A Review of the Energy System and Transport Sector in Uzbekistan in View of Future Hydrogen Uptake

energies

MDPI

Review

A Review of the Energy System and Transport Sector in Uzbekistan in View of Future Hydrogen Uptake

Jamshid Yakhshilikov , Marco Cavana and Pierluigi Leone *

Dipartimento di Energia, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy; jamshid.yakhshilikov@polito.it (J.Y.); marco.cavana@polito.it (M.C.)
* Correspondence: pierluigi.leone@polito.it

Abstract: This study explores the potential role of hydrogen in decarbonizing the transport sector in Uzbekistan by examining different aspects of the country's energy system and transport final use. In road transport, Uzbekistan has already gained experience with the use of alternative fuels through the "Compressed Natural Gas—Mobility" initiatives and has achieved a fleet coverage of 59%. These existing frameworks and knowledge can ease the integration of hydrogen into road transport. The rail sector also has the potential for hydrogen uptake, considering that 47% of rail lines are not electrified. The results of this study indicate that powering all CNG vehicles with a 10% hydrogen blend (HCNG) could reduce road transport emissions by 0.62 $MtCO_2eq$ per year, while replacing diesel trucks with hydrogen-based vehicles could contribute to an additional reduction of up to 0.32 $MtCO_2eq$ per year. In rail transport, hydrogen-powered trains could reduce emissions in non-electrified lines by up to 0.1 $kgCO_2eq/km$ of journey. In assessing the potential infrastructure for hydrogen logistics, this study also identifies opportunities for hydrogen export by repurposing the existing natural gas infrastructure. Focusing on Uzbekistan, this study provides a regional perspective on the potential for the integration of hydrogen into the transport sector in Central Asia.

Keywords: hydrogen; transport sector; Nationally Determined Contribution; Uzbekistan; Central Asia

Citation: Yakhshilikov, J.; Cavana, M.; Leone, P. A Review of the Energy System and Transport Sector in Uzbekistan in View of Future Hydrogen Uptake. *Energies* **2024**, *17*, 3987. https://doi.org/10.3390/en17163987

Academic Editor: Ashok Vijh

Received: 16 July 2024
Revised: 29 July 2024
Accepted: 10 August 2024
Published: 12 August 2024

1. Introduction

The 29th Conference of the Parties (COP29) will take place in Baku in 2024 [1] to follow up on the results of the first global stocktake in Dubai (COP28) [2] and prepare countries to submit updated Nationally Determined Contributions (NDCs) in 2025 [3] under the Paris Agreement [4]. Azerbaijan and other neighboring regions, such as Central Asia (CA), will certainly play a key role in the success of COP29. Therefore, the objective of this study is to understand the potential contribution that hydrogen can make to the decarbonization targets of CA countries, with a focus on the transport sector. Although the perspective is on the region as a whole, this study specifically addresses the role of Uzbekistan, which plays a pivotal role, as it is a manufacturing hub producing 80% of the market share for cars, 50% for trucks, and 55% for buses in the region [5,6].

All five CA countries—Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan—have signed the Paris Agreement and submitted their NDCs. In its second NDC, Uzbekistan has committed to reducing greenhouse gas (GHG) emissions per unit of GDP by 35% by 2030 compared to 2010 [7]. This target is to be achieved through sector-specific measures, such as reducing natural gas consumption in all sectors, increasing the share of renewable energy sources (RESs) in the national energy mix, introducing alternative fuels in the transport sector, and others. The country contributes 31% of the CA region's annual GHG emissions, compared to 45.3% in Kazakhstan and 17.6% in Turkmenistan [8]. The combustion of fossil natural gas is the main source of Uzbekistan's emissions, accounting for more than 83% of total emissions [9]. Natural gas forms the basis of Uzbekistan's energy sector and is responsible for 82% of energy supply, 85% of energy exports, 88% of electricity generation, and 59% of energy consumption in road transport in the form of compressed natural gas (CNG) [10].

Beyond producing 426,500 vehicles per year [5], the transport sector plays another key role in Uzbekistan. Indeed, the transport sector serves as a bridge between East Asia and Southeast Europe (via the Caspian Sea), Russia and South Asia (via Afghanistan), and connects the northern and eastern parts of CA with Iran and Pakistan. It contributes around 9% of Uzbekistan's GDP [5] and is responsible for 20% of the country's final energy consumption [11]. In the last ten years, it has recorded the highest growth rate in emissions of all sectors, reaching 18.38 $MtCO_2eq$ in 2022 [8]. The main contributors to GHG emissions in the transport sector are road transport with 54.2%, pipeline transport with 42%, and rail transport with 3.4% [12].

Road transport remains the predominant means of mobility and is heavily dependent on fossil fuels. In an effort to reduce the environment impact of the transport sector, Uzbekistan's "Green Economy" strategy [13] has identified Battery Electric Vehicles (BEVs) as a promising solution. Compared to Internal Combustion Engines (ICEs), they offer advantages in terms of efficiency, environmental sustainability, and zero emissions. However, the market penetration of BEVs beyond passenger cars is associated with a number of challenges. Long charging times and limited battery capacity for longer distances hinder their introduction in segments such as trucks and buses [14]. To achieve the decarbonization targets, the entire vehicle fleet must transition towards low- and zero-emission technologies. Therefore, in addition to promoting electrification, efforts should focus on diversifying fuel options for trucks and buses. Hydrogen, for example, offers greater range and faster refueling times than BEVs and is therefore better suited for heavy-duty and long-distance travel [15]. This advantage is important for the enterprise sector, including freight and public transportation, where refueling downtime can affect operational efficiency. Another advantage of hydrogen is the enrichment of CNG in the form of HCNG (Hydrogen Compressed Natural Gas) technology. Taib Iskandar et al. [16] found in an experimental study that a 10% enrichment of CNG with hydrogen can reduce CO_2 emissions by 8% and increase volumetric efficiency by 5% compared to CNG. In Uzbekistan, 0.3 million ICEs are produced annually, most of which are retrofitted with CNG.

Hydrogen can also be considered for the decarbonization of rail transport, especially on underutilized, non-electrified rail lines. EU-Rail reports [17] that fuel cell trains offer a more economical and sustainable solution for non-electrified rail lines longer than 100 km and with a utilization of fewer than 10 trains per day, where the costs associated with electrification are not viable. Uzbekistan is currently expanding its electrified rail network and purchasing electric trains. Nevertheless, 47% of the rail network will not yet be electrified [18]. This is mainly due to the remote locations of these lines, which represent an investment challenge for electrification due to their low-capacity utilization.

Furthermore, hydrogen can be integrated into the existing natural gas infrastructure. Vaccariello et al. [19] found that blending hydrogen with natural gas ensures a uniform gas composition without compromising quality if the hydrogen volume remains below 9% (specific gravity), 15% (higher heating value), and 22% (Wobbe index). This admixture reduces pressure and increases velocities without operational issues, proving feasible as long as the pipelines do not reach their full capacity. As Uzbekistan plans to ban natural gas exports [20], the future of its gas export pipelines is uncertain. Considering that the country has an infrastructure connected to the Chinese and Russian energy markets and the possibility to connect to India and the EU (European Union), hydrogen emerges as a promising new sustainable export commodity.

Numerous studies have been devoted worldwide to investigate hydrogen utilization within specific sectors, such as hydrogen for power generation [21], syngas production [22], methanol production [23], green ammonia [24], and drop-in fuel production [25]. The existing literature on the use of hydrogen in Uzbekistan focuses on sectors such as power, industry, and petrochemicals. For example, Alikulov et al. [26] studied the transition to hydrogen-based technologies in Uzbekistan's steel and power sectors. For the steel sector, they investigated the optimization of the hydrogen reduction process through laboratory-scale experiments at the hydrogen direct-reduction iron ore-electric arc furnace (HDRI-EAF), including an analysis of the levelized cost of steel production using the Tebinbulak DRI-EAF plant as an example. For the power sector, they optimized the energy and mass balance of a 100% hydrogen-fired gas turbine unit with a capacity of 7.6 MW, including levelized cost of electricity generation using the Fergana CHP plant as an example. The study concludes that hydrogen is more cost-effective in the steel sector than in the power sector. Kamolov et al. [27] conducted a comparative analysis of hydrogen and CO_2 utilization pathways in Uzbekistan, focusing on scalability, maturity, feasibility, and environmental benefits. The study highlighted Uzbekistan's leading role in CA's methanol production, suppling 67% of regional demand, and emphasized the need for sustainable hydrogen production as the main reactant with CO_2 for methanol synthesis, which could open up a large market. They also focused on CO_2 utilization for Enhanced Hydrocarbon Recovery. In this field, the work of Aliev et al. [28] showed the potential of using hydrogen to transform CO_2 into hydrocarbons through catalytic hydrogenation directly into a reservoir, where pressure and temperature conditions would facilitate the reactions.

Even though the mentioned technologies and solutions are at different Technological Readiness Levels, they show important potential for the use of sustainably produced hydrogen in the industrial sectors relevant to the Uzbek economy. Nevertheless, the untapped opportunities for the integration of hydrogen in the transport sector are still unexplored. Therefore, this study aims to investigate the potential role of hydrogen in decarbonizing the transport sector in Uzbekistan and CA and to serve as a basis for future scientific research in this direction. This study contributes to the body of knowledge in the following ways:

- In order to assess the readiness for green hydrogen production, this study provides an overview of Uzbekistan's energy transition, highlighting government policies and international collaborations. In particular, the study examines the share of renewable energy in the national energy mix, current projects, and future plans to expand the renewable generation capacity.
- In order to assess the readiness for hydrogen uptake in the final use of transport, the study provides an in-depth analysis of Uzbekistan's transport final uses and describes its fuel mix. It also examines past initiatives, including policy and technology measures aimed at reducing the sector's carbon footprint.
- The study provides a comprehensive set of data about the current fleet, segmented for cars, buses, and trucks, which have a high value for implementation in integrated assessment models.
- The transport sector is placed in the context of the broader CA region. This regional perspective helps to identify collaboration opportunities for sustainable mobility solutions and provides quantitative data for further studies aiming to develop scenario narratives and technology implementation roadmaps for the whole region.

The paper is structured as follows. Section 2 describes the research methodology and current limitations of the study. Section 3 provides an overview of Uzbekistan's energy system, highlighting primary energy sources and the actual energy mix, with a focus on gas infrastructure. Section 4 reports an analysis of the stated energy transition policies with a focus on the perspective of using hydrogen in Uzbekistan. Section 5 examines the current state of the transport sector, including road and rail transport modes. Section 6 extends the analysis of the considered transport sectors to the CA region. Section 7 discusses the results of the study with a highlight of potential hubs for hydrogen use in road transport, application in non-electrified rails, and possible corridors for hydrogen transport and exports connecting Central Asia countries and other potential hydrogen importing areas. Finally, Section 8 presents the conclusion.

Figure 1 illustrates the structure of the paper.

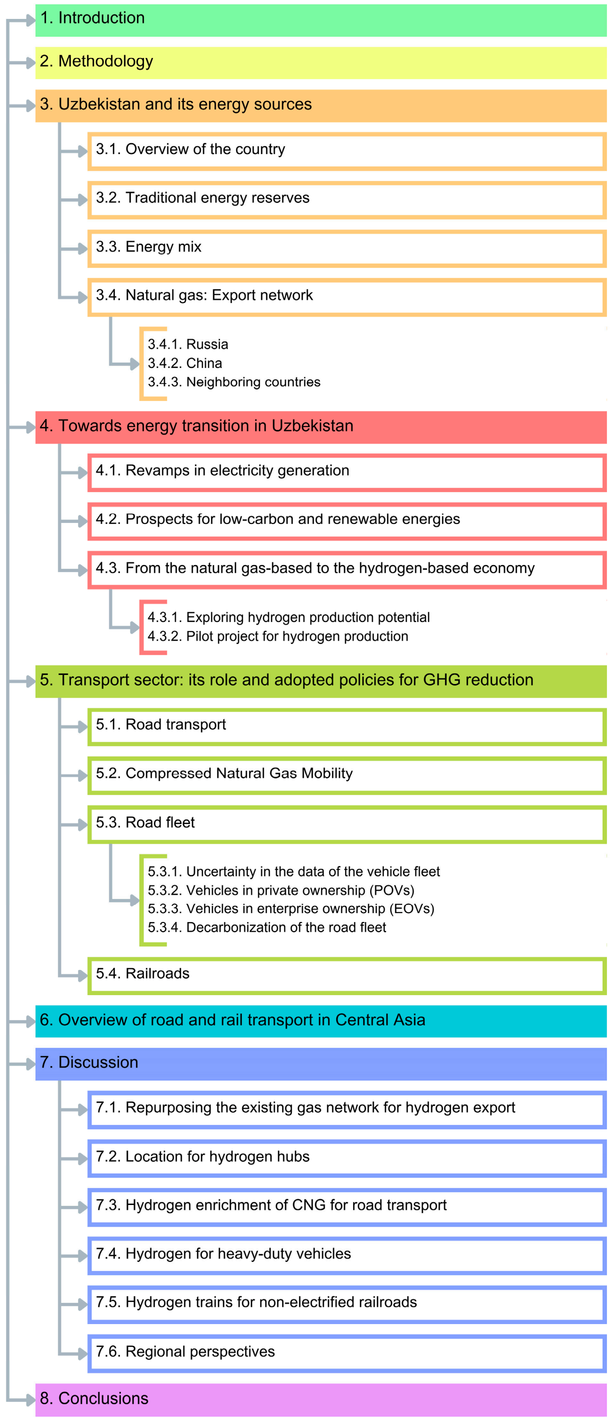


Figure 1. The structure of the paper.

2. Methodology

This study takes a multi-level approach that integrates both qualitative and quantitative analysis to provide an understanding of the energy and transportation landscape in Uzbekistan. The content of this study draws on publicly available information from numerous international and national reports, peer-reviewed academic journals, policy documents, government publications, statistical data, and press release websites. Whenever data are drawn from multiple sources, the authors have conducted a thorough comparison and commented on discrepancies.

This study has some limitations that affect the interpretation of its results. First, the total number of vehicles in Uzbekistan's fleet is not published in public data, requiring estimates based on assumptions about vehicle usage patterns and the country's energy balance. Second, while the study explores the potential role of hydrogen in decarbonizing Uzbekistan's transport sector, it does not thoroughly investigate the feasibility of each pathway due to the broad scope of the work, which is intended as a review. Therefore, the study provides a data-supported overview rather than an in-depth analysis of hydrogen implementation and is intended to serve as a basis for future scientific research in this area.

3. Uzbekistan and Its Energy Sources

3.1. Overview of the Country

Uzbekistan is a country in the heart of CA. It is doubly landlocked, bordering Kazakhstan to the north, Kyrgyzstan to the northeast, Tajikistan to the southeast, Afghanistan to the south, and Turkmenistan to the southwest. With 36 million inhabitants in an area of 448,978 km^2, the country has the highest population density in CA. Uzbekistan's geographical location has a strong impact on internal trade routes, forcing the country to rely heavily on the long east–west land routes that are part of the international transport corridors TRACECA (Transport Corridor Europe–Caucasus–Asia), CAREC (Central Asia Regional Economic Cooperation), and CCAWEC (China–Central Asia–West Asia Corridor of the Belt and Road Initiative).

Uzbekistan is the second largest economy in CA, with a steady growth in GDP per capita at purchasing power parity, reaching USD 9535 in 2022 [29]. Since 2012, net inflows of foreign direct investment as a percentage of GDP have increased from 1.1% to 3.1% [30]. In 2021, the cumulative value of announced energy investment projects in CA reached USD 52.8 billion, with Uzbekistan contributing 41% of the total value [31]. The country occupies a leading position in the automotive industry in CA, with an annual production of 400,000 cars, 5000 trucks, 1500 buses, and 20,000 other types of vehicles [5]. From 2020 onwards, several initiatives have been adopted to mitigate GHG emissions in the transport sector, accompanied by investment programs aimed at the production of e-fuels (USD 3.6 billion) [32], BEVs/HEVs (USD 0.16 billion) [33], high-efficiency vehicles (USD 0.7 billion), the electrification of railroads (USD 1.8 billion), and the acquisition of electric trains (USD 0.4 billion) [34].

