulsation speed and indicator Δg_{H_2}

Thus, the use of depleted HHCM in automotive internal combustion engines can ensure their operation with high operating fuel efficiency, parametric reliability and environmental and chemical safety.

7.5. Energy potential and environmental efficiency of the use of gasoline-hydrogen fuels

The addition of hydrogen to hydrocarbon fuel is accompanied by an increase in the the ratio of hydrogen atoms to carbon atoms (H/C) ratio and, accordingly, an increase in the stoichiometric coefficients and the absolute value of the total enthalpy of the composite fuel. The effect of hydrogen addition on the thermochemical characteristics of two-component fuel (at T = 298 K) (Tab. 7.3) [4].

Table 7.3.

The effect of hydrogen additives on the thermochemical properties of composite fuels

Indicator	Additive H_2, % (mas.)		
	0	10	20
Equivalent formula	$C_{7,16}H_{14}$	$C_{7,16}H_{25,1}$	$C_{7,16}H_{38,98}$
Relationship N/S	1.96	3.51	5.44
L_0, mol/mol	50.20	64.50	81.25
l_0, kg/kg	14.84	16.84	18.83
Total enthalpy, kJ/mol (kJ/kg)	–194.7 (–1948.9)	–175.2 (–1701.0)	– –155.8 (–1559.1)

Energy and environmental indicators of fuel combustion processes are largely determined by their thermotechnical and physicochemical characteristics. Consider the following characteristics of hydrocarbon-hydrogen-air fuel mixtures (HHAFM):

- $(l_0)_\Sigma$– stoichiometric coefficient;
- α_{HCH}– coefficient of excess air;
- N/C – ratio of hydrogen atoms to carbon atoms;
- g_{H_Σ}– mass fraction of hydrogen in hydrocarbon-hydrogen fuel (HHF), etc.

In the future, the following designations will be accepted: G_{H_2} – mass consumption of hydrogen; G_{HF_0} – mass flow rate of initial hydrocarbon fuel (HF) (without hydrogen addition); $G_{\mathrm{HF}} = G_{\mathrm{HF}_0} - a_1 \cdot G_{H_2}$ – mass flow of HF taking into account the heat introduced into the short circuit by hydrogen, where $a_1 = H_{H_2}/H_{\mathrm{HF}}$; $G_\Sigma = G_{\mathrm{HF}} + G_{H_2}$ – total mass consumption of HF and hydrogen; $g_{H_{HF}}$ – share of hydrogen in HF; $g_{H_2} = G_{H_2}/G_\Sigma$ – share of hydrogen in HHA; $g^{\mathrm{e}}_{\mathrm{H}_2} = G_{H_2}/G_{\mathrm{HF}_0}$ – the proportion of hydrogen additive in relation to the original HF (equivalent to replacing HF with hydrogen); $g^{\mathrm{e}}_{\mathrm{HF}} = (G_{\mathrm{HF}_0} - G_{HF})/G_{\mathrm{HF}_0} = a_1 \cdot g^{\mathrm{e}}_{\mathrm{H}_2}$ – equivalent fraction of HF replaced by hydrogen. Functional dependence of relative indicators $g^e_{H_2}$and g^{e}_T from the indicatorg_{H_2} can be represented by the following ratios:

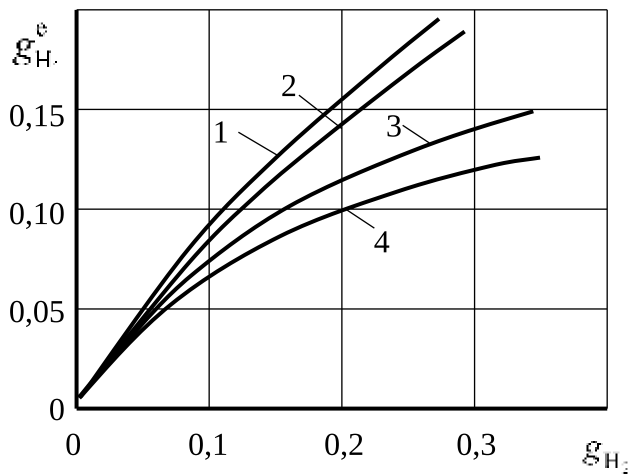
$$g^e_{H_2} = \frac{G_{H_2}}{G_{HF_0}} = \frac{G_{H_2}}{G_{\mathrm{HF}} + a_1 \cdot G_{H_2}} \frac{G_{\mathrm{HF}} + G_{H_2}}{G_{\mathrm{HF}} + G_{H_2}} =$$

$$= \frac{g_{H_2}}{\dfrac{G_{\mathrm{HF}} + G_{H_2} - G_{H_2}}{G_{\mathrm{HF}} + G_{H_2}} + \dfrac{a_1 \cdot G_{H_2}}{G_{\mathrm{HF}} + G_{H_2}}} =$$

$$= \frac{g_{H_2}}{(1 - g_{H_2}) + a_1 \cdot g_{H_2}} = \frac{g_{H_2}}{1 + (a_1 - 1) \cdot g_{H_2}},$$

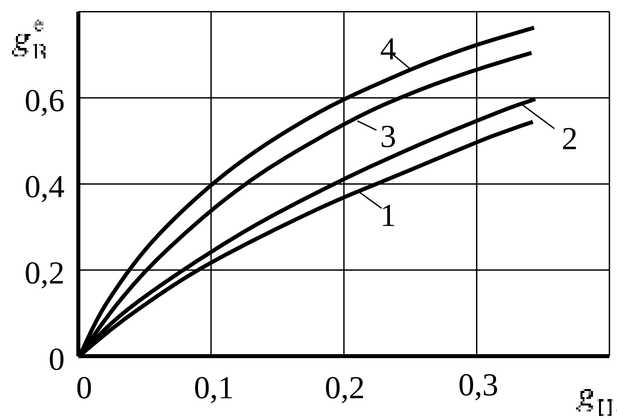
$$g_{\text{HF}}^{e} = \frac{G_{HF_0} - G_{\text{HF}}}{G_{\text{HF}_0}} = \frac{a_1 \cdot G_{H_2}}{G_{\text{HF}} + a_1 \cdot G_{H_2}} = \frac{a_1 \cdot g_{H_2}}{1 + (a_1 - 1) \cdot g_{H_2}}.$$

The estimated values of the indicators for the HHA series are shown in Fig. 7.4, 7.5.



1 – methane; **2** – diesel fuel;
3 – ethanol; **4** – methanol

Fig. 7.4. Dependence of the equivalent of replacing HF with hydrogen on the proportion of its addition



1 – methane; **2** – diesel fuel;
3 – ethanol; **4** – methanol

Fig. 7.5. Dependence of the equivalent fraction of VP substituted by hydrogen on the fraction of its additive

The amount of air theoretically required for the complete combustion of 1 kg of HF (stoichiometric coefficient) is determined by the formula:

$$l_{0\text{HF}} = \frac{\mu_A}{\varphi_O} \left(\frac{g_C}{A_C} + \frac{g_{H_{\text{HF}}}}{4 \cdot A_H} + \frac{g_O}{2 \cdot A_O} \right) \quad (7.1)$$

where μ_A – molecular weight of air ($\mu_A = 28{,}966$); ϕ_O – mass fraction of oxygen in air ($\varphi_O = 0{,}2095$); $g_C,\ g_{H_T},\ g_O$ – mass fraction in HF, respectively, of carbon, hydrogen, and oxygen; A_C, A_H, A_O – the mass of an atom, respectively, of carbon, hydrogen, and oxygen.

