

Communication

# A Perspective on Decarbonizing Mobility: An All-Electrification vs. an All-Hydrogenization Venue

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**Abstract:** The growing demand for low-carbon fuel is predicted by ultimate goals to fit the carbon neutrality by 2050 in many countries and regions including the European Union. According to the International Energy Agency, the CO<sub>2</sub> emissions related to transportation stand for around 30% of total annual emissions, and so, the decarbonization of the mobility sector has the highest priority. In this work, we attempt to evaluate the expected demand for low-carbon fuels, including blue and green hydrogen, and low-carbon electricity in order to compare the available and required capacities of low-carbon fuels and electricity. According to our calculations based on the figures from 2020, the transition toward H<sub>2</sub> mobility would require an amount of hydrogen equal to 366 million tons/annum, and by 2035, this requirement will increase up to 422 million tons/annum, which is several times larger than the existing H<sub>2</sub> production capacities. We have estimated the volume of the carbon capture and storage facilities required for full decarbonization of the mobility sector globally, and in the case of hydrogen mobility driven by blue hydrogen, it exceeds 4.0 billions tons of CO<sub>2</sub> per annum, while the decarbonization of coal-fired plants will require more than 10.0 billions tons of CO<sub>2</sub> per annum. In addition to the calculation of required resources, we have estimated the cost of the fuel and required capital investments and have compared different possible solutions from different points of view: economic viability, technical readiness, and social perception. Finally, it can be concluded that the decarbonization of the mobility sector would require a complex solution involving both low-carbon hydrogen and electrification, and the capacities of low-carbon fuel must be significantly increased in the following decade to fulfill the climate goals.

**Keywords:** hydrogen; cost analysis; circular economy; climate change; the levelized cost of hydrogen (LCOH)



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## 1. Introduction

The transition of the existing global business model toward a circular economy and carbon-neutral technologies is an enormous challenge. There is no doubt that the global problem of climate change must be solved very quickly to adhere to the Paris Agreement goal of keeping global warming well below 2.0 °C by 2100 [1]. Indeed, the energy sector is one of the big CO<sub>2</sub> emitters, with 31.5 gigatons of carbon dioxide produced in 2020 that is 81% of all anthropogenic carbon emissions [2]. Thus, most crucial actions must be directed to deal with emissions from the combustion of fossil fuels, although it might require significant investments and induce an increase in operational costs. The World Energy Scenarios 2019, published by the London-based World Energy Council (WEC), showed three possible scenarios of business actions: Modern Jazz (when a business has a strong interest in the balance of sustainability and economy efficiency, open economy, globalization), Unfinished Symphony (when the government actively supports a low-carbon economy through strong regulations to cut CO<sub>2</sub> emissions) and Hard Rock (when no actions for

sustainability are considered as a benefit and government support protectionism) [3]. Kober et al. have found that all presented scenarios could not ensure reaching the goal of 1.5 °C [3]. Hence, society must take even more actions to tackle the problem of climate change. Transportation contributes to nearly a quarter of all energy-related emissions, and the transition toward more sustainable transportations is among the strongest priorities [4].

Electrification and hydrogen come on top of the options considered for decarbonizing mobility. Ford announced that all their cars will be powered by electricity by 2030 [5]. Audi and Volkswagen declared to stop producing cars with internal combustion engines by 2033 and 2035, respectively [6,7], and they plan to move for electric vehicles (EV). Toyota invests in hydrogen mobility through so-called fuel cell electric vehicles (FCEV) [8]. These plans and announcements are following the aim of reaching carbon neutrality by 2050 as stated by the European Union [9]. Nowadays, hundreds of hydrogen and electric power stations are available in Europe and other countries to promote electrical and hydrogen mobility. Nevertheless, a great challenge of such a transition to EV and FCEV is the availability of carbon-free fuel (hydrogen) or renewable electricity to power those cars. The rapidly growing infrastructure for FCEV allows forecasting that the number of hydrogen-driven passenger cars will be over 800,000 by 2030 [10], and thus, the demand for low-carbon hydrogen would rapidly grow. There are several commercially available ways to generate hydrogen with minimized CO<sub>2</sub> emissions: green hydrogen produced by water electrolysis using green energy, blue hydrogen produced by steam methane reforming combined with carbon capture and storage (SMR-CCS), and yellow hydrogen produced by water electrolysis using nuclear energy [11]. At the same time, low-carbon electricity can be generated via renewable energy power plants (solar, wind, etc.), nuclear power plants, or gas/coal power plants combined with CCS. Moreover, some researchers consider that hydrogen is already market competitive with gasoline in the field of transport [12].