3.2. Traditional Energy Reserves

The country has 0.13 Mt of uranium reserves discovered in the Kyzylkum Desert in the Navoi region and exports 3500 t/y of uranium, making it the fifth largest uranium producer on the world market [35]. The country has 1375 Mt of coal reserves in the Baisun-Tau Mountains in the Surkhandarya region [36] and produces 5 Mt/y of coal, which is mainly used to generate electricity [10].

Uzbekistan's oil reserves amount to 84 Mt [37] and the most important are located in the Bukhara and Kashkadarya regions. In 2022, refineries produced 0.3 Mt of diesel fuel meeting the Euro-5 standard [38] and 1020 tons of Jet A-1 synthetic aviation fuel [39]. The export of oil products from Uzbekistan is low and there is a single oil pipeline that runs through Uzbekistan and connects the refinery in Shymkent (Kazakhstan) to the refinery in Turkmenabad (Turkmenistan) [40]. In 2022, gasoline, diesel, and liquefied petroleum gas (LPG) together accounted for 29% (1.67 Mtoe) of Uzbekistan's total energy imports. In the same year, road transport consumed 2.62 Mtoe of oil products [10].

The country's proven natural gas reserves amount to 1846 bcm [41]. A significant share of 70% of the extraction is concentrated in the Amu-Darya Basin, particularly in the Bukhara and Kashkadarya regions [42]. Natural gas is a cornerstone of the country's energy sector, accounting for 82% of the country's energy supply and 85% of energy exports [10]. In 2018, 14.4 bcm of natural gas was exported, distributed as follows: 7.2 bcm to China, 4.1 bcm to Russia, 2.9 bcm to Kazakhstan, and 0.2 bcm to other neighboring countries [43]. Figure 2 depicts the oil and gas facilities and the export routes of natural gas from Uzbekistan.

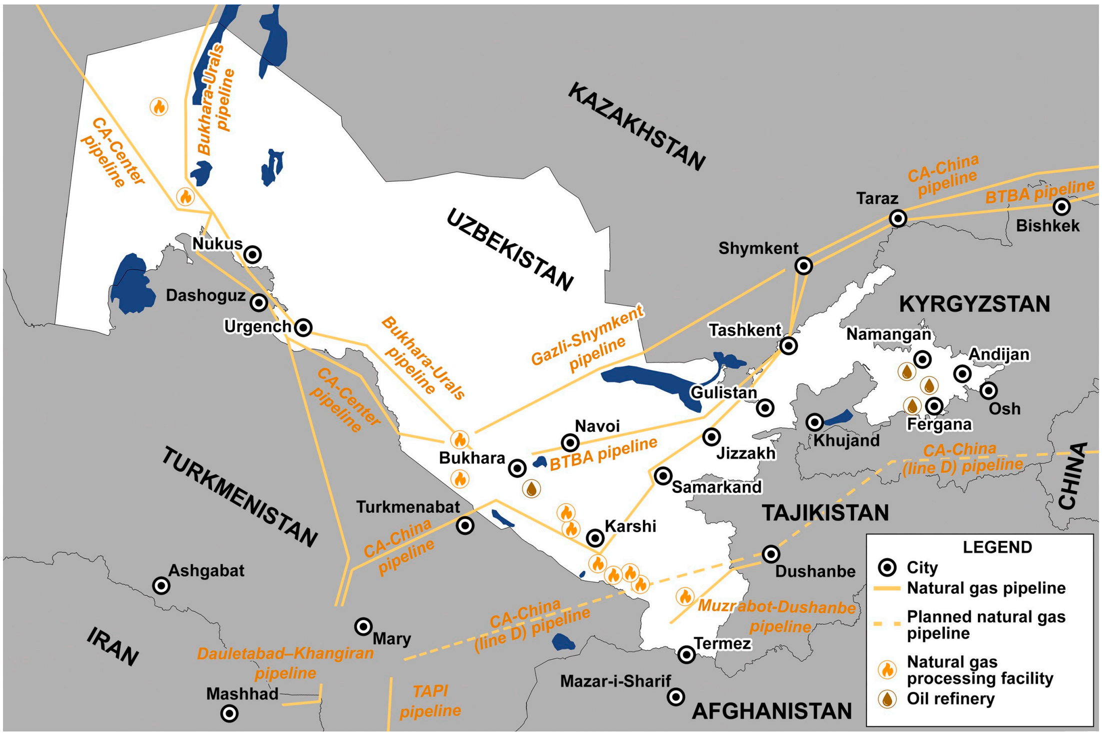


Figure 2. Key oil and gas facilities, including export pipelines. Authors' own elaboration, based on data from [40].

3.3. Energy Mix

Uzbekistan's total energy supply amounts to 48.8 Mtoe, 82% of which is accounted for by natural gas. Oil and coal contribute 9.4% and 7%, respectively, to the remaining energy supply, while renewable sources, especially hydropower, account for 1.6% [10]. In 2022, the country produced 39.6 bcm of natural gas, of which 3.2 bcm was exported and a further 1.6 bcm was imported. The remaining 37.2 bcm was consumed on the domestic market as follows: 12 bcm for energy transformation, mainly for electricity generation, 8.8 bcm for household consumption, 4.9 bcm for the manufacturing industry, 1.3 bcm for public and commercial services, and 3.5 bcm for road transport as CNG for vehicles [10]. Figure 3 shows the energy supply chain of natural gas in 2022, highlighting transformation pathways and direct use.

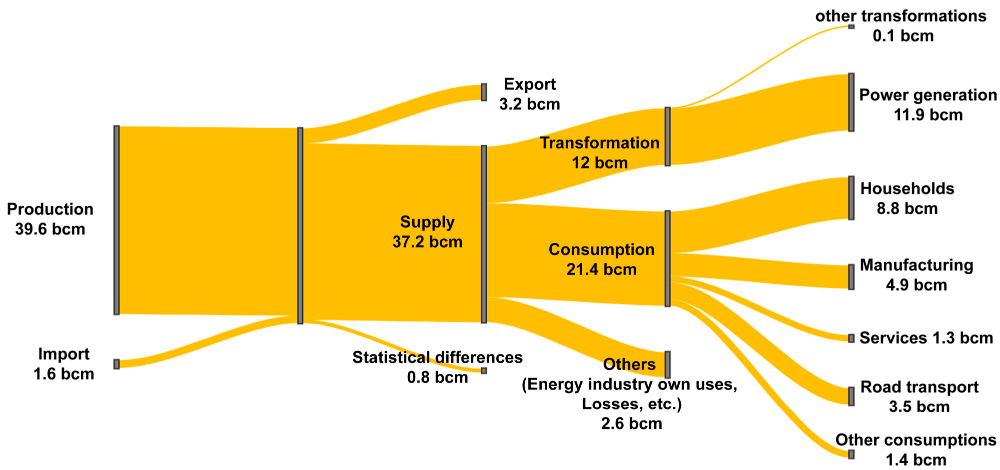


Figure 3. Distribution of natural gas in 2022. Authors' own elaboration, based on data from [10].

Uzbekistan's growing economy is increasing the demand for energy resources. According to forecasts, domestic demand for natural gas will increase to 56.5 bcm/y by 2030, while production is expected to reach 66.1 bcm/y [44]. To address the challenges and opportunities associated with rising energy demand, Uzbekistan has announced that it will stop exporting natural gas by 2025 and redirect resources to domestic processing to promote the production of high-value-added products [20]. This shift to downstream activities such as petrochemicals and GTL production aims to maximize the value of natural gas resources while creating opportunities for economic growth and diversification.

3.4. Natural Gas: Export Network

3.4.1. Russia

The export of natural gas from Uzbekistan to Russia has been facilitated by the CA–Center and the Bukhara–Urals pipeline systems since the 1960s. The CA–Center pipeline, which comprises five pipelines with a total capacity of 80 bcm/y, allocates 6 bcm/y from Uzbekistan [42], while the rest is provided by Turkmenistan. This network is connected to the Russian gas entry point at Alexandrov-Gay, where it integrates with the corridors to Europe, such as Soyuz, Brotherhood, Blue Stream, and TurkStream [45]. The Bukhara–Urals pipeline has a capacity of 15 bcm/y and transports gas to Yekaterinburg. As Russia has the largest gas reserves in the world and is the second largest producer in the world, Uzbek and Turkmen gas supplies only have a competitive advantage in the southern regions of Russia, which are closer to the CA gas sources than those in Western Siberia [42].

3.4.2. China

Since the early 2010s, China has overtaken Russia as the main consumer of natural gas from CA. The corridor for this trade is the CA–China pipeline, with a capacity of 55 bcm/y, connecting Turkmenistan to China via Uzbekistan and Kazakhstan. The pipeline consists of three parallel pipelines named A, B, and C (commissioned in 2009, 2010, and 2014, respectively) and has a total length of 1833 km, of which 530 km is located in Uzbekistan [46]. Since 2012, Uzbekistan has been using the 10 bcm/y capacity of Line-C to supply natural gas to China. A fourth pipeline (Line-D) with a capacity of 30 bcm/y has been under construction since 2018, with another, more southerly route running through Uzbekistan, Tajikistan, and Kyrgyzstan. Of the total length of 966 km, 205 km of the pipeline runs through Uzbekistan.

3.4.3. Neighboring Countries

The BTBA pipeline (Bukhara–Tashkent–Bishkek–Almaty), with a capacity of 12 bcm/y, serves as the most important gas supply route from Uzbekistan to Kyrgyzstan and southern Kazakhstan. The pipeline was commissioned in 1971 and has suffered from deterioration in the Kyrgyz section. In 2020–2021, the Uzbek section was extensively rehabilitated and a new branch of the gas pipeline was built on the Kyrgyz section to increase throughput [42]. Other low-capacity pipelines are available to supply neighboring countries, such as the Gazli-Shymkent pipeline to supply Kazakhstan [40] and the Muzrabot-Dushanbe pipeline to supply Tajikistan with gas [42]. Table 1 summarizes the natural gas export routes for existing pipelines and those under construction.

Table 1. Natural gas export routes.

Destination	Pipeline Name	Operation Year	Total Capacity, [bcm/y]	Capacity Used by Uzbekistan, [bcm/y]
Russia	Central Asia-Center	1969	80	6
	Bukhara–Urals	1963	15	15

Table 1. *Cont.*

Destination	Pipeline Name	Operation Year	Total Capacity, [bcm/y]	Capacity Used by Uzbekistan, [bcm/y]
China	Central Asia–China	2010	55	10
	Central Asia–China (Line-D)	under construction	30	no data
Kazakhstan and Kyrgyzstan	BTBA	1971	12	12
Kazakhstan	Gazli-Shymkent	1988	4.3	4.3
Tajikistan	Muzrabot-Dushanbe	1988	0.13	0.13

4. Towards Energy Transition in Uzbekistan

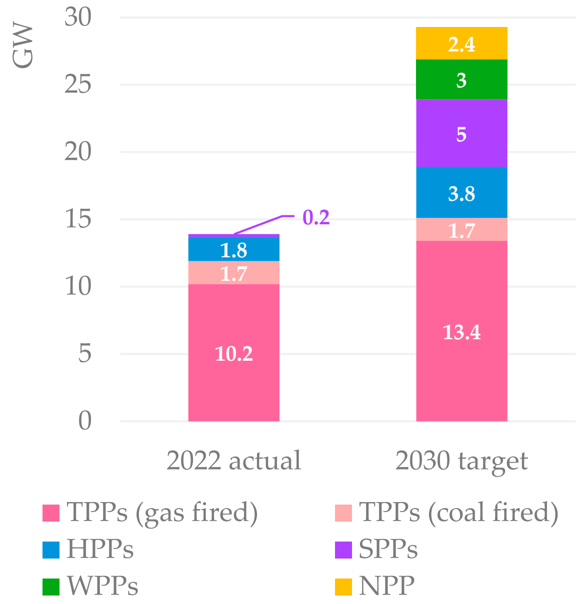
4.1. Revamps in Electricity Generation

Since 2010, electricity consumption in Uzbekistan has risen from 43 TWh/y to 56 TWh/y, accompanied by a corresponding uptick in electricity generation from 51 TWh/y to 62 TWh/y. On average, 87% of electricity is generated through the conversion of natural gas in thermal power plants (TPPs), while the rest is generated in hydroelectric power plants (HPPs) and through the conversion of coal in TPPs. The share of electricity imports and exports is almost equal and amounted to an average of 6 TWh/y in the last decade [11]. These import/export activities take place through a centralized power system known as the CAPS (Central Asia Power System) [47], which facilitates reciprocal electricity trade between the countries of the CA region. As natural gas consumption rises up to 0.07 bcm/day in winter [48] and electricity consumption peaks at 0.24 TWh/day in summer [49], Uzbekistan has started to import electricity from the CAPS. In contrast, the country normally exports electricity in spring and autumn. Uzbekistan is the key supplier of electricity to Afghanistan, and the implementation of the upcoming Surkhan-Puli Khumri transmission line will increase electricity exports to Afghanistan up to 6 TWh/y [47]. Along this route, there is also the prospect of electricity supplies through Afghanistan to Pakistan as part of the TUTAP (Turkmenistan–Uzbekistan–Tajikistan–Afghanistan–Pakistan) [50]. As of 2022, the country has a power generation capacity of 13.9 GW, of which 11.9 GW is provided by TPPs [51], 1.8 GW by HPPs [52], and the remainder (0.2 GW) by solar power plants (SPPs). Only two of the existing TPPs in Angren (Tashkent region) with a combined capacity of 1.7 GW can generate electricity from coal [53], while the others are powered by natural gas. The capacity of HPPs varies from 5 MW to 660 MW [54], with some HPPs being a cascade group of micro-HPPs used as run-of-river, and others being of the water reservoir type.

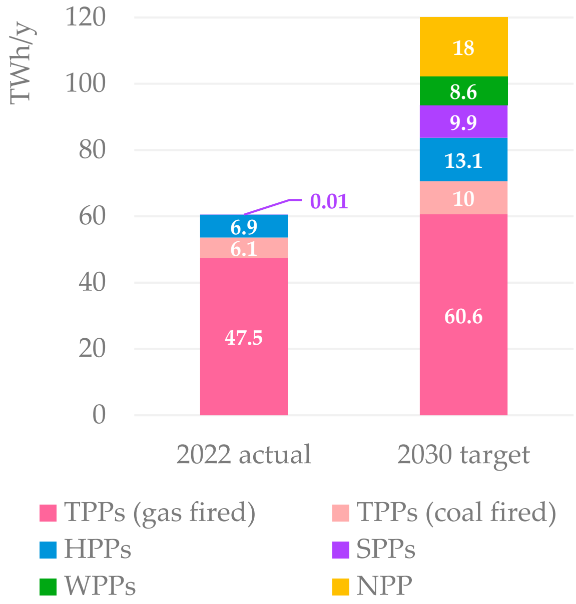
To ensure the transition of the power sector and in view of an annual growth in electricity demand of 7%, the country has adopted the "Concept of ensuring electricity supply in Uzbekistan for 2020–2030" [55]. The aim is to increase electricity generation capacity to 29.3 GW by 2030 and produce more than 120 TWh/y of electricity. This is to be achieved by implementing the following initiatives:

- thirteen projects for the construction/modernization of TPPs, with the intention of increasing capacity to 14.7 GW and reducing natural gas consumption to 12 bcm/y through the use of combined-cycle and gas turbines (CCGTs);
- 72 projects for the construction/modernization of HPPs, to increase capacity to 3.8 GW and achieve electricity production of 13.1 TWh/y;
- construction of solar power plants (SPPs), wind power plants (WPPs), and one nuclear power plant (NPP);
- upgrade of transmission and distribution grids and improvement of tariff policy in the power sector.