The stoichiometric coefficient for HF can be represented by dependencies:

$$l_{0\Sigma} = \frac{\mu_A}{\varphi_O} \left(\frac{G_{\text{ВП}} \cdot g_C}{A_C} + \frac{G_T \cdot g_{H_{\text{HF}}} + g_{H_2}}{4 \cdot A_H} + \frac{G_{\text{HF}} \cdot g_O}{2 \cdot A_O} \right),$$

$$l_{0\Sigma} = l_{0\text{HF}}(1 - g_{H_2}) + l_{0H_2} \cdot g_{H_2} = \sum_{i=1}^{2} l_{0i} \cdot g_i, \qquad (7.2)$$

where g_i – mass share of i-th type of fuel in HHA ($g_i = G_i / \sum_{i=1}^{2} G_i$); G_i – mass consumption of i-th type of fuel.

As a result of the calculation according to (7.1), the following values were obtained $l_{0\text{PA}}$: gas – 14.74; gasoline – 14.63; diesel fuel – 14.45; methane – 17.12; methanol – 6.27; ethanol – 8.86; hydrogen – 34.25 kg/kg (kilogram of air per kilogram of fuel). From Fig. 7.6 shows that with an increased g_{H_2} the indicator increases significantly $l_{0\Sigma}$.

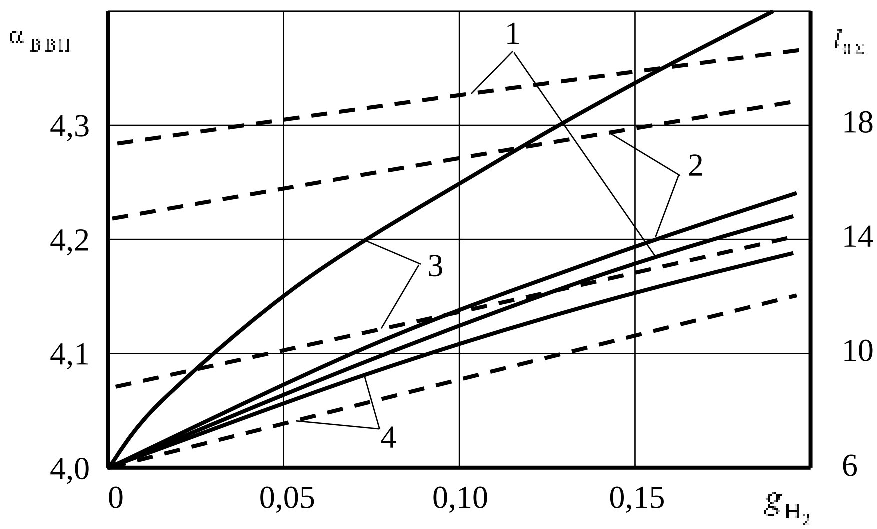


Fig. 7.6. Dependence of the coefficient of excess air (solid curves) and the stoichiometric coefficient (dashed curves)

The coefficient of excess air when burning 1 kg of fuel is the ratio of the actual amount of air G_A to the theoretically necessary:

$$\alpha_{\text{HF}} = \frac{G_A}{l_{0\text{HF}} \cdot G_{\text{HF}}}. \qquad (7.3)$$

The derivation of the dependence for the calculation of α_{HF} when using HF with the addition of hydrogen will be carried out under the condition of equality of air consumption and thermal fuel-air mixture in comparison with the conditions of combustion of only HF, i.e.:

$$G_{HF_0} \cdot H_{\text{HF}} = G_{\text{HF}} \cdot H_{\text{HF}} + G_{H_2} \cdot H_{H_2}.$$

Then the HF consumption when hydrogen is added to the combustion chamber:

$$G_{\mathrm{HF}} = \frac{G_{\mathrm{HF}_0} \cdot H_{\mathrm{HF}} - G_{H_2} \cdot H_{H_2}}{H_{\mathrm{HF}}} = G_{\mathrm{HF}_0} - a_1 \cdot G_{H_2}. \quad (7.4)$$

By substituting the values in (7.3). $l_{0\Sigma}$ i $G_{\mathrm{B\Pi HF}}$ from (8.2) i (8.4), we get the following dependence:

$$\alpha_{\mathrm{HHA}} = \frac{G_{\Pi}}{[l_{0\mathrm{B\Pi HF}}(1-g_{H_2}) + l_{0H_2} \cdot g_{H_2}](G_{\mathrm{B\Pi}_0} - a_1 \cdot G_{H_2} + G_{H_2})}. \quad (7.5)$$

After some transformations and entering the coefficient$a_2 = l_{0H_2}/l_{0\mathrm{HF}}$ we finally get:

$$\alpha_{\mathrm{HHA}} = \alpha_T \frac{1+(a_1-1) \cdot g_{H_2}}{1+(a_2-1) \cdot g_{H_2}}.$$

Results of calculated dependencies α_{HHA} from g_{H_2} for the HHA series are shown in Fig. 7.6. It can be seen that with an increase g_{H_2} the indicator also increases slightly α_{HHA}.

To analyze the possibilities of expansion of the flame propagation zone of lean fuel-air mixtures when they are saturated with hydrogen, it is necessary to obtain the dependence of the limit value of the excess air coefficient of this homogeneous mixture (α'_{HHA}) from the addition of hydrogen. According to Le Chatelier's rule, a homogeneous lean mixture of several gaseous fuels with air will be limiting if each fuel and the corresponding air part of the mixture are in a limiting ratio. For a two-component fuel mixture of HF and hydrogen equality:

$$G_{\Sigma} = G_{\mathrm{B\Pi}} + G_{H_2},$$

corresponds to the ratio:

$$G_{\Pi_{\Sigma}} = G_{\Pi_{\mathrm{HF}}} + G_{\Pi_{H_2}}, \quad (7.6)$$

where $G_{\Pi_{\Sigma}}$, $G_{\Pi_{\mathrm{HF}}}$, $G_{\Pi_{H_2}}$ – mass flow rates of air at the lower limit of flame propagation, respectively, for HHA, HF and hydrogen.

Let's express both parts of dependence (7.6) in terms of the coefficient of excess air at the lower limit of flame propagation α_i' and the stoichiometric ratio l_{0i}:

$$G_{\Pi\Sigma} \cdot \alpha_{\mathrm{HHA}}' \cdot l_{0\Sigma} = G_{\mathrm{HF}} \cdot \alpha_{\mathrm{HF}}' \cdot l_{0\mathrm{HF}} + G_{H_2} \cdot \alpha_{H_2}' \cdot l_{0H_2}.$$

From this expression:

$$\alpha_{\mathrm{HHA}}' = \frac{G_{\mathrm{HF}} \cdot \alpha_{\mathrm{HF}}' \cdot l_{0\mathrm{HF}} + G_{H_2} \cdot \alpha_{H_2}' \cdot l_{0H_2}}{G_{\Sigma} \cdot l_{0\Sigma}} =$$

$$= \frac{\alpha_{\mathrm{HF}}' \cdot l_{0\mathrm{HF}}(1 - g_{H_2}) + \alpha_{H_2}' \cdot l_{0H_2} \cdot g_{H_2}}{l_{0\Sigma}}. \quad (7.7)$$

For ease of calculation, dependence (7.7) after some transformations taking into account relation (7.2) is reduced to the form:

$$\alpha_{\mathrm{HHA}}' = \alpha_{H_2}' \left[1 + \frac{1}{a_2 \cdot a_3}\left(\frac{1}{g_{H_2}} - 1\right)\right] / \left[1 + \frac{1}{a_2}\left(\frac{1}{g_{H_2}} - 1\right)\right],$$

or

$$\alpha_{\mathrm{HHA}}' = \alpha_{\mathrm{HF}}' \left[a_2 \cdot a_3 + \left(\frac{1}{g_{H_2}} - 1\right)\right] / \left[a_2 + \left(\frac{1}{g_{H_2}} - 1\right)\right],$$

where $a_3 = \alpha_{H_2}' / \alpha_{\mathrm{HF}}'$.

