Sustainable Societal Transformation: Shaping Renewable Energy Technologies in Transport

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Abstract. Traditional transportation systems are increasingly scrutinized for their environmental footprint, driving the need for sustainable alternatives. Recent developments in renewable energy technologies have paved the way for Electric Vehicles, Hydrogen Fuel Cells, Biofuels, Solar-Powered Vehicles, and Hybrid Systems, all of which offer environmentally-friendly solutions. However, the successful integration of these technologies into existing transport systems presents challenges such as infrastructure development, policymaking, public perception, and societal acceptance. Sustainable transportation encompasses more than technology and economics. It addresses societal inclusivity, environmental conservation, and long-term viability. Social equality ensures equitable access to transport, economic considerations highlight short-term costs and long-term benefits, and health and well-being are affected by sustainable transportation patterns. Community engagement, though challenging, is essential to craft locally tailored solutions and foster a collective sense of ownership. These facets form the foundation for a greener, healthier, and more inclusive transport system. The global shift towards renewable transport technologies is multifaceted, integrating political, economic, social, technological, environmental, and legal dimensions. Using the PESTEL method, the complex transition towards renewable transport technologies can be understood, especially in contexts like Ukraine. Given its unique socio-political landscape, Ukraine's move towards sustainable transport is influenced by multiple factors, including international climate agreements, economic restructuring, public perception, and technological advancements. Ukraine's transport sector, heavily reliant on fossil fuels, has the potential to transform using its abundant renewable resources. Tapping into these resources can offer numerous benefits, though technological and infrastructural challenges persist. Strategic investments and embracing renewable technologies are key for Ukraine to build a sustainable transport and societal framework.

1 Introduction

1.1 Background of Sustainable Energy and Transport

In an era where the global community grapples with environmental challenges and the depletion of fossil fuels, the focus on sustainable energy and transport has become paramount. Sustainable energy encompasses harnessing renewable resources such as solar, wind, hydroelectric, and biomass, leading to a reduction in greenhouse gas emissions. The transport sector, as one of the major consumers of non-renewable energy, plays a vital role in shaping energy consumption patterns. Its transformation towards renewable energy utilization marks a significant step towards global sustainability. In the transportation sector, the use of renewable energy technologies leads to greater energy efficiency [1,2]. This improvement is achieved through innovative technical solutions that include the utilization of alternative fuels [1]. The global shift towards sustainable energy, particularly renewable sources like solar, wind, hydroelectric, and biomass, represents a critical response to environmental challenges and fossil fuel depletion [3]. Most authors promote for a shift to an entirely renewable economy as a long-term and definitive answer to existing challenges [4,5,6,7,8,9]. The rationale behind this choice is that renewables energy resources are already proven technologies that are developing rapidly and can leave no carbon footprint and that makes them particularly well suited to tackling climate change problems, arguably the most pressing challenge facing global society [4]. Transport, as a significant consumer of non-renewable energy, plays an essential role in energy consumption patterns [10]. The integration of renewable energy within the transport sector is considered a vital step towards global sustainability [11].

Transportation plays a pivotal role in the global economy, enabling mobility, trade, and connectivity [12]. Despite its, transport sector is also ranked as the second-largest carbon emitter due to its over-reliance on
traditional fossil fuels [13,14]. Every year, the transport sector is responsible for using about 30% of the world's total energy, ranking it as the second biggest energy consumer following the industrial sector [14,15]. This consumption leads to a substantial amount of gas emissions, which in turn cause significant harm to the environment and pose serious health risks [14,16]. According to reports by the International Energy Agency, road transport accounts for around 76% of CO2 emissions in 2021 [17]. The resultant environmental and health repercussions, combined with geopolitical issues associated with fossil fuel dependencies, have underscored the urgency for a sustainable energy transition in transport [11]. At the heart of this transformative journey lies the need to revolutionize transportation, a sector historically reliant on fossil fuels and a significant contributor to greenhouse gas emissions. Mobility is identified as one of the seven key strategic components in the European Commission's plan to reach climate neutrality in the EU by the middle of the century. The European Commission's plan for a new European Green Deal outlines a long-term approach to transition to an economy with net-zero greenhouse gas (GHG) emissions by 2050 [18,19]. This strategy aligns with the European Union's (EU) obligations for worldwide climate action as agreed upon in the Paris Agreement. As we confront the pressing challenges posed by the climate crisis, stabilising global warming below 2°C [20,21], the integration of renewable energy technologies in transport emerges as a pivotal pathway towards achieving a greener and more sustainable world [22,23]. Renewable energy technologies have surfaced as viable solutions to counter these challenges. Technological advancements in electric vehicles, biofuels, and hydrogen fuel cells are reshaping transportation's energy landscape, promising reduced emissions, enhanced energy security, and socio-economic benefits [24]. The journey towards shaping renewable energy technologies in transport is one of profound significance, transcending the traditional boundaries of engineering and policy-making. It is an endeavor that calls for the active engagement of individuals, governments, industries, and civil societies in a collaborative and concerted effort to build a cleaner, greener, and more resilient future. Government policies, international agreements, and corporate initiatives have started to align with the sustainability agenda, supporting the development and adoption of these technologies [25]. Yet, the transformation is slow, and the challenge of fully integrating renewable energy into transport systems remains complex [26].

