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Consequences of Transport Low-Carbon Transitions and the Carbon, Land and Water Footprints of Different Fuel Options in The Netherlands

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Abstract: Transport greenhouse gas emissions are mainly caused by the use of fossil fuels, e.g., gasoline and diesel. This case study for The Netherlands calculates how alternative fuels, e.g., electricity, hydrogen or biofuels, contribute to policy aims to decarbonize transport. Alternative fuels, produced in various ways, have different carbon (CF), land (LFs) and water footprints (WFs). This study assesses CFs, LFs and WFs for fuels ($kgCO_2e/m^2/m^3$ per GJ), showing differences among fuels dependent on primary energy sources. It calculates CFs, LFs and WFs for four scenarios with different fuels. The biofuel scenario is not attractive. CFs slightly decrease, while LFs and WFs increase enormously. The electricity scenario has small CFs and the smallest LFs and WFs, but this is only when using wind or solar energy. If storage is needed and hydrogen is produced using wind energy, CFs double from 3055 to 7074 kg CO_2e, LFs increase from 15×10^6 to 43×10^6 m^2 and WFs from 3×10^6 to 37×10^6 m^3 compared to the electricity scenario. The case study shows that wise fuel choices contribute to policy aims to decarbonize transport, although LFs and WFs are also important to consider. These case study results are relevant for sustainable transportation transitions worldwide.

Keywords: transport carbon footprint; transport fuels; transport energy policy; land footprint; water footprint; water–energy nexus

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Highlights

- Replacing 5% of gasoline or diesel in transport with a biofuel barely reduces carbon footprints.
- Even minor biofuel use in transport causes enormous land and water footprints.
- The use of electricity in transport is more sustainable with wind or solar energy.
- It is likely that renewable electricity cannot fully supply transport so that hydrogen is needed.
- The decarbonization of transport needs fuel choices that consider resources like land and water.

1. Introduction

Today, climate change is considered the most important challenge of our time. However, it is not the only challenge. Environmental change also includes issues like water scarcity and food security and thus the use of land [1]. Sustainable transitions—for example, a shift towards low-carbon transportation—are essential to safeguard the Earth for future generations [2]. Globally, transport accounts for 23% of CO_2 emissions, with emissions increasing with an annual growth of 2.5% between 2010 and 2015 [3]. Transport CO_2 emissions, or carbon footprints (CFs), are high on the international policy agenda. Policy aims to decarbonize transport and decrease emissions from 7.7 Gt CO_2 per year in 2017 to 2 Gt in 2050. For example, of the nationally determined contributions to the Paris Agreement, 75% focus on the transport sector [4]. Basically, there are four ways to decrease transport

CFs: (i) decrease transport activity; (ii) improve energy efficiency of transport modes; (iii) shift to less CF intensive transport modes; (iv) use less CF intensive fuels. Although behavioral changes are needed [5], most CF reduction scenarios focus on increasing energy efficiency and fuel shifts rather than activity reduction or modal shifts [6]. For example, the European Union (EU) promotes the use of transport fuels from renewable sources in an attempt to decrease CFs in its member states. The directive 2009/28/EC from 2009 is forcing countries like The Netherlands to derive at least 10% of their transport fuels from renewable energy sources by 2020 [7]. Initiatives include the blending of crude oil-based gasoline with bioethanol and the stimulation of transport modes using electricity [8].

A lower use of transport in combination with a shift towards more efficient transport or transport modes will certainly decrease CFs. When a shift towards less CF-intensive fuels is considered, an important issue in this respect is whether a shift away from traditional fuels towards alternative fuels using new technologies will contribute to strategies to mitigate climate change without having other environmental impacts like greater land or water use. Access to materials, processes and natural resources will nearly always encounter natural limits [2]. Hao et al. [9], for example, have shown that hydrogen fuel cell vehicles depend on the availability of platinum, a scarce natural resource with regional supply limitations. Recently, many studies have analyzed the effects of a shift from traditional transport fuels towards less CF-intensive fuels. Fuels included in these studies are biofuels, hydrogen and also electricity, which is sometimes defined as an alternative fuel, e.g., [10]. Biofuels derived from biomass might decrease CFs, but they have large land requirements. In the United States, for example, all the cropland used for maize and soybean is needed in order to produce only 12% of the gasoline and 6% of the total diesel demand [11]. A study of the land and water requirements of biofuels from algae also showed the large land and water requirements [12]. A recent study into the sustainability aspects of different generations of biofuels has shown that all generations have limitations—for example, because they do not satisfy the food–energy–water nexus [13]. These authors have concluded that it is essential to not only take CFs into account but also to consider the scale of the economy, the availability of bioresources and planetary boundaries. Biofuels are related to a relatively large water requirement, e.g., [14–16], showing the competition between water for food and water for energy. Mekonnen et al. [17] confirms that water constraints currently hardly play any role in the discussion about future energy scenarios. Surprisingly, the "greenest" electricity scenario of the International Energy Agency (IEA), i.e., the scenario with a relatively small growth in electricity demand and with the largest fraction of renewables in 2035, is associated with the largest water use [17]. When sustainable transport is promoted, not only CFs of the transport mode itself, i.e., the emissions related to transport fuel consumption, but entire production chains, from cradle to gate, need to be included in the analysis so that tradeoffs with other natural resources are also taken into account. For sustainable transport, two phases, the well-to-tank (WTT) and the tank-to-wheel (TTW) phases, need to be considered. WTT includes the production chain of a fuel and TTW the combustion of a fuel. Together, WTT and TTW are termed well-to-wheel (WTW) [18–21]. The study by Stephan and Crawford [22], for example, included a life cycle perspective, including water requirements for infrastructure for passenger transport modes in Melbourne, Australia, showing the importance of all the actors in a supply chain.

Electricity use is another option to decrease CFs because electric transport modes are more efficient than modes using traditional fuels, although consumer resistance may be important [23]. If electricity is applied to fuel transport, it is essential to generate electricity using renewable energy sources like solar or wind energy rather than applying electricity generated using fossil fuels. In Malaysia, for example, the national electricity composition is based on 40% coal, 52% natural gas and 2% crude oil, so the introduction of electric vehicles eliminates tailpipe emissions but increases emissions related to electricity generation at the same time [24]. This is also the case in China, where electric cars have become increasingly popular [3,25] but where electricity is still carbon-intensive [26]. An important drawback of electricity generated from solar or wind is its intermittency, i.e., that there is no supply when the sun does not shine or when the wind does not blow and the other way around. Another drawback, e.g., in public transport, is the limited driving range. Electric buses, for example, already need to recharge after 200 to 250 km [27]. Here, hydrogen as an energy carrier might be a solution. Variable renewable electricity can be used to generate hydrogen that can be stored and applied directly in the transport sector [28], while hydrogen allows for larger traveling distances than electricity [9,27].

The economy of The Netherlands, one of the countries of the EU, depends on an efficient transport system, because it is the carrier of the Dutch trading system, which reflects in the slogan "Netherlands distribution nation". Fast and reliable passenger and freight transport is vital in establishing Dutch personal visits and business relations [29]. Therefore, mobility is essential in the Dutch economic system. At the same time, Dutch policy aims at decreasing transport CFs—for example, by encouraging consumers to buy electric cars. With transport accounting for around 27% of the total CO_2 emissions in The Netherlands, the importance of a transition in this sector is evident [29]. Additionally, other environmental issues (land use, water use and CO_2 emissions) in the entire production chain and during the use of a fuel, from WTT and TTW, need further investigation, because trade-offs can occur if the focus is on decreasing CFs. The so-termed environmental footprint family provides a tool to assess natural resource use and emissions so that human use of these resources remains within planetary boundaries [30]. Important footprints are the resource use footprints (e.g., blue and green water footprints and land footprints) and emission footprints (e.g., carbon footprints and grey water footprints), which can be applied from local to global levels [30]— for example, in the transportation sector. This study aims to provide an environmental analysis of transport fuels, including the use of less CF-intensive fuels, that covers three environmental footprints—the carbon, water and land footprints—of transport in The Netherlands. It takes The Netherlands as the case study area because of the importance of transport for the country, the policy initiatives to decrease transport CFs and the availability of reliable data. In addition to investigating fuels that decrease CFs in transport, this study also includes tradeoffs among natural resources, combining carbon, land and water footprints to provide an overall analysis and, in addition, to calculate the consequences of using alternative fuels like hydrogen and electricity. The study answers the following research question: "Which fuels and technologies might be applied in alternative transport fuel scenarios and what are the consequences for the carbon, land and water footprints of the transport sector in The Netherlands compared to the reference situation in 2016?".

