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EFFORTS OF THE TRANSPORT AND ENERGY SECTORS TOWARD RENEWABLE ENERGY FOR CLIMATE NEUTRALITY

Summary. The integration and utilization of renewable energy sources in the energy and transport sectors are the main actions undertaken to attain climate neutrality by 2050. The connection and indication of the relations occurring in these two sectors constitute the novelty of the current research. Key actions include increasing the share of low- and zero-emission transport, such as electric cars, bicycles, trains, and buses; reducing emissions from aviation and shipping; and improving energy efficiency and transport safety by modernizing the vehicle fleet, introducing intelligent transport systems, applying emission and fuel quality standards, and promoting technological and digital innovation. A novel and significant aspect of the research is its comprehensive approach to key economic sectors that exert a profound influence on climate change. Through the conducted studies, it has been demonstrated what essential actions must be undertaken to transition towards a low or zero-emission economy. This paper points to a strong nexus between the transport sector, the energy sector, and climate change, underscoring the imperative for collaborative efforts and strategic initiatives among these sectors to address the pressing challenges associated with achieving climate neutrality.

1. INTRODUCTION

The increase in greenhouse gas emissions, caused mainly by human activity, has led to global warming, which is reflected in catastrophic consequences for the environment and society. Decisive actions towards achieving climate neutrality are needed in order to effectively counteract the dangerous effects of climate change [1]. The pursuit of climate neutrality requires the cooperation of all countries, industry sectors, businesses, and communities [2]. Achieving this goal requires revolutionary changes in the transition to the production and use of energy, transport, and the entire economy.

The current study encompasses a comprehensive evaluation of two paramount sectors, each exerting a significant influence on the environment while concurrently presenting substantial avenues for the reduction of greenhouse gas emissions. These sectors, namely the transport sector and the energy sector, are critical focal points in the endeavor to curtail the ecological footprint of human activities [3]. This study focuses on filling a significant gap in the field of science regarding the impact of two key sectors – transportation and energy – on the natural environment.

Previous research has often not been comprehensive enough to analyze the relationships and interactions between these sectors and climate change. An innovative research approach has enabled the identification of key areas of synergy between them and the determination of necessary actions to reduce greenhouse gas emissions and promote sustainable development. By focusing on these pivotal sectors, the present study embarks on a multidimensional analysis that scrutinizes their synergistic roles, elucidates the intertwined challenges, and uncovers the myriad opportunities to usher in a paradigm shift towards emissions reduction. The comprehensive analysis of the transport and energy sectors provides

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a robust foundation for informed decision-making, policy formulation, and innovative interventions that will collectively steer us toward a more sustainable and ecologically balanced future.

1.1. Actions taken in the transport sector

Several key actions can be taken in the transport sector. Firstly, the use of electric cars needs to be promoted for energy production to be based on clean energy. Governments, thanks to their legal and political capabilities, can provide various types of incentives, such as grants, technology and industrial parks or tax breaks, subsidies, and infrastructure support, to ease the transition to electric vehicles [4].

Second, support for the development of public transport systems is required. At the city level, it is recommended to invest in efficient and accessible public transport networks, including buses, trams, and trains. Prioritizing public transport infrastructure and making it affordable and reliable are essential [5]. Another element of improving the transport system is intelligent systems that can monitor and analyse traffic data and road conditions in real time. Based on this information, they can adjust traffic lights, optimizing the duration of the lights and changing them depending on the current situation. This helps to avoid unnecessary congestion and slowdowns, which lowers fuel consumption and emissions [6].

Third, the development and widespread adoption of advanced technologies, such as hydrogen fuel cells and biofuels, represent another pivotal strategy that can increase fuel efficiency and reduce emissions in the transportation sector. Hydrogen fuel cells offer a promising alternative to traditional internal combustion engines. Implementing hydrogen fuel cell-powered vehicles and establishing a robust refueling infrastructure can diversify the energy sources for transportation and help address the challenges posed by fossil fuels [7].

Fourth, support for the development of infrastructure supporting sustainable transport, such as charging stations for electric vehicles, bicycle paths, and pedestrian-friendly paths, is required. These actions have a positive impact on the transport system. The construction of infrastructure supporting sustainable means of transport directly influences activities that contribute to improving the situation by reducing greenhouse gas emissions and air pollution. Electric vehicle charging stations facilitate the adoption of electric cars that emit less emissions than traditional internal combustion engines or no emissions. Bicycle lanes and pedestrian-friendly paths encourage people to choose active modes of transport, reducing their dependence on fossil fuel-powered vehicles and, consequently, reducing air pollution and congestion [8].

1.2. Actions taken in the energy sector

In the energy sector, we can also distinguish several key actions that should be planned and taken to reduce the emission of harmful gases and protect the environment.

First of all, one of the decisive actions should be the transition to renewable energy sources. In the era of a low- or zero-emission economy, it can be seen that one of the most fundamental activities carried out by energy companies is moving away from high-emission fossil fuels to renewable energy sources. This transformation includes investment in and the expansion of renewable energy infrastructure, such as solar energy produced by photovoltaic panels from the sun's energy, wind energy produced by windmill generators, hydropower using the kinetic energy of flowing water, and geothermal energy from deep drilling in the ground. Energy production from biomass and waste is also very popular [9,10]. Energy companies are increasingly integrating renewables into their energy portfolios, promoting clean energy generation and reducing dependence on carbon-intensive sources. The transition to renewable energy is a significant step towards a sustainable energy future but comes with significant investment costs. The second step is decarbonizing operations. To achieve climate neutrality, energy companies are implementing strategies to decarbonize their operations [11]. This includes optimizing energy efficiency, reducing emissions from mining and production processes, and adopting cleaner technologies. The third important action is the carbon offset and reduction initiatives. Many energy companies engage in carbon offsetting and emission reduction initiatives. They invest in projects that aim to offset their emissions by supporting activities such as reforestation, afforestation, and conservation efforts. In addition, companies are exploring innovative ways to capture and use carbon dioxide and are investing in research and development to develop clean technologies.