Figure 4 shows a detailed breakdown of power generation capacity and power generation volume for 2022 and expectations for 2030.



(**a**)



(**b**)

Figure 4. (**a**) Power generation capacity. Authors' own elaboration, based on data from [55]; (**b**) power generation volume. Authors' own elaboration, based on data from [55].

4.2. Prospects for Low-Carbon and Renewable Energies

The country has a renewable energy potential of 179.3 Mtoe/y, of which solar energy accounts for almost 99% [43]. The first SPP was opened in 2021 in the Navoi region with a capacity of 100 MW, contributing to a reduction of 0.15 $MtCO_2$/y and electricity generation of 252 GWh/y [56]. A year later, a similar project was launched in the Samarkand region [57]. Uzbekistan currently has 0.2 GW of SPPs. To achieve the targets of 5 GW solar and 3 GW wind energy by 2030, the country has announced tenders and launched several initiatives. On this basis, thirteen SPPs with a total capacity of 4.7 GW and five WPPs with a total capacity of 3.1 GW will be built in the coming years together with Saudi Arabia, the United Arab Emirates, and France [58,59].

As one of the top five uranium suppliers in the world [35], Uzbekistan is exploring the possibility of nuclear energy as a low-carbon energy alternative to reduce GHG emissions and expand its power generation capacity. In 2017, Uzbekistan signed an agreement with Russia to build an NPP comprising two VVER-1200 (pressurized water reactor) power units with a total capacity of 2.4 GW [20]. The commissioning of the first unit of the NPP is planned for 2028 and the second unit for 2030 [60]. Figure 5 depicts the locations of the existing power plants and those under construction with a capacity of more than 100 MW.

4.3. From the Natural Gas-Based Economy to the Hydrogen-Based Economy

4.3.1. Exploring Hydrogen Production Potential

Hydrogen has been indicated as an energy carrier to boost Uzbekistan's transition to renewable energies. Decree UzPQ-5063 (Presidential Decree No. 5063 of the Republic of Uzbekistan, dated 9 April 2021) [61] was adopted to establish hydrogen production, to create a hydrogen energy infrastructure, and to increase the share of scientific and practical work in the field of hydrogen technologies. Considering the natural gas reserves of 1845 bcm and the potential of 179.3 Mtoe of renewable energy in Uzbekistan, the following options are the most suitable for hydrogen production:

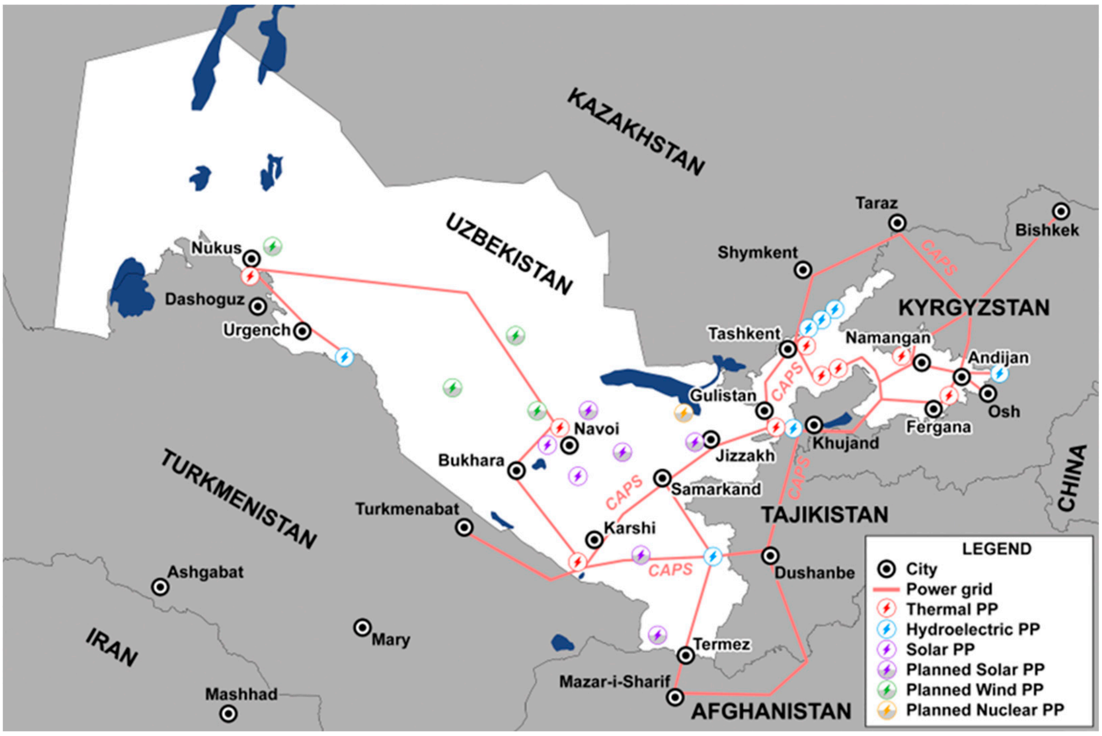


Figure 5. Locations of power plants over 100 MW. Authors' own elaboration, based on data from [40].

- Hydrogen from natural gas by Steam Methane Reforming (SMR): It involves the reaction of natural gas with steam at high temperature and pressure to produce hydrogen and CO_2. The SMR requires 2.9 kg of natural gas, 1.11 kWh of electricity, and 21.9 L of deionized water per kg of hydrogen [62]. This method releases 12.6 kg CO_2eq per kg of hydrogen ("gray" hydrogen). To make the process sustainable, there is the option of carbon capture to prevent the release of GHG into the environment ("blue" hydrogen [63]). The estimated cost of blue hydrogen is in the range of USD 1.5~2 per kg [64].
- Hydrogen from water by electrolysis: It involves splitting water molecules into hydrogen and oxygen in an electrochemical device, the "electrolyzer", using an electric current. This method (with the PEM electrolyzer) requires 54.6 kWh of electricity and 18 L of deionized water per kg of hydrogen [62]. Hydrogen that is produced without emitting GHG using electricity from RESs is referred to as "green" hydrogen. The estimated cost of green hydrogen is in the range of USD 2.5~4 per kg [64].

In 2022, the UNECE (United Nations Economic Commission for Europe) reported on the possibility of hydrogen production in Uzbekistan by 2040 [64], taking into account the minimum and maximum available resources. The report indicates that electrolysis is promising for long-term hydrogen production, while in the short to medium term the opportunities lie in SMR. This conclusion is in line with the World Bank's assessment from 2021 [65]. Table 2 contains data from the UNECE report, the study by Mehmeti et al., on the water footprint of hydrogen production methods [62] and the study by Ingale et al. on the GHG emissions of hydrogen production processes [63].

Table 2. Hydrogen production potential by 2040.

Hydrogen Type	Path	Input and Output Resources	Min.	Max.
Blue	SMR with carbon capture	Natural gas, [Mt/y] [1]	1.35	2.68
		Electricity, [GWh/y] [2]	0.493	0.838
		Deionized water, [Mt/y] [2]	9.723	16.534
		CO_2eq for capture, [Mt/y] [3]	5.6	9.5
		Hydrogen, [Mt/y] [2]	0.465	0.924
		LCOH, [USD/kgH_2] [1]	1.5~2	
Green	Electrolysis with renewable electricity	Electricity, [GWh/y] [1]	1821	72,051
		Deionized water, [Mt/y] [2]	0.594	23.580
		Hydrogen, [Mt/y] [2]	0.033	1.319
		LCOH, [USD/kgH_2] [1]	2.5~3	
	Electrolysis with nuclear electricity	Electricity, [GWh/y] [1]	900	1530
		Deionized water, [Mt/y] [2]	0.288	0.504
		Hydrogen, [Mt/y] [2]	0.016	0.028
		LCOH, USD/kgH_2] [1]	4	

[1] Based on the UNECE report [64]. [2] Authors' own estimate, based on the study by Mehmeti et al. [62]. [3] Authors' own estimate, based on the study by Ingale et al. [63].

4.3.2. Pilot Project for Hydrogen Production

In 2022, a hydrogen production unit was commissioned at the GTL plant in Kashkadarya, which can produce up to 26.9 Mt/y of hydrogen based on steam reforming of natural gas for use in the production of synthetic oil [66]. In 2023, agreements for a green hydrogen plant and a green ammonia pilot project were made. The green hydrogen project will be an integrated plant connected to an existing ammonia plant in Chirchik (Tashkent region) and will produce 3 kt/y of green hydrogen. The second project is a 500 kt green ammonia project that will reduce Uzbekistan's dependence on natural gas by 0.6 bcm/y and contribute to a reduction of 1.5 MtCO_2/y [67]. The implementation of these low-carbon hydrogen-related pilot projects will facilitate the expansion of the value chain once large-scale hydrogen production becomes feasible.

5. Transport Sector: Its Role and Adopted Policies for GHG Reduction

5.1. Road Transport

The transport sector accounts for 9% of Uzbekistan's GDP [5]. This contribution is mainly attributed to road transport, which is the most important mode of mobility for both freight and public transportation, as it can provide door-to-door services. Since 2010, 6 billion passengers have been transported by road each year, with an average distance of 22 km [68]. These journeys take place in densely populated areas, 34% of which are in the Fergana Valley (Andijan, Fergana, Namangan regions) and 20% in Tashkent [5]. The fleet of buses and trucks in Uzbekistan is on average 10 and 15 years old, respectively [53]. Freight delivery is mainly carried out by trucks, which account for 90% of the total volume. Since 2010, road freight has increased from 652.5 million tons to 1.28 billion tons [69]. The average weight of commercial vehicles is 25 tons [70,71] and the average distance traveled is 350 km [69]. The relatively short average distance traveled by both freight and public transport underscores the dominance of medium-sized trucks and buses in the country's road fleet.

The country has 32,062 trucks for international freight delivery, of which 5408 are located in Tashkent, 5164 in the Fergana Valley, and 4310 in the Bukhara region [72]. Due to their strategic location as entry points to the transport corridors, these regions are the most important logistical hubs in the country. One-tenth of Uzbekistan's highways, with a length of 3981 km, are part of the international road corridors [73]. As Uzbekistan's existing transit corridors are the main routes connecting the country's regional centers, they are heavily used for both inter-regional and intra-regional traffic. Over the years, the ADB (Asian Development Bank) [74] and UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific) [75] have recorded the annual average daily traffic (AADT) on Uzbekistan's roads. According to these reports, a 900 km long highway from Andijan to Bukhara, which runs through the regional centers of Tashkent, Gulistan, Jizzakh, Samarkand, and Navoi, is the most heavily trafficked route, with an AADT of 10,000 vehicles. This route is part of the TRACECA, CAREC, and CCAWEC corridors and carries a significant volume of traffic between Osh (Kyrgyzstan)–Tashkent–Turkmenabad (Turkmenistan) and Shymkent (Kazakhstan)–Tashkent–Turkmenabad (Turkmenistan). While other highways have lower traffic volumes, the route between Termez, Karshi, and Bukhara is also an important road, with an AADT of 5000 vehicles. Figure 6 depicts the main international highways and logistical hubs among them.

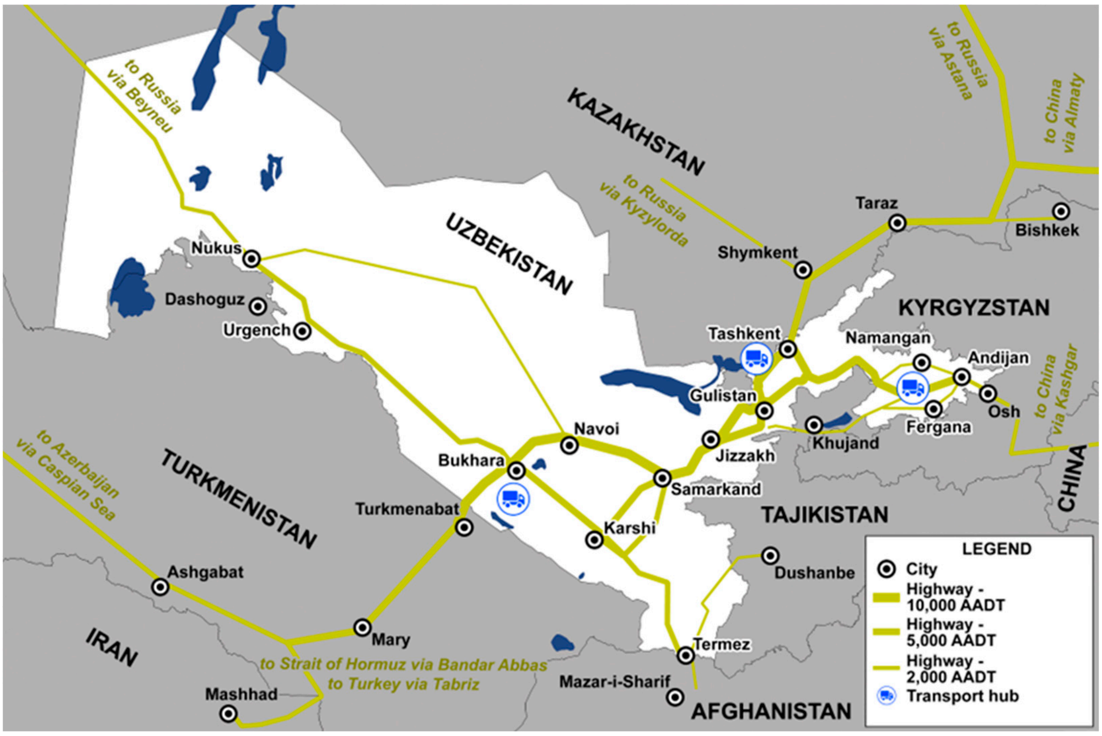


Figure 6. International highways and logistical hubs. Authors' own elaboration, based on data from [72–75].

5.2. Compressed Natural Gas Mobility

To reduce emissions from vehicles and protect the environment, and in view of the availability of 1846 bcm of natural gas reserves [41], Uzbekistan planned to promote the use of natural gas as a fuel in transport. To achieve this goal, the government has taken up various initiatives (in the form of decrees and regulations) to promote the development of CNG-powered vehicles. As a result of these efforts, CNG became the most popular alternative fuel for road transport, and LPG served as a transition fuel.

The development of CNG in road transport began in 1995 when Uzbekistan joined an agreement [76] with the CIS (Commonwealth of Independent States) countries to reduce CO_2 emissions and to meet the market's fuel demand by using natural gas as a vehicle fuel. One of the main objectives of the agreement was to cooperate in establishing a transnational network of CNG refueling stations on transit highways. The agreement included mutual support in the implementation of a unified regulatory and technical policy for the construction, operation, technology, and safety management of CNG refueling.

At the beginning of 2007, the country had 43 CNG and 300 LPG refueling stations. In the same year, resolution UzVMQ-30 (Resolution No. 30 of the Cabinet of Ministers of the Republic of Uzbekistan, dated 10 February 2007) [77] was adopted to further develop the infrastructure with CNG and LPG refueling stations and attract investment. It stipulated the construction of 138 new CNG and 952 LPG refueling stations along international and inter-regional highways within 6 years. In addition, 69,000 of the existing 1.18 million gasoline-powered vehicles were to be gradually converted to CNG and 119,000 vehicles to LPG by the end of 2012. To support the conversion of the vehicles, 80,998 CNG and LPG fuel tanks and 6612 LPG storage vessels were to be produced within 6 years.