1.2 Importance of Renewable Energy in Modern Society

Renewable energy's significance transcends environmental benefits. Its economic and social impact, such as fostering energy independence, mitigating climate change, and stimulating innovation and employment, has been widely acknowledged [27, 28]. Renewable energy stands as a pivotal element in modern society's pursuit of sustainable development [29]. The introduction of renewable energy technologies in the transport sector represents a turning point in human history, where innovation and environmental responsibility converge to shape the course of societal progress. This paradigm shift not only redefines the way we travel but also holds the potential to revolutionize the very fabric of our communities and the interconnectedness of our lives. By harnessing renewable energy sources and developing sustainable transportation solutions, we aim to create a harmonious synergy between human needs, environmental preservation, and economic prosperity. Within the context of the sustainable development agenda, sustainable transportation can be defined as the capacity to meet the mobility needs of today's society in such a way that preserving the environment and the mobility needs of future generations are not impaired [30]. Integrating renewable energy into the transport sector is not merely a technical endeavor. Societal transformation, encompassing changes in infrastructure, regulations, public perceptions, and behaviors, is equally crucial. Effective societal transformation requires a holistic understanding of the complex interplay between technology, policy, and society [31]. This comprehensive exploration of sustainable societal transformation delves into the multifaceted facets of renewable energy technologies in transport, examining not only their technical advancements but also their far-reaching implications on society. As we strive to transition from fossil fuel dependence to cleaner alternatives, we must contemplate the social dimensions that shape transportation behaviours, urban planning, and the equitable distribution of benefits. The deployment of electric vehicles, the adoption of biofuels, the emergence of hydrogen-powered transport, and the evolution of smart and sustainable infrastructure all contribute to reshaping the fabric of transportation within our societies. Each innovation serves as a stepping stone towards a more inclusive, accessible, and eco-conscious future, ensuring that no segment of society is left behind in the pursuit of sustainable progress. Furthermore, sustainable societal transformation goes beyond technological innovations. It encompasses the fostering of green consciousness, the promotion of eco-friendly consumer choices, and the cultivation of environmentally responsible policies at the grassroots level. Empowering communities to embrace renewable energy solutions and eco-mobility is essential to ensuring a sustainable and equitable transition. As we navigate the complexities of this transformative journey, we must recognize that societal transformation cannot thrive in isolation. Synergies between renewable energy technologies and other sustainable domains, such as urban planning, public health, and environmental conservation, must be embraced to achieve holistic and lasting change. In this collective endeavour, our choices and actions today will shape the world of tomorrow. By starting to shape renewable energy technologies in transport, we can build a legacy of resilience, sustainability and shared prosperity that nurtures our communities, guiding our societies towards a future
where the needs of humanity are balanced with the conservation of our planet's ecosystems.

2 Literature Review

Numerous studies have showed that the environmental impacts of transport and transport decarbonization have become well-established on research and political agendas [32]. Researchers conducted a Scopus search to review academic research on transport, emissions and decarbonisation between 2000 and 2021 and found that almost 50,000 publications on CO2 or GHG emissions were published between 2000 and 2021, with the number of publications increasing rapidly after 2010 [32]. The vast majority of studies on transport decarbonisation focus on GHG reduction potential and costs [32]. These studies point to the economic aspect as the main challenge to the competitiveness of alternative solutions, either low-carbon fuel solutions or purely renewable energy and electricity-based solutions (e-fuels, batteries, electrification) [32]. Recent examples include: on electrification of road transport and green hydrogen [33], on sustainable aviation fuels [34], and on the potential of electric fuels [35]. The researchers note that while such studies clearly identify the challenge of the high cost of renewable alternatives, the required electricity from renewables is generally not seen as a barrier [32]. A common assumption in studies based on renewable energy is not only the availability of renewable electricity but also the feasibility of a 100% renewable energy mix [32]. Renewable energy technologies have been the subject of extensive research, with significant advancements made in wind, solar, hydroelectric, and geothermal energy [36,37]. Several studies have also explored the optimization and integration of these technologies into existing energy grids [38,39]. In the context of transport, early works have investigated alternative fuels like biofuels, hydrogen, and electric power [13]. The integration of renewable energy into transport has seen substantial progress in recent years. The electrification of road transport, fuelled by renewable sources, has become a tangible reality in many regions [40,41]. Marine and air transport sectors are also exploring renewable energy alternatives, with ongoing research into biofuels and other sustainable energy sources [42,43]. Policies and regulations have played a crucial role in facilitating this transition, albeit with varying success across different countries [44,45].

While there is a robust body of knowledge on renewable energy technologies and their application in transport, gaps still exist. Most notably, there is limited research on the long-term sustainability and full lifecycle assessment of these technologies in different transport modes [46]. The integration challenges and the socio-economic impact of a complete transition to renewable energy within the transport sector require further exploration [32,47]. Moreover, there is a need to understand the interaction between technology, policy, culture, and the local context in implementing renewable energy solutions in transport [48].