The connection between these sectors and their clear impact on climate change are extremely important and constitute an impetus for taking immediate actions to mitigate the adverse effects on the environment. The shared dependence on fossil fuels in energy and transport and the resulting emissions underscore the critical need to shift to renewable energy sources and sustainable transport practices. The link between energy and transport highlights the need to prioritize climate policy reforms and introduce innovative technological solutions to mitigate environmental impacts. Only through coordinated and integrated efforts can a more sustainable, resilient, and environmentally responsible future be ensured for the next generations. This work explores the actions that should be taken in the transport and energy sectors to achieve the intended effects of a zero-emission economy. What is both novel and significant is the collaboration between both sectors to reduce greenhouse gas emissions. It is essential to show the possibilities of using alternative fuels in transport, encourage the use of new materials for the production of aircraft and ships, and implement many technical and technological solutions related to traffic management. The energy sector must be developed alongside the implementation of innovative solutions. Following the guidelines described in this article will allow business managers to implement hydrogen in transport, electric cars, new technologies in aviation, etc.

This investigation is significant in that it reveals the ongoing relationship between the energy and transport sectors, both of which play a vital role in emissions reduction efforts. Traditionally, these sectors have been treated independently, but their interconnectedness is undeniable. This study sheds light on how advances in clean energy technologies are not only decarbonizing the energy sector but also having a profound impact on greenhouse gas emissions from transportation through the introduction of electric vehicles and sustainable alternative fuels.

2. MATERIALS AND METHODS

This research was conducted with meticulous precision, employing the adept utilization of the desk research method. This approach, characterized by a reliance on pre-existing resources such as books, magazines, reports, databases, and the expansive reach of the Internet, has emerged as a key aspect. Desk research is typically more cost-effective and time-efficient than primary research methods like surveys or experiments. It often serves as an essential step in research to provide background information, context, and a foundation for further investigation. By harnessing the potency inherent in this research methodology, a dual advantage materialized: a reduction in research costs was realized alongside unimpeded access to an extensive repository of databases.

The crux of desk research lies in its inherent capacity to tap into a diverse spectrum of data and information sources. This encompassing approach, which includes but is not limited to academic articles, industry reports, government publications, statistical databases, press articles, and a plethora of online resources, serves as the foundation of knowledge acquisition. Given the underpinning reliance on secondary sources, the precision and accuracy of the acquired information hinge intrinsically on the proper segregation and credibility of the utilized sources.

Throughout this study, a pivotal facet was subjecting these sources to rigorous and systematic scrutiny. This process involved a judicious examination of potential errors, inaccuracies, or the presence of outdated information that has the potential to cast doubt upon the validity of the findings. To effectively counteract the potential risks posed by unsuitable sources, a strong emphasis was placed on the selection of reputable and dependable publishing houses. These sources, notable for their stringent peer review mechanisms, inherently provided a robust assurance of delivering data characterized by accuracy and dependability.

Furthermore, the credibility of the source materials underwent a comprehensive evaluation. This encompassed a judicious analysis encompassing considerations of the author's expertise, the breadth of references employed, and the affiliations pertinent to the source. Within the realm of the desk research method, several pivotal phases of the research trajectory emerged prominently. Initially, a meticulous identification of the research problem was seamlessly integrated with an exhaustive review of the extant literature. Subsequently, bolstered by insights gleaned from this literature review, a theoretical framework was crystallized. This framework emerged as an invaluable tool, facilitating the unraveling of the intricate web of factors influencing decisions related to innovation and the adoption of emerging technologies—efforts driven by the noble aim of mitigating adverse environmental impacts. With the framework firmly established, the research progressed to the next critical juncture: the meticulous collection and subsequent analysis of data. The raw materials, which were assiduously gathered, served as the foundational bedrock upon which the findings were rigorously interpreted and distilled into cogent and coherent conclusions.

The culmination of this scholarly pursuit finds its manifestation in the encapsulation of the research analysis within the pages of this article. Serving as both a testament to the unwavering commitment to knowledge advancement and a valuable contribution to the academic discourse, this article is a tangible testament to the intricacies of the desk research method and the wealth of insights it has bestowed upon innovation, technology implementation, and environmental sustainability. The individual stages of the desk research method can be presented as four main elements: find, assess, use, and validate.

Desk research allows one to analyze a large amount of data and information, which can provide a broad perspective and view on the subject under study. In order to obtain valuable results, desk research should be carried out with care concerning the quality of sources, data accuracy, and timeliness. Also, one should be aware of the variety of sources to avoid a one-sided or distorted image. All these aspects have been presented in Figure 1 and have been reflected in the conducted research.

In this study, methodologies commonly employed in the field of management sciences were applied. Among these methodologies, desk research and observations were distinguished as fundamental tools for the analysis of data and information related to the studied areas. Desk research involves a systematic exploration of available literature, documents, reports, and other sources of information, enabling the accumulation of knowledge in a structured and comprehensive manner.