In 2017, a new resolution, UzVMQ-815 (Resolution No. 815 of the Cabinet of Ministers of the Republic of Uzbekistan, dated 11 October 2017) [78], was adopted. It considered the growing demand for LPG in the residential sector, the production of CNG tanks that comply with the requirements of UNECE R-110 (Regulation No. 110 of the UNECE for CNG vehicles) [79], and the expansion of the production of CNG-powered cars, buses, and trucks. The resolution aimed to increase production from 41,000 to 200,000 CNG fuel tanks per year, convert a further 800,467 vehicles to CNG systems, and construct a further 178 CNG refueling stations in addition to the existing 569 CNG stations across the country. As of October 2022, there were 1059 CNG refueling stations in Uzbekistan, 171 of which were located along international highways [80]. Table 3 provides an overview of the most important decisions to promote "CNG Mobility" and their objectives.

Table 3. The measures to promote CNG and LPG fuels.

Resolution	Objectives to Promote CNG	Objectives to Promote LPG
UzVMQ-30 dated 10 February 2007 [77]	Construction of 138 refueling stations	Construction of 952 refueling stations
	Retrofit 69,000 gasoline-powered vehicles	Retrofit 119,000 gasoline-powered vehicles
	Production of fuel tanks	Production of fuel tanks
	Pilot production of CNG vehicles	Production of 6612 storage vessels
UzVMQ-815 dated 11 October 2017 [78]	Construction of 178 refueling stations	no LPG promotion
	Retrofit 800,467 gasoline-powered vehicles	
	Increase the annual production of fuel tanks from 41,000 to 200,000	
	Increase production of CNG vehicles	

5.3. Road Fleet

5.3.1. Uncertainty in the Data of the Vehicle Fleet

The number of vehicles in Uzbekistan is published by organizations such as the UNECE, the IRF (International Road Federation), and UzStat (Statistics Agency of the Republic of Uzbekistan), focusing on vehicles of private ownership (POVs) and excluding enterprise-owned vehicles (EOVs). The same applies to the data on "vehicles per 1000 inhabitants". The total vehicle fleet is not publicly available from either OICA (International Organization of Motor Vehicle Manufacturers) or FOURIN (Asian Automotive Analysis Weekly by FOURIN Inc.). The only public data on the total vehicle fleet date back to 1998 and were published by the World Bank [81]. It reports that heavy-duty vehicles accounted for 22% of the 1.14 million vehicles and that a significant proportion of vehicles were twenty years old; some were decommissioned but still registered. A clear difference between gasoline-powered POVs and EOVs was noted in the 2007 UzVMQ-30 resolution, in which POVs comprised 1,037,487 vehicles, predominantly passenger cars, while EOVs comprised

143,918 vehicles, predominantly heavy-duty vehicles (trucks and buses) [77]. Table 4 presents the data gaps and findings from public reports on the vehicle fleet in Uzbekistan.

Table 4. Data gaps in the public reports on the road fleet in Uzbekistan.

	1998	2007	2018	2021
Light-duty (POVs)	No data	988,100 [1]	2,133,507	2,767,126
Light-duty (EOVs)	No data	55,542 [1]	No data	No data
Light-duty (Total)	889,286	No data	No data	No data
Heavy-duty (POVs)	No data	49,387 [1]	139,912	188,169
Heavy-duty (EOVs)	No data	88,376 [1]	No data	32,062 [2]
Heavy-duty (Total)	250,563	No data	No data	No data
Total vehicle stock	1,139,849	No data	No data	No data

[1] Only gasoline-powered vehicles based on UzVMQ-30 [77]. [2] Only international freight forwarder trucks [72].

In the context of promoting hydrogen mobility, the role of EOVs is crucial for several reasons.

First, EOVs represent primary drivers of fleet activities, including both freight and public transportation, thereby making their integration of hydrogen technologies impactful in market advancements and scaling up infrastructure development.

Second, EOVs are often operated by large organizations that have the financial means to invest in new technologies and infrastructure. This makes them early adopters of hydrogen mobility solutions, as they may withstand higher upfront capital investment requirements. Their willingness to invest in such initiatives will stimulate industry interest and investment, leading to economies of scale and cost reductions over time.

Third, EOVs wield higher influence within their respective sectors. The endorsement of hydrogen mobility by major enterprises through integration into their vehicle fleets sends a powerful signal to stakeholders, suppliers, and policymakers. This will create a positive feedback loop, encouraging further innovation and regulatory support for hydrogen technologies in the transport sector.

Fourth, EOVs are motivated to improve their environmental footprint, driven by incentives such as sustainability targets, regulatory compliance, and corporate social responsibility. The advent of hydrogen mobility presents a positive trajectory towards mitigating carbon emissions, improving air quality, and achieving environmental benchmarks, making it an attractive option for enterprises looking to align with these objectives.

Given the inconsistencies in public data, this study describes the fuel mix and consumption of POVs by consolidating data from UNECE and UzStat. Subsequently, the study attempts to estimate similar data for EOVs by subtracting the consumption of POVs from the total consumption reported in the country energy balance.

5.3.2. Vehicles of Private Ownership (POVs)

Between 2018 and 2021, energy consumption in road transport in Uzbekistan increased by 18% from 4.85 Mtoe to 5.74 Mtoe [11]. The increase was due to the transition to CNG, driven by the effectiveness of the "CNG Mobility" measures. In contrast, the consumption of gasoline, diesel, and LPG remained relatively stable. This is due to the higher volumetric energy density of gasoline, diesel, and LPG compared to CNG [82], which leads vehicle groups (i.e., EOVs) requiring higher on-board energy storage to continue to rely on these fuels despite the growing prominence of CNG. Figure 7 shows energy consumption in road transport in Uzbekistan between 2018 and 2020.

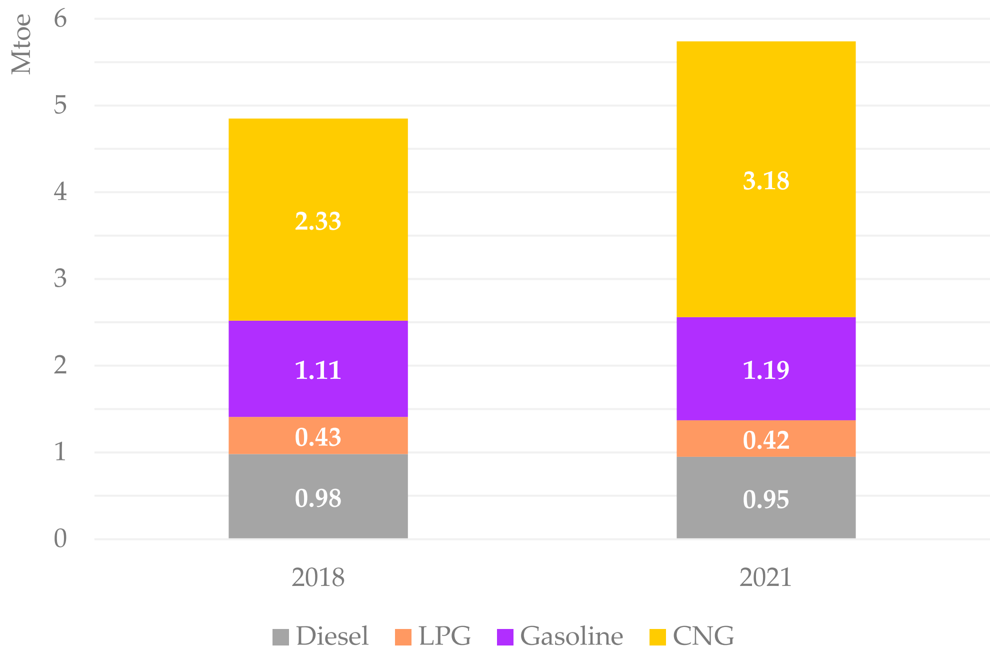


Figure 7. Energy consumption in road transport. Authors' own elaboration, based on data from [11].

UzStat reports that POVs accounted for 2.27 million vehicles in 2018, including 2.13 million cars [83], 116,339 trucks [84], 20,328 buses, and 3245 other vehicles [85]. As reported by the UNECE [53], CNG was the predominant fuel in 2018 with 50.9%, followed by gasoline with 33.2%, LPG with 13.7%, and diesel with 2.3%. Trucks and buses consumed 31.2% of the energy among POVs, making them the most energy-intensive vehicles, as they require higher mileage than other vehicles. By 2021, the number of POVs had risen to 2.95 million, including 2.76 million cars [83], 168,810 trucks [84], 14,229 buses, and 5130 other vehicles [85]. Of these, 65% were powered by CNG, 24.4% by gasoline, 8.4% by LPG, and 2.2% by diesel [86]. Figure 8 shows the changes in POVs between 2018 and 2021.

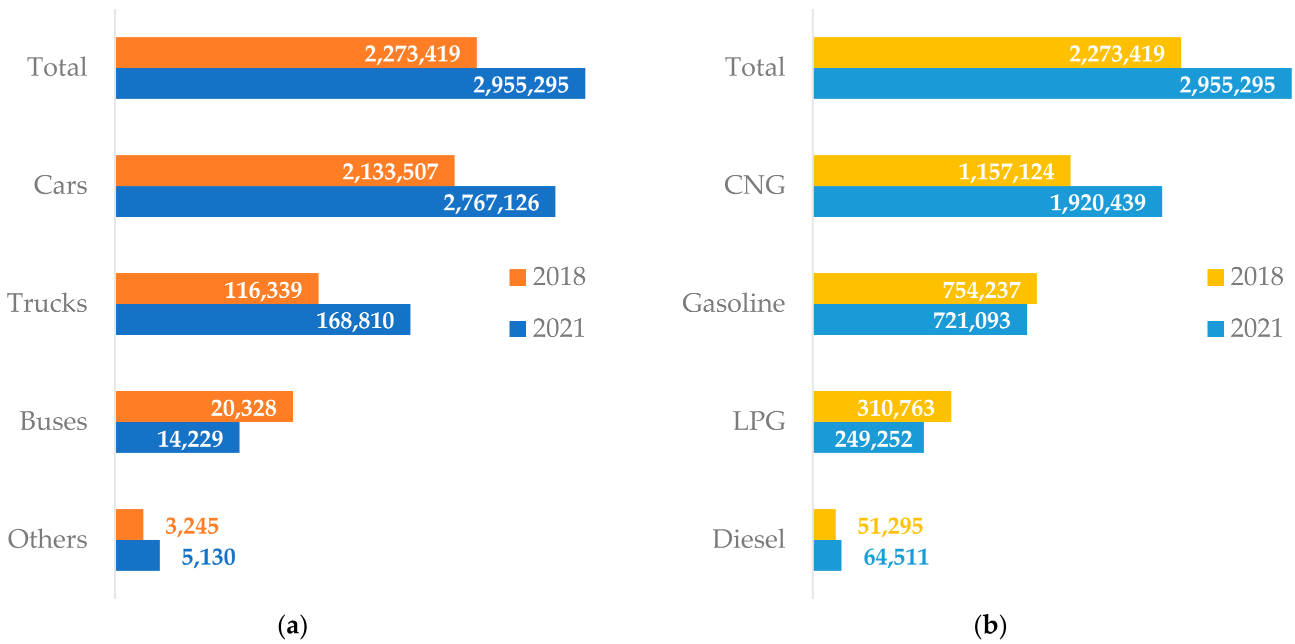


Figure 8. (**a**) POVs by vehicle type. Authors' own elaboration, based on data from [83–85]. (**b**) POVs by fuel mix. Authors' own elaboration, based on data from [53,86].

As shown in Figure 8, the number of POVs increased by 681,876 vehicles between 2018 and 2021, while 6099 buses were decommissioned. In terms of fuel switching, 33,144 gasoline and 61,511 LPG vehicles were converted to CNG. Although the number of trucks increased by 52,471, the increase in diesel vehicles was only 13,216, indicating that only 25% of new trucks in private ownership opted for diesel fuel, while the others preferred to run on CNG. Despite the high conversion rate to CNG among POVs (763,315 vehicles), which exceeds the growth rate of POVs themselves (681,876 vehicles), the constant fuel consumption of gasoline (1.1 Mtoe on average), diesel (0.9 Mtoe on average), and LPG (0.4 Mtoe on average) indicates that the fleet has a certain group of vehicles (i.e., EOVs) that require a higher on-board energy storage to carry out their activity.

High on-board energy content ensures that the vehicle can cover longer distances and be operated for longer periods of time without refueling. As enterprises tend to use their operating time efficiently, EOVs are very willing to run on gasoline, LPG, and diesel.

5.3.3. Vehicles of Enterprise Ownership (EOVs)

The estimation of EOVs requires the integration of different data sources and methods. One approach is to subtract the energy consumption of POVs from the total energy consumption of the transport sector. To implement this method, data on fuel consumption and vehicle mileage are required. The average fuel consumption per kilometer was taken from the vehicle data sheets of UzAutosanoat JSC [87–91], the main vehicle manufacturer in Uzbekistan and CA. The annual mileage of passenger cars was determined based on a report by UzCERR (Center for Economic Research and Reform of the Republic of Uzbekistan) [92]. For trucks and buses, a global perspective was taken, using the average annual mileage observed worldwide as a reasonable assumption [93]. This assumption was validated by a comparative analysis with data from the UNECE report [53]. By integrating all data, a detailed breakdown of energy consumption by vehicle type is calculated using Equations (1) and (2) from the IEA report [94].

$$\text{Vehicle kilometers} = \text{Average annual mileage} \times \text{Vehicle stock}, \tag{1}$$

$$\text{Energy consumption} = \text{Average fuel consumption} \times \text{Vehicle kilometers}, \tag{2}$$

Table 5 summarizes the results, showing the energy consumption for different types of vehicles in Uzbekistan.

Table 5. Fleet energy consumption by vehicle type.

Vehicle Type	Average Annual Mileage, [km/y]	Average Fuel Consumption, [MJ/km]	POVs Stock in 2018 (Figure 8a)	POVs Stock in 2021 (Figure 8a)	Energy Consumption of POVs in 2018, [Mtoe]	Energy Consumption of POVs in 2021, [Mtoe]
Cars	12,000	3.1	2,133,507	2,767,126	1.90 [2]	2.46 [2]
Trucks	25,000 [1]	10.3	116,339	168,810	0.72 [2]	1.04 [2]
Buses	35,000 [1]	9.9	20,328	14,229	0.17 [2]	0.12 [2]
Others	8000	6.5	3245	5130	0.004 [2]	0.006 [2]
				Consumption by POVs:	2.78	3.62
				Total consumption by road transport (Figure 7):	4.85	5.74
				Consumption by EOVs:	2.07	2.12

[1] The assumption is based on an IEA report, which was validated by a UNECE report. [2] MJ converted to Mtoe.

The annual mileage of trucks and buses was validated by comparing data from the UNECE 2018 report, which outlines that trucks were responsible for 25.2% and buses for 6% of the energy consumption of POVs [53]. This study found that in 2018, trucks consumed 25.9% (0.72 Mtoe) and buses 6.1% (0.17 Mtoe) of the POVs' energy consumption. These results help to extrapolate the annual energy consumption trends of EOVs in Uzbekistan, which fluctuate around 2.1 Mtoe (Table 5).

While a breakdown of EOVs by type and fuel mix is unclear, assumptions can be made based on operational realities. Enterprises use vehicles primarily for freight and public transportation, which suggests that they are more likely to own trucks and buses than cars. With an annual mileage of 35,000 km and an energy consumption of 10.3 MJ/km, the 2.1 Mtoe could therefore supply around 212,000 trucks and buses.

Regarding the fuel mix of EOVs, taking into account factors such as the energy content of the fuels, the distance traveled per tank of fuel, and operating efficiency, it is likely that most EOVs will run on conventional oil-based fuels rather than CNG. This assumption is supported by empirical observations showing that typical CNG vehicles need to refuel three times as often as their counterparts to cover the same distance [95].

It is therefore crucial to prioritize strategies for the transition from oil-powered EOVs to more environmentally friendly alternatives, especially hydrogen-based solutions. Such strategies will reduce dependence on fossil fuels and promote a greener transport sector in Uzbekistan and beyond.