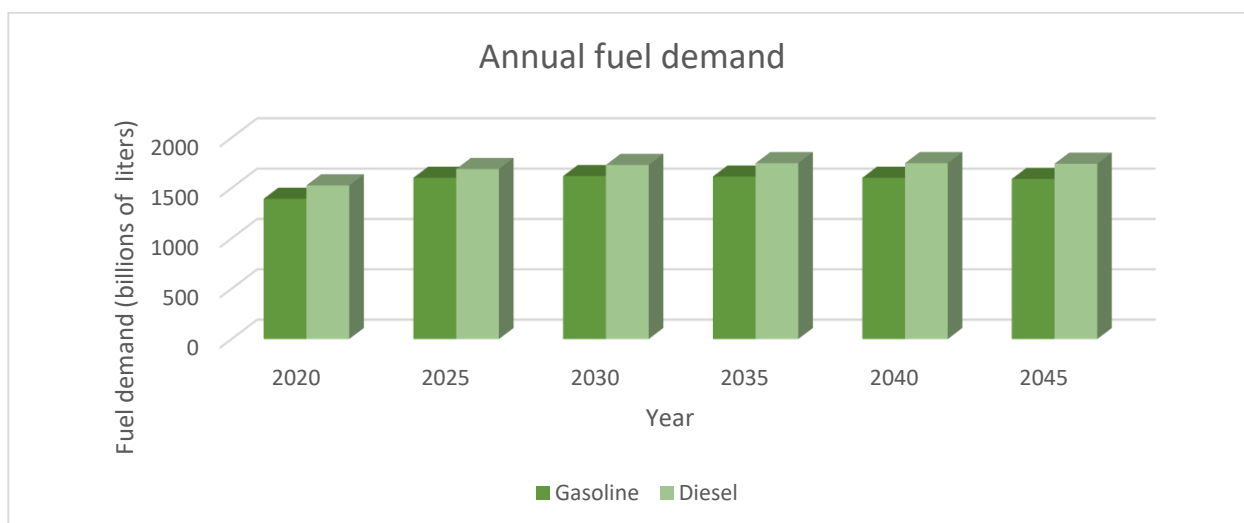
Recently, many countries and companies committed to achieve the carbon neutrality within 35–40 years, and indeed, the availability of sufficient capacities of low-carbon hydrogen and electricity is absolutely necessary to fulfill these challenging goals. However, the existing capacities and the required amount of low-carbon hydrogen and energy should be compared to understand the scale of the challenge [13]. Although numerous research articles discovered the scenarios for mobility sector decarbonization at a country level [14–17], it did not allow understanding the availability of hydrogen/electricity capacities with a strong complexation due to the importing of electricity and/or hydrogen and natural gas. Indeed, the literature survey did not reveal a “big picture” showing the global demand for hydrogen and/or electricity required to decarbonize the mobility sector globally.

In this work, we evaluated the demand for electric power and hydrogen required for the full transition of fossil fuel mobility toward sustainable alternatives: EV and FCEV. We analyzed the current and projected demand for gasoline and diesel and estimated the required annual capacity of hydrogen and/or electric power plants required to compensate fossil fuels.

## 2. Materials and Methods

### 2.1. Estimation of Annual Fuel Demand

The annual fuel demand was estimated according to open-source data published by N. Sönnichsen [18]. For the sake of simplicity in this work, we focused only on gasoline and diesel, which are the most commonly used fuels in consumer cars. The data presented in Statista [18] were converted to liters per year, and the results are given in Figure 1. (Note that these projections are consistent with those provided for the base case for many energy forecasters including IEA Energy Outlook, 2021.)



**Figure 1.** Global gasoline and diesel annual demand outlook.

### 2.2. Estimation of Required Electrical Energy to Compensate Diesel and Gasoline

The required equivalent electric energy to compensate for diesel and gasoline was estimated according to Equations (1) and (2), respectively. The estimation was calculated via evaluation of distance that gasoline or diesel cars (with fixed technical parameters) would complete after consumption of the projected demand for fossil fuel. Then, the calculated distance was used to estimate the required amount of electricity that must be consumed to drive using the EV. For this purpose, the distance was divided by the electric power consumption of EVs with similar technical parameters resulting in the amount of energy required to complete the same distance.

Gasoline and diesel consumption was set to 6.0 and 6.1 l/100 km, respectively, which corresponds to 150 h.p. cars with 1.4 L turbocharged stratified injected (TSI) and 2.0 L Turbocharged Direct Injection (TDI) engines, particularly Volkswagen Tiguan [19]. Those engines produced by the Volkswagen Group are among the most popular power aggregates equipping consumers of cars. The benchmark for electric vehicles was KIA EV6 (standard range) with a power equivalent to 170 h.p. and electricity consumption of 18.1 kWh/100 km [20].

Indeed, this estimation is quite crude, because ensembles of different cars with electrical, gasoline, and diesel engines are very heterogeneous, and the accuracy will depend on the equivalent consumption of EVs from different segments (commercial transport, sport cars, etc.). Of course, the ensemble of EVs is just beginning to develop, and an enhancement of estimation accuracy would be possible only in the following years. Nevertheless, our estimation will help to understand to what extent electrical energy capacity would be required to compensate the demand by EV when gasoline and diesel cars would be completely discarded.

$$\text{Electricity demand(gasoline)} = \frac{\frac{\text{gasoline global consumption}}{\text{consumption of diesel 150 h.p. car}} * 100}{\text{power consumption of EV}} \quad (1)$$

$$\text{Electricity demand(diesel)} = \frac{\frac{\text{diesel global consumption}}{\text{consumption of diesel 150 h.p. car}} * 100}{\text{power consumption of EV}} \quad (2)$$

### 2.3. Estimation of Required Hydrogen Amount to Compensate Diesel and Gasoline

The amount of hydrogen required for the transition of all fuel cars to FCEVs was estimated similar to EVs with the only change that instead of electric power consumption, we used hydrogen consumption, as shown in Equations (3) and (4) for hydrogen demands required to compensate gasoline and diesel, respectively. FCEV hydrogen consumption was set to 0.76 kgH<sub>2</sub>/100 km, which corresponds to the consumption of Toyota MIRAI

(155 h.p.) in the combined cycle [21]. The benchmarks for diesel and gasoline cars were the same as in Section 2.2.

$$\text{Hydrogen demand (gasoline)} = \frac{\frac{\text{gasoline global consumption}}{\text{consumption of gasoline 150 h.p. car}} * 100}{\text{hydrogen consumption of FCEV}} \quad (3)$$

$$\text{Hydrogen demand (diesel)} = \frac{\frac{\text{diesel global consumption}}{\text{consumption of diesel 150 h.p. car}} * 100}{\text{hydrogen consumption of FCEV}} \quad (4)$$

It is worth noting that different types of hydrogen are classified: (1) green hydrogen—H<sub>2</sub> produced by electrolysis of water using renewable energy, (2) yellow hydrogen—H<sub>2</sub> produced by electrolysis of water using nuclear energy, (3) gray hydrogen—H<sub>2</sub> produced by steam methane reforming (or autothermal reforming), (4) blue hydrogen—H<sub>2</sub> steam methane reforming (or autothermal reforming) with the capturing and storage of emitted CO<sub>2</sub>, (5) turquoise hydrogen—H<sub>2</sub> produced by methane pyrolysis and (6) brown hydrogen—H<sub>2</sub> produced by coal gasification.