Observations, as a second methodological element, permit the direct recording of phenomena, behaviors, or processes in the real research environment. This approach facilitates the acquisition of firsthand data, which is pivotal for understanding real practices, actions, and interactions in a given context.

Based on the data acquired through these methods, an analysis was conducted, leading to conclusions—a characteristic element of the research methodology. This approach to conducting research falls within the category of inductive methods, wherein conclusions are deduced from accumulated facts and observations, resulting in generalizations and an understanding of the researched issues. Such an inductive research strategy allows for the systematic extraction of pertinent information, contributing to a more comprehensive understanding of the analyzed phenomena within the context of management sciences.

3. RESULTS AND DISCUSSION

3.1. Transport sector

The EU has set an ambitious target to reduce emissions in the transport sector by 90% between 1990 and 2050. Actions to achieve this goal are part of an overall plan to achieve climate neutrality by 2050. [12]. In 2019, the transport sector in the EU emitted 25% of greenhouse gases. Most emissions in this sector come from road transport (almost 72%), while the shares of emissions from maritime transport and aviation are 14% and slightly more than 13%. Railways represent only 0.5% (only emissions from trains with internal combustion engines). Measures are being taken to implement innovative solutions in road transport in order to significantly reduce greenhouse gas emissions, as it is the main emitter of pollution. Road transport primarily comprises freight transport, public transport, and passenger transport. CO_2 emissions from road transport vary greatly depending on the type of transport used. Passenger cars are a major source of pollution, accounting for 60.6% of all CO_2 emissions from road transport in Europe. This is followed by large trucks (27.1% of emissions), light commercial vehicles (11.0%), and motorcycles (1.3%) [12]. Reduction efforts in road transport must take into account the current market situation and the condition of the vehicle fleet in Europe. The breakdown of emissions by transport mode is presented in Fig. 1.

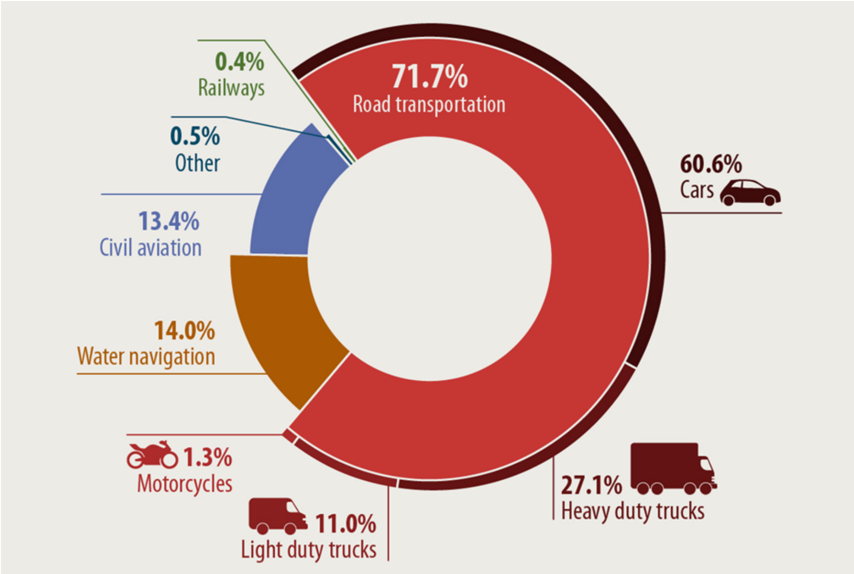

Fig. 1. Transport issue in the EU in 2019. Source: [12]

Figure 2 indicates that the road transport sector dominates in terms of its share of CO_2 emissions. Consequently, understanding the projected emissions growth until 2035 in this specific sector is crucial. The substantial contribution of road transport to emissions underscores the necessity for a detailed analysis of factors influencing its dynamics to formulate sustainable emission reduction strategies. Examining this issue allows the identification of key areas requiring a prioritized approach and the implementation of effective remedial measures. The analysis of the anticipated emissions growth until 2035 in the road transport sector may stimulate the development of comprehensive emission reduction strategies, taking into account the specific challenges associated with this sector, thereby contributing to a more sustainable transportation model.

From 2000 to 2022, an increase in emissions from the road transport sector, which is responsible for the majority of CO_2 emissions, was observed, rising from 4.24 to 5.87 $GtCO_2$. However, if the pandemic had not occurred, which resulted in a significant decline in emissions from 2020–2021, the projected emissions in 2035 would have exceeded 7.5 $GtCO_2$ (indicated by the dashed orange line in Figure 2). The pandemic imposed restrictions on the transport sector, leading to a reduction in emissions. Consequently, the estimated emissions for 2035 (indicated by the dashed blue line in Figure 2) stand at approximately 7 $GtCO_2$.

This dynamic context illustrates the impact of external events, such as the pandemic, on the trajectory of emissions in the road transport sector. This phenomenon underscores the significance of analysing variable factors that can substantially influence greenhouse gas emissions, particularly in road transport, which serves as a major contributor to CO_2 emissions in the transportation sector. Additionally, observed trends suggest that without emission-reduction measures, the road transport sector could have sustained an upward trend, highlighting the urgent need for the implementation of effective emission-reduction strategies in this sector. In this context, the consequences of the pandemic help illustrate the influence of crisis events on aspects of sustainable development, particularly in the context of the road transport sector, a significant source of greenhouse gas emissions.