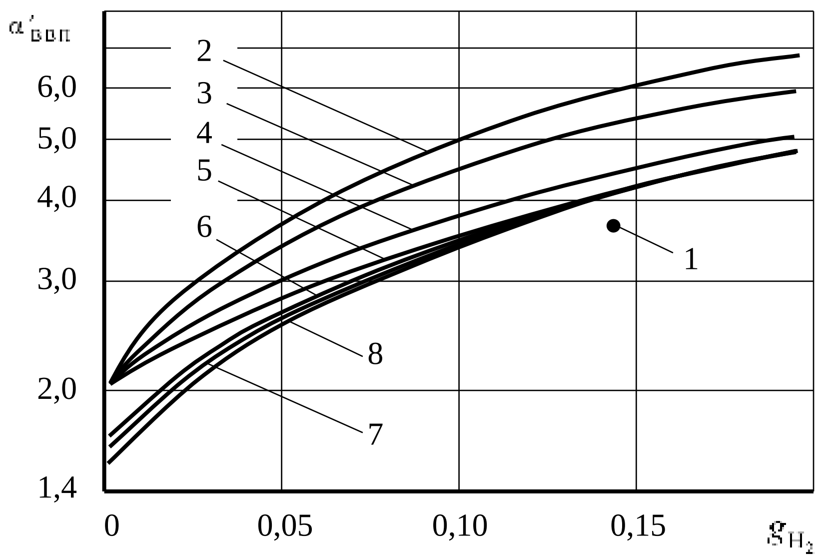
Limit values α_i' for each of the components, the fuel mixture is calculated according to the formula:

$$\alpha_i' = \left(\frac{100}{C_{\text{н}i}} - 1\right) \frac{\mu_A}{\mu_i \cdot l_{0i}},$$

where $C_{\text{н}i}$ – the lower concentration limit of one of the fuels in the mixture, % (vol.); μ_A, μ_i – molecular masses of air and HF or hydrogen, respectively.

The dependence obtained as a result of calculations $\alpha_{\mathrm{HHA}}' = f(g_{H_2})$ for the lower concentration limit of flame propagation, the HHA series is presented in fig. 7.7.

It can be seen that with an increase g_{H_2} the indicator increases significantly $\alpha_{\mathrm{FORM.}}'$, i.e., the zone of sustainable combustion of depleted ones is expanding HHAFM [9].



1 – experimental point for kerosene-hydrogen fuel; **2** – methanol; **3** – ethanol; **4** – gasoline; **5** – methane; **6** – kerosene; 7 – JP-5; **8** – diesel fuel

Fig. 7.7. Dependence of the limiting coefficient of excess air on depletion from the proportion of hydrogen additive in HHAFM

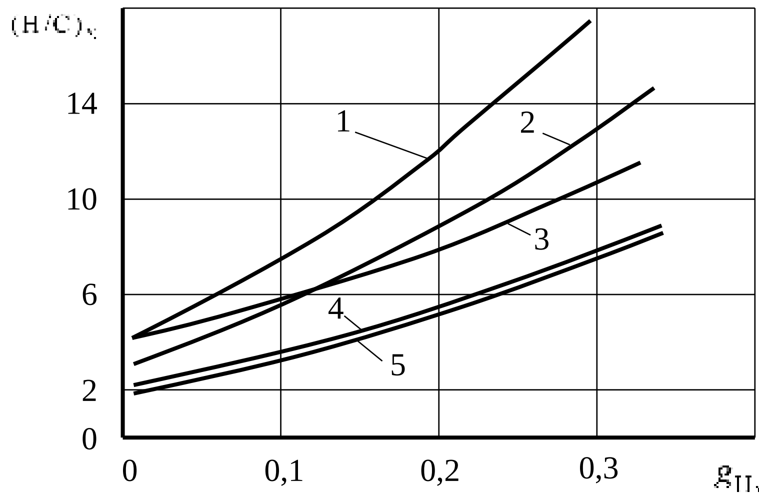
One of the important thermochemical indicators is the ratio of the number of hydrogen and carbon atoms (H/C) in HHA. With the known mass content of hydrogen and carbon in the fuel, this indicator is determined by the dependence:

$$(\mathrm{H/C})_{\mathrm{HF}} = \frac{g_{H_{HF}}}{A_H} : \frac{g_C}{A_C} = \frac{A_C}{A_H}\frac{g_{H_{\mathrm{HF}}}}{g_C}. \qquad (7.8)$$

For HHA, this indicator can be calculated based on dependence:

$$(\mathrm{H/C})_{\Sigma} = \frac{A_C}{A_H}\left(\frac{g_{H_{\mathrm{HF}}} \cdot G_{\mathrm{B\Pi}} + G_{H_2}}{g_C \cdot G_{\mathrm{HF}}}\right) = \frac{A_C \cdot g_{H_{\mathrm{B\Pi}}}}{A_H \cdot g_C} + \frac{A_C \cdot G_{H_2}}{A_H \cdot g_C \cdot G_{\mathrm{B\Pi}}} =$$
$$= (\mathrm{H/C})_{\mathrm{B\Pi}} + \frac{A_C \cdot g_{H_{\mathrm{HF}}}}{A_H \cdot g_C}\frac{G_{H_2}}{g_{H_{\mathrm{HF}}} \cdot G_{\mathrm{HF}}} = (\mathrm{H/C})_{\mathrm{HF}} \cdot \left[1 + \frac{1}{g_{H_{\mathrm{HF}}}\left(1/g_{H_2} - 1\right)}\right].$$

Thus, an expression for direct determination is obtained $(\mathrm{H/C})_{\Sigma}$ due to the mass fraction of the hydrogen additive. Dependence $(\mathrm{H/C})_{\Sigma} = f\left(g_{H_2}\right)$ for the HHA series is shown in Fig. 7.8. It can be seen that the dependence of the H/C indicator on the addition of hydrogen is significant.



1 – methanol; **2** – ethanol; **3** – methane; **4** – kerosene; **5** – diesel fuel

Fig. 7.22. Dependence of the HHAFM hydrogen index on the proportion of hydrogen additive in HF

A qualitative indicator of HF and HHA is the mass fraction of hydrogen. The following dependence was obtained for HHA:

$$g_{H_\Sigma} = \frac{G_{\mathrm{HF}} \cdot g_{H_{\mathrm{HF}}} + G_{H_2}}{G_{\mathrm{HF}} + G_{H_2}}.$$

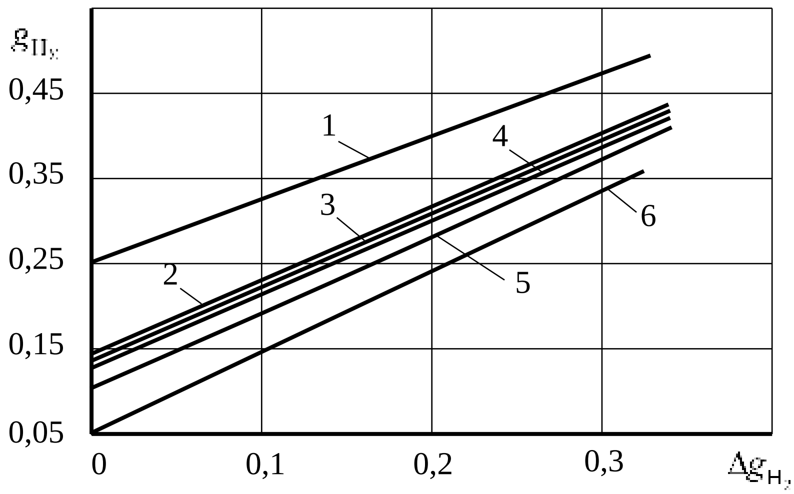
Transforming this expression, we get:

$$g_{H_\Sigma} = \frac{G_{HF} + G_{H_2} - G_{H_2}}{G_{HF} + G_{H_2}} \cdot g_{H_{HF}} + g_{H_2} = g_{H_2} + g_{H_{HF}}(1 - g_{H_2}) \qquad (7.9)$$

Expression (7.9) represents the dependence of the mass fraction of hydrogen in HHA on the addition of hydrogen. If necessary, the creation of a combustible mixture with a given value g_{H_Σ} the necessary addition of hydrogen to HF is determined by the formula:

$$g_{H_2} = \frac{g_{H_\Sigma} - g_{H_{\mathrm{HF}}}}{1 - g_{H_{\mathrm{HF}}}}.$$

In fig. 7.9 shows that the dependence $g_{H_\Sigma} = f(g_{H_2})$ for a number of HHA is significant [8, 9].