5.3.4. Decarbonization of the Road Fleet

In order to achieve its NDC targets and transition road transport to a "Green Economy", Uzbekistan issued decrees UzPQ-443 (Presidential Decree No. 443 of the Republic of Uzbekistan, dated 19 December 2022) [96] and UzPQ-444 (Presidential Decree No. 444 of the Republic of Uzbekistan, dated 19 December 2022) [97] on the decarbonization of the transport sector. These decrees focus on the electrification of the fleet through various incentives, such as:

- Promotion of electric vehicles: To encourage the adoption of BEVs and HEVs, customs duty exemptions are granted for their spare parts, and service providers using BEVs/HEVs are exempted from license fees.
- Expansion of infrastructure: Construction of 2500 charging stations by 2024, coupled with tax rebates for charging service providers.
- Research and development: The establishment of dedicated research laboratories to foster the production of BEVs/HEVs.

Although domestic market interest in BEVs has led to a rapid increase in imports, reaching 2000 vehicles per year over the last five years [98], certain challenges are hindering their widespread adoption across all vehicle groups. Factors such as longer charging times and the need to expand infrastructure for long-distance travel have limited the uptake of BEVs primarily to passenger cars, leaving trucks and buses (electric city buses are an exception) largely unaffected by the electrification trend [14]. This situation underscores the need for a more comprehensive approach to decarbonizing all segments of the transport sector, especially fossil fuel-powered trucks and buses, which need to transition to environmentally friendly fuels due to their large impact on energy consumption and GHG emissions.

In the course of "CNG Mobility", Uzbekistan has taken various measures, and CNG has become the main fuel source [80]. This successful experience could serve as a model for the transition to more environmentally friendly fuels, such as hydrogen. There are various approaches to the use of hydrogen as a fuel in the transport sector. Given the dynamics of the Uzbek vehicle fleet, the following alternatives for hydrogen mobility are possible:

(a) Hydrogen enrichment pathway: Building on the success of "CNG Mobility", the adoption of HCNG (Hydrogen-Compressed Natural Gas) technology [16] could serve as an intermediate step towards a hydrogen economy. To assess the feasibility, a dedicated case study tailored to the context of Uzbekistan is required, including the repurposing of existing CNG infrastructure for HCNG.

(b) Pure hydrogen pathway: Investigating the feasibility of hydrogen-powered vehicles [15] is a perspective for sectors that are heavily dependent on oil-based fuels. This approach not only reduces emissions, but also opens up the possibility of using renewable energies for "green" hydrogen production and thus becoming "well-to-wheel" emission-free in the transport sector.

These initiatives will pave the way for a decarbonization of the transport sector, which is in line with global climate objectives and contributes to Uzbekistan's long-term environmental goals.

5.4. Railroads

The National GHG Inventory Reports highlight the significant contribution of rail emissions, which account for more than 3.4% of total GHG emissions from the transport sector. This makes rail transport the third largest contributor to GHG emissions, after road transport with 54.2% and pipeline with 42% [12]. Diesel consumption, which accounts for 58% (0.092 Mtoe in 2022) of the energy utilized in rail transport, underlines the need to assess the evolving landscape of rail transport, focusing on the potential integration of hydrogen as an alternative energy source.

In contrast to road transport, the Uzbek railroads play a crucial role in the delivery of bulk goods in international trade [74]. In 2018, for example, the railroads transported 68.4 Mt of freight, 58% of which was domestic, while the remaining 42% was for import, export, and transit freight [18]. The Andijan–Tashkent–Bukhara line, which connects the eastern and central parts of the country, is considered the busiest section of the railroad line. The line carries between 2 and 5 Mtkm of freight [74] and is also frequently used for the import of vehicle spare parts from South Korea and China, as the most important vehicle factories are located in Andijan, Tashkent, Jizzakh, and Samarkand [99]. The ongoing China–Kyrgyzstan–Uzbekistan railroad project, as part of the Belt and Road Initiative [18], will further increase the volume of freight traffic via this route. Despite the presence of an industrial zone in Navoi, Urgench, and Nukus, the northwestern railroad lines along the Navoi–Uchkuduk–Turtkul–Kungirot route have the least rail traffic [74]. Of the 4718 km of existing railroad lines, only 2530 km are electrified [18] and connect eastern, central, and southwestern cities such as Andijan, Tashkent, Samarkand, Bukhara, and Termez.

As part of Uzbekistan's commitment to reducing GHG emissions, efforts are being made to expand the electrified rail network. By 2026, the country plans to electrify a 661 km line between Bukhara, Urgench, Khiva, and Nukus. This will ensure the movement of high-speed trains and allow Nukus to be reached from Tashkent in 7 h (currently 16 h) [18]. Figure 9 depicts the main electrified and non-electrified railroad lines and the volume of freight traffic on these lines.

The electrification of railroads increases the demand for new types of trains. According to the OSJD (Organization for Cooperation between Railways), the average daily railroad fleet in operation in Uzbekistan in 2018 consisted of 188 diesel locomotives, 83 electric locomotives, and 18 electric multiple units [100]. According to the CAREC report (end of 2018), the total railroad fleet in operation instead consisted of 82 mainline diesel locomotives, 98 mainline electric locomotives, 21 electric multiple units, and 172 shunting locomotives. However, two-thirds of the diesel locomotives, 91% of the shunting locomotives, and 35% of the electric locomotives were over 30 years old and approaching the end of their service life [18]. Although the OSJD provided data on average daily trains, the large difference in the number of diesel trains in the two sources is due to the fact that most shunting locomotives run on diesel fuel. To improve the performance of the rail system and reduce the GHG emissions in the rail sector, the country plans to purchase 30 new electric locomotives by 2025 [101]. In 2022, a total of 103 electric locomotives were in daily use in the country [102].

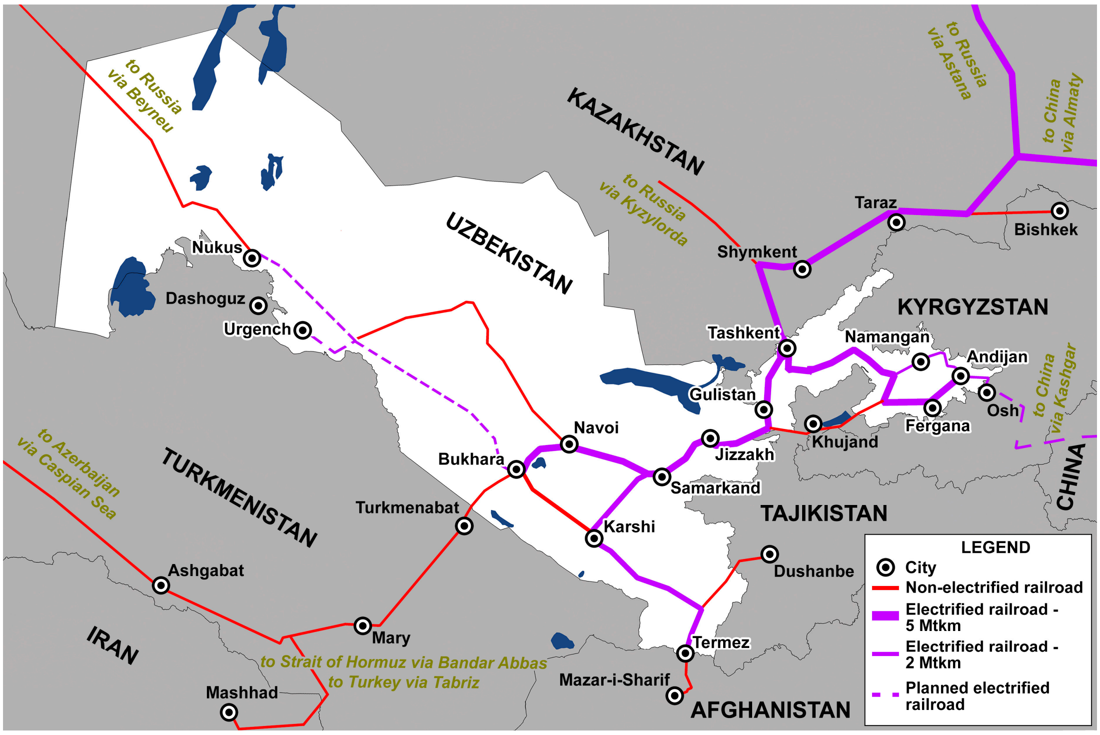


Figure 9. Non-electrified and electrified railroads. Authors' own elaboration, based on data from [18,74].

Despite these efforts to reduce GHG emissions, there are no plans to electrify 47% of railroad lines in the near future. This is mainly due to the fact that they are outside the existing international rail corridors and are not connected to the country's regional centers. Another reason is that these lines run through mountainous or desert-like areas, which makes electrification very expensive and ineffective. On rail lines where electrification and the purchase of new electric trains is not efficient, locomotives using alternative fuels such as hydrogen should be considered as a replacement for diesel trains. Although hydrogen trains can be more expensive than electric or diesel trains, previous studies suggest that hydrogen FC-trains could still be a more cost-effective option than fully electrifying an entire line and purchasing electric trains [103]. In addition, FC-trains with electric motors could run on partially electrified lines and switch to hydrogen on the non-electrified sections, creating a hybrid solution. However, in order to achieve the desired results in terms of environment and economic growth, the transition to hydrogen mobility should also be considered at the CA level. Therefore, a brief summary of the road and rail fleet in CA for 2018 is provided in Section 6.

6. Overview of Road and Rail Transport in Central Asia

In 2018, road transport consumption in Kazakhstan amounted to 5.53 Mtoe of oil products and 0.28 Mtoe of natural gas [11]. The country had 440,600 trucks and 90,400 buses. Kazakhstan's road transport strategy aims to reduce the number of trucks operated over 12 years from 63% to 35% and to meet the fuel requirements for Euro-5 vehicles [104]. In 2018, Kyrgyzstan, the largest oil importer in CA, imported 1.34 Mtoe of oil products. Of this, 0.4 Mtoe of oil was consumed for road transport [11]. Similar to UzStat, Kyrgyzstan only reports POVs [105], which are mostly imported pre-owned vehicles, comprising 97,000 trucks and 30,000 buses [106]. Tajikistan, the second largest oil importer, purchased 0.96 Mtoe of oil products and consumed 0.41 Mtoe in road transport [11]. Tajikistan also reports only POVs [107], with 36,000 trucks and 16,000 buses, although the fleet is struggling with obsolescence due to the import of pre-owned vehicles [108]. The number of vehicles in Turkmenistan is not publicly known; in 2018, oil consumption amounted to 2.64 Mtoe [11]. Table 6 provides an overview of the vehicle fleet in the CA countries in 2018.

Table 6. Vehicle fleet, its energy consumption, and CO_2 emissions in Central Asia for 2018.

Central Asian Countries	Road Vehicle Stock				Energy Consumption	
	Cars	Trucks	Buses	Others	CNG, [Mtoe]	Oil-Based Fuels, [Mtoe]
Uzbekistan [1]	2,133,507	116,339	20,328	3245	2.09	2.52
	212,000 [2]					
Kazakhstan	3,851,600	440,600	90,400	10,600	0.28	5.53
Kyrgyzstan [1]	1,200,000	97,000	30,000	no data	0	0.40
Tajikistan [1]	340,000	36,000	16,000	4000	0	0.41
Turkmenistan	no data				0	2.64

[1] The country reports POVs only. [2] Authors' own estimate, given in Section 5.3.3.

The consumption of the Uzbek railroad sector in 2018 was 90.9 ktoe of diesel, 3.3 ktoe of coal, and 71 ktoe of electricity, while the consumption data for the other four countries are quite interesting. For example, the railroads in Kazakhstan consumed 12 ktoe of coal and 278 ktoe of electricity [11]. However, according to the UIC (International Union of Railways) and CAREC, only 4200 km of the total 16,000 km Russia–Astana–Almaty–Tashkent railroad line is electrified. The country also has 1200 diesel locomotives, 61% of which have been in use for at least 25 years [109]. The country has production facilities for trains and has launched initiatives with Alstom to renew the railroad fleet [110]. The Kyrgyz railroads are divided into two parts. One part is connected to Uzbekistan and the other to Kazakhstan. These sections consist of single-track, non-electrified lines with a total length of 424 km [111]. In 2018, there were 53 diesel-powered locomotives [112], which consumed 1 ktoe of oil [11]. The consumption of the railroads in Tajikistan is recorded solely in the form of electricity [11]. However, the railroad system consists of three separate single-track sections, each of which is connected to the Uzbek railroad network. The total length of these sections is 978 km and none of the lines are electrified [113]. Tajikistan had 42 diesel-powered locomotives in 2018 [114]. Turkmenistan has 119 diesel locomotives that are less than 15 years old [115] and the total length of the rail network is 7600 km [112]. According to various sources, the electrification rate of Turkmenistan's railroads is zero [112,115]. Nevertheless, the country's energy balance records electricity consumption in the railroad sector (28 ktoe in 2018) [11]. Due to the uncertainty between the energy balance and the electrification of the railroads, the authors have classified the electrification rate of Turkmenistan's railroads as unknown. Table 7 provides an overview of the railroads in the CA countries in 2018.

Table 7. Railroad fleet, its energy consumption, and railroad electrification in Central Asia for 2018.

Central Asian Countries	Diesel Locomotives Stock	Railroads		Energy Consumption	
		Total, [km]	Electrified, [km]	Electricity, [ktoe]	Coal and Oil, [ktoe]
Uzbekistan	188	4730	2530	71	94
Kazakhstan	1200	16,000	4200	278	12
Kyrgyzstan	53	424	0	0.8	1
Tajikistan	42	978	0	0.6	0
Turkmenistan	119	7600	no data	28	0

It is evident that the consumption of oil products holds immense significance in the road transport of the region, and the integration of hydrogen-powered vehicles will play a crucial role in reducing dependence on fossil fuels and GHG emissions. In rails, all countries except Uzbekistan display astonishingly low or zero reliance on oil [11] compared to the level of railroad electrification and number of diesel locomotives [74,112]. The implementation of hydrogen-powered trains can bypass the unviable expenses associated with line electrification, making it an advantageous option for low-density railroads.

7. Discussion

Uzbekistan is endeavoring to transition to renewable energies in line with global efforts towards climate change mitigation. The country is using its available energy resources and geographical location to integrate solar, wind, nuclear, and hydropower into its energy system. However, the transport sector remains heavily dependent on fossil fuels and has seen the highest increase in emissions of any sector over the last decade [8]. Since 2020, more than USD 6.6 billion has been allocated to initiatives such as the production of GTL fuels, BEVs/HEVs, high-efficiency vehicles, electrification of railroads, and the acquisition of electric trains. These investments are supported by sector-specific measures introduced as part of Uzbekistan's climate commitments [32–34]. Although hydrogen pilot projects have already begun [66,67] and studies from the World Bank show that the transport sector will require USD 122.1 billion over 30 years to achieve carbon neutrality by 2060 [116], a hydrogen roadmap indicating a policy and technical framework has yet to be established to set sector-specific targets.

In the absence of a clear policy framework and targets, scaling up hydrogen technologies faces economic, technical, normative, and other barriers that could impede their integration into the transport sector. The development of such a framework often depends on evidence-based insights, feasibility studies, public awareness, and assessing the impact of technological pathways. Therefore, the discussion section examines the potential contributions of hydrogen utilization to the decarbonization of Uzbekistan's transport sector and suggests future research directions in this area. It also provides regional perspectives within the CA countries.

7.1. Repurposing the Existing Gas Network for Hydrogen Export

Uzbekistan could benefit from repurposing the existing natural gas network to supply hydrogen by blending it with natural gas or in pure gaseous form. The country has the infrastructure to connect China via the CA–China pipeline, Russia via the CA–Center pipeline, and other neighboring countries [40]. As for the overall CA region, there is also the possibility of connecting to India via the TAPI (Turkmenistan–Afghanistan–Pakistan–India) pipeline and to the EU via the East and South-East Gas Corridor.