The discernible reduction in emissions signifies a promising avenue for addressing the negative environmental repercussions associated with human activities. This decline underscores the feasibility of implementing effective mitigation strategies and achieving tangible progress toward environmental sustainability goals. The efficacy of the measures implemented is reflected in the anticipated effects, emphasizing the potential for positive outcomes in terms of reduced environmental impact. As such, these findings underscore the importance of continued efforts in adopting and refining emission reduction initiatives to foster a more sustainable and environmentally conscious trajectory.

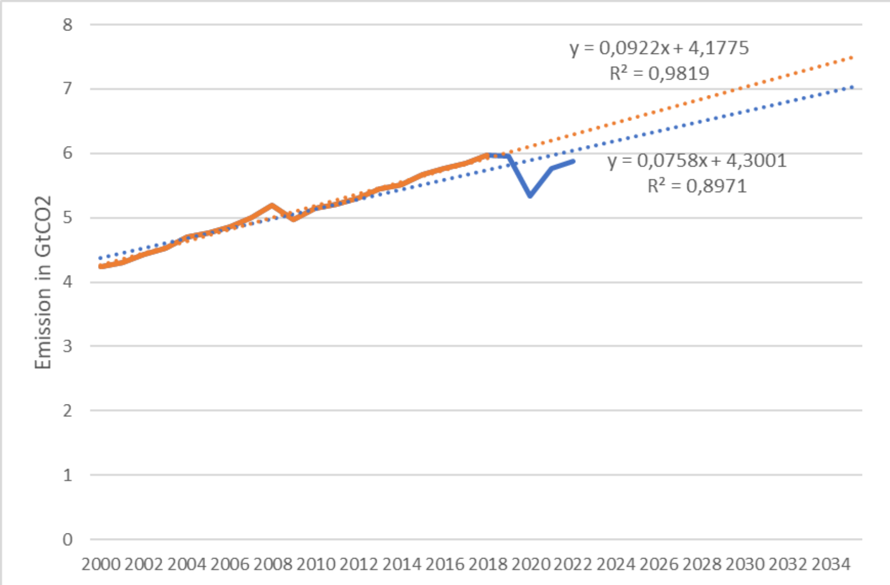

Fig. 2. Carbon dioxide emissions from the road transportation sector worldwide from 2000 to 2022. Source: own elaboration based on [13]

One of the important actions taken in the road transport sector is the transition to electric or hybrid vehicles. Hybrid technology can help bridge the gap between traditional internal combustion engines and fully electric vehicles. Encouraging the use of electric or hybrid vehicles can significantly reduce carbon dioxide (CO_2) emissions and other pollutants if electricity comes from renewable sources. Electric cars emit about three times less CO_2 than petrol cars. In countries where most of the electricity comes from renewable sources, such as Sweden or France, electric cars can reduce CO_2 emissions by up to 70–80% compared to petrol cars. Electric cars purchased in 2030 are projected to cut CO_2 emissions by a factor of four thanks to an EU grid increasingly reliant on renewables [14]. As battery technology continues to improve, electric vehicles will become more accessible and offer greater ranges. In 2023, over 14 million electric cars may be delivered to customers around the world [15]. The largest number of cars will arrive in China, EU countries, and the USA. The expected percentage ratio of electric cars to other cars by 2050 on a global scale is presented in Table 1.

Table 1

The market share of electric vehicles

2030	**2040**	**2050**
26 %	72.2 %	81.5 %

Source [16]

For cars purchased in 2030, the fuel industry predicts that a hybrid electric vehicle powered by a blend of e-fuels and gasoline is likely to reduce life cycle emissions by just 5% compared to running the same vehicle on gasoline. If the hybrid vehicle were powered only by renewable e-fuel, which is a hypothetical and unlikely scenario, it could emit 82% less emissions. Even then, the cleanest battery electric vehicle would still be 27% cleaner than an e-fuel-only hybrid, mainly due to the low efficiency of the e-fuel production process [17]. The development and use of sustainable fuels, such as biofuels or synthetic fuels produced from renewable sources, can help reduce the carbon footprint of transport. These fuels can be used in existing internal combustion engines with minimal modification. It is also important to support technologies and research aimed at increasing the fuel efficiency of internal combustion vehicles. Another solution in wheeled transport is hydrogen-powered cars, also known as hydrogen cars or fuel cell vehicles. Hydrogen solutions are a promising alternative to traditional vehicles powered by internal combustion engines and electric vehicles with batteries. Hydrogen cars offer a longer range compared to traditional battery electric vehicles. The hydrogen tank can be refueled quickly, and the refueling time is comparable to gasoline or diesel refueling times. The refueling time for various types of hydrogen vehicles is presented in Table 2.

Table 2

Chosen hydrogen-powered vehicles, their mileage, and the time required for refueling

	Range for One Refuelling [km]	**Refuelling Time [minutes]**
City bus (NesoBus)	450	15
Truck (Kenworth)	560	15
Car (Toyota Mirai)	650	5

Source [7]