3 The Aim and Objectives of the Study

The aim of this research—to identify and analyze the various renewable energy technologies that can be applied in the transport sector, towards sustainability, ensuring ecological balance and societal well-being. To achieve this goal, the following tasks are defined:

- to identify the various renewable energy technologies available for implementation in the transport sector;
- to identify various aspects of sustainable societal transformation in the realm of transportation;
- to identify areas of the impact to achieving a sustainable transformation in Ukraine's transport system by embracing renewable energy technologies and promoting socio-economic development;
- to develop sustainable societal transformation promoting renewable energy technologies opportunities in transport in Ukraine.

4 Materials and Methods

The research methodology includes the PESTEL method, abstraction, comprehensive review of the scientific literature on energy transition, renewable energy technologies, sustainable energy, sustainable societal transformation, sustainable development in transport sector. The concept of that PESTEL method is to identify external factors or challenges that may have an impact on the transition from fossil fuels to renewable energy while taking into account its political, economic, social, technical, environmental, and legal environment [49]. The abstraction aims to focus on the main, essential features of the phenomenon under consideration, revealing their essence and creating generalized concepts, theories, classifications, categories, principles, etc. [50]. The scientific literature analysis is the basis on which new knowledge related to the research being conducted is based [51].

5 The Results of the Study on Sustainable Societal Transformation and Renewable Energy Technologies in transport

5.1 Renewable Energy Technologies in the Transport Sector

Traditional methods of transportation are grappling with numerous difficulties in decreasing fuel use, noise, and emissions in order to meet growing environmental and economic standards. The need to adhere to these demands has led a multitude of researchers and producers in the transportation industry to search for alternatives that are more environmentally friendly, efficient, and sustainable. Renewable energy technologies for transportation have diversified significantly in the past decade. The main sources include electric energy (from wind, solar, hydro), biofuels, hydrogen, and hybrid systems [52,53]. Rail and
public transport are increasingly being powered by electricity, hydrogen, and biofuels [54].

**Electric Vehicles (EVs).** In many countries around the world, the electrification of mobility, particularly in passenger road transport, has been extensively endorsed and encouraged over the past ten years [55]. Relying mainly on battery technologies, EVs are becoming more widespread with advancements in battery efficiency and charging infrastructure [40]. Although EVs are not new technology, through significant improvements of battery performances, electric vehicles have got a new chance recently [55]. EVs are gaining momentum due to several factors, including the price reduction as well as the climate and environmental awareness [56]. In general, electric vehicles have potential to reduce local air pollution and depending on the energy sources used for electricity generation, they can also contribute to the reduction of the global GHG emissions [55]. However, as the authors A. Ajanovic and R. Haas (2021) state, it is important to notice that different types of electric vehicles, such as hybrid electric vehicles (HEV), plug-in hybrid vehicles (PHEV), battery electric vehicle (BEV) and fuel cell electric vehicles (FCEV), have different characteristics and different impact on the environment [55].

**Hydrogen Fuel Cells.** Hydrogen fuel produced from renewable energy sources has the potential to become the primary fuel of the twenty-first century. Hydrogen fuel cells combine hydrogen and oxygen to produce electricity [57]. These are used in buses, trains, and increasingly in passenger cars. While the technology is likely to remain somewhat expensive, according to the researchers, it is predicted that hydrogen fuel cells will play a significant role in emissions reduction and energy poverty mitigation on a global scale [58]. According to the International Hydrogen Council's prediction, by 2050, the use of hydrogen energy will reduce approximately 6 billion tons of carbon dioxide emissions globally [59]. In 2014, the United States released the All-of-the-above Energy Strategy, which identified the leading role of hydrogen energy in the transportation transformation of the United States; in 2019, Japan revised its Strategic Roadmap for Hydrogen and Fuel Cells, which describes a three-step strategy for hydrogen technology; in 2020, the EU issued the Energy Systems Integration Strategy and the EU Hydrogen Strategy, which set the direction for the development of clean energy, especially hydrogen energy, in Europe in the next 30 years [59]. Due to its clean consumption process, it is considered as the “future energy” [59]. Hydrogen fuel cells have advantages such as high energy efficiency, zero emissions, wide energy sources, fast refuelling, and good low-temperature adaptability [60]. Hydrogen fuel cells are seen as a key part of the future of sustainable cars because they can be refuelled quickly and allow for longer drives than the batteries in all-electric vehicles [61,62].