#### 2.4. Estimation of the Equivalent Electricity Cost

The electricity cost was characterized by the levelized cost of electricity (LCOE). LCOE is the total cost to build and operate a power plant over its lifetime divided by the total electricity output dispatched from the plant over that period—hence, typically, cost per megawatt-hour. Here, we employed the median LCOE estimated for the U.S. location calculated by the International Energy Agency (IEA). The LCOE, CO<sub>2</sub> emissions for each type of electrical energy generation, lifetime, and other important parameters were employed from the IEA and international renewable energy agency (IRENA) reports and scientific literature [22–26] and summarized in Table 1.

**Table 1.** The projected LCOE employed from [22–26].

Energy Source	Coal-Fired Power Plant	Coal-Fired Power Plant with CCS	NG Power Plant	Solar Power Plant	Nuclear Power Plant
LCOE, USD/MWh	65.3	89.1	50.2	86.1	71.3
Capacity factor (%)	58.4%	58.4%	56.2%	23%	92%
Mass of CO <sub>2</sub> emitting per 1 MWh, tons of CO <sub>2</sub>	0.952	0.095	0.560	0.048	0.012
Lifetime (years)	40	40	30	25	60
Construction period (years)	4	4	3	1	7
Lowest CAPEX-factor USD/kW	500	800	1066	883	2021

The cost of the required electric energy was estimated by multiplying the required energy by LCOE. To estimate the required CAPEX investment, we used CAPEX-factor (USD/kW) from open sources [22–26] and employed Equation (5), where electricity demand is a sum of electricity required annually to power EV substituting gasoline and diesel, 8000 is the number of hours in a year, and the capacity factor is a factor of power plant efficiency.

$$\text{CAPEX (Power Plant)} = \text{CAPEX\_factor} \left( \frac{\text{USD}}{\text{kW}} \right) \times \frac{\text{Electricity demand (KWh)} / 8000(\text{h})}{\text{capacity factor}(\%)} \times 100\% \quad (5)$$

The cost of retrofitting coal-fired power plants with CCS leads to an increase in LCOE by 20–25 USD/MWh. Thus, to calculate the cost of electrical energy produced with a

retrofit of a coal-fired plant, one needs to multiply the required electric energy amount by 25 USD/MWh [25].

According to the literature [27], the introduction of CCS to the coal plant increases the CAPEX by 48%. The CAPEX cost for a coal-fired plant is between 500 and 1000 USD/kW.

According to the recent IRENA report [28], the LCOE of solar power has an extremely broad range starting from 30 USD/MWh (for solar power plants located in India) and going up to 150 USD/MWh [15]. The capacity factors vary significantly (from 9.9 to 20.8%) and are expected to grow each year. In this work, we considered the capacity factor for solar power equal to 23% and LCOE of 86.1 USD/MWh, and CAPEX-factor of 883 USD/kW (among the lowest values for the US) [28].

### 2.5. Estimation of the CAPEX for Blue Hydrogen Plant

In contrast to widely investigated and thoroughly analyzed real cases of various power plants, the information regarding the estimated CAPEX for blue hydrogen production is limited. From our point of view, the highest accuracy of CAPEX estimation for blue hydrogen plants (inside and outside of battery limits) can be found in the IEA hydrogen report [29]. In 2020, the CAPEX factor for blue hydrogen was estimated at 1680 USD/kW<sub>H<sub>2</sub></sub>. This number can be converted into USD/tta (USD per thousands of tons per annum), and it is equal to 403,600 USD/tta. Thus, to build the capacities required to compensate the entire gasoline and diesel market, the estimated hydrogen demand (in tta) must be multiplied by 403,600 USD/tta.

### 2.6. Estimation of Electrolyzer CAPEX

The lowest cost of green hydrogen production can be obtained when a proton exchange membrane (PEM) electrolyzer is employed [30]. To estimate the capital investment required for the production of green hydrogen, we estimated the CAPEX of electrolyzers required to produce the annual demand for hydrogen. It was assumed that the maximum capacity of the electrolyzer equals 1 GW. The CAPEX was calculated according to Equation (6) [31].

$$\text{CAPEX (PEM)} = 1.2 \cdot 10^6 (\text{USD}) \cdot P(\text{MW})^{0.85} \quad (6)$$

The production rate of 1 GW electrolyzer was estimated by multiplying existing data for 100 MW electrolyzer by 10. The resulting productivity equals 19 tons/h, i.e., 152,000 tons of H<sub>2</sub> per annum. Such capacity is comparable with typical hydrogen plant production by steam methane reforming [32].