1 – methane; **2** – gasoline; **3** – diesel fuel; **4** – methanol; **5, 6** – synthetic fuels with an initial hydrogen content of 0.10 and 0.05, respectively

Fig. 7.9. Dependence of the mass fraction of hydrogen in HHAFM from its addition to HHA

Thus, in order for the mentioned above, for example, when using HF з $g_{H_{\mathrm{HF}}} = 0.1$, contained g_{H_Σ} equal 0.15, addition of hydrogen is required$g_{H_2} \approx 0.05$, i.e ≈ 5 % from the total fuel consumption (HF + H_2).

7.6. Highly aromatized petroleum fuels with hydrogen additives

It was previously noted that a characteristic feature of modern liquid motor fuels obtained from oil, as well as broad-fraction synthetic fuels obtained from coal and shale, is an increased content of aromatic hydrocarbons (AH) with reduced hydrogen indicators ($g_{H_{\mathrm{HF}}}$, H/C). It was established that the pyrolysis processes of the specified fuels (especially fuels with an AH content of more than 30 %), as well as the processes of oxidation of the precursors of the formation of PM and HF in the short circuit of heat engines are due to the high sensitivity of these processes to changes in the content of AH and hydrogen in the source fuel. It should be especially noted that the processes of formation of PAHs (in comparison with the formation of PM) are more sensitive to the content of AH and hydrogen in the fuel. Thus, with an increase in the AH content in diesel fuel from 32 % to 57 % (with a correspondingly reduced hydrogen index), the levels of emissions of aerosol particles from the vehicle's EG increase by 3-4 times, and the BP levels, as an indicator of the presence of CV, by 5-8 times Moreover, at low levels of AH content in liquid fuels ($g_{\text{AH}} \leq 30$ %), the emission levels of both PM and HF from EG cars are relatively low. At the same time, the indicator of the hydrogen content in the fuel is$g_{\text{AH}} = 30$ % can be taken as basic-effective$[g_{H_{\text{HF}}}]_{\text{ef.}}$. Therefore, a criterion is proposed that characterizes the change in the levels of effective hydrogen content in liquid aromatized fuel, taking into account the sensitivity of surfactant formation processes to the AH content when burning fuels with $g_{\text{AH}} > 30$ %

$$g_{H_{\text{HF(ef.)}}} = [g_{H_{\text{HF}}} - (g_{\text{AB}} - 30)^n], \qquad (7.10)$$

where g_i – corresponding shares in %, n = 0,4 ± 0,02.

One of the ways to minimize the levels of HF emissions, as well as PM, with the combustion products of liquid motor fuels with an increased content of AH ($g_{\text{AH}} >$ 30 %) is the use of hydrogen (or natural gas) as an additional energy carrier. At the same time, the minimum mass fraction of the hydrogen additive is required (Δg_{H_2}) in relation to the original highly aromatized motor fuel can be estimated by the equation:

$$\Delta g_{H_2} = \Delta g_{H_{\text{HF}}} = \{[g_{H_{\text{HF}}}]_{\text{ef.}} - g_{H_{\text{HF(ef.)}}}\}/100, \qquad (7.11)$$

where Δg_{H_2}, $\Delta g_{H_{\text{HF}}}$ – respectively in mass fractions.

The ratio of hydrogen atoms to carbon atoms in the original hydrocarbon fuel will be determined according to (7.8), and in the composite (hydrocarbon-hydrogen) fuel according to this dependence:

$$\left(\frac{H}{C}\right)_{\Sigma} = \left(\frac{A_C}{A_H}\right) \cdot \left(\frac{g_{H_{\text{HF}}} + \Delta g_{H_{\text{HF}}}}{g_C}\right) = \left(\frac{H}{C}\right)_{\text{HF}} \cdot \left(1 + \frac{\Delta g_{H_{\text{HF}}}}{g_{H_{\text{HF}}}}\right),$$

where g_i – corresponding mass fractions of the components [10, 11].

An example №1.

When using wide-fraction liquid motor fuel with AH content ($g_{\text{AH}} = 50$ %) and, accordingly, hydrogen ($g_{H_{HF}} = 12$ %), with the selected basic effective hydrogen content $[g_{H_{\text{HF}}}]_{\text{ef.}} = 13{,}5$ %, the level of effective hydrogen content is determined by (7.12) as:

$$g_{H_{\text{HF(ef.)}}} = [12 - (50 - 30)^{0{,}4}] = 12 - 3{,}3 = 8{,}7\ \%,$$

or

$$g_{H_{\text{HF(ef.)}}} = 0{,}087 \text{ (in mass fractions)}.$$

Then (according to 7.11) $g_{H_2}^{e} = 13{,}5 - 8{,}7 = 4{,}8$ % or $g_{H_2}^{e} = 0{,}048$ (in mass fractions).

At the same time, the ratio of hydrogen atoms to carbon atoms in the original hydrocarbon fuel corresponds to:

$$(H/C)_{ВП} = (A_C/A_H) \cdot (g_{H_{ВП}}/g_C) = 12 \cdot 12/88 = 1.64,$$

and the specified ratio for composite fuel will be determined according to the corresponding dependence:

$$(H/C)_{\Sigma} = 1,.64 \cdot [1 + (0.048/0{,}12)] \cong 2{,}3.$$

In fig. 7.10 shows the calculated nomogram of relationships between hydrogen indicators ($g_{H_{ВП}}$) starting broad-fraction fuels with $g_{AH} \geq 30$ % and the necessary additions of hydrogen ($g_{H_2}^{e}$) to base-effective levels $[g_{H_{HF}}]_{ef.}$ in composite hydrocarbon-hydrogen fuels with the aim of minimizing the levels of HF and PM emissions with their combustion products.