**Biofuels.** Biodiesel is gaining prominence as a superior alternative source of energy to replace petroleum-based fuel in transportation [63]. Biofuels such as ethanol and biodiesel are produced from renewable biological sources and are used in various transportation modes [42,64]. They can be used in traditional internal combustion engines. The production and utilization of biofuels in transportation are primarily driven by the goals of enhancing energy security and reducing greenhouse gas emissions [65]. The importance of these drivers varies based on the specific national context, the natural resources at hand, and the stage of development. For instance, in the context of biofuel production and consumption, regional solutions are necessary to not only improve energy and environmental security but also to foster income generation and create employment opportunities, especially in developing countries. Modern and sustainable biofuels can contribute, in a definite way, to the world's task of overcoming the challenge of promoting, in a reasonable time, the transition from fossil energy toward renewable energy in transport, a sector in which gasoline and diesel oil still largely dominate [65].

**Solar-Powered Vehicles.** Solar cells can be integrated into the design of some vehicles, mainly as a supplementary energy source. Solar powered vehicles are currently being developed towards entirely self-sustaining vehicles that harness their energy directly from the sun [66]. For such vehicles, it is important to optimise their solar exposure while driving, thereby reducing their energy consumption through fossil fuels [66]. Despite being one of the most favored forms of renewable energy, solar power still falls behind fossil fuels in popularity. According to estimates from the International Energy Agency (IEA), renewables account for 29% of global electricity production, with solar power ranking as the third-most-used renewable technology. It comes after hydropower and onshore wind and managed to surpass bioenergy in 2019.

**Hybrid Systems.** Hybrid systems combine conventional fuels with electric or other renewable energy sources to enhance efficiency. Hybrid systems in transport typically refer to vehicles that utilize two or more distinct power sources, such as an internal combustion engine coupled with an electric motor [67,68]. These systems aim to combine the benefits of multiple energy types to enhance efficiency, reduce emissions, and improve overall performance. Well-known types of hybrid systems are parallel hybrid system (both the internal combustion engine and electric motor are connected to the transmission, allowing either or both to drive the vehicle, for example, many modern hybrid passenger cars); series hybrid system (the internal combustion engine drives a generator that charges the battery, while the electric motor drives the vehicle, for example, some buses and commercial vehicles); plug-in hybrid electric vehicle (combines features of a conventional hybrid vehicle with an all-electric vehicle, enabling the vehicle to be plugged in and recharged); mild hybrid (a smaller electric motor provides assistance to the internal combustion engine, improving efficiency but without enabling all-electric driving); diesel-electric hybrid (commonly found in locomotives and marine vessels, uses a diesel engine to generate electricity and an electric motor to propel the vehicle, for example, some modern trains and tugboats) [67,68]. Hybrid systems may be widely applicable [67,68].
can afford sustainable modes of transport. Strategies such as subsidized public transport and inclusive urban planning are vital for ensuring that transport systems benefit everyone [70]. Also an important factor is cultural inclusion. It ensures that transportation systems respect and accommodate the diverse cultural needs and preferences of the community. This can include everything from providing multilingual information and services to respecting cultural norms and practices in transport design and operation [71]. Equally important is social inclusion, which in transportation also means integrating transport planning with broader urban development goals. This involves creating complete neighbourhoods where essential services and opportunities are within walking distance, and public transport is readily available and convenient, making the community more cohesive and inclusive [72]. Public participation is vital in the planning and decision-making processes. It ensures that the community's needs are adequately addressed. This democratic approach enables different segments of society, especially marginalized groups, to have a say in how their transportation systems are designed and operated [73].

**Economic Impact and Financing.** The transition to sustainable transport is both an economic challenge and an opportunity. On the one hand, investments in green transport infrastructure can be initially costly, but have been shown to boost economic growth [74]. The long-term benefits, including energy savings, lower healthcare costs and job creation, have a high economic value. For example, the European Commission (2014) estimated that achieving the 2030 climate and energy targets could increase GDP by 0.5% and create additional jobs in various sectors. The transition to sustainable transport creates new job opportunities in manufacturing, operations, and maintenance of green vehicles, public transportation, cycling infrastructure, and more. A report by the International Labour Organisation (ILO) highlights that sustainable practices in the transport sector could create millions of new jobs by 2030 [75].

The development and implementation of sustainable transport systems require significant financial investment in research, infrastructure, technology, and more. Financing these projects can be a challenge for governments, particularly in developing countries. Public-private partnerships, grants, loans, and green bonds are some of the mechanisms that have been utilized to secure necessary funding.

The shift towards sustainable transport can have negative repercussions on traditional industries such as oil and gas. This transition necessitates careful planning and policies to manage potential economic dislocation and support affected workers and regions. A comprehensive economic evaluation of sustainable transport initiatives includes cost-benefit analysis (CBA), weighing the costs of implementation against benefits such as reduced emissions, decreased congestion, improved health, and more. Such analyses support decision-making by revealing the true economic value of sustainable transport initiatives [76]. Government incentives and subsidies play a vital role in promoting sustainable transport. Tax breaks, subsidies,
and other financial incentives can make sustainable options more attractive to consumers and industries, thereby accelerating the transition. Also, governments and private sectors must work together to provide the necessary funding for sustainable transportation initiatives. Innovative financing mechanisms, such as public-private partnerships and green bonds, can be vital in this context [77].