This study focuses on the entire production chain, from well to tank (WTT), and the consumption, from tank to wheel (TTW), of transport fuels, and it calculates the carbon, land and water footprints of different fuel production methods for three alternative fuel supply scenarios, dominated by different fuels per scenario, using the situation in The Netherlands in 2016 as the basis for the calculations. Fuels, e.g., electricity, as an alternative fuel, can be produced in different ways, so that the results give a range of outcomes per scenario. Although the study uses The Netherlands as the case study area, it provides information that can be applied to other countries and regions as well—for example, to the other 27 EU countries that need to comply with the same directive to replace 10% of their transport fuels with renewables.

2. System Analysis

2.1. The Dutch Transport System

The Dutch transport system includes passenger and freight transport. In 2016, the Dutch travelled 185×10^9 km, or 11,000 km per capita per year [29]. Almost 75% of the total distance is travelled by car [29]. Annually, 560×10^6 tons of goods enter The Netherlands [29]. Freight transport consists of 81% road traffic (lorries) and 18% inland shipping. The other 1% is railway traffic [29].

Transport using energy is an issue of standard physics in which moving a mass—in this case, a vehicle—requires a certain amount of energy [31]. Energy use for transport depends on the efficiency of the transport mode in combination with the energy requirements of the fuel applied [31].

2.2. Transport Fuels

Energy for transport is obtained from energy sources, primary energy sources (PESs) and secondary energy carriers or transport fuels [32]. Fossil PESs include coal, crude oil and natural gas. Renewable PESs, like wood, sunlight or wind, are naturally occurring and theoretically inexhaustible [32]. PESs usually need conversion technology in order to produce a transport fuel [32]. For example, crude oil is the input of an oil refinery that produces fuels like gasoline, diesel or liquefied petroleum gas (LPG) [31]. Coal is an energy source for a coal-fired power plant that generates electricity, and wind is harnessed by a wind turbine to generate electricity [31]. When converting a PES into a fuel and then applying it in transport to cause movement, energy is lost two times. Energy losses take place not only when a PES is converted into a fuel, i.e., during the well-to-tank (WTT) phase, but also when energy is converted into work in the tank-to-wheel phase (TTW). For example, in order to produce electricity, efficiency losses occur when converting a PES, e.g., coal, to electricity. Gasoline cars have an efficiency of around 20%–35%, which means that only 20%–35% of the combustion energy is converted into work (i.e., movement). Electric cars have a larger efficiency of about 77% [33] to 95% [31]. The ratio of usable energy (i.e., input energy minus the energy losses) and input energy are often referred to as energy efficiency [31].

In 2016, Dutch transport was mainly powered by gasoline, diesel and LPG, a mixture of butane and propane obtained from natural gas (60%) and oil (40%) [29]. A total of 79% of all passenger cars used gasoline and 16% used diesel [29] (CBS, 2016). The share of new technologies, like electric and hydrogen vehicles, is small; in 2016, they were used by only 2.6% of vehicles [29]. The number of electric cars is rising rapidly, however. In 2007, 8000 electric vehicles were registered, and in 2016, the number had risen to 211,000 [29].

2.3. Electricity for Transport

Electric vehicles differ from conventional transport in their use of electric engines to power the vehicle instead of a combustion engine [34]. There are two types of electric vehicles, full electric vehicles (FEV) and hybrid electric vehicles, which use an electric engine in combination with a combustion engine [34]. During the 1990s, the "all electric car" gained attention for its promise of a clean fuel, classified as "zero-emission" because the use of electricity in vehicles does not involve direct CO_2 emission. However, the electricity that powers the batteries is derived from renewable or fossil PESs or from a mix of both. To evaluate whether an electric vehicle has low emissions, we need to consider the whole production chain, that is, not only the TTW but also the WTT phase. This is because the electricity must also be generated by a PES with low CO_2 emissions, e.g., by a renewable PES like sun or wind [35], which also need energy for the construction of wind turbines and PV (photovoltaic) panels [20,36]. However, there is electricity demand when the sun is not shining and the wind is not blowing, or there may be a supply when there is no demand. This is where the need for the storage of renewable energy arises, e.g., in the form of hydrogen generated by electrolysis [35].

2.4. Hydrogen for Transport

Hydrogen can "store" renewable electricity and is a potential fuel for transport [37]. The development of using hydrogen as a fuel is relatively new compared to electricity. Though the Dutch government has set up ambitious targets which aim for a total of 2000 hydrogen cars, 100 hydrogen buses and 20 hydrogen trucks in 2020 [38], there are only two commercially available hydrogen cars [39]. Hydrogen vehicles are in fact electric vehicles that use hydrogen (H_2) as an energy source instead of electricity [34]. The hydrogen is combined with oxygen (O_2) from the air in a fuel cell and converted to water (H_2O). This conversion produces the electricity which powers the engine. Waste products are water, vapor and heat [34]. The conversion does not emit CO_2. However, hydrogen can be produced by using renewable energy or fossil PESs to power the electrolysis process in which H_2O is converted to H_2 [34]. Producing hydrogen using fossil PESs can also be achieved by transforming natural gas (CH_4) or coal into H_2 and CO_2 under high pressure and temperatures [34].

2.5. Biofuels

A biofuel is a gas, liquid or solid fuel derived from presently available natural sources such as plants or (agricultural) residues. In other words, they are fuels produced from recently living plant matter, as opposed to ancient plant matter in the case of fossil fuels [40]. Biofuel use in transport is growing since the EU guidelines require that the share of renewable energy in 2020 in the transport sector is 10% [29]. Therefore, Dutch regulations require a mix of renewable energy (biofuels) and gasoline or diesel. In 2017, around 8% of the gasoline and diesel consisted of biofuels, growing by 0.75% per year towards 10% in 2020 [29]. There are three biofuel types often applied in transport: biodiesel, bioethanol and bio-CNG (compressed natural gas). Biodiesel refers to a vegetable oil or animal fat-based oil that has been converted into a fuel [40]. Biodiesel can be used instead of “fossil diesel” or blended with regular diesel for application in regular diesel engines. There are first, second and third generation biodiesels [12]. First generation biodiesels are made of vegetable oil or animal fat, and they are also used for human consumption. Second generation biodiesels are made of residues or waste streams that are not suitable for human consumption. Third generation biodiesel is made of cultivated algae and has only recently entered the biofuel market [40].

Bioethanol is a gasoline substitute mainly consisting of ethanol produced from different sources like crops or agricultural residues. It can be mixed with normal fuel, often up to 5% to 10% [34]. There are also vehicles with adjusted engines that allow for a fuel mix with 85% bioethanol. Bioethanol includes first and second generation bioethanol. First generation bioethanol is produced directly from (food) crops, e.g., from sugar beet. Second generation bioethanol includes fuels manufactured from various types of biomass—for example, from agricultural residues like straw [40].

Bio-CNG is made in a biogas digester using a relatively simple, mature technology [41]. In a large tank or digester, bacteria convert organic residues into methane by anaerobic digestion. The organic residues are diverse and include manure and agricultural crop residues. The product is referred to as bio-CNG (compressed natural gas) [41].