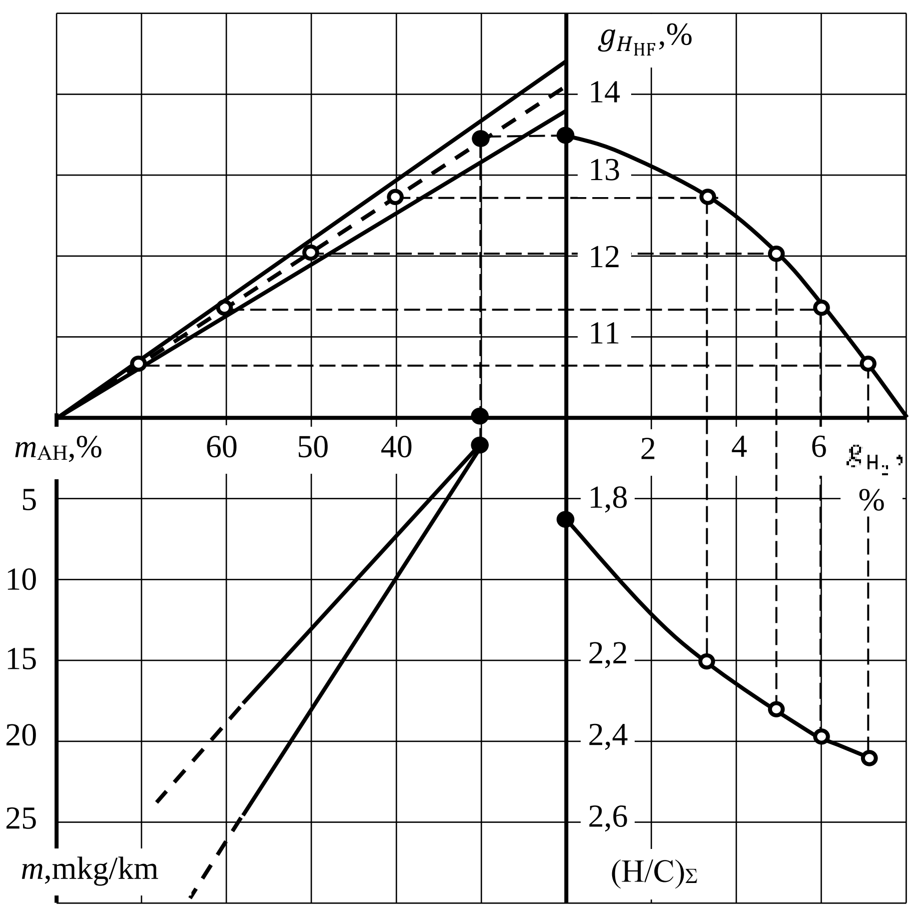


Fig. 7.10. Change in hydrogen indicators of composite fuels depending on the content of AH in the original fuels and levels of hydrogen additive

If you use methane as an additive to broad-fraction motor fuels with $g_{AH} > 30$ %, when:

$$g^{e}_{CH_4} = \Delta g_{CH_4} = 4 \cdot \{[g_{H_{HF}}]_{ef.} - g_{H_{HF(ef.)}}\}/100. \qquad (7.12)$$

The ratio of hydrogen atoms to carbon atoms in the original hydrocarbon fuel will be determined according to (7.8), and in the composite (hydrocarbon-methane) fuel according to this dependence:

$$(H/C)_{\Sigma} = (A_C/A_H) \cdot [(g_{H_{HF}} + 0{,}25 \cdot g^{e}_{CH_4})/(g_{C_{HF}} + 0{,}75 \cdot g^{e}_{CH_4})], \qquad (7.13)$$

where g_i – corresponding mass fractions of the components.

An example № 2.

According to the data (example No. 1), the required mass fraction of methane additive according to (7.12) will be:

$$g^{e}_{CH_4} = 4 \cdot g^{э}_{H_2} = 4 \cdot 0.048 = 0.192 \text{ (in mass particles)}.$$

At the same time, the ratio of hydrogen atoms to carbon atoms in composite (hydrocarbon-methane) fuel according to (7.13) will be:

$$(H/C)_{\Sigma} = 12 \cdot (0.168/1.024) \cong 1.97.$$

Thus, when using methane as an additional energy carrier to highly aromatic fuel with $g_{AH} > 30$ % and ensuring the proportion of hydrogen in the composite fuel at the level $[g_{H_{HF}}]_{ef.}$, the fuel index (H/C) increases less significantly than with the corresponding hydrogen additions.

7.8. Conclusions

The study analyzed the prospects and technical features of the use of alternative motor fuels as a factor in ensuring the climate neutrality of the development of the motor vehicle sector. Among the investigated aspects of this issue, the following were investigated:

- features and prospects of using natural gas as motor fuel;
- ecological and climatic aspects of the use of alcohol and benzo-alcohol fuels;

- environmental risks and prospects for the use of hydrogen and gasoline-hydrogen fuels in transport;
- studied the energy potential and ecological efficiency of the use of gasoline-hydrogen fuels;
- the ecological, operational and climatic prospects of the use of highly aromatic petroleum fuels with hydrogen additives were investigated.

On the basis of calculations, it was established that when using methane as an additional energy carrier to highly aromatic fuel and ensuring the proportion of hydrogen in the composite fuel at the appropriate level, the fuel index (H/C) increases less significantly than with the corresponding hydrogen additives, which indicates the expediency of its use to increase the environmental and energy performance of motor fuels.

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PART 8
CLIMATE CHANGE MITIGATION TECHNOLOGIES: LANDFILL LEACHATE PROCESSING TECHNOLOGY

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8.1. Introduction

Municipal solid waste (MSW) landfills are big sources of chemical and biological environmental pollution (Degtyar et al., 2019; Grynchyshyn et al., 2019). MSW landfills are particularly dangerous in terms of their impact on the surface water bodies and groundwater in the area of influence of these environmentally hazardous objects (Samoilyk et al., 2017; Vaverková et al., 2020). According to expert estimations, more than 99 % of Ukrainian MSW landfills do not meet European requirements, and the volume of household waste tends to increase (National Strategy, 2017).

Leachate is the most harmful factor of the impact of landfills and dumps on the environment. Leachate actively forms in the landfill body when moisture content of deposited solid waste is more than 55 %, and due to precipitation that exceeds the evaporation from the landfill surface (Household Solid Waste Landfills, 2005). Landfill leachates are highly concentrated water solutions of various toxic organic and inorganic substances (Melnyk et al., 2014, Popovych et al., 2020, Teng et al., 2021). In the absence of strict control of hydrosphere pollution (Iurchenko et al., 2017; Tulaydan et al., 2017) and due to the problems with monitoring of this pollution (Odnorih et al., 2020), development of effective methods to prevent contamination of surface waters and aquifers by leachates is especially important.

The most common technologies for leachate treatment are biological anaerobic and aerobic methods and membrane processes, continuing with final stage of secondary treatment at municipal wastewater treatment plants (WWTP) (Dereli et al., 2020; Malovanyy et al., 2018) or artificial wetlands (Popovych et al., 2020; Malovanyy et al., 2021). Membrane treatments including the most widespread reverse osmosis are energy-expensive, and implementation of these processes requires significant capital and operating costs (Dushkyn et al., 2011). It is also advisable to use different energy-saving systems (Shchur et al., 2021). Anaerobic biological treatment of leachate (Mojiri et al., 2021; Zamri et al., 2017) could be economical due to the obtaining of biogas, a renewable energy source (Voytovych et al., 2020). However, its implementation on an industrial scale requires strict adherence to the process parameters, and since the leachate composition can vary widely upon time, this technology is challenging to implement.

Aerobic methods of biological leachate treatment have a number of advantages comparing anaerobic methods: flexibility of use, convenience of an output to a steady mode of maintanance, and quick adaptation to variable leachate composition and flow rate (Miao et al., 2019; Wang et al., 2018). Aerobic reactors are much simpler in design and less expensive than anaerobic ones, they can be automated and operated much easier. It is interesting to note the study on leachate treatment from Pulau Burung Landfill Site (PBLS), located in Bayram Forest Reserve, Malaysia (Zamri et al., 2017). The researchers selected this site because it is semi-aerobic and recirculates the leachate. PBLS has been in operation for over 20 years and the resulting leachate is mature, with a high COD and concentration of ammonium nitrogen and a low BOD_5/COD ratio. However, the use of adsorbent material, in this case, ion exchange resin, as a second stage after aeration requires the development of methods for its processing or disposal, which involves additional costs.

An effective way to increase the effect of biological treatment of landfill leachate is the use of sequencing batch reactors SBR (Jagaba et al., 2021; Tałałaj et al., 2021), SBR with carriers (Koc-Jurczyk and Jurczyk, 2020), microaeration (Wei et al., 2021) etc. A combination of aerobic and anaerobic methods of leachate treatment is both promising and effective (Fatma et al., 2016; Hongwei Sun et al., 2015). However, treating solid waste landfill leachate in this coordinated manner is energy-intensive and more expensive than aerobic treatment. Treatment using the aeration method with higher plants is interesting (Xinyi Chen et al., 2022). However, this method is more suitable for domestic wastewater treatment, as it has a more predictable chemical composition.