Health and Well-Being. Transportation is a major source of air pollution, contributing significantly to respiratory and cardiovascular illnesses. Sustainable transport patterns, such as the use of electric vehicles, can significantly reduce air pollution and improve air quality, with major health benefits. According to the World Health Organization [78], air pollution contributes to millions of premature deaths worldwide. A shift towards cleaner modes of transport can have a profound impact on public health by reducing respiratory and cardiovascular diseases [79]. A study by the American Lung Association (2019) estimated that transitioning to electric vehicles could prevent thousands of premature deaths annually. Promoting cycling, walking, and public transport encourages physical activity, which is essential for overall health. Integrating these modes of transport can lead to lower obesity rates, decreased risk of chronic diseases, and improved mental well-being [80]. Sustainable transport often focuses on reducing noise pollution, which is linked to stress, sleep disturbances, and cardiovascular diseases. Urban planning that prioritizes green spaces and restricts heavy traffic in residential areas can have positive effects on the community's well-being [81]. Long commutes and traffic congestion are associated with increased stress levels and reduced quality of life. Enhancing public transportation and creating more efficient transport networks can alleviate these issues, positively affecting mental health [82].

Sustainable transport also emphasizes road safety, aiming to reduce traffic accidents and fatalities. Safe infrastructure for cyclists and pedestrians, along with effective regulations and enforcement, can significantly decrease the risk of traffic-related injuries [83].

Community Engagement. The success of sustainable transport often hinges on the active participation and acceptance of local communities. Community engagement refers to the process of involving community members, including residents, businesses, and other stakeholders, in decision-making and planning. It ensures that policies and interventions align with the unique needs, values, and priorities of the local community. In the context of sustainable transport, community engagement helps create transportation systems that are not only environmentally responsible but also socially equitable and economically viable. Public engagement in the planning and implementation stages ensures that transportation systems are tailored to the specific needs and preferences of the community [84]. Collaborative decision-making has been shown to lead to more successful outcomes and increased public satisfaction with transportation services. On the one hand, community engagement provides valuable insights that inform decisions, ensuring they reflect local needs and preferences. Transparent and inclusive processes build trust between policymakers, planners, and the community, enhancing the likelihood of project success. Encouraging community participation promotes social cohesion and a sense of ownership, reinforcing the community’s connection to their surroundings [85]. By including diverse voices and perspectives, potential conflicts can be identified and addressed early in the process, preventing future issues. On other hand, community engagement can pose challenges. It can be difficult to ensure that all segments of the community, including marginalized and vulnerable groups, are represented, but is crucial for equity [86]. Also, language, cultural differences, and accessibility to technology can present barriers that must be thoughtfully addressed [87].

5.3 Areas of the Impact of Achieving a Sustainable Transformation in Ukraine's Transport System by Embracing Renewable Energy Technologies and Promoting Socio-Economic Development

The transition to renewable energy technologies in transport is not just an environmental necessity but a holistic opportunity to reshape societies sustainably. While challenges persist, a coordinated approach that considers political, economic, social, technological, environmental, and legal factors can steer the world towards a cleaner, equitable, and prosperous future. PESTEL method, which focuses on political, economic, social, technological, environmental, and legal factors, is a comprehensive tool that can help stakeholders understand the multi-faceted challenges and opportunities of transitioning to sustainable transport solutions. These are essential external factors that influence the development, adoption, and evolution of technologies, especially those in sustainable sectors like renewable energy for transportation. Taking into account Ukraine's unique socio-political and economic context, PESTEL analysis becomes an important tool. PESTEL Application to Ukraine on “Sustainable Transformation of Society: Shaping Renewable Energy Technologies in the Transport Sector” will present country-specific areas related to the rehabilitation and development of Ukraine's transport infrastructure.

5.3.1 Political Factors

Political support: governments around the world recognize the urgency of tackling climate change and are increasingly adopting legislation and incentives to support renewable energy technologies in transport. Governments are setting emission standards, providing tax incentives for electric vehicles (EVs) and investing in infrastructure such as EV charging stations. However, political will varies from country to country, with some actively promoting the green transport revolution and others lagging behind. Political systems and policies can promote or inhibit the transition to renewable energy [88]. For example, subsidies for electric vehicles,
Energy independence: Given the geopolitical challenges, in particular with Russia over energy supplies, Ukraine has a political incentive to reduce its dependence on fossil fuels, with a preference for renewables in transport [91]. A favourable renewable energy policy can attract investment and promote sustainable growth. Political stability ensures consistent decision-making and long-term planning of infrastructure projects.

5.3.2 Economic Factors

Economic competitiveness: the global economy is undergoing changes as the viability of renewable energy sources increases. While renewable technologies in transport were initially considered expensive, the falling cost of solar panels, batteries and wind turbines has made green technologies more competitive. In addition, the savings that can be made in the long term by reducing the consumption of fossil fuels are substantial. For renewable energy technologies to be adopted on a large scale, they need to be priced at the same level as fossil-fuelled transport. Innovations that are priced at the same level as fossil fuel technologies can accelerate their market acceptance [92]. Ukraine's economic challenges and the ongoing transition may affect the country's receptivity to renewable energy technologies. Economic downturns can affect the availability of finance and the viability of projects. The scale of infrastructure development will be determined by government budget allocations and the availability of funding sources, including international aid and private investment. The energy transition may be affected by economic restructuring [93]. As Ukraine diversifies its energy sources, the economic feasibility of renewable transport technologies becomes crucial. Economic factors such as inflation, exchange rates and GDP growth can affect investment and pricing in the sector. Economic analysis can help highlight current economic barriers and potential cost reduction strategies.