As in the case of natural gas, Uzbekistan's competitiveness in exporting hydrogen via pipelines could be limited in Russia's southern industrial regions, considering that Russia has also launched hydrogen production initiatives and has already set itself an export target of 2 Mt/y by 2035 [117].

China is the world's largest producer and consumer of hydrogen [118], and gas pipelines in this direction are already in operation. Investigating the feasibility of adapting the current pipelines for pure or blended hydrogen transport would promote the export of hydrogen. It would be useful to consider a hydrogen-ready infrastructure during the construction of Line-D of the CA–China gas pipeline for the benefit of both sides.

The EU has set an import target of green hydrogen of 10 Mt/y by 2030 [119]. The closest hydrogen pipeline connecting CA to Europe is the East and South-East Gas Corridor, the gates of which are located in Azerbaijan. In 2022, Azerbaijan hosted Italian and French delegations to explore opportunities for expanding transmission capacity, including the supply of a 10% hydrogen blend [120,121]. There is currently no direct pipeline connection between Uzbekistan and Azerbaijan. However, a trilateral agreement between Azerbaijan, Iran, and Turkmenistan, signed in 2021, mandates the supply of 6 bcm/y of Turkmen gas to Azerbaijan via Iran [122]. In the long term, this could serve as a possibility for a pipeline connection between Uzbekistan and Europe.

An alternative export route that could be realized for Uzbekistan is a pipeline to India. The TAPI pipeline, with a length of 1800 km, which is supported by the ADB (Asian Development Bank), has been under discussion for a long time. The planned capacity of the

TAPI is 33 bcm/y of natural gas [47], and the feasibility of hydrogen blending is unknown. As the ADB reports, the construction of the pipeline is becoming very expensive due to its long "standstill" status. Thus, the implementation of this project depends on many factors, but it is worth considering this route of hydrogen export as well.

To determine the best export route, a feasibility study on repurposing to hydrogen must be carried out for each gas corridor. This requires an analysis that includes data such as the composition of existing pipelines, compliance with safety standards, assessment of infrastructure integrity, estimation of repurposing costs, and forecasting of market demand.

7.2. Location for Hydrogen Hubs

The establishment of hydrogen hubs enables a centralized production, storage, and distribution infrastructure that optimizes economies of scale and reduces the costs associated with the hydrogen supply chain. The locations for hydrogen hubs depend on the integration of supply-side factors such as proximity to gas fields for blue hydrogen and/or renewable energy for green hydrogen. On the demand side, positioning near major road and rail hubs will leverage the potential of hydrogen as a clean fuel for transport, in line with sustainable mobility and decarbonization goals.

In Uzbekistan, the Bukhara and Kashkadarya regions account for around 70% of the country's natural gas production, making them prime locations for the production of "blue" hydrogen through steam reforming [42]. The region hosts a GTL plant in Kashkadarya, which is capable of producing up to 26.9 Mt/y of hydrogen based on steam reforming of natural gas for the production of synthetic oil [66]. In addition, the ongoing renewable energy projects in the region [40] offer opportunities for future "green" hydrogen production through electrolysis.

On the demand side, infrastructure also plays a crucial role in the viability of hydrogen hubs. The 900 km long highway from Andijan to Bukhara, which connects 10 regions, is the densest route in Uzbekistan. This section is part of three international transport corridors, with Andijan, Tashkent, and Bukhara serving as key entry points into the country. As freight and public transit mainly takes place in these areas, the most important logistical hubs are strategically located nearby [72,73]. In addition, the approximately 160 km long non-electrified railroad line between Bukhara and Kashkadarya offers the possibility of using hydrogen to power trains on this route [18]. Considering these factors, it would be desirable to establish the first hydrogen mobility hub between Bukhara and Kashkadarya.

7.3. Hydrogen Enrichment of CNG for Road Transport

Uzbekistan is a leading automotive manufacturer in CA, producing more than 0.4 million vehicles and 0.3 million ICEs annually, with most of these vehicles being retrofitted to CNG. This successful experience can serve as a model for transition to more environmentally friendly fuels, such as hydrogen.

Existing CNG technologies could be repurposed for hydrogen-compressed natural gas (HCNG) technology, where hydrogen is blended with CNG. The integration of HCNG technology is a promising step towards reducing GHG emissions and entering the hydrogen economy. Experimental studies around the world [16] show that converting retrofitted CNG systems to HCNG could reduce CO_2 emissions by up to 8%. For example, if all CNG-powered vehicles in Uzbekistan had used HCNG with a 10% hydrogen blend, the fleet would have consumed about 0.32 Mtoe of hydrogen, resulting in a reduction in emissions to 0.62 $MtCO_2eq$, as HCNG contributes to an 8% reduction in CO_2 emissions [16], and tank-to-wheel emissions for CNG are 58.6 gCO_2eq/MJ [123].

Despite numerous international studies on HCNG, a dedicated case study tailored to Uzbekistan is essential to assess the feasibility of replacing CNG tanks with alternatives designed for the hydrogen blending, as the current CNG tanks comply with UNECE R-110 (Regulation No. 110 of the UNECE for CNG vehicles) and GOST 33986 (International Technical Standard No. 33986 for CNG tanks used in vehicles of the CIS countries) [124], which stipulate that the hydrogen must be limited to 2% by volume if the CNG tanks are made of steel with an ultimate tensile strength of over 950 MPa [79,125]. Another challenge is repurposing existing CNG infrastructure for hydrogen blending. Currently, Uzbek CNG refueling stations operate at a pressure of 200–250 bar [124], which corresponds to the operating pressures of HCNG pilot plants [126,127]. For HCNG, hydrogen can be blended with methane on a large scale and then injected into existing pipelines, or it can be produced and blended on-site on a small scale. While the on-site option does not require repurposing existing gas pipelines, small-scale production may not benefit from the economies of scale that centralized production does [128]. Therefore, there is an additional need for a techno-economic study to compare both centralized and on-site HCNG refueling stations in the context of Uzbekistan. This requires an analysis that considers data such as available land area, access to the water resources, and demand for HCNG fuel to optimize the size of on-site hydrogen production.

7.4. Hydrogen for Heavy-Duty Vehicles

Although the domestic market's interest in BEVs has led to a rapid increase in imports, studies suggest that hydrogen powertrains offer longer driving ranges and shorter refueling times than BEVs, making them more suitable for heavy-duty vehicles [15]. This advantage is important for the enterprise sector, where refueling downtime can impact operational efficiency. Exploring hydrogen options for trucks and buses will help reduce GHG emissions. For example, if 25% of trucks in private ownership were powered by hydrogen (i.e., FC-truck) instead of diesel, 0.11 Mtoe of hydrogen would be consumed and emissions would drop to 0.32 $MtCO_2eq$. This estimate is based on 13,216 diesel-powered trucks (Figure 8b) with an annual mileage of 35,000 km and an energy consumption of 10.3 MJ/km, considering that tank-to-wheel emissions for diesel are 68.4 gCO_2eq/MJ [123].

However, notwithstanding the promising results of global studies [15], the specific context of Uzbekistan and CA requires a well-to-wheel analysis that takes into account hydrogen production with and without renewable energy. Such an analysis is essential to understand the full environmental and economic impact of the introduction of hydrogen vehicles in the region.

7.5. Hydrogen Trains for Non-Electrified Railroads

Despite ongoing efforts to electrify the railroads, 47% of Uzbekistan's railroad lines are not scheduled for electrification in the near future. This is mainly due to their location outside the existing international railroad corridors and the unjustified costs associated with electrification, which often prove to be ineffective investments. On railroad lines where electrification and the purchase of new electric trains are not efficient solutions, hydrogen-powered trains should be considered as a replacement for diesel trains.

The existing literature [17] shows that the capital expenditure required for the electrification of railroad lines is often not justified for lines with a capacity utilization of 10 trains/day. In such scenarios, FC-trains are a more economical option, especially on longer, non-electrified lines of more than 100 km. For example, if FC-trains were used instead of diesel trains on the 160 km non-electrified railroad line between Bukhara and Karshi, each journey on this route would save 0.2 tons of diesel and reduce emissions by up to 0.1 $kgCO_2eq/km$ of journey. This is based on the data that a T-478 class diesel–electric locomotive consumes 1.22 kg/km and emits 98 gCO_2eq/km [129]. In addition, FC-trains enable the use of regenerative braking energy compared to diesel trains in order to enhance their energy efficiency. There are various solutions for the use of regenerative braking energy, such as timetable optimization, energy storage systems, and reversible substations [130]. Among these, the energy storage-based method, in which regenerative braking energy is stored in an electrical storage medium such as a supercapacitor and/or battery and released when needed, is the preferred solution due to its technical maturity and control performance [131]. Studies have shown that on-board energy storage systems can save around 30% of the energy consumed by the train [130].

To assess the economic viability of this pathway, it is important to conduct a case study to compare the total cost of ownership for hydrogen-powered trains versus the option of electrifying a non-electrified railroad line and purchasing a new electric train.

7.6. Regional Perspectives

CA had more than 9 million vehicles [83–85,104–108], which collectively consume about 14 Mtoe/y [11]. Oil-based fuels are the main source for the road fleet, with 11.5 Mtoe/y in the region [11]. Kazakhstan, which has the largest vehicle fleet with 48.8% of all vehicles in CA [104], consumes the most oil at 5.53 Mtoe/y [11], contributing significantly to regional emissions. In contrast, Kyrgyzstan and Tajikistan relied on net oil imports to meet their energy needs, while Turkmenistan and Uzbekistan had comparable oil consumption for road transport at 2.64 Mtoe/y and 2.52 Mtoe/y, respectively [11]. Although the HCNG pathway could only be beneficial for Uzbekistan, the introduction of hydrogen vehicles in heavy-duty transport could benefit all five CA countries due to the high penetration of oil-based fuels. In such a scenario, regional cooperation is needed to maximize the benefits of this transition.

Rail transport in the region is less dependent on oil products compared to road transport. Nevertheless, CA has 23,002 km of non-electrified rail lines [112], of which 51.3% are in Kazakhstan, 33% in Turkmenistan, 9.6% in Uzbekistan, and the remaining lines in Kyrgyzstan and Tajikistan. In addition, there are around 1600 diesel trains in the region [112], of which 75% are in Kazakhstan, 8% in Turkmenistan, 12% in Uzbekistan, and the rest to Kyrgyzstan and Tajikistan. Many of these trains have been in operation for more than 25 years and are nearing the end of their service life, so a detailed analysis of the benefits of hydrogen-powered trains at the regional level is required.

The automotive industry of Uzbekistan produces 80% of the market share for cars, 50% for trucks, and 55% for buses in the region [5,6], while Kazakhstan, on the other hand, operates plants that focus on the production of electric locomotives in cooperation with Alstom [110]. CA therefore has production capacities that are relevant for the development of hydrogen mobility technologies.

Similar to the CAPS for reciprocal electricity trade [47] and the CNG agreement for technology transfer and standardization between the CIS countries [76], the development of hydrogen technologies also requires a cooperative framework at the regional level. While Uzbekistan and Kazakhstan, with their extensive experience in vehicle/train manufacturing, are well positioned to develop the demand side of the hydrogen economy, all CA countries have unique potential in the upstream part. Turkmenistan, with its substantial natural gas reserves [132], could lead in blue hydrogen production, while Tajikistan and Kyrgyzstan can focus on green hydrogen due to their abundant water resources [133]. Uzbekistan, which is currently transitioning its power sector to renewables and has an extensive gas-based economy, could produce both green and blue hydrogen. Of these countries, only Kazakhstan has so far defined its national hydrogen strategy and aims to become carbon neutral by 2060 [134]. The availability of water and electrolysis for green hydrogen production, the presence of natural gas and carbon capture for blue hydrogen production, and affordable infrastructure/technologies are crucial for achieving carbon-free transportation at both national and regional levels. Each CA country should formulate national hydrogen strategies aligned with its capabilities and resources by harmonizing them at the CA level to ensure a coherent approach to feedstock utilization, infrastructure development, and technology implementation across the region.

8. Conclusions

Uzbekistan aims to mitigate climate change by integrating renewable energy while facing challenges in the transport sector, where fossil fuels dominate and contribute significantly to emissions.

To accelerate the transition to decarbonization of the transport sector, the conversion of the existing CNG technologies/infrastructure to HCNG, the use of hydrogen vehicles in heavy-duty transport, and the exploration of hydrogen-powered trains for non-electrified rail lines are viable pathways. The establishment of hydrogen hubs in regions rich in natural gas and renewable energy could optimize the efficiency of production and distribution. The strategic positioning of these hydrogen hubs near major road and rail intersections could facilitate integration into the transport sector. Another option is to repurpose the existing natural gas network for hydrogen blending in order to use export potential.

Regional cooperation between CA countries is crucial for accelerating the cross-border deployment of hydrogen technologies. By investing in research and pilot projects and utilizing automobile and train manufacturing hubs, CA can create a cleaner, more sustainable transport sector that meets global climate goals. The first step towards this goal should be the formalization of national strategies aligned at the CA level.

Author Contributions: Conceptualization, J.Y., M.C. and P.L.; formal analysis, J.Y., M.C. and P.L.; investigation, J.Y.; writing—original draft preparation, J.Y.; writing—review and editing, M.C. and P.L; visualization, J.Y.; supervision, P.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. United Nations Climate Change Conference Baku—November 2024. Available online: https://unfccc.int/cop29 (accessed on 1 July 2024).
2. United Nations. *1/CMA.5 Outcome of the First Global Stocktake*; United Nations Climate Change: New York, NY, USA, 2024. Available online: https://unfccc.int/documents/637073 (accessed on 1 July 2024).
3. United Nations Nationally Determined Contributions. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs (accessed on 1 July 2024).
4. United Nations. *The Paris Agreement*; United Nations Climate Change: New York, NY, USA, 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement (accessed on 1 July 2024).
5. Statistics Agency of the Republic of Uzbekistan. *Socio-Economic Situation of the Republic of Uzbekistan*; UzStat: Tashkent, Uzbekistan. Available online: https://stat.uz/en/quarterly-reports (accessed on 1 July 2024).
6. The Association of Kazakhstan Automobile Business. Auto Market Production. Available online: https://akab.kz/en/avtorynok-rk-itogi-2022-goda/ (accessed on 1 July 2024).
7. The Republic of Uzbekistan. *Updated Nationally Determined Contribution 2021*; United Nations Climate Change: New York, NY, USA, 2022; pp. 10–14. Available online: https://unfccc.int/documents/498027 (accessed on 1 July 2024).
8. Crippa, M.; Guizzardi, D.; Schaaf, E.; Monforti-Ferrario, F.; Quadrelli, R.; Risquez Martin, A.; Rossi, S.; Vignati, E.; Muntean, M.; Brandao De Melo, J.; et al. *GHG Emissions of All World Countries 2023*; Publications Office of the European Union: Luxembourg, 2023. [CrossRef]
9. International Energy Agency—Energy Statistics Data Browser. Available online: https://iea.org/data-and-statistics/data-tools/energy-statistics-data-browser (accessed on 1 July 2024).
10. Statistics Agency of the Republic of Uzbekistan—Fuel and Energy Balance of the Republic of Uzbekistan for 2022. Available online: https://api.stat.uz/api/v1.0/data/2022-yil-uchun-ozbekiston-respublikasi-yoqilg?lang=en&format=pdf (accessed on 1 July 2024).
11. International Energy Agency. *World Energy Balances (Database)*; IEA: Paris, France, 2024. [CrossRef]
12. Chub, V.E.; Taryannikova, R.V.; Kovalevskaya, Y.I.; Belarussova, O.A.; Rakhmatova, N.I.; Shardakova, L.Y.; Abdullaeva, S.K.; Panteeva, N.V.; Usmanova, L.V.; Juravlyova, E.V.; et al. *Inventory of Anthropogenic Emissions Sources and Sinks of Greenhouse Gases in the Republic of Uzbekistan 1990–2012*; United Nations Climate Change: New York, NY, USA, 2016; pp. 39–40. Available online: https://unfccc.int/documents/38273 (accessed on 1 July 2024).
13. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No. 4477 of the Republic of Uzbekistan, Dated 04/10/2019. Available online: https://lex.uz/docs/4539502 (accessed on 1 July 2024).
14. Larson, P.D.; Parsons, R.V.; Kalluri, D. Zero-Emission Heavy-Duty, Long-Haul Trucking: Obstacles and Opportunities for Logistics in North America. *Logistics* **2024**, *8*, 64. [CrossRef]
15. Lajevardi, S.M.; Axsen, J.; Crawford, C. Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: Simulations of freight routes in British Columbia. *Transp. Res. D Transp. Environ.* **2019**, *76*, 19–55. [CrossRef]
16. Mohamad, T.I.; Moria, H. Performance and emissions of a hydrogen-enriched natural gas spark ignition engine with a dynamic-homogeneous mixer. *Energy Procedia* **2019**, *158*, 1924–1929. [CrossRef]