The main deficiency of aerobic and anaerobic biological methods of landfill leachate treatment is the need for additional stages for more deep treatment to meet the requirements for discharge into open water courses (Lebron et al., 2021; Malovanyy et al., 2018). The most common solution is the use of combined multi-stage treatment methods, where biological methods are combined with reverse osmosis (Tałałaj et al., 2021), treatment with strong oxidants, including ozonation (Yang et al., 2022)), Fenton process (El Mrabet et al., 2020), followed by precipitation enhanced by coagulation and flocculation (De et al., 2019; Malovanyy et al., 2018). Oxidation and sorption are especially necessary and effective for the treatment of mature leachate and for the removal of heavy metal ions (Taghavi et al., 2021).

Aerated lagoons is a simple, economic and effective method for aerobic biological treatment of landfill leachate from the organic contaminants and ammonium nitrogen (Broughton and Tracer, 2022; Malovanyy et al., 2018). A typical example of the long-time treatment of mature leachate in aerated lagoons is the Bell House landfill (England), which became operational in 1995. The publication (Mehmood et al., 2009) presents the monitoring parameters at this station from May 1999 to December 2000. Leachate was treated in 4 aerated lagoons connected in series. At the entrance of the plant COD of leachate varied in the range of 800–3400 mg/L during the analysis period, and the average COD value was 1740 mg/L. At the exit of the first lagoon the average COD value was 620 mg/L, after the second – 510 mg/L, after the third – 492 mg/L and after the fourth – 426 mg/L. The degree of treatment by COD, as a percentage of the input value, was equal: after the first lagoon – 64.4 %, after the second – 70.7 %, after the third – 71.7 % and at the exit of the plant – 75.5 %. In the leachate of the Bell House landfill, the average ammonium nitrogen concentration during the study period was 965.2 mg/L. The degree of treatment by ammonium nitrogen after the first lagoon was equal 80.8 %, after the second – 97.4 %, after the third – 99.6 %, and after the fourth – 99.0 %. The most effective process of leachate treatment took place in the first lagoon. Since the volume of the first lagoon was 80 m^3 and the average value of the hydraulic retention time was 7.3 days, the achieved effects of leachate treatment by COD (64.4 %) and by ammonium nitrogen (80.8 %) are quite high with a relatively small volume of the lagoon and low operating costs.

Technology of biological aerobic treatment of landfill leachate in laboratory conditions, simulating the process in an aerated lagoon was studied by Malovanyy et al. (2018). The information on its successful application predicts the prospects for its application as a pretreatment stage in the complex technology of leachate treatment at Hrybovychi MSW landfill (Lviv region, Ukraine). After pretreatment, leachate was diluted by municipal wastewater and sent for a final treatment at the wastewater treatment plant.

8.2. Methodology

Hrybovychi MSW landfill leachate was used in this study as tested leachate. Hrybovychi MSW landfill with total area of about 38 ha is located in the west part of Ukraine, 2 km to the north from Lviv city (49.90N; 24.04E). It served as main MSW landfill of Lviv city from 1958 till 2016, and now it is under technical remediation process. Main parameters of raw Hrybovychi MSW landfill leachate are presented in Tab. 8.1.

Thus, significantly excessive concentrations of contaminants were detected in the Hrybovychi MSW landfill leachate. The study of biological leachate treatment under aeration conditions was aimed to find the treatment effects by BOD_5, COD and TKN as key pollutant indicators.

Pilot-scale aeration treatment unit

Biological aerobic treatment of Hrybovychi MSW landfill leachate was studied at the pilot treatment unit with capacity of 400 L/day. Aeration was carried out in the bioreactor with diameter D = 1.6 m and total depth H = 1.8 m, equipped with a jet pump aerator (P = 2.2 kW), as shown in Fig. 8.1.

Table 8.1.

The average chemical composition of Hrybovychi MSW landfill leachate

Pollution indicators	Unit	Value	TLV*
Ammonium nitrogen	mg/L	548.1	2
Total Kjeldahl nitrogen (TKN)	mg/L	889.3	10
BOD_5	mg/L	192.0	15
COD	mg/L	5082	80
Suspended solids (SS)	mg/L	3011	–
Iron	mg/L	10.7	0.3
Cadmium	mg/L	0.005	0.001
Cobalt	mg/L	0.028	0.1
Manganese	mg/L	0.015	0.1
Nickel	mg/L	0.09	0.1
Lead	mg/L	0.12	0.03
Strontium	mg/L	0.022	7
Total dissolved solids (TDS)	mg/L	15245	–
Chlorides	mg/L	3900	350

**TLV – threshold limit value for the output in open water courses in Ukraine*

Fig. 8.1. Leachate aeration in the pilot-scale bioreactor tank

The optimal aeration parameters (timing and intensity) were determined during the research. Previous laboratory studies have shown that the optimal duration of the non-stationary period for the start of the process of aerobic biological treatment is

7–15 days (Malovanyy et al., 2018). Pilot studies have confirmed these figures. Microbiocenosis was gradually self-inoculated in the bioreactor in the process of aeration (Dos Santos et al., 2022; Malovanyy et al., 2018), which resulted in a gradual biological treatment of leachate.

Periodical aeration process was used, with 12 hours of aeration per day. Control samples of leachate were taken for the laboratory analysis every 24 hours. Standard methods for the examination of water and wastewater (Standard Methods, 2017) were used for the analysis of key pollutant indicators, namely BOD_5, BOD_{tot}, COD, SS, TKN, and pH.

8.3. Results and discussion

Dependencies of key pollution indicators during the 30-day periodical aeration process were obtained experimentally. First 15 days treatment unit was working in the batch reactor mode treating the same initial volume of raw leachate. Another 15 days treatment unit worked in the continuous reactor mode and 400 L of aerobically pre-treated leachate were pumped once a day to the next treatment stage, and consequently the same volume of raw leachate was added in the bioreactor tank.

Experimental dependence of the TKN on the duration of biochemical aerobic treatment of leachate is presented in Fig.8 2. During the non-stationary period of aerobic leachate treatment, the concentration of TKN decreased from 889.3 mg/L to 397.2 mg/L, i.e., by 2.24 times, corresponding to a treatment effect of 55.3 %. It was evident that the changes in both forms of nitrogen occur by a similar mechanism. The results obtained in this non-stationary period can be approximated by the simple exponential dependence, corresponding to the first-order reaction:

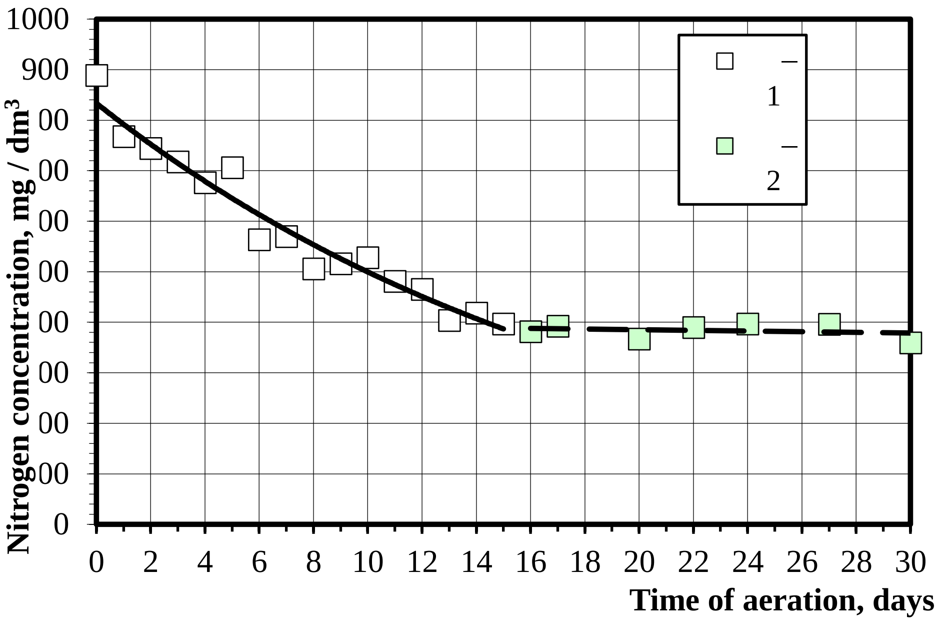
$$C_N = 833.5\, e^{-0.051\, t} \qquad (8.1)$$

where C_N is the TKN concentration in mg/L; t is time in days; coefficient of determination of the dependence (1) $R^2 = 0.959$.