The data in Table 2 show that the refueling time for public transport vehicles and trucks does not exceed 15 minutes, which is much better compared to charging electric vehicles. Moreover, the range of routes that can be covered on one refueling is sufficient for the purposes of these vehicles. Similarly, in the case of passenger cars, it can be seen that a short refueling time can be a competitive advantage. Moreover, a refueled car can move freely over long distances, which is another advantage of this solution. It can therefore be concluded that hydrogen finds wider use in the transport sector as an ecological alternative fuel, not only because it is environmentally friendly but also for time reasons and the fact that the distance traveled on one refueling is approximately 450–650 km (depending on the vehicle type). Many countries are introducing increasingly stringent regulations on vehicle emissions. Bans for vehicles with internal combustion engines entering city centers, low-emission zones, and CO_2 emission standards are forcing drivers and car manufacturers to look for alternative sources of drive. Developing investments in infrastructure for vehicles powered by alternative fuels, such as charging stations for electric vehicles (as of February 2024, in Poland there were 6,213 publicly available charging points) or hydrogen refueling stations, make the use of alternative fuels more convenient and attractive to consumers. The developed infrastructure encourages people to switch to more ecological means of transport. As the number of vehicle manufacturers and models increases, alternative vehicles are becoming more accessible to a wider range of consumers. Electric vehicle sales grew by 55%, reaching a record high of more than 10 million. Moreover, for the first time ever, the announced manufacturing capacity for electric vehicle batteries is sufficient to fulfill expected demand requirements in 2030. Nearly 95% of electric car sales in 2022 occurred in China, the United States, and Europe. Many automakers are introducing more and more electric or hybrid options to their offerings, which directly contributes to the growing demand for alternative fuels. An example of reducing CO_2 emissions in the transport sector is the use of innovative solutions, thanks to which emissions from new passenger cars decreased from 139.6 g of CO_2 per 100 km in 2010 to 122.1 in 2019; a further decrease to 59.4 g in 2030 is planned. Another solution that reduces emissions is intelligent traffic management systems. These systems collect vast amounts of traffic-related data that can be used to analyze trends and identify areas for improvement. Based on these analyses, informed decisions can be made regarding road infrastructure and long-term urban planning, leading to a more efficient use of resources and reduced emissions. Intelligent traffic management systems can be used to communicate with drivers and passengers through dynamic traffic information on electronic signs, mobile applications, etc. Thanks to the implementation of innovative technical and technological solutions, it will be possible to reduce CO_2 emissions from the transport sector to the level of about 1 Gt in 2070, as shown in Fig. 3.

Currently, on a global scale, means of transport emit about 7 Gt of carbon dioxide per year. However, thanks to technological innovation, the use of low-carbon fuels, and the scaling up of electrification, emissions from this sector have the potential to fall to 1 Gt of CO_2 per year [18]. Governments can introduce financial incentives, such as tax breaks, subsidies for the purchase of electric vehicles, and develop charging infrastructure. By 2070, several modes of transport are projected to be completely fossil-free.

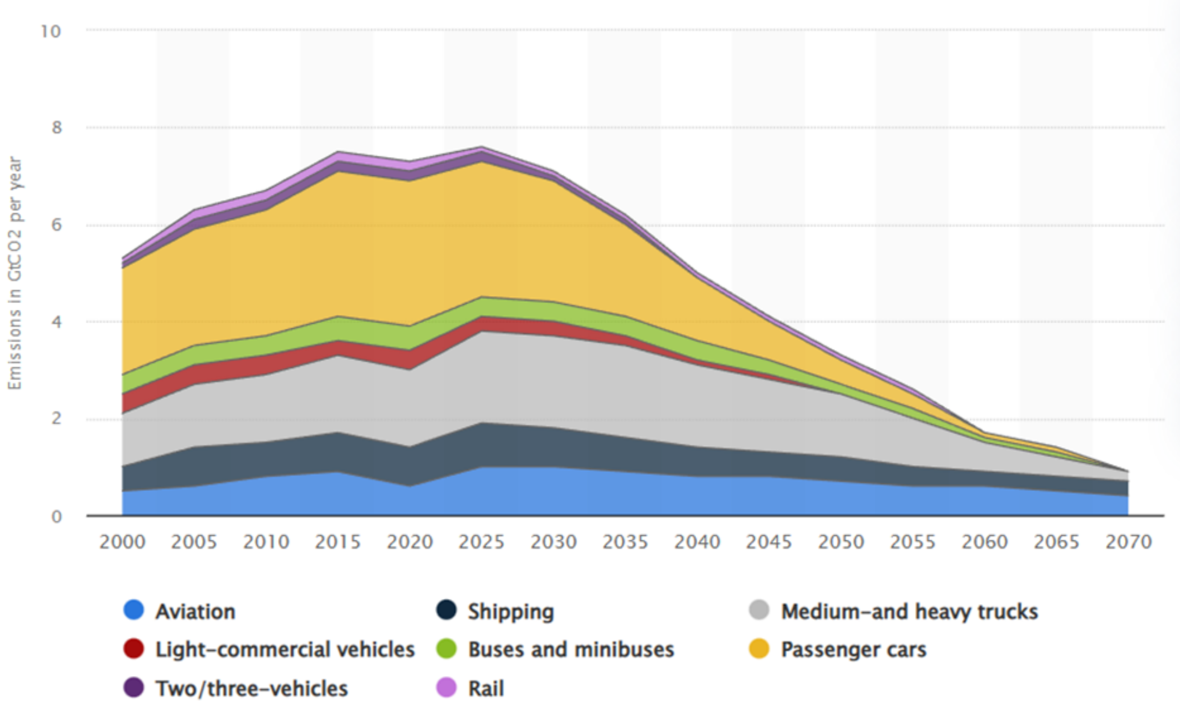

Fig. 3. Global transportation CO_2 emissions by mode from 2000 to 2070 in the Sustainable Development Scenario. Source: [18]