17. Ruf, Y.; Zorn, T.; Akcayoz De Neve, P.; Andrae, P.; Erofeeva, S.; Garrison, F. *Study on the Use of Fuel Cells and Hydrogen in the Railway Environment Report-2*; Europe's Rail Joint Undertaking: Brussels, Belgium, 2019; pp. 12–13. Available online: https://rail-research.europa.eu/publications/study-on-the-use-of-fuel-cells-and-hydrogen-in-the-railway-environment/ (accessed on 1 July 2024).
18. Central Asia Regional Economic Cooperation. *Railway Sector Assessment for Uzbekistan*; CAREC Institute: Urumqi, China, 2021; pp. 2–27. Available online: https://carecprogram.org/?publication=railway-sector-assessment-for-uzbekistan (accessed on 1 July 2024).
19. Vaccariello, E.; Trinchero, R.; Stievano, I.S.; Leone, P. A Statistical Assessment of Blending Hydrogen into Gas Networks. *Energies* **2021**, *14*, 5055. [CrossRef]
20. International Energy Agency. *Uzbekistan 2022 Energy Policy Review*; OECD Publishing: Paris, France, 2022; pp. 12–71. [CrossRef]
21. Pashchenko, D. Green hydrogen as a power plant fuel: What is energy efficiency from production to utilization. *Renew. Energy* **2024**, *223*, 120033. [CrossRef]
22. Barbaresi, A.; Morini, M.; Gambarotta, A. Review on the Status of the Research on Power-to-Gas Experimental Activities. *Energies* **2022**, *15*, 5942. [CrossRef]
23. Ullah, A.; Hashim, N.A.; Rabuni, M.F.; Mohd Junaidi, M.U. A Review on Methanol as a Clean Energy Carrier: Roles of Zeolite in Improving Production Efficiency. *Energies* **2023**, *16*, 1482. [CrossRef]
24. Estevez, R.; López-Tenllado, F.J.; Aguado-Deblas, L.; Bautista, F.M.; Romero, A.A.; Luna, D. Current Research on Green Ammonia (NH3) as a Potential Vector Energy for Power Storage and Engine Fuels: A Review. *Energies* **2023**, *16*, 5451. [CrossRef]
25. Dieterich, V.; Buttler, A.; Hanel, A.; Spliethoff, H.; Fendt, S. Power-to-liquid via synthesis of methanol, DME or Fischer–Tropsch-fuels: A review. *Energy Environ. Sci.* **2020**, *13*, 3207–3252. [CrossRef]
26. Alikulov, K.; Aminov, Z.; Anh, L.H.; Xuan, T.D.; Kim, W. Comparative Technical and Economic Analyses of Hydrogen-Based Steel and Power Sectors. *Energies* **2024**, *17*, 1242. [CrossRef]
27. Kamolov, A.; Turakulov, Z.; Norkobilov, A.; Variny, M.; Fallanza, M. Evaluation of Potential Carbon Dioxide Utilization Pathways in Uzbekistan. *Eng. Proc.* **2023**, *56*, 194. [CrossRef]
28. Aliev, F.; Kholmurodov, T.; Mirzayev, O.; Tajik, A.; Mukhamadiev, N.; Slavkina, O.; Nourgalieva, N.; Vakhin, A. Enhanced Oil Recovery by In-Reservoir Hydrogenation of Carbon Dioxide Using Na-Fe_3O_4. *Catalysts* **2023**, *13*, 153. [CrossRef]
29. The World Bank—GDP per Capita, PPP (Current International $)—Uzbekistan. Available online: https://data.worldbank.org/indicator/NY.GDP.PCAP.PP.CD?locations=UZ (accessed on 1 July 2024).
30. The World Bank—Foreign Direct Investment, Net Inflows (% of GDP)—Uzbekistan. Available online: https://data.worldbank.org/indicator/BX.KLT.DINV.WD.GD.ZS?locations=UZ (accessed on 1 July 2024).
31. Vinokurov, E.; Ahunbaev, A.; Usmanov, N.; Tsukarev, T.; Sarsembekov, T. *Investment in the Water and Energy Complex of Central Asia*; EDB: Almaty, Kazakhstan, 2021; pp. 59–60. Available online: https://eabr.org/en/analytics/special-reports/investment-in-the-water-and-energy-complex-of-central-asia/ (accessed on 1 July 2024).
32. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.2706 of the Republic of Uzbekistan, dated 29/12/2016. Available online: https://lex.uz/docs/3470786 (accessed on 25 July 2024).
33. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.132 of the Republic of Uzbekistan, dated 18/03/2024. Available online: https://lex.uz/docs/6842808 (accessed on 25 July 2024).
34. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.459 of the Republic of Uzbekistan, dated 28/12/2022. Available online: https://lex.uz/docs/6329448 (accessed on 25 July 2024).
35. International Atomic Energy Agency; Nuclear Energy Agency. *Uranium 2022 Resources Production and Demand*; OECD Publishing: Paris, France, 2023; pp. 507–514. [CrossRef]
36. Thomas, L. Coal Resources and Reserves. In *Coal Geology*, 3rd ed.; Thomas, L., Ed.; Wiley: Hoboken, NJ, USA, 2020; pp. 89–236, ISBN 978-1-119-42430-7. [CrossRef]
37. World proved crude oil reserves. *Oil Energy Trends Annu. Stat. Rev.* **2023**, *44*, 19–22. [CrossRef]
38. UzDaily—Bukhara Oil Refinery Registers a Record Figure in the History of the Plant for the Production of Motor Gasoline. Available online: https://uzdaily.uz/en/post/78436 (accessed on 1 July 2024).
39. UzDaily—Bukhara Refinery Produces Semi-Synthetic Aviation Fuel for Gas Turbine Engines Jet A-1-SSF. Available online: https://uzdaily.uz/en/post/75953 (accessed on 1 July 2024).
40. Global Energy Monitoring—Energy Projects. Available online: https://globalenergymonitor.org/projects/ (accessed on 1 July 2024).
41. Organization of the Petroleum Exporting Countries. *2023 OPEC Annual Statistical Bulletin*, 58th ed.; OPEC: Vienna, Austria, 2023; pp. 22–76. Available online: https://asb.opec.org/ (accessed on 1 July 2024).
42. Pirani, S. *Central Asian Gas Prospects for the 2020s*; OIES: Oxford, UK, 2019; pp. 14–38, ISBN 978-1-78467-152-5. [CrossRef]
43. International Energy Agency. *Uzbekistan Energy Profile*; IEA: Paris, France, 2021; pp. 6–37. Available online: https://iea.org/reports/uzbekistan-energy-profile (accessed on 1 July 2024).
44. Ministry of Energy of the Republic of Uzbekistan—About Uzbekistan's Energy Sector. Available online: https://minenergy.uz/en/news/view/2122 (accessed on 1 July 2024).
45. Roman, M.D.; Stanculescu, D.M. An Analysis of Countries' Bargaining Power Derived from the Natural Gas Transportation System Using a Cooperative Game Theory Model. *Energies* **2021**, *14*, 3595. [CrossRef]

46. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.824 of the Republic of Uzbekistan, dated 27/03/2008. Available online: https://lex.uz/docs/1378049 (accessed on 1 July 2024).
47. Central Asia Regional Economic Cooperation, Asian Development Bank. *CAREC Energy Outlook 2030*; ADB: Manila, Philippines, 2022; pp. 270–330, ISBN 978-92-9269-956-7. [CrossRef]
48. Ministry of Energy of the Republic of Uzbekistan—Daily Consumption has Increased from 46 to 70 Million Cubic Meters. Available online: https://telegra.ph/OFICIALNOE-SOOBSHCHENIE-AO-HUDUDGAZTAMINOT-11-21-2 (accessed on 1 July 2024).
49. KunUz—Daily Electricity Consumption Updated a Record. Available online: https://kun.uz/en/61349336 (accessed on 1 July 2024).
50. Sabory, N.R.; Ershad, A.M.; Danish, M.S.S.; Senjyu, T. Improving the Criteria for Transmission Line Routing beyond the Techno-Economics: The Case of Afghanistan. *Sustainability* **2022**, *14*, 14933. [CrossRef]
51. Thermal Power Plants—Industrial Indicators. Available online: https://tpp.uz/en/page/industrial-indicators (accessed on 1 July 2024).
52. UzHydroEnergy—System Organizations of Uzbekhydroenergo JSC. Available online: https://uzgidro.uz/ges/index (accessed on 1 July 2024).
53. United Nations Economic Commission for Europe. *Environmental Performance Reviews Uzbekistan Third Review*; UNECE: Geneva, Switzerland, 2020; pp. 175–436, ISBN 978-92-1-004862-0. [CrossRef]
54. UzHydroEnergy—Annual Report 2022. Available online: https://uzgidro.uz/post/view/119 (accessed on 1 July 2024).
55. Ministry of Energy of the Republic of Uzbekistan—Concept of Ensuring Electricity Supply in Uzbekistan for 2020–2030. Available online: https://minenergy.uz/en/lists/view/77 (accessed on 1 July 2024).
56. Masdar—100 MW Nur Navoi Solar Project. Available online: https://masdar.ae/en/renewables/our-projects/100-mw-nur-navoi-solar-project (accessed on 1 July 2024).
57. Ministry of Energy of the Republic of Uzbekistan—Solar PV Plant Was Launched in Samarkand Region. Available online: https://minenergy.uz/news/view/1957 (accessed on 1 July 2024).
58. International Energy Agency. *Solar Energy Policy in Uzbekistan A Roadmap*; OECD Publishing: Paris, France, 2022; pp. 15–18. [CrossRef]
59. United Nations Economic Commission for Europe; REN21. *UNECE Renewable Energy Status Report 2022*; REN21 Secretariat: Paris, France, 2022; pp. 32–73, ISBN 978-3-948393-06-9. Available online: https://ren21.net/2022-unece-renewable-energy-status-report/ (accessed on 1 July 2024).
60. The Republic of Uzbekistan. *The Second National Report of the Republic of Uzbekistan on Compliance with the Obligations of the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management (for 7th Review Meeting 2022)*; IAEA: Vienna, Austria, 2020; pp. 7–8. Available online: https://iaea.org/topics/nuclear-safety-conventions/joint-convention-safety-spent-fuel-management-and-safety-radioactive-waste/documents (accessed on 1 July 2024).
61. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.5063 of the Republic of Uzbekistan, Dated 09/04/2021. Available online: https://lex.uz/docs/5362032 (accessed on 1 July 2024).
62. Mehmeti, A.; Angelis-Dimakis, A.; Arampatzis, G.; McPhail, S.J.; Ulgiati, S. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. *Environments* **2018**, *5*, 24. [CrossRef]
63. Ingale, G.U.; Kwon, H.-M.; Jeong, S.; Park, D.; Kim, W.; Bang, B.; Lim, Y.-I.; Kim, S.W.; Kang, Y.-B.; Mun, J.; et al. Assessment of Greenhouse Gas Emissions from Hydrogen Production Processes: Turquoise Hydrogen vs. Steam Methane Reforming. *Energies* **2022**, *15*, 8679. [CrossRef]
64. United Nations Economic Commission for Europe. *Sustainable Hydrogen Production Pathways in Eastern Europe the Caucasus and Central Asia*; UNECE: Geneva, Switzerland, 2023; pp. 51–57, ISBN 9789210023795. [CrossRef]
65. Izvorski, I.; Vatyan, A.; Trushin, E.; Abdul-Hamid, H.; Dalvit, N.; Safarov, M.; Iootty, M.; Novikova, M.; Melecky, M.; Ahmedov, M.; et al. *Assessing Uzbekistan's Transition Country Economic Memorandum*; World Bank Group: Washington, DC, USA, 2021; pp. 203–204. [CrossRef]
66. Uzbekistan GTL—Uzbekistan GTL Plant Started up Hydrogen Production Unit. Available online: https://uzgtl.com/news/na-zavode-uzbekistan-gtl-vvedena-v-ekspluataciyu-ustanovka-po-proizvodstvu-vodoroda-posle-polnogo-vv (accessed on 1 July 2024).
67. ACWA Power—Uzbekistan's First Green Hydrogen and Green Ammonia Projects. Available online: https://acwapower.com/news/acwa-power-to-develop-uzbekistans-first-green-hydrogen-and-green-ammonia-projects/ (accessed on 1 July 2024).
68. Statistics Agency of the Republic of Uzbekistan—Passenger Turnover and Passengers Transported by Road (Annual). Available online: https://api.siat.stat.uz/media/uploads/sdmx/sdmx_data_599.pdf (accessed on 1 July 2024).
69. Statistics Agency of the Republic of Uzbekistan—Freight Turnover and Cargo Transported by Road (Annual). Available online: https://api.siat.stat.uz/media/uploads/sdmx/sdmx_data_479.pdf (accessed on 1 July 2024).
70. Sze, A. *Uzbekistan Trade Facilitation and Logistics Development Strategy Report*; CAREC Institute: Urumqi, China, 2009; pp. 6–7, ISBN 978-971-561-814-4. Available online: https://carecprogram.org/?publication=uzbekistan-trade-facilitation-and-logistics-development-strategy-report (accessed on 1 July 2024).