Job creation: Job creation in the renewable energy sector can boost economic growth [94]. The renewable energy sector has a higher job creation potential than the fossil fuel sector. Understanding these dynamics can further substantiate the case for renewables in transport. However, the challenge remains to ensure that renewable energy technologies can create jobs and economic opportunities, especially in regions historically dependent on the fossil fuel industry.

Foreign investment: Ukraine's transition to renewable energy can attract foreign investors, especially from European countries interested in green technologies. Foreign investment and economic partnerships can be potential catalysts for renewable energy deployment, especially with EU countries.

5.3.3 Social Factors

Public perception: public opinion is crucial for public acceptance of renewable transport. How the public perceives the benefits, risks and trade-offs of these technologies will influence the level of deployment. Consumer preferences, including environmental concerns, have a strong influence on the level of EV adoption [95]. Following the Euromaidan protests in 2014, there has been a clear shift in public perception towards Western standards and modernisation. This may have an impact on public acceptance of renewable energy technologies in transport.

Behavioural changes: The shift towards sustainability may lead people to favour public transport, ride-sharing or other sustainable options. Consumers are now more likely to choose sustainable modes of transport, from electric cars to bicycles. Cities are also promoting public transport powered by clean energy. Social trends such as urbanisation and increasing environmental awareness are driving demand for cleaner transport solutions. Understanding these social trends is essential. However, the social challenges associated with this transition, such as potential job losses in traditional transport sectors, need to be addressed and new technologies need to be made accessible to all, regardless of income.

Urbanisation trends: Urbanisation trends in cities influence which transport solutions are viable and sustainable [96]. Growing urban populations require efficient and sustainable transport systems to reduce congestion and pollution.

5.3.4 Technological Factors

Innovation and research and development (R&D): A clear understanding of these technological trajectories is essential for future planning. Battery technology is advancing rapidly, increasing the range of electric vehicles and reducing their charging times. The unexpectedly rapid decline in battery costs has transformed the electric vehicle industry [40]. Hydrogen fuel cells are another promising option for clean
transport, especially for heavier vehicles such as trucks. In addition, smart grids can optimise charging infrastructure, while advances in biofuels offer possible sustainable solutions for aviation. The integration of smart technologies, digital solutions and sustainable transport options can increase the efficiency, safety and environmental sustainability of transport infrastructure. However, it is essential to ensure that technology transfer takes place so that developing countries can access and benefit from these innovations.

**Infrastructure development**: For example, sufficient charging infrastructure needs to be in place if electric vehicles are to become widespread. The pace and nature of this development is crucial.

**Investing in R&D**: Ukraine has a history of technological innovation. Investing in R&D in the transport sector can foster local solutions adapted to the Ukrainian context. Access to cutting-edge technologies can facilitate the development of modern, resilient and adaptable transport systems.

**Barriers to uptake**: Identification of Ukrainespecific technological barriers will be crucial. For example, cold winters may require specific solutions related to the battery efficiency of electric vehicles.

### 5.3.5 Environmental Factors

**Reducing emissions**: the environmental imperative for the use of renewable energy in the transport sector is clear. Transport is a major contributor to global CO2 emissions and global warming. According to the International Energy Agency (IEA), reducing carbon emissions from transport is essential to meet global climate change targets. Switching to renewables can significantly reduce emissions and mitigate climate impacts. In addition, reducing dependence on oil and gas can reduce environmental disasters such as oil spills. However, it must be recognised that renewable technologies, such as the mining of minerals for batteries, have a negative impact on the environment and efforts must be made to reduce this impact.

**Resource depletion**: The depletion of non-renewable resources poses a major challenge to global social and economic progress. Ensuring their availability for present and future generations is therefore an urgent concern. The use of renewable energy sources such as wind, solar and water reduces dependence on fossil fuels. This is very important because fossil fuels are non-renewable resources.

**Air quality**: Major cities in Ukraine face air quality problems. Renewable transport technologies can help alleviate some of these problems.

**Land use**: Ukraine has a large amount of agricultural land and therefore has potential for biofuel production, but this also poses environmental problems and challenges.

**Sustainability requirements**: As identified by the IEA, the contribution of the transport sector to CO2 emissions makes it a key sector for achieving Ukraine's environmental goals. The development of transport infrastructure focused on reducing environmental impacts, reducing emissions and promoting clean transport modes is in line with global environmental objectives.