2.6. Environmental Impacts of Transport Fuels

Major contributors to climate change are greenhouse gas (GHG) emissions, in which carbon dioxide (CO_2) is the most commonly known GHG. Other GHGs include methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) [42]. The IPCC [43] recognizes four principal greenhouse gases related to human activities: CO_2, CH_4, N_2O and the halocarbons (e.g., fluorine, chlorine and bromine). In terms of transport fuels, only CO_2, CH_4 and N_2O are relevant [18]. The mitigation of climate change therefore needs to focus on the reduction of all GHG emissions (CO_2e). The Dutch transport system is mainly based on fossil oil products (diesel and gasoline) [29], making the transport and mobility sector responsible for 27% of all CO_2 emissions in The Netherlands [29]. However, alternative transport fuels that can potentially lower CFs might have an impact on natural resources, i.e., on land and water [44]. The water–food–energy nexus is an approach that considers the interactions between water, land and energy, while also taking the trade-offs into account [45]. Fossil PESs often use water for extraction, while power plants need water for cooling [46]. The cultivation of biomass for biofuels requires both land and water [40], while wind turbines require space. Therefore, land and water also have a connection. Energy and land are connected in the sense that energy is used in the production and transport chain of crops. The reduction of GHGs, therefore, has effects on land and water.

The footprint family includes emission footprints, i.e., the carbon and grey water footprint, and resource use footprints, i.e., the land and blue and green water footprints [30]. The carbon footprint calculates greenhouse gas emissions into the atmosphere [47]; the grey water footprint calculates the amount of freshwater needed in order to dilute polluted water to accepted water quality standards [48]. The land footprint assesses the amount of land needed to supply human needs in physical units [49].

The green water footprints calculate the amount of green water (precipitation) and the blue water footprint the amount of surface or groundwater needed to produce goods or services for human consumption [48].

3. Methods and Data

This study calculates the effects of fuel choices in the transport system on carbon (CFs), land (LFs) and total water footprints (WFs), using The Netherlands in 2016 as a case study. The study considers electricity as an alternative fuel; although it is categorized as a fuel, it is not a real fuel from an energy perspective. The study uses four scenarios with different fuel characteristics. The study includes road transport (cars, vans, trucks, buses), railway transport and inland shipping, but it excludes aviation and overseas shipping. The study includes the fuels used in The Netherlands in 2016: diesel, gasoline, marine diesel oil, bioethanol from sugar beet, biodiesel from rapeseed oil and biogas from manure [29]. Next, it assesses the effects of alternative fuel use on CFs, LFs and WFs. This is carried out for four different scenarios, based on the following fuels: scenario 1, the reference scenario with fuel use in 2016; scenario 2, hydrogen generated by electrolysis using the PESs coal, natural gas, wind and sun (PV); scenario 3, electricity from gas, coal, wind and sun; scenario 4, first generation bioethanol from wheat and second generation bioethanol from wheat straw.

The calculations are conducted in three steps. To calculate the carbon footprint, Step 1 collects and calculates CO_2e emissions and LFs and WFs for each fuel. Step 2 calculates the energy demand per scenario, and Step 3 assesses the CFs, LFs and WFs per scenario. Figure 1 shows the three calculation steps, the fuels included and the related PESs.

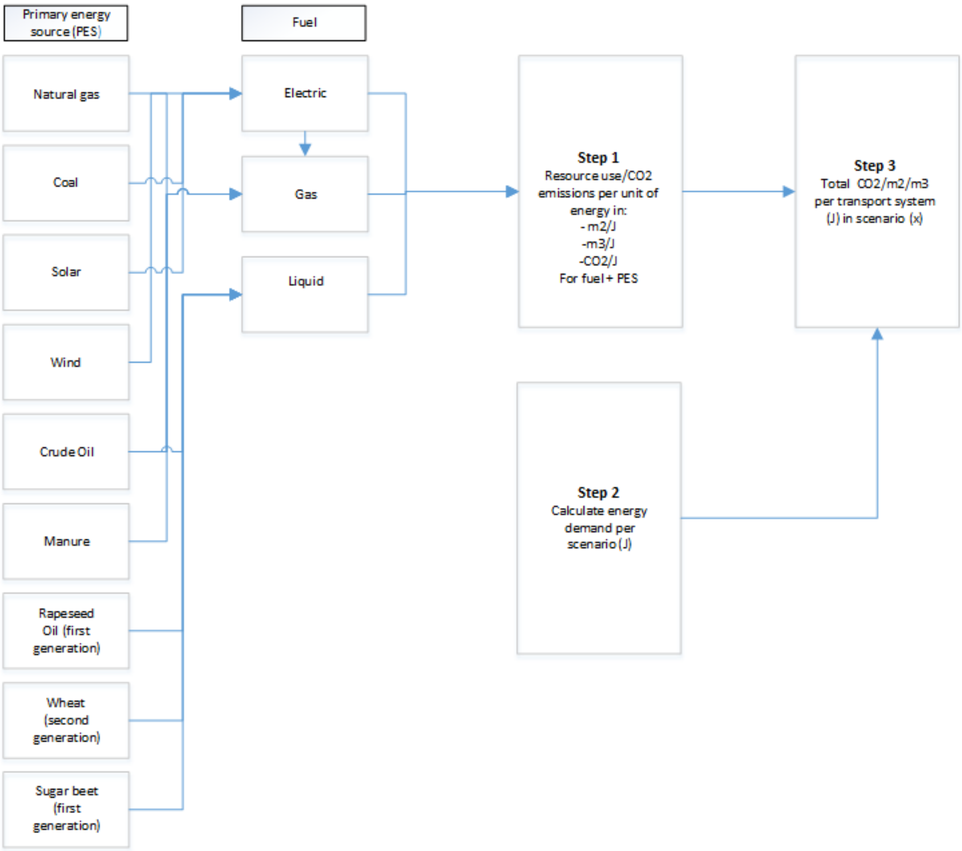

Figure 1. Three calculation steps, the fuels applied and the related PESs for the assessment of carbon, land and water footprints related to different fuel options for transport in The Netherlands using base year 2016 (note: wheat includes the wheat crop for first generation bioethanol and wheat straw for second generation bioethanol).

3.1. Step 1

Step 1 collects and calculates the CFs, LFs and total WFs for each fuel by taking the entire fuel production chain and fuel consumption (TTW and WTT) into account. CFs, LFs and WFs are expressed per unit of energy as kg CO_2e/GJ, m^2/GJ and m^3/GJ. Data on CO_2e emissions were derived from the Joint Research Centre [18–21] and on PV panel and wind turbine construction from Turconi et al. [36]. For the land use of diesel, gasoline, MDO (marine diesel oil) and LPG, we used the typical land use intensity of crude oil from the United Nations Convention to Combat Desertification [50]. Data on the LFs of biofuels were taken from Börjesson and Tufvesson [51], who have provided LFs for biofuels from crops and conversion routes in Northern Europe using current cultivation practices. Data on the LFs of electricity from natural gas, coal, wind energy and solar energy were taken from Kaza and Curtis [52], who provide data ranges rather than one number. LFs and blue WFs of manure were based on data from BioEnergyFarm [53], data on hydrogen production from Mehmeti et al. [54] and data on blue WFs of diesel, gasoline, MDO and LPG from Williams and Simons [55]. Data on WFs of Dutch biofuels was extracted from Mekonnen and Hoekstra [56] and data on blue WFs of electricity from Mekonnen et al. [17] (see also Appendices A–C). For biofuels, it is important to consider the country of production, because yields and weather conditions have a significant impact on LFs and WFs. We assumed that all biofuels used were produced in The Netherlands itself, because the country produces more biofuels itself than it imports or exports [57]. For the LF and WF of wheat straw, we applied an allocation step in which the LF and WF of the total biomass of wheat was allocated over the wheat yield and the wheat residue (straw), using the method developed by Mathioudakis et al. [58], who allocated WFs over the main product and the residue according to the value and weight fraction and used a conversion efficiency of ethanol production from straw of 18.6%. For the WF of hydrogen, we assumed that all hydrogen is generated by electrolysis, taking the electricity use of the conversion of water into hydrogen and oxygen of 4.8 kWh/m^3 H_2 (1.6 MJ/MJ H_2) from Wang et al. [59]. We calculated the WF of hydrogen per PES using the WF of the specific PES and added the WF of the electrolysis in which two molecules of water are converted in four molecules of hydrogen and one molecule of oxygen.