Dependence of the COD of the leachate on the duration of its aerobic biochemical treatment at the pilot-scale treatment unit (Fig. 8.3) shows that in first 15 days of the non-stationary period the value of COD decreased by about 27 %, which is quite typical for medium and mature leachates. For the non-stationary period, the approximate equation is:

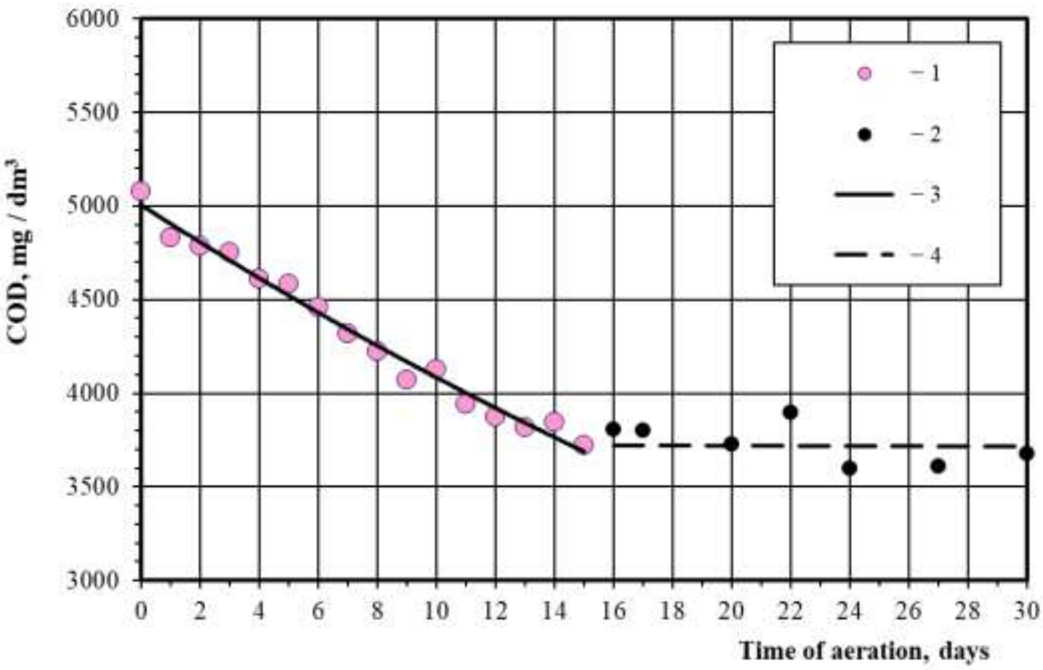
$$C_{COD} = 5007\, e^{-0.0204\, t} \qquad (8/2)$$

where C_{COD} is the value of COD, mg/L (Fig. 8/3), and coefficient $R^2 = 0.9829$.



1 – non-stationary period; **2** – stationary period;
3 – trend line (1); **4** – the average value of 385 mg/L

Fig. 8.2. Content of total Kjeldahl nitrogen in Hrybovychi leachate during its aeration in the pilot-scale treatment unit

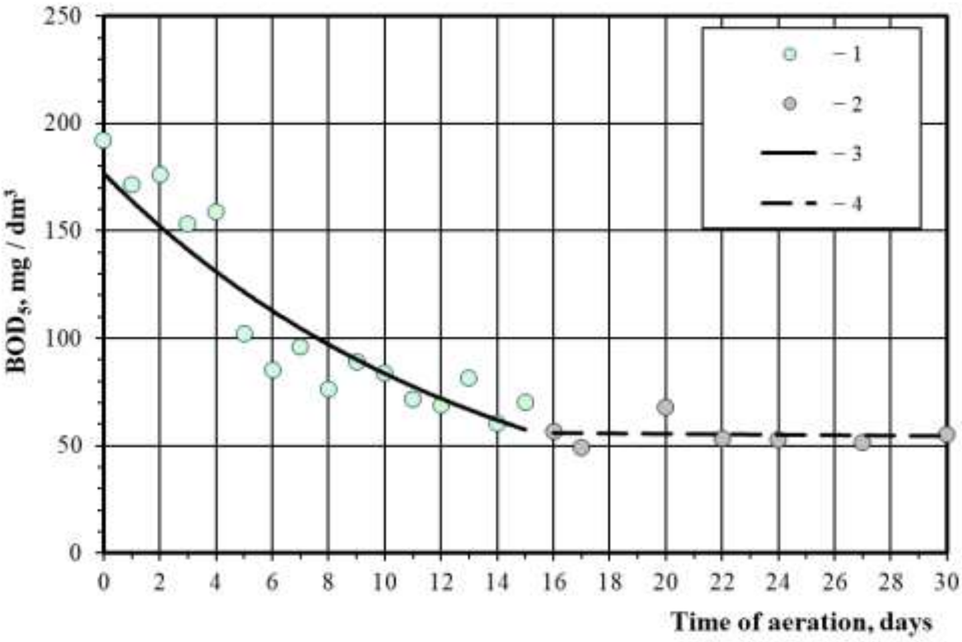


1 – non-stationary period; **2** – stationary period;
3 – trend line (2); **4** – the average value of 3732 mg/L

Fig. 8.3. Change of COD in Hrybovychi leachate during the aeration process at the pilot-scale treatment unit

BOD_5 of leachate during the 15 days of the non-stationary period decreased by 63.3 % (Figure 4), which is much higher comparing the treatment effect by COD, and exponential approximation with R^2 = 0.849 is obtained:

$$C_{BOD5} = 176.9\, e^{-0.075\, t} \quad (8.3)$$



1 – non-stationary period; **2** – stationary period;
3 – trend line (3); **4** – the average value of 57.3 mg/L

Fig. 8.4. Change of BOD_5 in Hrybovychi leachate during the aeration process at the pilot-scale treatment unit

Similar results were obtained for BOD_{tot} (Fig. 8.5):

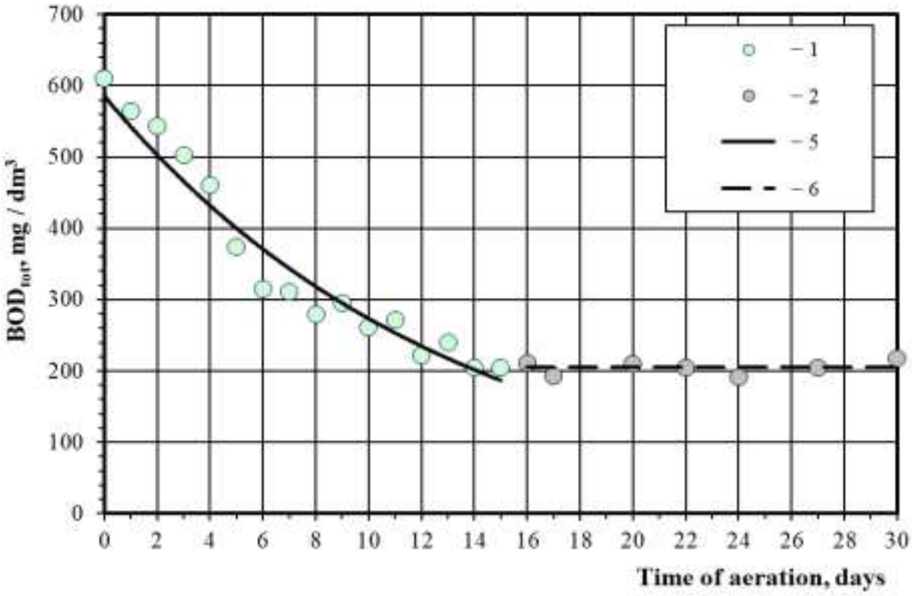
$$C_{BODtot} = 586\, e^{-0.076\, t} \quad (8.4)$$

where C_{BODtot} is the value of BOD_{tot}, mg/L; R^2 = 0.9487.