### 5.3.6 Legal Factors

**Regulation and standards**: Legal frameworks can make or break the transition to renewable energy in transport. Legislation mandating emission reductions, promoting research and development and standardising new technologies is essential. Legal frameworks that regulate vehicle emission standards or safety protocols are essential for industry growth [97]. Many countries have already set deadlines for the discontinuation of new petrol and diesel vehicles. While these legislative measures are essential to promote change, they need to be carefully drafted to avoid unintended consequences and to ensure fairness in the transition period.

**Liability and safety**: As new technologies emerge, legal issues relating to safety, liability and consumer protection become more important. For example, rules on the safe transport and storage of hydrogen in fuel cells are essential.

**Regulatory environment**: Local and international regulations, permits and environmental standards need to be respected when planning and implementing transport infrastructure projects. Renewable transport technologies will be strongly influenced by the regulatory environment in Ukraine, particularly in the context of EU aspirations. Legal processes related to land acquisition and rights of way may affect project timelines and costs.

**Safety protocols**: As technologies emerge, issues such as vehicle safety, emission standards and consumer protection need to be regulated.

### 5.4 Developing of Sustainable Societal Transformation Promoting Renewable Energy Technologies Opportunities in Transport in Ukraine

The transport sector is one of the most energy-consuming and carbon-intensive sectors in Ukraine. The increasing demand for transport services and the growing use of fossil fuels are contributing to environmental pollution and exacerbating climate change. Implementing renewable energy technologies in the transport sector could help to reduce carbon emissions, decrease dependency on fossil fuels, and create a more sustainable societal shape in Ukraine. Ukraine, rich in natural resources and strategically located in Europe, has great potential for integrating renewable energy.

#### 5.4.1 Renewable Energy Potentials in Ukraine

**Solar Power**: With an average of more than 1,500 hours of sunshine a year, Ukraine has significant solar energy potential, especially in the southern regions [98,99].
Wind Power: Coastal and certain inland areas, especially in the south and west, offer promising wind energy opportunities [100].

Biomass & Biogas: Agricultural residues, given Ukraine’s agricultural prominence, can serve as feedstock for biomass and biogas solutions [101].

Hydroelectric Power: Existing infrastructure and river systems present hydropower prospects, albeit limited in scale [102].

Renewable energy technologies, including biofuels, hydrogen, and electric vehicles powered by renewable sources, offer promising solutions for the transport sector in Ukraine. As Ukraine has significant agricultural potential, biofuels can be produced locally from agricultural residues. Hydrogen can be obtained from renewable energy sources such as wind and solar power and utilized in fuel cells to power vehicles. Additionally, electric vehicles can be charged with renewable electricity from wind, solar, or hydropower.

The adoption of renewable energy technologies in the transport sector could bring societal benefits in:

Environmental: Reduction in greenhouse gas emissions leading to improved air quality and health benefits. Electric buses, trams, and trains powered by renewable sources can drastically reduce emissions [103,104]. Shifting to renewable energy in transport could significantly reduce carbon emissions, contributing to the mitigation of climate change. Conversion of agricultural waste into biofuels can serve as an alternative to conventional petrol and diesel [105]. As well, cities can be redesigned with green transport in mind, with more pedestrian areas, cycle paths and efficient public transport routes. This can lead to healthier urban spaces with less pollution and better living conditions.

Economic: Diversification from fossil fuels can reduce energy import bills. Also, investing in renewable energy technologies could stimulate economic growth and create job opportunities, including in the research, development, manufacturing, and installation of renewable energy systems. The renewable energy sector can create jobs from production to maintenance. Retraining and retraining programmes can ensure that workers in traditional energy sectors find opportunities in the new green economy.

Social: Decreasing dependency on fossil fuels could increase energy security, making Ukraine less vulnerable to energy price fluctuations and geopolitical tensions. Renewable technologies make it possible to decentralise energy production. Solar panels or wind turbines can be installed on-site, reducing the need for centralised fossil-fuel power plants. Such decentralisation can empower local communities, lead to rural development, improved quality of life and create energy independence. Also, renewable energy can democratise energy access. Ensuring that renewable transport options are tailored to different income levels can ensure a fairer transition for society.

Despite the potential benefits, the transition to renewable energy technologies in the transport sector faces several barriers, such as:

Technological Challenges: The limited efficiency and storage capacity of renewable energy technologies can hinder their widespread adoption.

Economic Costs: The high initial investment and costs of renewable energy technologies may pose challenges to their implementation.

Infrastructure Needs: Building adequate infrastructure, such as charging stations for electric vehicles, is necessary to support the transition to renewable energy in transport.

To overcome the barriers and promote renewable energy technologies in the transport sector, the following recommendations are proposed:

Investment in Research and Development: Increased investment in research and development could enhance the efficiency, storage capacity, and cost-effectiveness of renewable energy technologies.

Financial Incentives: Government support through subsidies, tax incentives, and grants could lower the financial barriers to the adoption of renewable energy technologies.