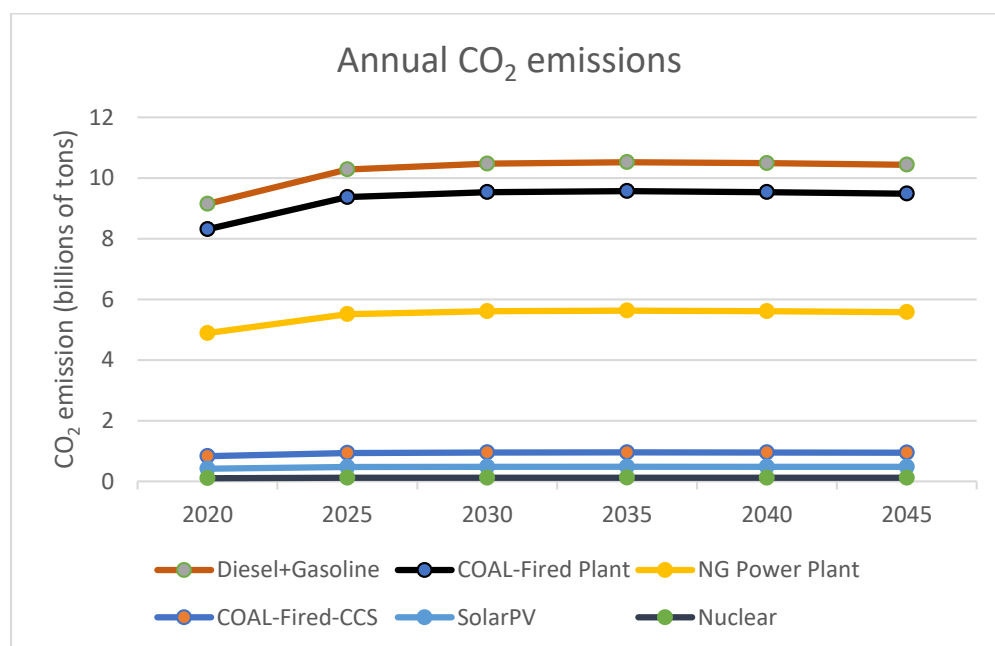
## 3. Results

### 3.1. Analysis of a Transition toward E-Mobility

As shown in Figure 1, in 2020, the annual demands of gasoline and diesel equaled 1392 and 1526 billion liters, respectively. According to open-source data [18], the demand for both types of fuel will grow until 2035, and it would slowly decrease afterward. The amount of CO<sub>2</sub> produced by liquid fuel burning in 2020 was 9.1 Gt, and it is expected to grow up to 10.4 Gt by 2035 (see Figure 2). Of course, the substitution of liquid fuel by other cleaner energy sources may reduce those emissions.

Not surprisingly, the substitution of ICE cars by EVs driven by the electricity produced from coal-fired plants leads to a very minor reduction in CO<sub>2</sub> emissions. Although EVs exhibit better energy efficiency as compared to ICE mobility, the extremely high CO<sub>2</sub> footprint of this type of electricity (0.92 ton CO<sub>2</sub>/MWh) levels out the positive effect of the transition to EV mobility. Of course, the application of CCS to the coal-fired plant enables a significant reduction in CO<sub>2</sub> emissions related to EV mobility (by 90%). Some positive effects can be achieved even when the EVs are driven by natural gas (NG) power plant electricity, as the CO<sub>2</sub> emission from mobility can be decreased by ≈48%. The most efficient reduction can be achieved when nuclear or renewable (solar) power plants are employed to generate electricity for mobility. To evaluate the economical perspectives, the required

amount of electrical power, its cost, and required investments for the CAPEX of new energy production installations were calculated.



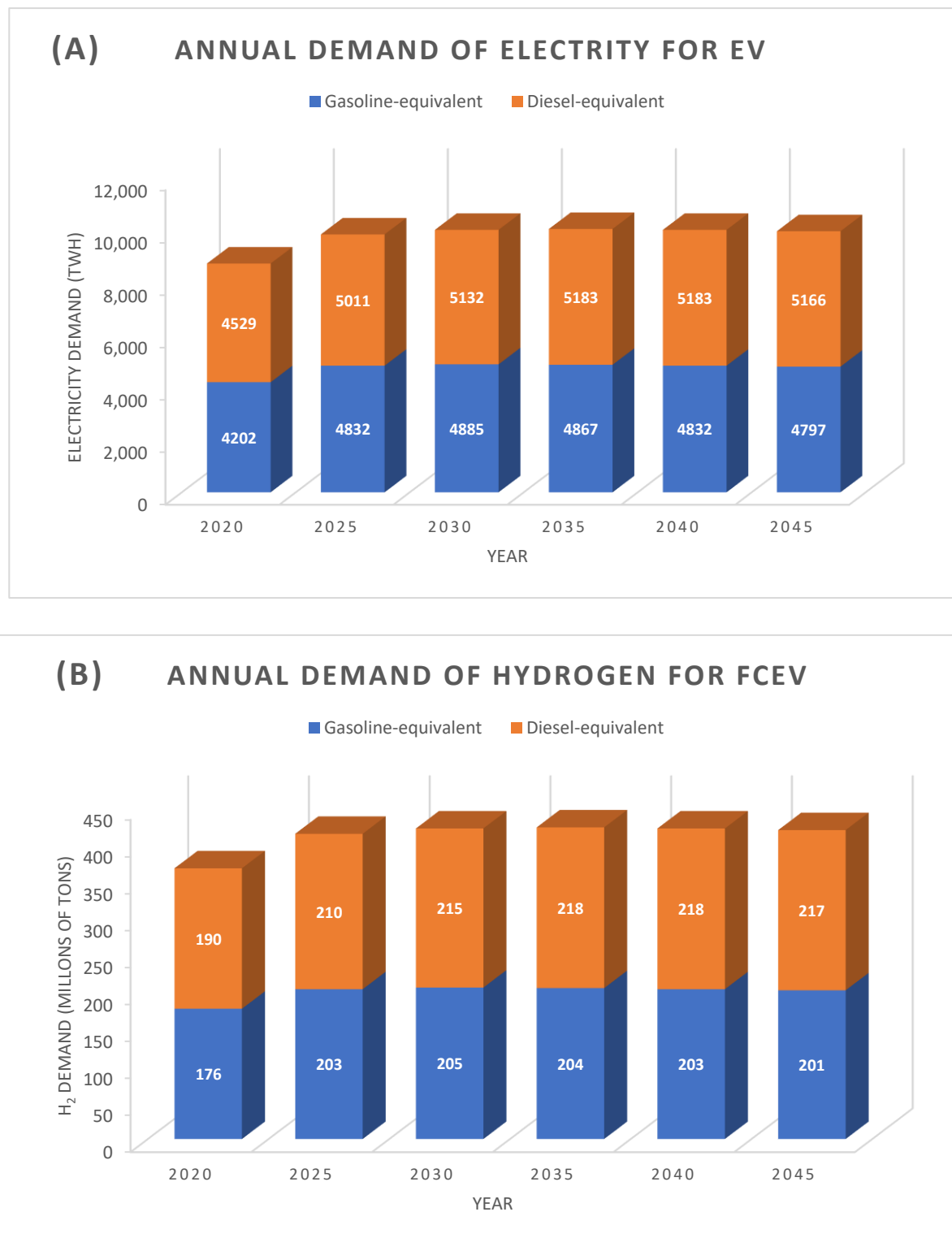
**Figure 2.** CO<sub>2</sub> emissions projected for a different type of mobility. The results obtained by calculations on the basis of the Equations (1)–(4), Table 1 and data obtained from [18].