Maritime transport is another pollutant emitter. The European Commission has presented a project on the use of renewable and low-emission fuels in maritime transport [19]. The document discusses the proposal to reduce the intensity of greenhouse gas emissions from the energy used on ships by up to 75% by 2050 by promoting the use of more environmentally friendly fuels. Similarly, the strategy developed by the International Maritime Organization regarding the reduction of greenhouse gas emissions involves reducing the intensity of carbon dioxide emissions in international shipping (reduction of CO_2 emissions per transport work by at least 40% on average by 2030, aiming at 70% by 2050, compared to 2008). It also recommends that total annual greenhouse gas emissions from international shipping be reduced by at least 50% by 2050 compared to 2008 [20]. Implementing strict emission standards and emission monitoring systems in the shipping sector can help reduce air pollution and greenhouse gases. A shift from traditional heavy fuels to low-carbon alternative fuels is essential. This may include the use of cleaner fuels such as liquefied natural gas (LNG), biofuels, or hydrogen. In addition, research and investment in new technologies such as ammonia and methanol as marine fuels are recommended, which will also contribute to decarbonization efforts. In addition, new technologies should be used to reduce emissions by optimizing ship designs, using advanced propulsion systems, and implementing energy-efficient technologies such as waste heat recovery systems and innovative air lubrication systems. The design and construction of more aerodynamic and hydrodynamic hulls reduce water and wind resistance, which directly translates into lower fuel consumption. It is recommended to implement projects where energy efficiency, streamlined hulls, hybrid propulsion systems, and lightweight materials that can contribute to lower fuel consumption and harmful emissions are a priority. Innovative solutions can also be implemented by using automatic sails (such as Flettner rotors or kites) in order to use wind energy to support ship propulsion and reduce fuel consumption [21]. Continuous investment in research and development is key to identifying and developing new technologies and practices to further reduce emissions from shipping. This includes research into alternative fuels, innovative propulsion systems, and more efficient operating practices. Under energy efficiency regulations, existing ships must have an energy efficiency management plan, which includes elements such as better voyage planning, more frequent cleaning of the ship's underwater and propeller parts, technical measures such as waste heat recovery of systems, and even the fitting of a new propeller.

Air transport is another significant emitter of greenhouse gases. Sustainable aviation fuels (synthetic aviation fuels) can significantly reduce harmful emissions from air traffic. Hydrogen-powered aviation is of great interest in the industry, as it is considered an innovative solution to the challenge of decarbonization and reduce the negative impact of aviation on the climate. According to the European Parliament, synthetic aviation fuels, which are produced through chemical reactions and can be obtained from both non-renewable and renewable energy sources, use renewable hydrogen or renewable electricity in the production process. Moreover, they may be fuels of non-biological origin in accordance with the RED II Directive [22]. The use of clean, friendly hydrogen as an energy carrier in air transport has several advantages. Namely, the combustion of hydrogen in jet engines would enable the production of steam, which would eliminate harmful emissions. The use of new solutions is associated with limitations, such as new structures and the need to install larger hydrogen storage tanks [23].

It will also be possible for certain biofuels, produced from animal fats or distillates, to be included in the aviation fuel blend. Currently, however, the potential of synthetic aviation fuels is largely untapped: such fuels account for only 0.05% of the total fuels used in the aviation sector. In order to minimize the negative impact of international civil aviation on the global climate and promote the sector's sustainable growth, the International Civil Aviation Organization is working on a number of measures, including:

- aircraft technological improvements;
- operational improvements;
- sustainable aviation fuels.

In Europe, the ReFuelEU the aviation initiative [24] is part of the climate package, due to which work is being carried out to make fuels used in aviation more ecological. According to the provisions, fuel suppliers will be obliged to comply with the regulations regarding the participation of EU airports in the project related to the minimum share of sustainable aviation fuels from 2% in 2025 to 34% by 2040 and 70% by 2050 [24]. Renewable and environmentally friendly hydrogen will be part of a sustainable fuel mix. Airports in EU countries will be obliged to support air transport in accessing sustainable aviation fuels, including the possibility of hydrogen refueling and expanding infrastructure related to the electric charging system. Currently, many airlines, aircraft manufacturers, and research institutions are testing and implementing prototypes of hydrogen-powered aircraft. The results of these tests are promising, and future deployments may be accelerated once the technology is fully adapted to aviation requirements. While hydrogen fuels in aviation still face some technological and infra-structural challenges, their development could change the aviation and make it more sustainable and environmentally friendly. As technology advances and social acceptance in-creases, hydrogen-powered aircraft can play a key role in meeting zero-emission goals in the aviation sector. Reducing the negative impact in the aviation sector mainly consists of reducing CO_2 emissions during flights, for example, by implementing sustainable aviation fuels and implementing innovative technological solutions or reducing the weight of aircraft with lightweight components.

Rail transportation is the most environmentally friendly mode of transit. As shown in figures reported by the European Environment Agency, in 2017, merely 0.5% of the EU's overall greenhouse gas emissions stemmed from the railway industry. In most countries, rail transport is powered by electricity, so trains do not emit exhaust fumes directly. If electricity is produced from sources such as hydro, wind, solar, or nuclear power, they generate less CO_2 emissions than traditional sources such as fossil fuels. Rail transport can be developed by increasing rail capacity, either by building completely new lines or by doubling existing lines. Given such high capital costs for rail infrastructure, doubling the routes parallel to the existing infrastructure is usually a priority. It is much cheaper and logistically easier than building completely new lines because there is no need to run a difficult and time-consuming procedure to buy new land [25]. In recent years, many railway networks have undergone modernization, which has allowed the use of more energy-efficient and green technologies. Rail modernization is an investment in infrastructure and includes the extension, repair, and improvement of rail networks by improving track conditions and upgrading and electrifying lines [26]. Rail modernization also concerns the construction of new connections to enable the faster and more economical movement of trains. In addition, replacing older vehicles with more modern, energy-efficient, and green trainsets is key to reducing emissions. Modern trains use advanced technologies, such as energy regeneration during braking or the use of lightweight and durable materials.