For fuels, the study used the following system boundaries. Firstly, for fuels derived from biomass, direct and indirect land use changes were excluded, e.g., emissions associated with deforestation. Secondly, the study assumed fuel production using state-of-the-art technology. The study also considered byproducts, meaning that CFs, LFs and WFs are allocated over products and byproducts according to the value and weight fraction. CFs for natural gas transportation were considered negligible because most of the gas is from The Netherlands itself and does not need to be transported over long distances. The study included CFs for solar panel and wind turbine production, using data from Turconi et al. [36]. The WTT emission factors of solar and wind energy are due to the inclusion of the production of wind turbines and solar panels. The emissions associated with the production of the mining and extraction infrastructure of natural gas and oil are also negligible [60,61] and were therefore excluded.

Appendix A gives the specific CFs for the transport fuels included, Appendix B the LFs and Appendix C the WFs.

3.2. Step 2

Step 2 designs three scenarios characterized by the use of a specific fuel with different PESs in The Netherlands in 2016, based on the Dutch 2016 fuel mix in the reference scenario (1). The other three scenarios are as follows: (2) the hydrogen scenario; (3) the electricity scenario; (4) the biofuel scenario. If vehicles are technically not capable of using a certain fuel, their reference fuel is used (i.e., the fuel used in the reference scenario). Table 1 shows the four scenarios, fuels and PESs.

Table 1. Four scenarios, fuels and primary energy sources included in this study.

Scenario	Dominant Fuel	Primary Energy Sources (PESs)
Scenario 1	Dutch transport fuel mix 2016	Diesel, gasoline, (marine diesel oil (MDO), liquefied petroleum gas (LPG), bioethanol, biodiesel, biogas, electricity (mix of coal, gas, solar, wind)
Scenario 2	Hydrogen	Electricity (natural gas, coal, wind, solar)
Scenario 3	Electricity	Natural gas, coal, wind, solar
Scenario 4	Biofuels	Bioethanol (sugar beet, wheat, wheat straw), biodiesel (rapeseed oil)

Step 2 calculates the total energy demand of the reference scenario (x) (Joules) in The Netherlands in 2016, *Etransport (x)*, by summing the energy demand of *fuel (a)* per transport mode *(s)* and next summing the energy demand of all transport modes:

$$Etransport\ (x) = \sum_{s=1}^{t}\sum_{a=1}^{n} Fuel(a,s) \tag{1}$$

Data on the fuel energy demand for transport modes were taken from Statistics Netherlands (CBS) [29], Statline [62–66] (2016) and Rijkswaterstaat [67]. The total energy demands of the scenarios differ from the total demand of the reference scenario due to differences in the energy losses during the TTW stages. The study calculated the total energy demand per scenario for *Etransport (s)*, taking the efficiencies of the reference scenario *E(x)* and the efficiency of the scenario *E(s)* into account by:

$$Etransport\ (s) = Etransport\ (x) \times E(x) \times 1/E(s) \tag{2}$$

For TTW efficiencies of transport using biodiesel, bioethanol, diesel and gasoline, we used a value of 28% from Wang [68] and Sadiq [69] et al. and a value of 37% for hydrogen and 77% for electricity, taken from Ambel [33]. For the electric scenario, we assumed that trucks and inland shipping do not use electricity but the fuel of the reference scenario.

3.3. Step 3

Step 3 combines results from Step 1 and 2 to obtain the CFs, LFs and WFs per scenario. Total CFs are calculated by multiplying the energy demand of transport mode (s) of scenario (x) (PJ) for fuel (a), *Etransport (x,s,a)*, by the environmental impact parameter, $EimpactCO_2$, that correlates with the PES (e) for fuel (a) (kg CO_2e/GJ):

$$CO_2e\ emissions\ (x) = \sum\nolimits_{s=1}^{n} Etransport\ (x,s,a) \times EimpactCO_2(e,a) \tag{3}$$

The CFs are expressed as Mt CO_2e. The total LFs and WFs are calculated in the same way and are expressed as 10^9 m^2 and 10^9 m^3.

4. Results

Figure 2 shows the specific carbon footprints of fuels, including the WTT and TTW emissions (kg CO_2e/GJ).

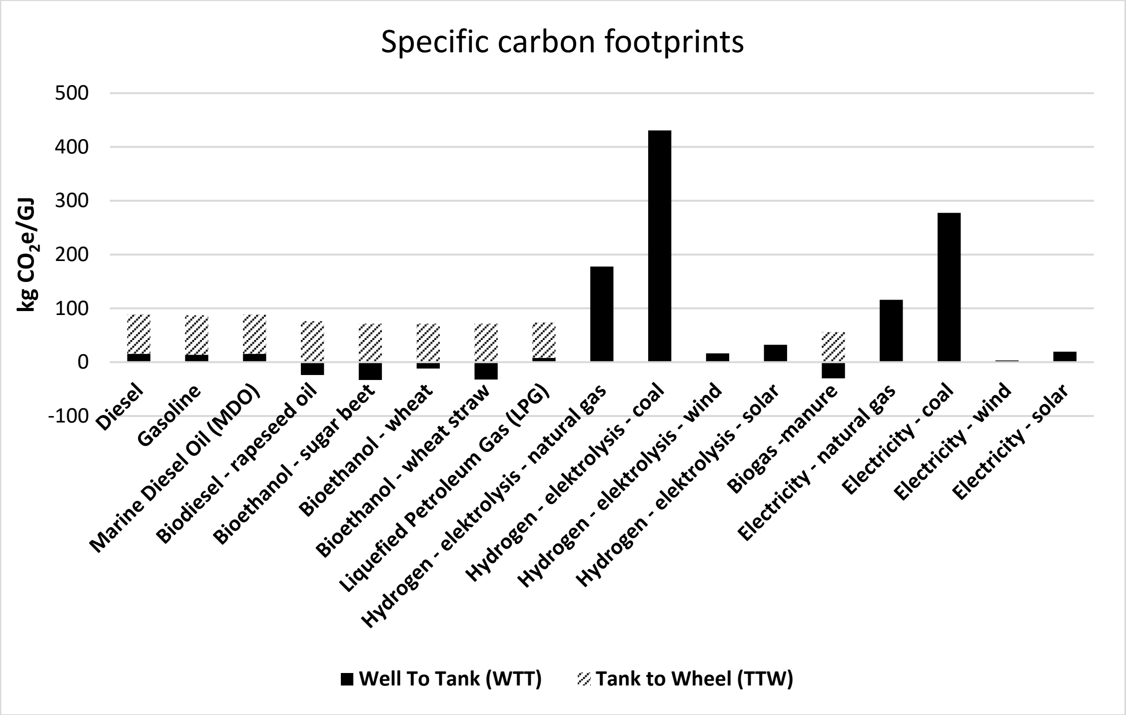

Figure 2. Specific carbon footprints of fuels, showing the well to tank (WTT) (emissions in the production chain of a fuel) and tank to wheel (TTW) (emissions during the combustion of a fuel) per gigajoule (GJ) of energy provided to the transport system (kg CO_2/GJ).