The amount of electricity or hydrogen required to substitute all this annual demand of fuel was calculated according to Equations (1)–(4) and is presented in Figure 3.

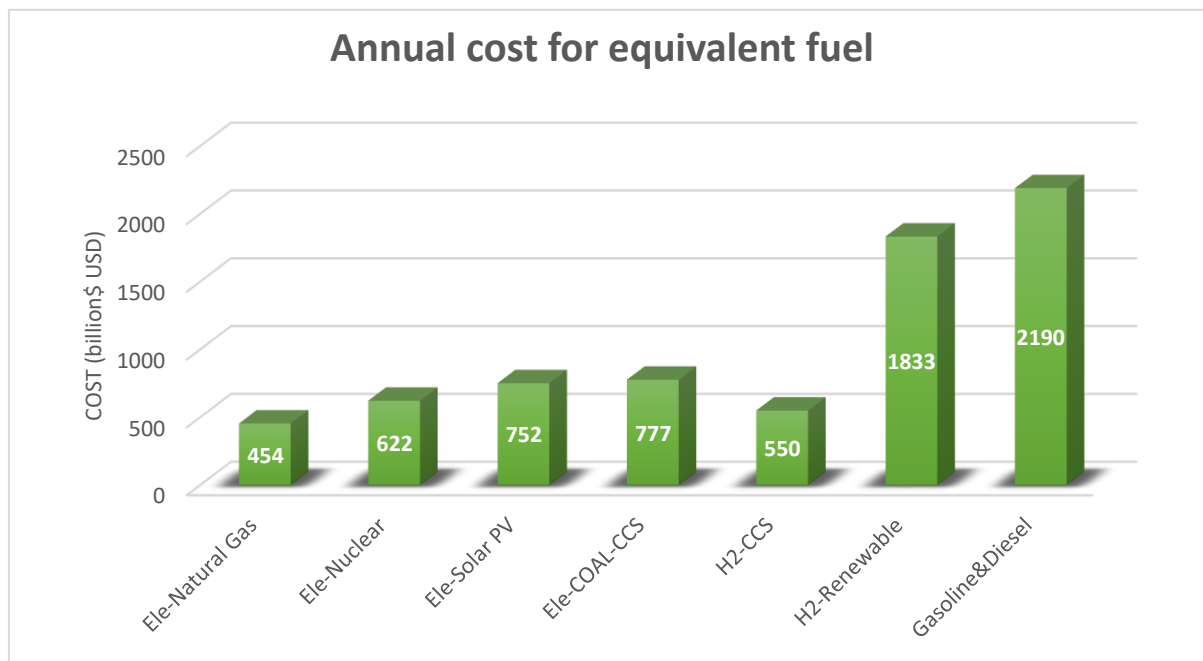
The amount of electric power necessary to compensate for all liquid fuel would increase from 8731 in 2020 to 10,050 Terawatt hours (TWh) in 2045. According to IEA, the global electricity production and demand in 2018 were 26 125 and 24,738 TWh, respectively [33], indicating an unused balance of 1387 TWh remaining to meet future demand.

Nevertheless, the required demand for electric power to meet full electrification of mobility in 2025 and beyond is significantly higher than the available capacity of existing power plants. If the entire electrical energy demand is supposed to be produced by new electrical power plants, the cost of required electrical energy can be estimated by multiplying LCOE by the value of energy (MWh) presented in Figure 3. We estimated the cost of electricity that would be required if the entire gasoline and diesel consumption would be switched to the electric power consumed by EVs. As shown in Figure 4, the lowest cost is expected for EVs driven by electricity produced by NG power plants due to the lower LCOE. However, the NG power plant would still produce high CO<sub>2</sub> emissions (see Figure 2), and this option is shown just as a reference for the real low-carbon energy sources. Nuclear, solar PV, and coal-CCS power plants produce energy at a higher cost but allow significantly decreasing CO<sub>2</sub> emissions from mobility. From Figure 4, it becomes clear that the most cost-efficient low-carbon fuel could be a blue H<sub>2</sub>, while the green H<sub>2</sub> would be a significantly more expensive option.