The total effect of leachate treatment by BOD was equal to 63.3 %. It should be noted the high value of the ratio BOD_{tot} / BOD_5 = 3.57 when entering the regular steady-state operating mode of the aerobic biological treatment.

Clear trends of relatively rapid increasing of the pH value at the beginning of the aeration and slow asymptotic increasing to the 12–15 days of aeration are obtained (Figure 6). Variation of pH is probably caused by the nature of biochemical processes of the leachate oxidation by aerobic microbiocenosis, and for the first 12 days of aeration the exponential association equation is obtained (R^2 = 0.971):

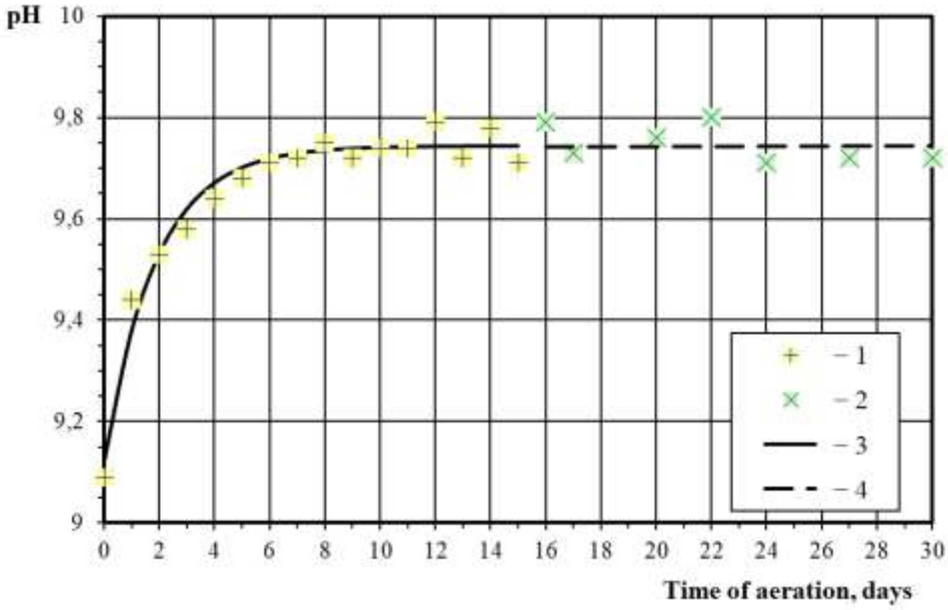
$$pH = 0.623\, (15.64 - e^{-0.536\, t}) \quad (8.5)$$



1 – non-stationary period; **2** – stationary period;
5 – trend line (4); **6** – the average value of 204.4 mg/L

Fig. 8.5. Change of BOD$_{tot}$ in Hrybovychi leachate during the aeration process at the pilot-scale treatment unit

After 12 days of aeration pH of leachate was stabilized at an average value of 9.74 with small (± 0.05) variations in both directions (Fig. 8.6).



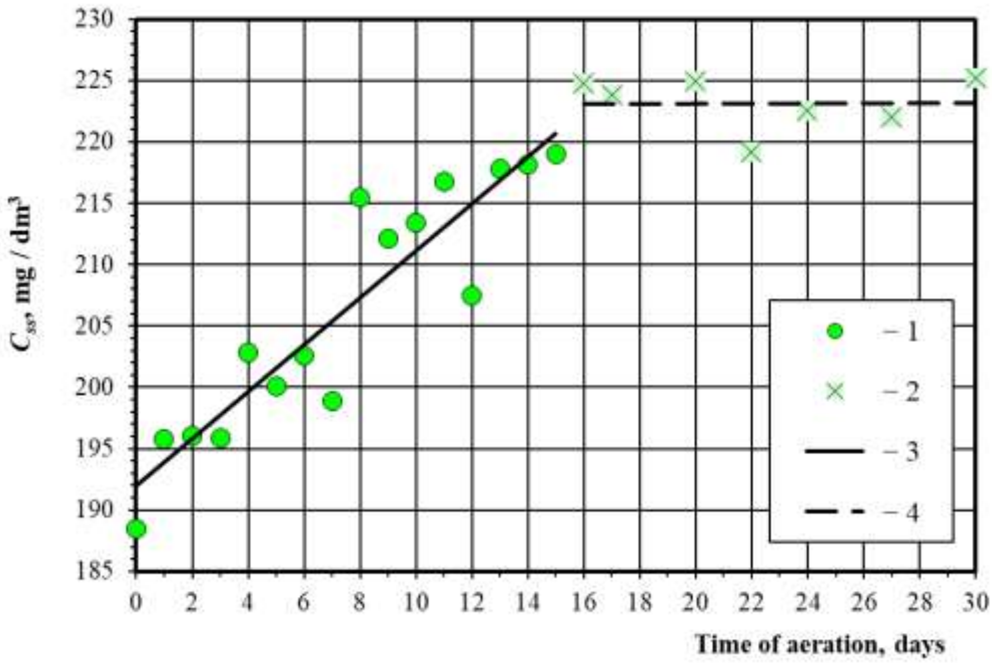
1 – non-stationary period; **2** – stationary period; **3** – trend line (5); **4** – average value 9.74

Fig. 8.6. Change of pH in Hrybovychi leachate during the aeration process at the pilot-scale treatment unit

During the phase of biochemical purification of the filtrate, a monotonic, temporally insignificant increase in the content of suspended solids and pop-up substances was observed (Fig. 8.7). This can be explained by the gradual increase in the biomass of the microbiocoenosis involved in the biochemical purification of the filtrate from impurities. Simple linear trend can be used to approximate the experimental results:

$$C_{SS} = 192 + 1.91\, t\,, \tag{8.6}$$

where C_{SS} is suspended solids content, mg/L; R^2 = 0.8448.



1 – non-stationary period; **2** – stationary period; **3** – trend line (6); **4** – average values – 223 mg/L

Fig. 8.7. Change of C_{SS} in Hrybovychi leachate during the aeration process at the pilot-scale treatment unit

8.4. Conclusions

The results of the systematic pilot-scale studies of the treatment efficiency of Hrybovychi MSW landfill leachate (Ukraine) at the stage of aerobic biological treatment confirmed the effectiveness of the developed technology for the treatment of such types of highly contaminated waste waters.

Based on the analysis of the pilot-scale results optimal parameters for the aerobic biological treatment of leachates of typical Ukrainian MSW landfills are obtained. Periodical leachate aeration using a jet-type aerators is found to be the most effective, with 12 hours of aeration per day. Initial non-stationary period in the batch mode should continue about 15 days to reach sufficiently high treatment effects on baseline pollution indicators.

Aerobic biological treatment of landfill leachate using the developed method allows achieving a significant treatment effects, namely 55.3 % by the total Kjeldahl nitrogen, 27 % by COD and 63.03 % by BOD. Time dependences of TKN, COD, BOD_5 and BOD_{tot} with sufficiently high accuracy can be described by simple exponential dependences, respectively (1)–(4), which correspond to the conditions of the first-order reactions.

Time dependencies of pH and suspended solids during the aeration treatment process of leachate are obtained. The peculiarities of the change of these parameters at the non-stationary stage of the treatment process are explained by the self-inoculation of the activated sludge microbiocenosis, which provides the biological treatment of leachate.

Landfill leachate, aerobically pre-treated in the pilot-scale treatment unit, can be discharged for the final treatment to the bio-plateau or to the wastewater treatment plant.

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