71. United Nations Economic and Social Commission for Asia and the Pacific. *Strengthening the Capacity of ESCAP Member States to Harmonize Standards on Weights, Dimensions and Emissions of Road Vehicles for Facilitation of Transport along the Asian Highway Network Study Report*; UNESCAP: Bangkok, Thailand, 2020; pp. 92–93. Available online: https://hdl.handle.net/20.500.12870/285 (accessed on 1 July 2024).
72. Ministry of Transport of the Republic of Uzbekistan—International Freight-Forwarders. Available online: https://mintrans.uz/yuk-tashuvchilar (accessed on 1 July 2024).
73. Committee of Roads of the Republic of Uzbekistan—An Electronic Map of the Roads. Available online: https://uzavtoyul.uz/en/open-data/open-electronic-map-showing-state-of-roads/avtomobil-yollarining-holatini-korsatuvchi-ochiq-e (accessed on 1 July 2024).
74. Asian Development Bank. *CAREC Performance Measurement and Monitoring a Forward-Looking Retrospective*; ADB: Manilla, Philippines, 2014; pp. 9–12, ISBN 978-92-9254-689-2. Available online: https://adb.org/publications/carec-corridor-performance-measurement-and-monitoring-forward-looking-retrospective (accessed on 1 July 2024).
75. United Nations Economic and Social Commission for Asia and the Pacific. *Asian Highway Database*; UNESCAP: Bangkok, Thailand, 2014. Available online: https://hdl.handle.net/20.500.12870/4743 (accessed on 1 July 2024).
76. National Database of Legislation of the Republic of Uzbekistan—Agreement on Cooperation in the Field of Utilization of CNG as Motor Fuel for Motor Vehicles among the Member States of the Commonwealth of Independent States. Available online: https://lex.uz/docs/2755720 (accessed on 1 July 2024).
77. National Database of Legislation of the Republic of Uzbekistan—Resolution No.30 of the Cabinet of Ministers of the Republic of Uzbekistan, Dated 10/02/2007. Available online: https://lex.uz/docs/1127274 (accessed on 1 July 2024).
78. National Database of Legislation of the Republic of Uzbekistan—Resolution No.815 of the Cabinet of Ministers of the Republic of Uzbekistan, Dated 11/10/2017. Available online: https://lex.uz/docs/3377221 (accessed on 1 July 2024).
79. United Nations Economic Commission for Europe—Regulation No.110 Addendum 109 Revision 7. Available online: https://unece.org/transport/documents/2024/05/standards/addendum-109-regulation-no-110-revision-7 (accessed on 1 July 2024).
80. Ministry of Energy of the Republic of Uzbekistan—HududGazTaminot Supplies 1,059 CNG Stations, 171 of Which Are Located along International Highways. Available online: https://minenergy.uz/ru/news/view/2219 (accessed on 1 July 2024).
81. Bacon, R.W.; Fodor, M.; Kojima, M.; Lovei, M. *Cleaner Transport Fuels for Cleaner Air in Central Asia and the Caucasus*; A World Free of Poverty Series; World Bank Group: Washington, DC, USA, 2000; pp. 11–12, ISBN 0-8213-4783-7. Available online: http://documents.worldbank.org/curated/en/883201468022480907/Cleaner-transport-fuels-for-cleaner-air-in-Central-Asia-and-the-Caucasus (accessed on 1 July 2024).
82. Khan, M.I.; Yasmeen, T.; Shakoor, A. Technical overview of compressed natural gas (CNG) as a transportation fuel. *Renew. Sustain. Energy Rev.* **2015**, *51*, 785–797. [CrossRef]
83. Statistics Agency of the Republic of Uzbekistan—Passenger Cars Owned by Individuals 2019 (as of 31 December 2018). Available online: https://stat.uz/en/press-center/news-of-committee/12158-respublikamizda-aholiga-tegishli-bo-lgan-2-8-millionta-yengil-avtomobillar-bor-3 (accessed on 1 July 2024).
84. Statistics Agency of the Republic of Uzbekistan—Trucks Owned by Individuals 2019 (as of 31 December 2018). Available online: https://stat.uz/en/press-center/news-of-committee/12328-o-zbekistonda-aholiga-tegishli-bo-lgan-168-810-ta-yuk-avtomobillari-bor-3 (accessed on 1 July 2024).
85. United Nations Economic Commission for Europe—Road Vehicle Fleet at 31 December by Vehicle Category and Age Group. Available online: https://w3.unece.org/PXWeb2015/pxweb/en/STAT/STAT__40-TRTRANS__03-TRRoadFleet/02_en_TRRoadtypVeh_r.px/ (accessed on 1 July 2024).
86. Statistics Agency of the Republic of Uzbekistan—Fuel Source of Vehicles Owned by Individuals (as of 31 December 2021). Available online: https://stat.uz/en/press-center/news-of-committee/22562-o-zbekistonda-qaysi-yonilg-i-turidan-ko-p-foydalaniladi-3 (accessed on 1 July 2024).
87. Datasheet from Chevrolet. Available online: https://chevrolet.uz/brochure (accessed on 1 July 2024).
88. Datasheet from Volkswagen. Available online: https://volkswagen.uz/ru/models.html (accessed on 1 July 2024).
89. Datasheet from SamAuto. Available online: https://samauto.uz/en/products (accessed on 1 July 2024).
90. Datasheet from ManAuto. Available online: https://uztbm.uz/en/catalog/ (accessed on 1 July 2024).
91. Datasheet from Sinotruk. Available online: https://uztbm.uz/sinotruk/en/ (accessed on 1 July 2024).
92. UzDaily—How the Situation in the Passenger Car Market Has Changed over the Year in Uzbekistan: Prices, Wear out and Mileage. Available online: https://uzdaily.uz/en/post/78264 (accessed on 1 July 2024).
93. International Energy Agency. *The Future of Trucks Implications for Energy and the Environment*; IEA: Paris, France, 2017; pp. 28–29, ISBN 9789264279452. [CrossRef]
94. Elghozi, T. How to Calculate the Indicators for the Transport Sector. In Proceedings of the Joint APEC—IEA Training Workshop on End-use Energy Consumption Data (19th APEC Workshop on Energy Statistics), Tokyo, Japan, 28–30 June 2021. Available online: https://iea.org/events/joint-apec-iea-training-workshop-on-end-use-energy-consumption-data-19th-apec-workshop-on-energy-statistics (accessed on 1 July 2024).
95. Farzaneh-Gord, M.; Rahbari, H.R.; Nikofard, H. The effect of important parameters on the natural gas vehicles driving range. *Pol. J. Chem. Technol.* **2012**, *14*, 61–68. [CrossRef]

96. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.443 of the Republic of Uzbekistan, Dated 19/12/2022. Available online: https://lex.uz/docs/6316583 (accessed on 1 July 2024).
97. National Database of Legislation of the Republic of Uzbekistan—Presidential Decree No.444 of the Republic of Uzbekistan, Dated 19/12/2022. Available online: https://lex.uz/docs/6316592 (accessed on 1 July 2024).
98. Statistics Agency of the Republic of Uzbekistan—In 2022, Uzbeks Have Spent $61.3 Million on Importing Electric Vehicles. Available online: https://stat.uz/en/press-center/news-of-committee/32335-o-zbekistonliklar-o-tgan-11-oyda-elektromobillar-importiga-61-3-mln-aqsh-dollari-sarflagan-3 (accessed on 1 July 2024).
99. United Nations Economic Commission for Europe. *Euro-Asian Transport Linkages Operationalization of Inland Transport between Europe and Asia Phase 3 Report*; UNECE: Geneva, Switzerland, 2019; pp. 43–44, ISBN 978-92-1-047592-1. [CrossRef]
100. Organisation for Cooperation between Railways. *OSJD Bulletin of Statistical Data on Railway Transport for 2018*; OSJD: Warsaw, Poland, 2018; pp. 76–77. Available online: https://en.osjd.org/dbmm/download?vp=68&col_id=121&id=462 (accessed on 1 July 2024).
101. National Database of Legislation of the Republic of Uzbekistan—Resolution No.586 of the Cabinet of Ministers of the Republic of Uzbekistan, Dated 15/07/2019. Available online: https://lex.uz/docs/4419984 (accessed on 1 July 2024).
102. Organisation for Cooperation between Railways. *OSJD Bulletin of Statistical Data on Railway Transport for 2022*; OSJD: Warsaw, Poland, 2022; pp. 70–71. Available online: https://en.osjd.org/api/media/resources/2729?action=download (accessed on 1 July 2024).
103. Ruf, Y.; Zorn, T.; Akcayoz De Neve, P.; Andrae, P.; Erofeeva, S.; Garrison, F. *Study on the Use of Fuel Cells and Hydrogen in the Railway Environment*; Publications Office of the European Union: Luxembourg, 2019; pp. 8–9, ISBN 978-92-95215-11-5. [CrossRef]
104. United Nations Economic Commission for Europe. *Logistics and Transport Competitiveness in Kazakhstan*; UNECE: Geneva, Switzerland, 2019; pp. 41–43, ISBN 978-92-1-004218-5. [CrossRef]
105. Statistic Committee of the Kyrgyz Republic—1.05.04.10: Number of Registered Cars of Individual Owners. Available online: https://stat.gov.kg/en/statistics/transport-i-svyaz/ (accessed on 1 July 2024).
106. United Nations Economic Commission for Europe. *Logistics and Transport Competitiveness in Kyrgyzstan*; UNECE: Geneva, Switzerland, 2020; pp. 117–118, ISBN 978-92-1-004219-2. [CrossRef]
107. Statistics Agency of the Republic of Tajikistan—Provision of Population with Individual Vehicles, 1998–2020. Available online: http://old.stat.tj/en/database-real-sector (accessed on 1 July 2024).
108. Asian Development Bank. *Tajikistan Transport Sector Assessment*; ADB: Manila, Philippines, 2021; pp. 24–25, ISBN 978-92-9269-216-2. [CrossRef]
109. Central Asia Regional Economic Cooperation. *Railway Sector Assessment for Republic of Kazakhstan*; CAREC Institute: Urumqi, China, 2021; pp. 2–3. Available online: https://carecprogram.org/?publication=railway-sector-assessment-for-republic-of-kazakhstan (accessed on 1 July 2024).
110. Alstom—Alstom and Kazakhstan Railways Expand Their Partnership. Available online: https://alstom.com/press-releases-news/2022/11/alstom-and-kazakhstan-railways-expand-their-partnership (accessed on 1 July 2024).
111. Central Asia Regional Economic Cooperation. *Railway Sector Assessment for Kyrgyz Republic*; CAREC Institute: Urumqi, China, 2021; pp. 1–3. Available online: https://carecprogram.org/?publication=railway-sector-assessment-for-kyrgyz-republic (accessed on 1 July 2024).
112. International Union of Railways—Transport Stock Diesel Locomotives End of Year 2018 Kazakhstan; Kyrgyzstan; Tajikistan; Turkmenistan; Uzbekistan. Available online: https://uic-stats.uic.org/ (accessed on 1 July 2024).
113. United Nations Economic and Social Commission for Asia and the Pacific. *Strengthening Capacity for Operationalizing Sustainable Transport Connectivity along the China-Central Asia-West Asia Economic Corridor to Achieve the 2030 Agenda Study Report 2022*; UNESCAP: Bangkok, Thailand, 2022; pp. 28–29. Available online: https://hdl.handle.net/20.500.12870/4163 (accessed on 1 July 2024).
114. Central Asia Regional Economic Cooperation. *Railway Sector Assessment for Tajikistan*; CAREC Institute: Urumqi, China, 2021; pp. 2–3. Available online: https://carecprogram.org/?publication=railway-sector-assessment-for-tajikistan (accessed on 1 July 2024).
115. Central Asia Regional Economic Cooperation. *Railway Sector Assessment for Turkmenistan*; CAREC Institute: Urumqi, China, 2021; pp. 3–4. Available online: https://carecprogram.org/?publication=railway-sector-assessment-for-turkmenistan (accessed on 1 July 2024).
116. World Bank. *Uzbekistan Country Climate and Development Report*; World Bank Group: Washington, DC, USA, 2023; pp. 23–33. [CrossRef]
117. Vechkinzova, E.; Steblyakova, L.P.; Roslyakova, N.; Omarova, B. Prospects for the Development of Hydrogen Energy: Overview of Global Trends and the Russian Market State. *Energies* **2022**, *15*, 8503. [CrossRef]
118. Yang, L.; Wang, S.; Zhang, Z.; Lin, K.; Zheng, M. Current Development Status, Policy Support and Promotion Path of China's Green Hydrogen Industries under the Target of Carbon Emission Peaking and Carbon Neutrality. *Sustainability* **2023**, *15*, 10118. [CrossRef]
119. Rabbi, M.F.; Popp, J.; Máté, D.; Kovács, S. Energy Security and Energy Transition to Achieve Carbon Neutrality. *Energies* **2022**, *15*, 8126. [CrossRef]

120. Ministry of Energy of the Republic of Azerbaijan—Italian Minister of Foreign Affairs and International Cooperation Discussed the Expansion of TAP. Available online: https://minenergy.gov.az/en/xeberler-arxivi/azerbaycanin-energetika-naziri-ile-italiyanin-xarici-isler-ve-beynelxalq-emekdasliq-naziri-tap-in-genislendirilmesini-muzakire-edibler (accessed on 1 July 2024).
121. Ministry of Energy of the Republic of Azerbaijan—The French Delegation Discussed Azerbaijan's Energy Supply Plans. Available online: https://minenergy.gov.az/en/xeberler-arxivi/energetika-nazirliyinde-fransa-numayende-heyeti-ile-azerbaycanin-enerji-techizati-planlari-muzakire-edilib (accessed on 1 July 2024).
122. Reuters—Iran, Turkmenistan and Azerbaijan Sign Gas Swap Deal. Available online: https://reuters.com/markets/commodities/iran-turkmenistan-azerbaijan-sign-gas-swap-deal-2021-11-28/ (accessed on 1 July 2024).
123. Bieker, G. *A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars*; ICCT: Washington, DC, USA, 2021; pp. 72–73. Available online: https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/ (accessed on 1 July 2024).
124. National Database of Legislation of the Republic of Uzbekistan—Resolution No.326 of the Cabinet of Ministers of the Republic of Uzbekistan, Dated 11/11/2015. Available online: https://lex.uz/docs/2813673 (accessed on 1 July 2024).
125. GOST 33986-2016. Available online: https://mgscatalog.by/katalogstand_detail.php?UrlRN=362360 (accessed on 1 July 2024).
126. Pal, N.K. Successful Adoption of CNG and Emerging CNG-H2 Program in India. In Proceedings of the International Workshop on Compressed Natural Gas and Hydrogen Fuels: Lessons Learned for the Safe Deployment of Vehicles, Washington, DC, USA, 10–11 December 2009. Available online: https://www.energy.gov/sites/prod/files/2014/03/f9/cng_h2_workshop_6_pal.pdf (accessed on 25 July 2024).
127. Mao, Z.Q. Status and Progress in Research, Development and Demonstration of Hydrogen-Compressed Natural Gas Vehicles in China. In Proceedings of the International Hydrogen Fuel and Pressure Vessel Forum, Beijing, China, 27–29 September 2010. Available online: https://www.energy.gov/eere/fuelcells/international-hydrogen-fuel-and-pressure-vessel-forum-presentations (accessed on 25 July 2024).
128. Sgaramella, A.; Pastore, L.M.; Basso, G.L.; Mojtahed, A.; De Santoli, L. HCNG refuelling station to accelerate the transition towards a real hydrogen economy: A techno-economic analysis. *Int. J. Hydrogen Energy* **2024**, *69*, 1403–1416. [CrossRef]
129. Vojtisek-Lom, M.; Jirků, J.; Pechout, M. Real-World Exhaust Emissions of Diesel Locomotives and Motorized Railcars during Scheduled Passenger Train Runs on Czech Railroads. *Atmosphere* **2020**, *11*, 582. [CrossRef]
130. Khodaparastan, M.; Mohamed, A.; Brandauer, W. Recuperation of Regenerative Braking Energy in Electric Rail Transit Systems. *IEEE Trans. Intell. Transp. Syst.* **2019**, *20*, 2831–2847. [CrossRef]
131. Chen, J. Power Flow Control-Based Regenerative Braking Energy Utilization in AC Electrified Railways: Review and Future Trends. *IEEE Trans. Intell. Transp. Syst.* **2024**, *25*, 6345–6365. [CrossRef]
132. Iwaszczuk, N.; Wolak, J.; Iwaszczuk, A. Turkmenistan's Gas Sector Development Scenarios Based on Econometric and SWOT Analysis. *Energies* **2021**, *14*, 2740. [CrossRef]
133. Rakhmatullaev, S.; Huneau, F.; Le Coustumer, P.; Motelica-Heino, M.; Bakiev, M. Facts and Perspectives of Water Reservoirs in Central Asia: A Special Focus on Uzbekistan. *Water* **2010**, *2*, 307–320. [CrossRef]
134. Tleubergenova, A.; Abuov, Y.; Danenova, S.; Khoyashov, N.; Togay, A.; Lee, W. Resource assessment for green hydrogen production in Kazakhstan. *Int. J. Hydrogen Energy* **2023**, *48*, 16232–16245. [CrossRef]