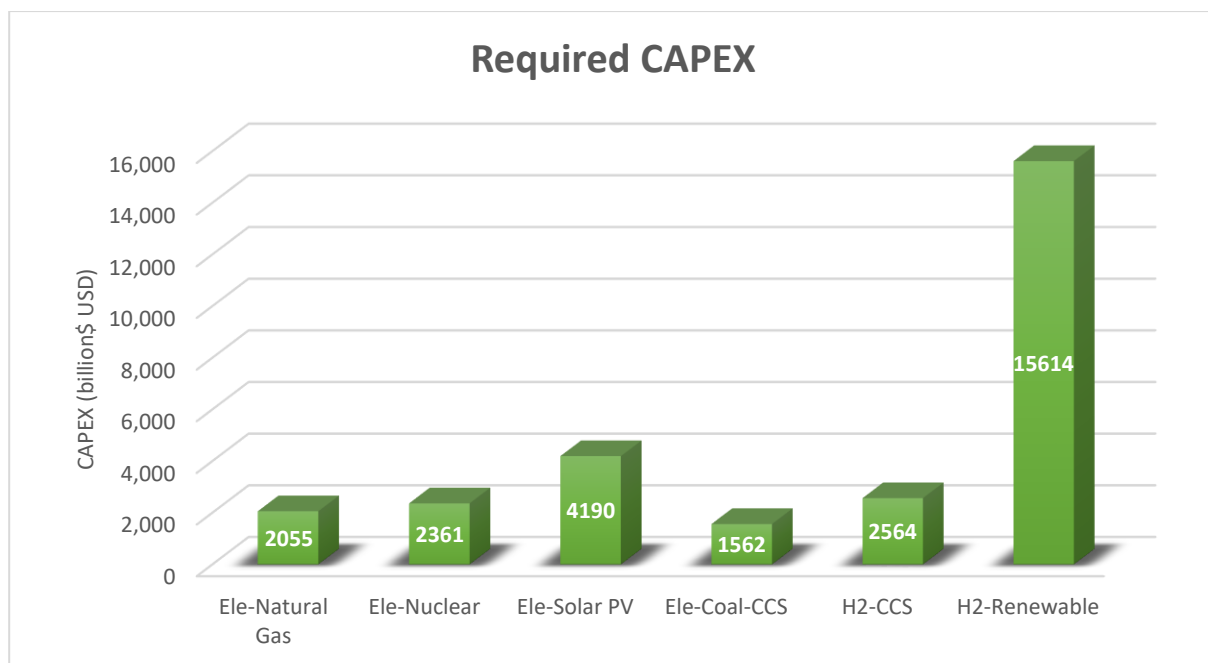
However, the transition toward EVs would also depend on the CAPEX required for each energy transition solution. The CAPEX for each type of energy source was estimated according to Equation (4), and the results are given in Figure 5.



**Figure 3.** The calculated demand of electricity required for EV (A) and hydrogen for FCEV (B) required to substitute 100% of gasoline and diesel. The results were obtained by calculating using Equations (1)–(4) and the data provided in [18].



**Figure 4.** The annual cost of electricity or hydrogen for the substitution of gasoline and diesel.

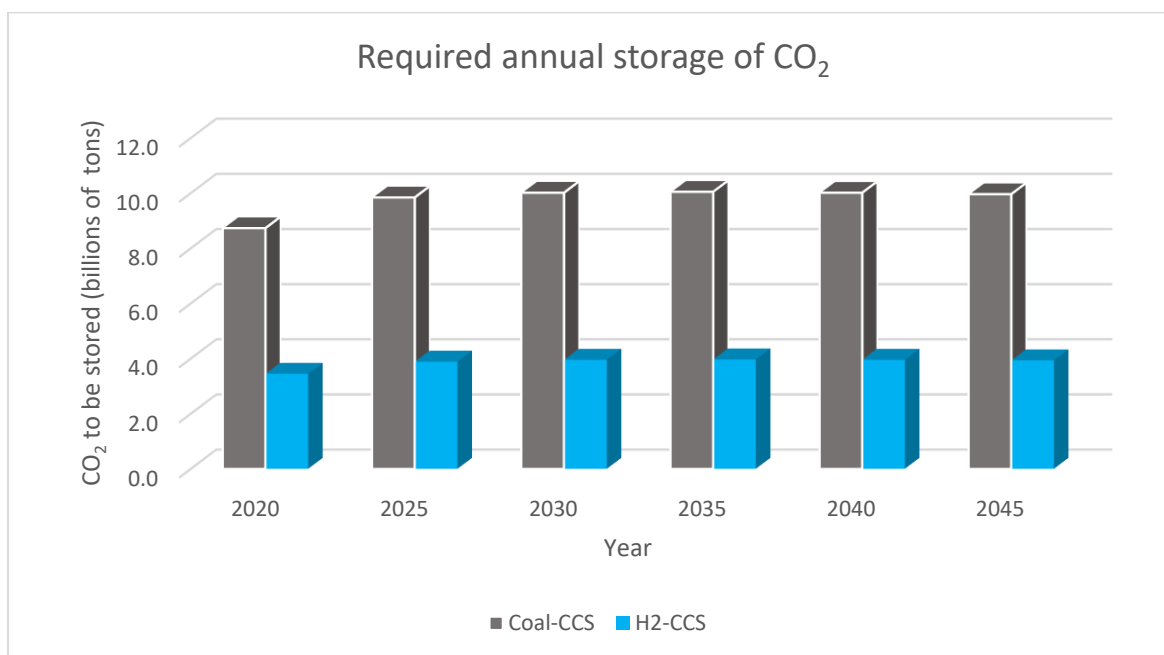


**Figure 5.** The estimation of capital investments for generating electricity and hydrogen in the amount required for substitution of all gasoline and diesel ICE cars by EVs or FCEV, respectively.

The lowest capital investment is estimated for coal-fired power plants with CCS integration. To build enough coal-CCS plants to power all EVs would require 1.562 trillion USD. However, one should keep in mind that the cost estimation was calculated for the most efficient CCS cases with big reservoirs and low costs for CO<sub>2</sub> transportation, which might not be the case for all coal-fired plants globally. Moreover, as shown in Figure 6, the quantity of stored CO<sub>2</sub> will exceed 10 Gt/annum by 2035, leading to quick filling of discovered reservoirs suitable for CO<sub>2</sub> storage (according to the Global CCS Institute report, it is ≈310 Gt [34]). Building nuclear power plants would require 2.361 trillion USD.