Furthermore, research and continuous development in the field of electromobility contribute to the development of electric and hybrid trains that further reduce gas emissions [27]. In order to ensure continuous development, it will also be necessary to implement green financing mechanisms that allow the implementation of innovative projects and low-emission technologies in the transport sector.

By supporting innovation and investment in these advanced technologies, governments, industries, and research institutions can accelerate the transition to cleaner and more efficient modes of transport. This change not only promotes environmental sustainability but also stimulates economic growth and job creation in the growing sectors related to renewable energy and transport technology.

Ultimately, a holistic approach that combines intelligent traffic management systems, improved public transport (including rail and air transport), and the integration of hydrogen fuel cells and biofuels can pave the way to a more sustainable and energy-efficient future in the transport sector.

3.2. Alternative fuels infrastructure

In the transportation industry, there is a growing trend toward employing novel propulsion systems driven by alternative fuels (i.e., by integrating internal combustion engines with electric motors, utilizing electricity, or harnessing gas). These alternative fuels encompass various options such as electromobility, hydrogen, biofuels (including bioethanol, bio esters, biogas, biohydrogen, and synthetic biofuels), as well as natural gas (including biomethane) available in compressed natural gas, LNG, and liquefied petroleum gas forms. Biomethane derived from refined biogas can also serve as a viable transportation fuel. In regions of production, it often presents a more economical option compared to gasoline and diesel. Ideally, alternative fuels should not only possess properties enabling them to substitute hydrocarbon fuels but should also exhibit high efficiency, reasonable pricing, and renewable attributes [28]. The European Commission has proposed an amendment to the regulations on the development of alternative fuel infrastructure. It aims to ensure the development of publicly accessible charging and refueling infrastructure across the EU for alternative fuels for road, air, and water transport. It also aims to ensure that the infrastructure is interoperable and user-friendly. Alternative fuels have many advantages. For example, they emit few exhaust fumes, they are produced in an environmentally friendly manner with low production costs, and they allow the user to maintain energy independence, which makes it possible for the user to create their own plant producing unconventional fuel, although this requires special supervision. Biofuel is often used as fuel. The EU biofuel market is dominated by the ester (biodiesel) sector. It includes both traditional methyl esters and hydrogenated vegetable oils, obtained by hydrorefining vegetable oils or animal fats. Hydrogen is also one of the most important and popular fuels in recent years. The production of hydrogen, which would take place through environmentally friendly processes, is a challenge for the economy. Ecological substrates should be used in order to obtain hydrogen that can be produced without negative effects on the environment. Various forms of hydrogen are discernible based on how they are made, the techniques applied, and their outcomes, and each is distinguished by its distinct hue. Biomass and by-products yield white hydrogen, while nuclear energy contributes to the production of pink hydrogen. Meanwhile, green hydrogen stems from renewable sources. Lately, there has been a surge of enthusiasm for pioneering methods to derive hydrogen from renewable electricity, commonly referred to as green hydrogen. Despite the burgeoning interest and a flurry of ambitious projects by numerous companies, the technology for green hydrogen production predominantly resides within the realm of research and experimental implementation [29].

3.3. Energy sector

In the energy sector, systematic actions are also carried out to reduce the release of harmful emissions into the atmosphere. The energy industry, which is often blamed for its detrimental environmental effects – notably, the excessive release of greenhouse gases—must deal with significant hurdles. Since this sector relies predominantly on fossil fuels for energy generation, it significantly contributes to climate change. Hence, optimizing energy usage and transitioning away from traditional energy sources is imperative. Energy firms are actively engaging in adaptation efforts to align production with ecological standards. Consequently, the energy sector should aim to reduce its reliance on coal and oil and transition towards renewable alternatives. Increasing the use of renewable energy sources such as solar, wind, hydro, and geothermal energy can significantly reduce emissions. These sources produce electricity with virtually no greenhouse gas emissions and can replace fossil fuel generation. Global photovoltaic production in 2021 increased by almost 180 TWh, which is a record increase of 22%. This means that globally, the production of energy in photovoltaic panels exceeded 1,000 TWh. In most countries, photovoltaics is becoming the cheapest option for generating electricity, which affects the development of the sector and is expected to drive investments in the coming years. Also, concerning wind energy, the total installed capacity in Europe is growing steadily. Over the past decade, it has grown to over 200 GW. Currently, the largest onshore wind farm in Europe is the Fântânele-Cogealac wind farm in Romania, consisting of 240 turbines, each with a capacity of 2.5 MW. By comparison, the largest offshore wind farm in Europe and the world is Walney Extension in Great Britain, with a capacity of 659 MW and consisting of 200 turbines. The global production of electricity from wind energy amounted to 426 TWh. Thanks to this visible increase in production, the wind industry now has a significant share in the energy mix of the European continent and is the most important renewable energy source, recently overtaking hydropower [30]. However, hydropower is also very popular. Despite the problems with access to water in some European countries, hydropower is widely used. In European countries, the annual production (installed capacity) of hydropower is quite diverse and ranges from 33,391 MW in Norway, to 2,385 MW in Poland, 97 MW in Belarus, and 4 MW in Estonia. New hydropower plants opened in 2021 in Norway and Turkey. The International Energy Agency [31] report on hydropower predicts an increase of around 8% in total installed capacity in Europe by 2030 thanks to greenfield hydropower projects and the modernization and expansion of existing infrastructure. Hydropower is based on well-established technologies that are characterized by high overall efficiency of over 80% and even up to 90%. The efficiency of a hydraulic turbine is about five times higher than that of photovoltaic panels and about three times higher than wind technologies [32]. Thanks to its higher efficiency, it is more effective and can contribute more to reducing greenhouse gas emissions.