Figure 2 shows large differences among CFs for fuel types and related primary energy sources. Hydrogen and electricity do not have TTW emissions, while liquid and gaseous fuels do. The CFs of diesel and gasoline, the traditional liquid fuels, are smaller than some of the new fuels, like hydrogen, from electrolysis using coal or natural gas, or electricity from coal. The difference in CFs between electricity from wind and hydrogen from coal, for example, is more than a factor 20. Only when renewable PESs are used are CFs small. For the biofuels, the emissions in the WTT stage are negative, because crops take up CO_2 that is released again when the fuel is combusted. Appendix A gives the CFs per fuel type. Figure 3 shows the specific land footprints for fuels per primary energy source (m^2/GJ) on a logarithmic scale.

The differences between the land footprints (LFs) are larger in comparison to the carbon footprints (CFs). In particular, fuels derived from agriculture have large LFs. Bioethanol from wheat, for example, requires a factor 10,000 more land per unit of energy than diesel (from crude oil). Fossil fuels have the smallest LFs, while the LFs of wind and solar energy find themselves in between the two extremes. Appendix B gives the specific land footprints. Figure 4 shows the specific water footprints per fuel and related primary energy source on a logarithmic scale (m^3/GJ).

WFs of biofuels have a large green component and a small grey component, while all other WFs are blue. The differences among WFs are significant. Bioethanol from rapeseed oil, for example, requires a factor 10,000 more water than diesel from crude oil. In general, WFs are the largest for fuels derived from agriculture and the smallest for electricity from wind. The figure also shows that if renewable energy is stored as hydrogen, the WF increases. Appendix C gives the specific water footprints, including green, blue and grey WFs. Figure 5 shows the total energy demand per scenario, in which the reference scenario's energy demand forms the basis for the energy demand of the other three scenarios.

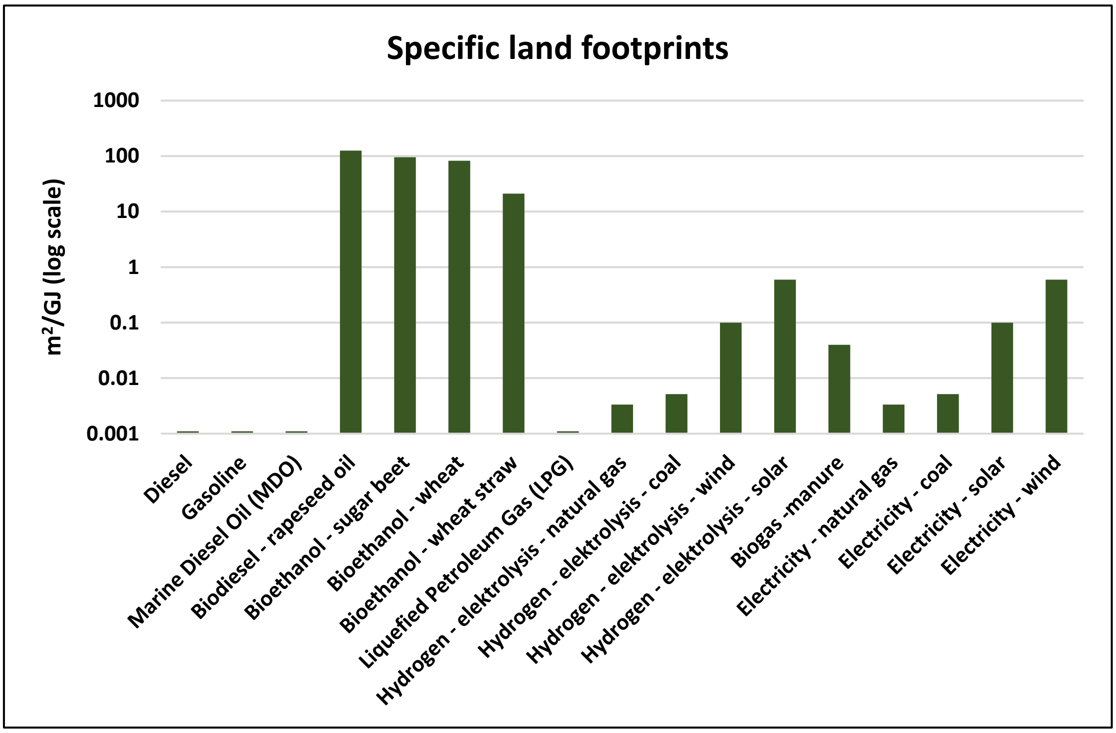

Figure 3. Land footprints per fuel and according to primary energy source (m^2/GJ, logarithmic scale).

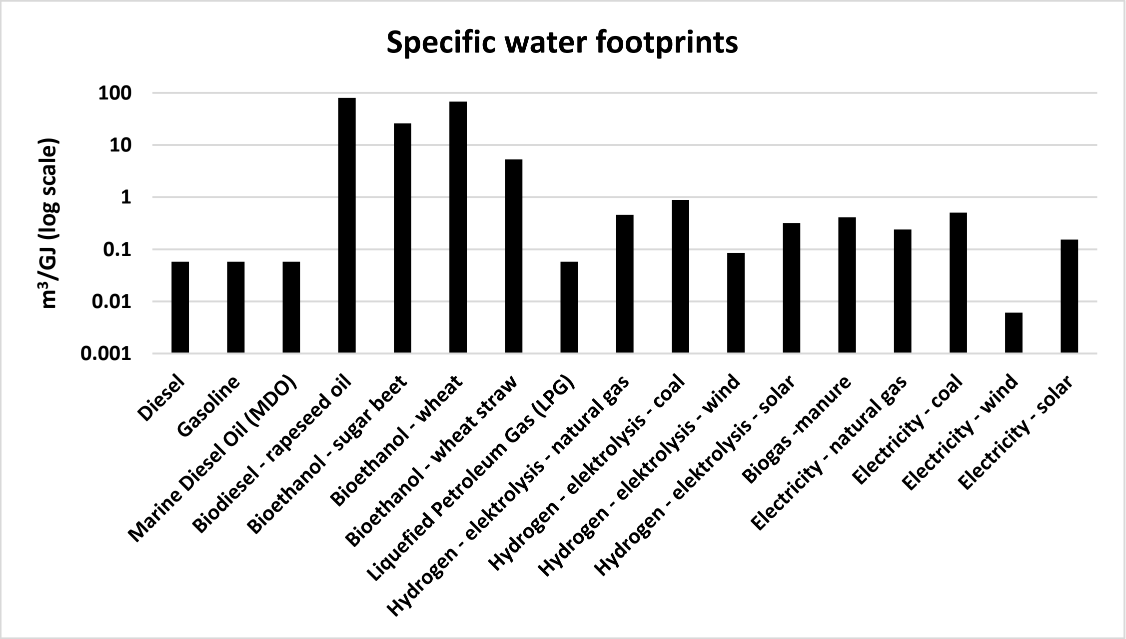

Figure 4. Specific total water footprints per fuel and related primary energy source on a logarithmic scale (m^3/GJ).