Infrastructure Development: Building charging stations for electric vehicles and developing infrastructure for hydrogen distribution could facilitate the transition to renewable energy in transport. Renewable energy technologies, including biofuels, hydrogen, and electric vehicles powered by renewable sources, offer promising solutions for the transport sector in Ukraine. As Ukraine has significant agricultural potential, biofuels can be produced locally from agricultural residues. Hydrogen can be obtained from renewable energy sources such as wind and solar power and utilized in fuel cells to power vehicles. Additionally, electric vehicles can be charged with renewable electricity from wind, solar, or hydropower.

Ukraine’s transport sector has immense potential to transform into a sustainable model powered by renewable energy. With the right policy framework, investment, and public-private partnerships, the nation can become a frontrunner in green transport, paving the way for a sustainable societal structure.

6 Conclusions

1. Traditional modes of transportation face increasing pressures to reduce their environmental footprint in the form of fuel consumption, noise, and emissions, necessitating alternative, sustainable solutions. Recent advancements in renewable energy technologies for transportation have been both diverse and promising. Electric Vehicles (EVs) are experiencing widespread adoption due to battery advancements and growing environmental consciousness. Hydrogen Fuel Cells offer promising potential as a primary fuel source of the future, evidenced by global commitments and their inherent environmental benefits. Biofuels like biodiesel are establishing themselves as viable, sustainable alternatives to conventional fuels, offering energy security and emission reductions. Solar-Powered Vehicles, while still in developmental stages, represent a shift towards self-sustaining, eco-friendly mobility
solutions. Hybrid Systems provide a balanced solution, integrating the strengths of multiple energy sources for enhanced efficiency and reduced emissions. Nonetheless, integrating these renewable technologies into prevailing transport systems is not without its challenges. Infrastructure development, effective policymaking, public perception, and societal acceptance are pivotal in ensuring the successful implementation of these sustainable transportation alternatives.

2. Sustainable transportation is not just about technology and economics. It's a multidimensional approach that addresses societal inclusivity, environmental preservation, and long-term viability. Prioritizing social equality ensures all demographic groups have equitable access to transport options. Economic perspectives reveal the short-term costs and long-term benefits of such transformations, bringing both challenges and opportunities. Health and well-being are profoundly impacted by transportation patterns, with sustainable systems offering vast benefits in reducing air and noise pollution, promoting physical activity, and ensuring road safety. Integral to the entire process is community engagement, which, while posing its own challenges, is indispensable for tailoring solutions that cater to specific local needs and fostering a collective sense of ownership. Together, these pillars form the foundation for a transport system that propels us towards a greener, healthier, and more inclusive future.

3. The global push towards renewable energy technologies in the transport sector is a multifaceted endeavor, integrating political, economic, social, technological, environmental, and legal aspects. The PESTEL framework offers a holistic perspective to guide stakeholders through this complex journey. For Ukraine, in light of its unique socio-political and economic situation, applying PESTEL becomes particularly significant. The international community's drive to combat climate change sets the tone for political support, and international agreements further cement commitments. For Ukraine, aligning with the European Union and seeking energy independence in the face of geopolitical tensions could provide a strong impetus for the transition. While the initial economic barriers to adopting renewable technologies are notable, falling costs, potential for job creation, and foreign investment prospects can counterbalance these challenges. Ukraine's economic restructuring can influence its trajectory, emphasizing the importance of budgetary allocations and financing opportunities. The collective perception and behavioral shifts of the public towards sustainability play a critical role in the successful adoption of renewables. As urban populations grow, there's a rising need for cleaner, more efficient transport solutions. Rapid advancements in battery technology, infrastructure requirements, and innovation across the board are reshaping the transport sector. However, ensuring that Ukraine has access to and benefits from these advancements will be crucial. Beyond the evident need to reduce CO2 emissions, there's a pressing requirement to address resource depletion, improve air quality, and manage land use sustainably. Ukraine's vast agricultural landscape presents both opportunities and challenges in the renewable transport domain. Legal frameworks, from regulation to liability considerations, can either propel or hinder the move towards sustainable transport solutions. As Ukraine aspires for closer ties with the EU, it will need to align its regulatory environment to match global standards and ensure the safe, efficient adoption of new technologies. In essence, the transition to sustainable transport via renewable energy technologies is both a challenge and an opportunity. By understanding and navigating the intertwined PESTEL factors, Ukraine can reshape its transport landscape and stride confidently towards a sustainable future.

4. Ukraine's transport sector, a significant contributor to carbon emissions due to its heavy reliance on fossil fuels, stands at the cusp of a transformation. With abundant renewable energy potentials, such as solar, wind, biomass, biogas, and hydroelectric power, the nation has the opportunity to revolutionize its transport model. Harnessing these sources can result in environmental benefits like reduced greenhouse emissions, economic advantages by diminishing fossil fuel dependency and creating job opportunities, and social gains by improving energy security and democratizing energy access. However, technological, economic, and infrastructural challenges pose substantial barriers. Overcoming these requires strategic investment in research and development, financial incentives, and infrastructural developments. By adopting renewable energy technologies like biofuels, hydrogen, and electric vehicles, Ukraine not only addresses its environmental concerns but also lays the foundation for a sustainable societal framework.

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