Energy companies, if they switch to the production of energy from renewable sources and increase energy efficiency, will be able to play a key role in combating climate change by taking the aforementioned actions to achieve climate neutrality. By shifting to renewables, decarbonizing, engaging in carbon offsetting, and supporting innovative decarbonization solutions, these companies are driving the energy transition and contributing to global efforts to mitigate climate change. However, further and accelerated action is needed to ensure a sustainable and climate-neutral future. In addition to energy companies, other companies will also have to adapt their activities to new legal, environmental, and political requirements. The manufacturing industry is estimated to be responsible for 20% of total CO_2 emissions. Energy efficiency measures are increasingly recognized not only as a way to ensure sustainable energy supplies, reduce greenhouse gas emissions, and increase the security of supply but also as an important factor in reducing energy import costs. Improving the energy efficiency of industrial processes and transport can lead to significant emission reductions. Many companies undertake new initiatives aimed at reducing the negative impact on the environment, including reducing energy consumption, and energy companies are increasingly entering markets related to renewable energy sources. Governments, consumers, and investors must support these initiatives, while energy companies themselves must maintain their commitment to long-term sustainable development goals. The 'Clean energy for all Europeans' package [33] developed by European countries set a new strategic goal for better, more economical use of energy by at least 32.5% by 2030. Implementing a flexible energy strategy that curtails peak consumption presents an opportunity for even greater cost savings. Collaborative efforts can pave the way for a more sustainable and resilient energy sector aligned with global climate objectives. This requires energy companies to adapt their production methods to meet environmental standards and embrace new technologies or innovative eco-friendly solutions. The integration of new technologies will enhance competitiveness in resource utilization across various domains. Businesses spanning multiple sectors are increasingly leveraging technological advancements to achieve their net-zero emission targets. Advancements in technology, coupled with initiatives like mission innovation and breakthrough energy programs introduced at COP26, will synergize to expedite the commercialization of clean energy technologies, prioritizing areas such as green hydrogen, sustainable aviation fuel, the direct air capture of CO_2, and long-term energy storage [34]. By 2050, hydrogen and its derivatives are projected to constitute 12% of all energy consumption. However, progress in EU countries towards energy and climate policy solutions—including reducing greenhouse gas emissions, enhancing energy efficiency, and transitioning to renewable energy sources by 2030—has been sluggish. Hence, there is a pressing need to accelerate these efforts. The International Energy Agency, in its 2021 report "Net Zero by 2050: A Roadmap for the Global Energy Sector" authored by Bouckaert, underscores that achieving climate neutrality requires all nations to achieve net-zero emissions from electricity production by 2040, with developed countries aiming for this milestone even earlier, by five years. The use of carbon capture and storage (CCS) technology involves capturing carbon dioxide (CO_2) emissions generated by power plants and industrial plants, and then placing them in underground deposits or using them for other purposes. Carbon capture and storage can help reduce emissions from fossil fuel power generation until cleaner alternatives are fully adopted. Another example for the energy industry is pilots' implementation of innovative projects in the field of direct air carbon capture and storage, which in 2040, will reduce European energy emissions by as much as 153 million tons of CO_2.

Hydrogen, carbon capture, biomass, and electricity are four essential pillars for achieving a zero-emission economy. These technologies and approaches play a critical role in reducing greenhouse gas emissions and combating climate change while transitioning to a sustainable and environmentally friendly energy system.

4. CONCLUSIONS

The present study addresses a critical void within the realm of scientific inquiry concerning the intricate interplay between two pivotal sectors—transportation and energy—and their repercussions on the natural environment. Prior research endeavors have often fallen short in offering a comprehensive analysis of the intricate dynamics and interdependencies between these sectors and the overarching issue of climate change.

By implementing innovative and holistic strategies, this study has revealed crucial synergies between the transportation and energy sectors, highlighting imperative measures to mitigate greenhouse gas emissions and promote sustainable development. Notably, the adoption of efficient shipping practices could lead to a significant reduction in emissions (up to 75%), while aviation could achieve a reduction of around 70%. In the automotive sector, electric vehicles are 27% cleaner than hybrid vehicles powered by e-fuels and can reduce CO_2 emissions by 70–80% compared to petrol cars. Additionally, achieving a more efficient energy sector by 2050 is crucial for realizing long-term sustainable development goals. Hydroelectric power will increase its efficiency by up to 90%, while the utilization of hydrogen in final energy will rise to 12%. This comprehensive approach underscores the importance of integrating transportation and energy policies to address environmental challenges and pave the way for a greener future.

By bridging the existing gap in the literature, this study enriches our understanding of the multifaceted relationships within which these sectors operate. It also lays the groundwork for the formulation of more efficacious environmental management strategies and decision-making frameworks (switch to renewable energy, use of clean hydrogen, adapting the transport and energy sectors to climate requirements). Consequently, it serves as a cornerstone for the development of forward-thinking policies aimed at mitigating the adverse effects of human activity on the environment. Through its insightful findings, this study contributes significantly to the expansion of knowledge regarding the intricate nexus between human efforts and environmental preservation, thereby paving the way for more informed and conscientious actions geared towards nature conservation and ecological sustainability.

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