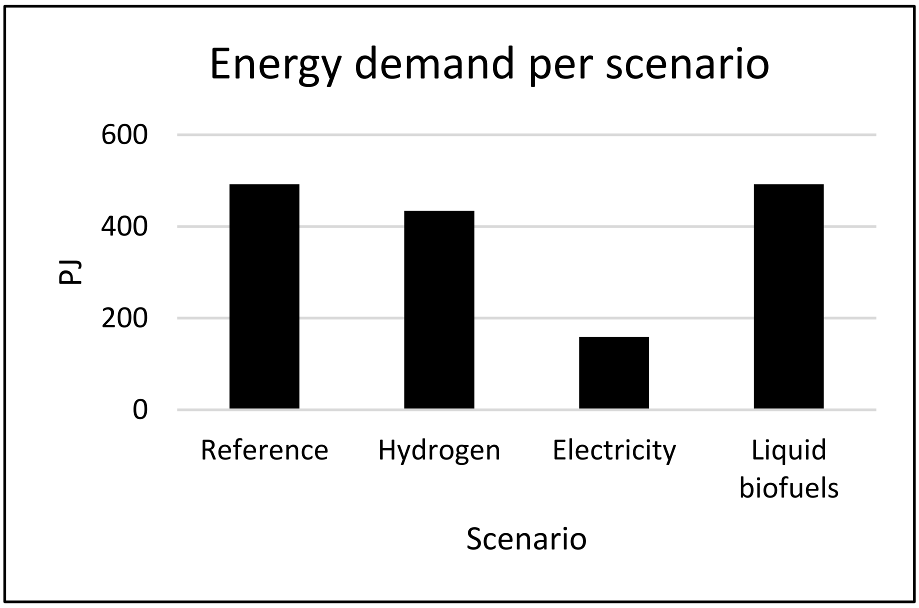

Figure 5. Total energy demand per fuel scenario for the reference situation in The Netherlands in 2016 and scenarios using hydrogen, electricity and liquid biofuels (in petajoules (PJ)).

Figure 5 shows that transport using electricity is the most energy efficient, with a total annual energy use of 159 PJ, while the reference scenario (492 PJ), the scenario with liquid biofuels (492 PJ) and the hydrogen scenario (434 PJ) are less energy efficient. If the electricity scenario is not possible, a hybrid scenario (242 PJ) is most favorable.

Figure 6a–d shows the total annual energy demand per fuel in (PJ), the annual CF (kt CO_2e), the annual LF (m^2) and annual WF (m^3) for scenario 1 (reference scenario), with regard to the situation in The Netherlands in 2016.

Figure 6a shows that energy use for transport in The Netherlands is dominated by the use of gasoline and diesel, which also contribute the most to the carbon footprint (CF). The contribution of the other fuels is small. However, Figure 6c,d show that the use of small amounts of bioethanol and biodiesel cause large LFs and WFs compared to gasoline and diesel.

Figure 7 shows the annual CF of the four scenarios, including the reference scenario (kt CO_2e).

The figure shows that CFs decrease compared to the situation in 2016 if the alternatives are chosen wisely. If hydrogen that is generated using fossil fuels is applied, however, the total emissions increase. Additionally, a shift towards electricity does not always decrease the emissions substantially. This is only the case when wind and solar energy are applied. In addition, the use of bioenergy decreases CFs.

Figure 8 shows the annual LF of the four scenarios for transport fuels in The Netherlands, including the reference scenario for fuel use in 2016 on a logarithmic scale (10^9 m^2).

The LF of scenario 1, the reference scenario for 2016, is relatively large when compared to the LFs of scenarios 2 and 3, which do not include any biofuels. This is caused by the use of a mixture of gasoline and ethanol, and diesel and biodiesel, in The Netherlands. All LFs in biofuel scenario 4 are large compared to the LFs of scenarios 2 and 3, because this scenario relies on crops from agriculture.

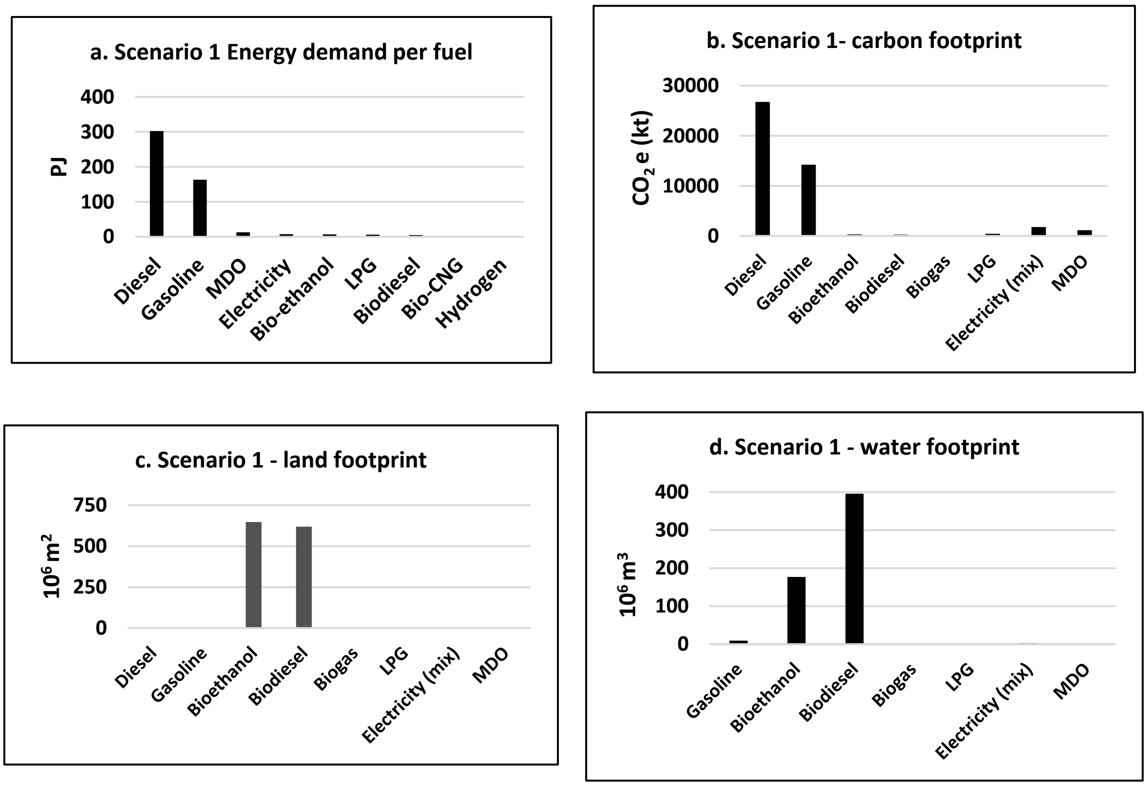

Figure 6. Here, (**a**) shows the total annual energy demand per fuel in scenario 1, the reference scenario (PJ); (**b**) shows the annual carbon footprint in scenario 1, the reference scenario (kt CO_2e); (**c**) shows the annual land footprint in scenario 1, the reference scenario (m^2); (**d**) shows the total annual water footprint (green, blue and grey) in scenario 1, the reference scenario (m^3).

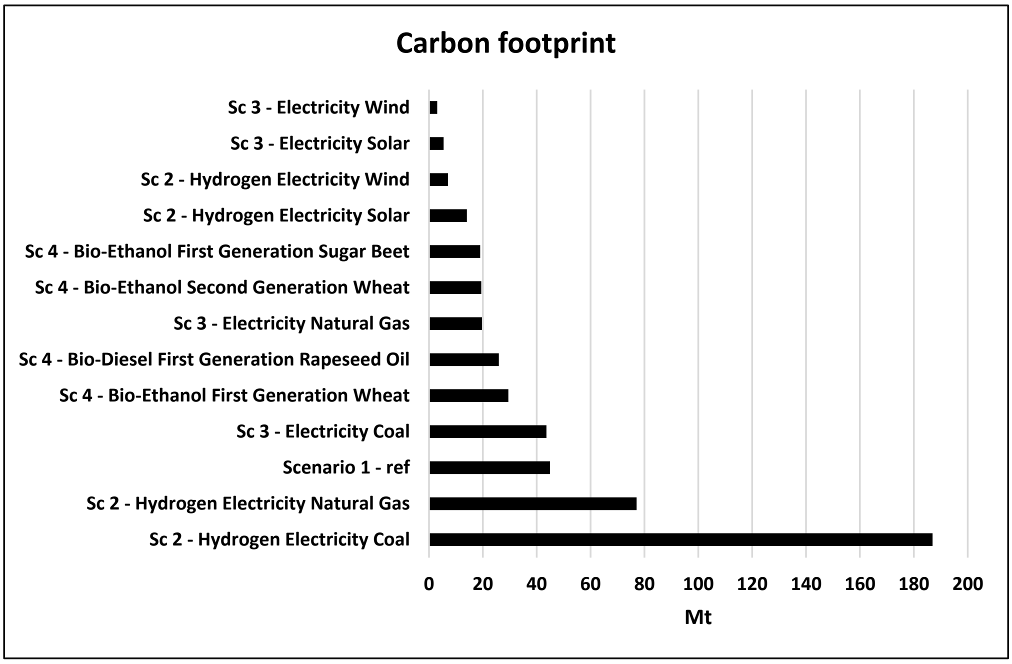

Figure 7. Annual carbon footprint of the four scenarios for transport fuels in The Netherlands, including the reference scenario for fuel use in 2016 (Mt CO_2e).