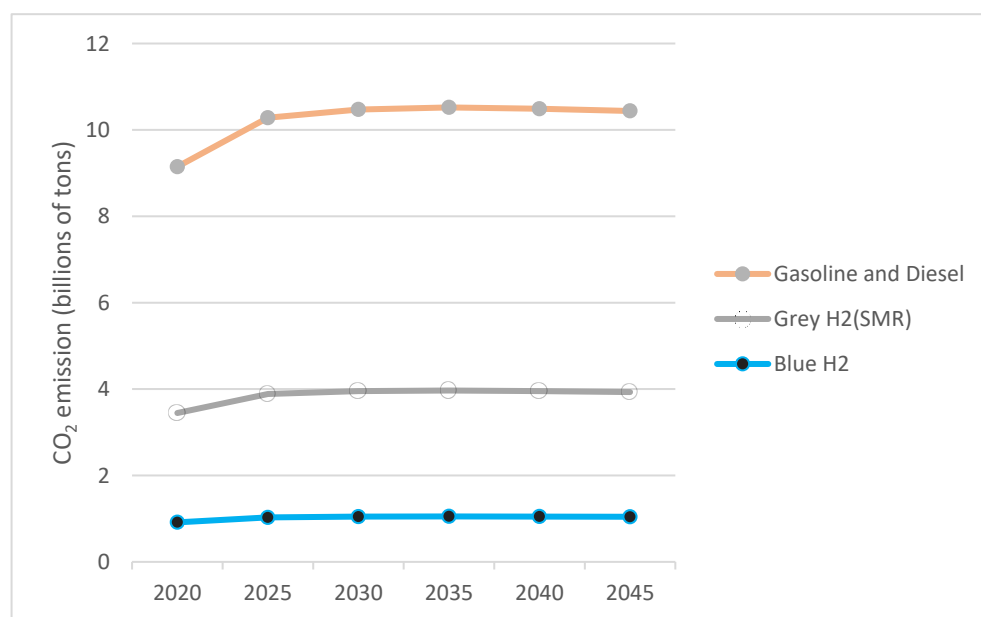
In addition to substantial capital investments, the construction of nuclear power plants requires significantly longer periods (7–10 years), and thus, to achieve required electric power production by 2050 (a year when carbon neutrality is supposed to be achieved in EU), about 150 plants each with a power of 2 GW must be under construction simultaneously for the following 30 years, and it might be a great challenge to find enough specialists and engineers to carry numerous constructions. Finally, public concerns would also be an issue to push forward such big nuclear power projects, especially taking into account the fact that the required amount of electrical power is four times bigger than the current nuclear power production. In contrast, public perception of renewable energy would be the strongest point to carry out the construction of renewable energy power, although building enough solar PV power for mobility will require 4.190 trillion USD. The enormous capital investment would not be the only challenge that PV projects would face, as the surface required for the PV modules only for such great solar PV power would exceed 100,000 km<sup>2</sup>, which is a size comparable with a big country. Of course, one might consider using the sunny area of desert in Africa to accommodate solar PV panels and produce hydrogen from renewable energy and then transfer it elsewhere. This option was considered to be the main driver for the production of green hydrogen that we evaluated in the following section.



**Figure 6.** Mass of CO<sub>2</sub> to be stored from the CCS retrofit of coal-fired power plants and blue hydrogen production.

### 3.2. Analysis of A Transition toward Hydrogen-Mobility

The transition toward hydrogen mobility can be performed by switching the ICE cars to the FCEV driven by gray, blue or green hydrogen. The production of gray hydrogen emits 9.4 kg CO<sub>2</sub> per 1 kg of H<sub>2</sub>. However, despite those emissions, a significant reduction in CO<sub>2</sub> emissions related to mobility can be realized from gray H<sub>2</sub> compared to diesel and gasoline: the FCEC driven by gray H<sub>2</sub> emits 4.0 Gt instead of 10.5 Gt by diesel and gasoline transport (Figure 7). Nevertheless, the effect of CO<sub>2</sub> emission reduction by blue H<sub>2</sub> would be tremendous: 1.1 Gt instead of 10.5 Gt. The further transition toward green hydrogen would further reduce emissions, yet the reduction would be quite negligible compared to reduction when transitioning from gasoline and diesel to either gray or blue hydrogen.



**Figure 7.** A comparison of CO<sub>2</sub> emission related to mobility driven by gasoline and diesel, gray and blue hydrogen.

The amount of hydrogen required for the transition toward H<sub>2</sub> mobility in 2020 equaled 366 million tons/annum, whereas it will increase up to 422 million tons/annum by 2035 (Figure 3B). This quantity is tremendously higher than all the existing hydrogen capacities that are around 80 million tons/annum [29]. The cost of annual blue hydrogen demand for 2020 would be 550 billion USD. As shown in Figure 4, the cost of such transition toward sustainable mobility will be the lowest among all those available. In contrast, the production of green H<sub>2</sub> (via electrolysis employing renewable energy) will be the most expensive solution. The CAPEX to build the capacity for blue hydrogen would be ≈2.56 trillion USD, which is higher than coal CCS plants but comparable with capital investments for nuclear powered plants. The CAPEX estimated for green hydrogen production exceeds 15.6 trillion USD due to the high CAPEX of electrolyzers, high cost of renewable energy plants, and relatively low electrolysis efficiency. The investment required for a full transition toward the H<sub>2</sub> mobility driven by green hydrogen thus currently seems prohibitive.