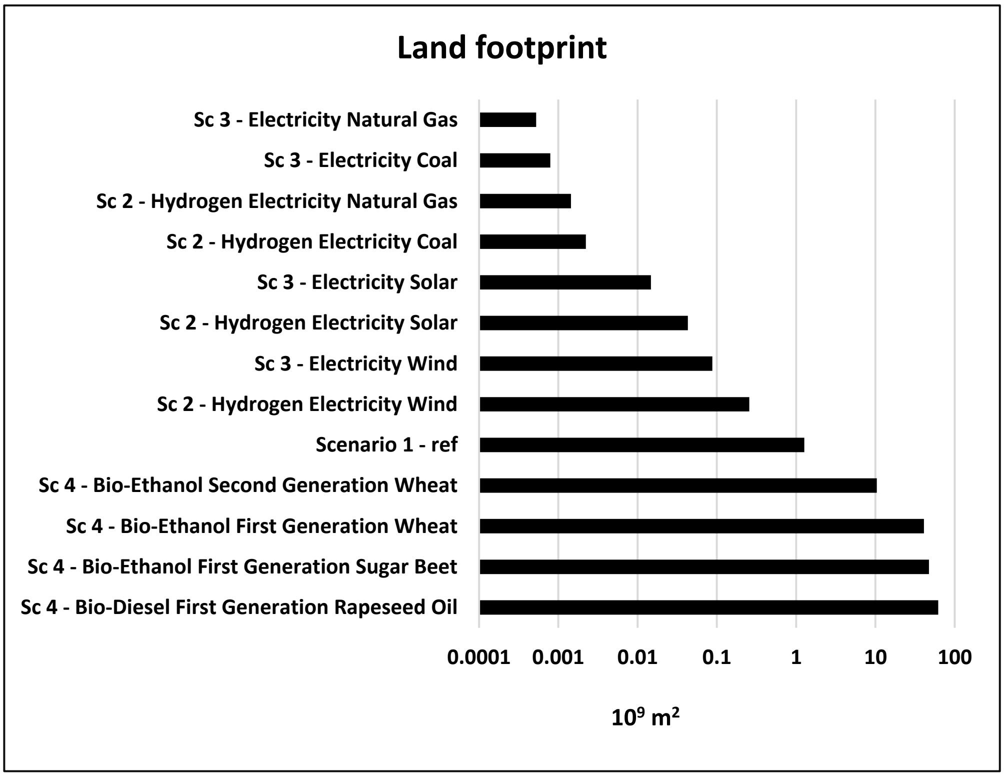

Figure 8. Annual land footprint of the four scenarios for transport fuels in The Netherlands, including the reference scenario for fuel use in 2016 (10^9 m^2 logarithmic scale).

Figure 9 shows the annual total WF of the four scenarios for transport fuels in The Netherlands, including the reference scenario for fuel use in 2016, on a logarithmic scale (10^9 m^3)

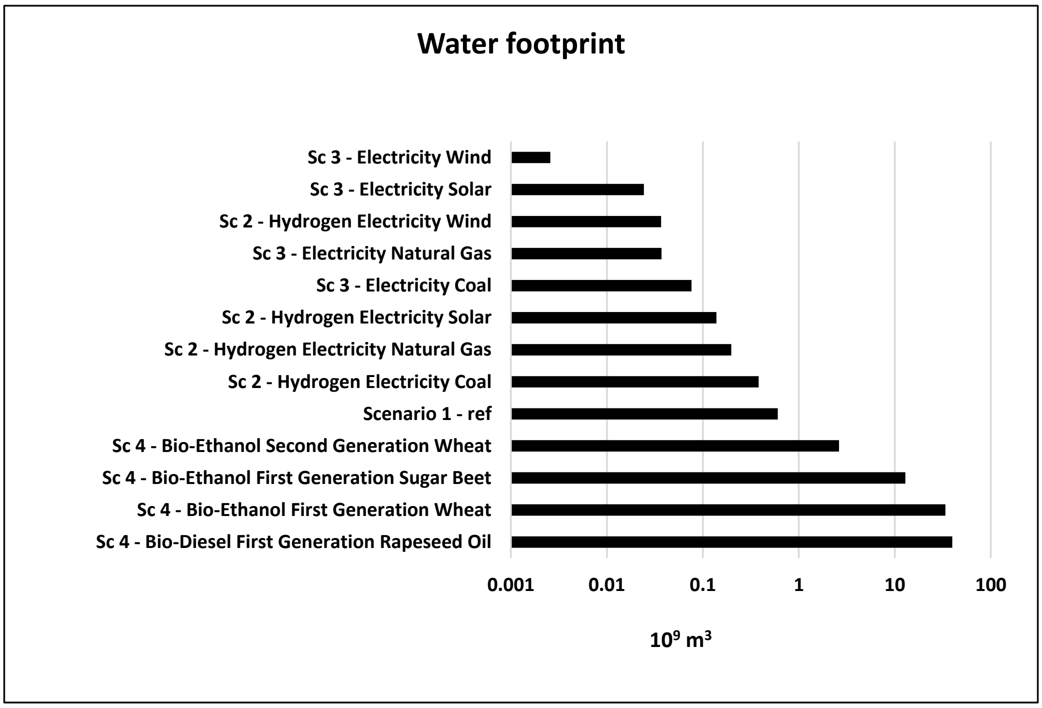

Figure 9. Annual water footprint of the four scenarios for transport fuels in The Netherlands, including the reference scenario for fuel use in 2016 (10^9 m^3 logarithmic scale).

Scenario 4, using crops from agriculture, has the largest WFs (mainly green), followed by scenario 1, the reference scenario, which also includes some biofuels. The scenario using hydrogen from coal, natural gas or solar photovoltaics has blue WFs which are smaller than the reference. When electricity from wind or sun is applied, WFs are smallest.

The main message of this article is the importance of combining different environmental assessments in a complex assessment. Policy aims to decrease CFs. Figure 6 shows the present CF and the related LF and WF. Figure 7 shows the different options for decreasing CFs, compared to the situation in 2016 (reference scenario), indicating that not all options are favorable and that the choice of PES is important. Figures 8 and 9 show the consequences of a specific fuel choice on LFs and WFs. In order to decrease CFs, a shift towards biofuels generates large LFs and WFs. This is the case even for the reference scenario, in which a contribution of only 2.5% of the energy in the form of biofuel to the total energy use of transport generates large LFs and WFs. If a decrease in CFs is the policy's priority, the best fuel choices, if LFs and WFs are also taken into account, are electricity from wind or sun, followed by hydrogen from wind or solar.