#### 4. Discussion

The analysis of electricity and hydrogen required for the transition toward sustainable mobility showed that each solution (EVs driven by nuclear, renewable, or other types of energy or FCEVs driven by gray, blue or green hydrogen) has certain pros and cons. From an economic point of view, the transition toward hydrogen mobility driven by green H<sub>2</sub> seemed to be the least probable option due to the high capital cost and the very low margin between the green H<sub>2</sub> production cost and current fuel price required for driving the same distance, i.e., potential economic margin. Nevertheless, this does not mean that green H<sub>2</sub> should be discarded from the roadmap of the transition toward sustainable mobility. This option should be chosen only when this solution will be more cost-effective compared to other options or when the efficiency of electrolyzers will be significantly improved. To date, there are no high-capacity efficient electrolyzers, and both energy and economic efficiencies need to be significantly improved. The production of green H<sub>2</sub> at a large scale is only under development, and it can be expected that in the following decades, we will see a growing interest in this technology. However, the usage of green H<sub>2</sub> as the main source to achieve carbon neutrality by 2050 or even 2070 seemed unrealistic.

Indeed, the simplified calculations performed in this manuscript have certain limitations due to very simplistic calculation of the equivalent of fossil fuels, because it was

calculated on the basis of one single type of vehicle (a passenger car) rather than dividing the consumption into different mobility sectors (public transport, lorries, etc.). Additionally, one should remember that the CO<sub>2</sub> emissions related to the mobility sector and the economic aspects of the decarbonization would strongly depend on the location, logistic shoulders and market conditions. Nevertheless, our calculation allowed better understanding a “big picture” for the EV and FCEV transitions options and required resources to achieve the challenging net-zero transportation in the committed periods.

To solve the transition toward sustainable E-mobility by using solely renewable energy would be more probable than transition via green H<sub>2</sub>, but its current high financial and resource (surface area, materials, especially silicon) demands constitute a high barrier for faster employment of this technology for the decarbonization of transport. As mentioned above, to generate the required amount of renewable power of 10,000 TWh required for powering all EVs substituting both diesel and gasoline vehicles, the area comparable to the size of Germany would be necessary, whereas capital investments would exceed 4 trillion USD. Thus, this option should be considered for the countries with available free land and a high yield of sun rays. The nuclear power plant is well-established technology for generating low-carbon electricity, but the societal perception of this technology is at its lowest level due to safety concerns raised after the Chernobyl and Fukushima disasters. Thus, in some countries, it is almost forbidden to launch new nuclear power capacities. Hence, this option, surely, would not be a solution to cover all required energy demand in the coming decades, especially taking into account that currently, the world’s nuclear power production is only about 2710 TWh, while the transition toward E-mobility demands 10,000 TWh. Additionally, the speed for siting and building new nuclear power is considerably low, as it would take 7–10 years to make a new nuclear power plant.

The production of blue hydrogen appears to be, at least in the short term to medium term, the mainstream option to decarbonize transport thanks to its high margin between the cost of blue H<sub>2</sub> production and the price of diesel/gasoline required for driving the same distance. For example, in Germany, the average gasoline price is around 1.77 USD/liter (the data for August 2021, according to [35]). The consumption of a gasoline car is 6.0 L/100 km, while FCEV consumes 0.76 kg of H<sub>2</sub> per 100 km. Hence, the equivalent price for a consumer can be up to  $1.77 \times 6/0.76 = 14$  USD/kgH<sub>2</sub>. Hence, in Germany, the margin between blue hydrogen cost and consumer price may exceed 930%. This margin may attract numerous investors and should secure the business model of hydrogen producers and retailers.

It is worth noting that blue H<sub>2</sub> production is fully commercialized, and it builds a new value chain for the energy sector, as both feedstocks for blue hydrogen and resources required for the storage of the emitted CO<sub>2</sub> are under the control of the oil and gas sector. Although the required capital investments are considerably high, it is still a better option from an economic and societal point of view, as the implementation of this technology would not require a sacrifice of the big area of our lands, and draining the silicon resources will not produce nuclear waste.

Many oil and gas companies demonstrated the versatility of this technology by producing blue hydrogen at a commercial scale and offering the licensing of this technology to the market. For example, Saudi Aramco demonstrated the feasibility of producing blue hydrogen and blue ammonia and shipping it to Japan [36]. Blue ammonia can be considered a great option when large volumes of hydrogen need to be shipped a long distance. The burning of ammonia leads to the generation of water and nitrogen only, and so this is a great CO<sub>2</sub>-free energy source. To produce blue ammonia, one will need to use blue hydrogen, of course. The transition toward blue H<sub>2</sub> and blue ammonia will depend on the market demand, and, at present, this market does not yet exist at a large scale. Indeed, the demand for low-carbon fuels needs to be driven by policy changes.

## 5. Conclusions

In this work, we analyzed the global demand for low-carbon electricity and hydrogen that can be used for shifting transportation toward a more sustainable model with the use

of electric and hydrogen mobility. According to our calculations, the required amount of electricity and hydrogen is nearly 30% of current global electricity production. To fulfill the required amount of hydrogen production, the capacities of hydrogen production must be doubled. The cheapest solution would be based on the transition toward blue hydrogen, because its CAPEX is quite low, and the margin for the produced H<sub>2</sub> for the mobility may exceed 930%, ensuring a secure business model for hydrogen mobility. The production of the required 400 million tons per annum of blue H<sub>2</sub> in 30 years is challenging because still there is no significant demand for blue H<sub>2</sub>, and there is no market for low-carbon transport fuels. Most probably in following decades, both the electrification and hydrogenation plus other low-carbon fuel options will be exploited for the decarbonization of the mobility sector, and the percentage of each option (green/blue H<sub>2</sub> or low-carbon electricity, bio-based fuels) will depend on their availability, economics, environmental footprint, and social acceptability.

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