5. Discussion

The study assessed the carbon, land and water footprints related to policy goals to decrease CO_2 emissions for different fuel options by assuming that the transport system itself does not change. Other possible options to decrease CFs, such as a decrease in transport activity, increased energy efficiency of transport modes or a shift towards less CO_2 intensive ways of transport, were excluded. We only considered fuel shifts; however, we did include the related efficiency improvements by taking the tank-to-wheel efficiencies into account. For example, we included the larger efficiencies of electric vehicles compared to traditional cars using gasoline. This means that the scenario results might differ from a future situation in which other factors also play a role, such as technological developments in the automotive industry.

For the assessment of CFs, we mainly applied data from the Joint Research Centre (JRC) [18–21] that provide emission factors in the context of the EU. For the LFs and WFs of wind, solar and hydrogen, we used data that provide a general LF and WF. For biofuels, however, we used data for The Netherlands. In The Netherlands, crop yields are relatively large [70] and, therefore, the LFs per unit of biofuel are relatively small. In addition, WFs are also relatively small for Dutch biofuels and are dominated by green WFs [56]. This means that if the results are applied to other countries, the LFs and WFs of biofuels will probably be underestimated.

The EU policy to promote renewables for transport, such as the use of bioethanol, decreases CFs but has a large contribution to LFs and WFs. The term renewable energy is widely used, but it might be problematic in the context of sustainability [71]. This means that there is a difference between renewable energy and sustainable energy. The choice to encourage the use of renewable fuels for transport might have significant consequences for other resources, not only for land and water but also for scarce raw materials [9,71]. The Dutch policy to encourage the use of electricity for transport must also be seen in a broader context. Electric cars are more efficient than their fossil fuel-based counterparts, so the total energy use will decrease. However, it is important to consider how the electricity is generated, and the impact of this on whether or not CFs decrease. If coal is used to generate electricity, emissions do not decrease. Only if large scale wind and solar energy are applied do emissions substantially decrease. However, at present, The Netherlands does not generate these large amounts of renewable energy. The renewable energy sources, wind and solar, are crucial in reducing CFs and have acceptable impacts on land and water. However, currently, a minor proportion (6.6%) of all energy in The Netherlands is renewable [72]. The share of renewable energy must increase in order to supply enough energy for all different energy-consuming sectors. Therefore, it is likely that the use of renewable energy (solar and wind) will become susceptible to competition between different sectors, including transport.

Another issue is the variability of wind and solar energy or intermittency, requiring energy storage, e.g., in the form of hydrogen. This means that it is not possible to simply scale up renewable electricity production, even though this is theoretically the most efficient option. Here, hydrogen might be introduced, but with smaller efficiencies. However, the infrastructure does not yet exist for electric and hydrogen-based technologies, meaning that there are not yet enough wind turbines and solar panels to provide the entire transport system with sufficient energy. Moreover, electric and, to a larger extent, hydrogen vehicles have not yet penetrated the vehicle market, representing only 8% of the total vehicles [73], a negligible percentage of all Dutch vehicles. In addition, for hydrogen, the fueling infrastructure is not abundant enough in The Netherlands. Therefore, these options can be considered long-term solutions.

This study assessed the LF; however, land could also be defined as use of space. This is especially relevant when it comes to wind turbines, which are very commonly placed in the sea as well as on land. For example, the coastal sea area of The Netherlands (the Exclusive Economic Zone) includes approximately 1400 km^2 of available space for wind turbines [74]. The required space for the wind turbines in the electricity–wind scenario is 43.2 km^2, showing that the Dutch area of the North Sea is sufficient to supply enough electricity for the Dutch transport system. In line with results from the literature, e.g., [17,40,52,75,76], basing the Dutch transport system on liquid biofuels is not an option, because its land and water requirements will compete excessively with our basic water and food requirements.

When WFs are put into perspective, the present transport system in The Netherlands has a green WF of 520 × 10^6 m^3 per year, a blue WF of 31 × 10^6 m^3 and a grey WF of 59 × 10^6 m^3 per year. Biofuels dominate the total WF and contribute 95%. If hydrogen is chosen as a transport fuel, generated by electrolysis from coal, the total WFs decrease to 381 × 10^6 m^3 per year, but the WF is completely blue and increases tenfold compared to the blue WF of the present transport system. Electricity from wind has the smallest blue WF, at only 2.6 × 10^6 m^3 per year. If biofuels are adopted, e.g., bioethanol from sugar beet, the WFs would increase enormously. In 2011, the green WF in The Netherlands was 17,591 × 10^6 m^3, the blue WF 2147 × 10^6 m^3 and the grey WF 4680 × 10^6 m^3 [77]. These WFs are mainly external: 95% of the water is used outside the country [77]. The scenario providing ethanol from sugar beet has a green WF of 10,416 and a grey WF of 2480 × 10^6 m^3 or 59% and 52% of the Dutch green and grey WFs in 2011, respectively. This would put a large amount of pressure on the WFs.

When LFs are put into perspective, the present Dutch transport system has a LF of 1267 km^2, or 3% of the surface area of The Netherlands, at 41,000 km^2 [12]. This LF is dominated by biofuel use. The scenarios based on biofuels have LFs similar to or exceeding the Dutch surface area, indicating that it is not possible to produce all fuels in The Netherlands itself. For CFs, it does not matter whether emissions take place in The Netherlands or abroad, because emissions have a global impact. For CFs, the smallest footprints are the most favorable.

The example for The Netherlands is relevant for other EU countries too. Total transport energy use in the EU in 2030 could be around 24,000 PJ per year [12] or fifty times the present Dutch energy use. All countries must comply with the same EU directive to replace 10% of the fuel with renewables, so wise choices must be made in order to prevent LFs or WFs becoming too large.

6. Conclusions

Traditional transport fuels, including diesel, gasoline, marine diesel oil and liquefied gasoline gas, have CFs between 74 (LPG) and 89 (diesel) kg CO_2e per GJ. The CFs of bioethanol and biodiesel are smaller, at between 40 and 60 kg CO_2e per GJ, and are related to energy use in the life cycle of the production of the biofuel. For electricity, emissions range between 3 (electricity from wind), 19 (solar), 116 (natural gas fired power plants) and 277 (electricity from coal fired power plants) kg CO_2e per GJ. This means that if energy policy promotes electric transport, it is important to apply a primary energy source with small CFs, otherwise emissions will increase rather than decrease. This is even more relevant if hydrogen is applied. CFs range between 16 (electrolysis using electricity from wind), 32 (solar), 178 (natural gas fired power plants) and 431 (electricity from coal fired power plants) kg CO_2e per GJ.

Traditional transport fuels have relatively small LFs, at 0.0011 m^2 per GJ. Wind turbines and solar panels need space and have LFs of 0.1 and 0.6 m^2 per GJ, respectively. The LFs of Dutch biofuels are large, between 21 (ethanol from wheat straw) and 125 (biodiesel from rapeseed) m^2 per GJ. Dutch biofuels also have large WFs, between 5 (ethanol from wheat straw) and 80 (biodiesel from rapeseed) m^3 per GJ. The WFs for hydrogen vary between 0.1 (electrolysis using wind energy) and 0.8 (electrolysis using electricity from a coal fired power plant) m^3 per GJ. Other fuels have small WFs compared to biofuels.

The total energy demand for transport in The Netherlands in 2016, excluding air transport, was 492 PJ. If biofuels are applied, energy demand remains the same; for a hydrogen scenario, 434 PJ is needed. The electricity scenario is the most efficient with an energy demand of 159 PJ. From a sustainability point of view, the biofuel scenario is not attractive. The total energy demand remains the same, CFs only slightly decrease, and LFs and WFs increase enormously. This can already be observed in the reference scenario, where biofuels contribute only 2.5% to the total energy demand, but they dominate the LFs and WFs, with 99.9% of the total LF and 95% of the total WF. The electricity scenario has the smallest CFs, but only if wind or solar energy is applied. If electricity is generated using existing coal fired power plants, emissions do not decrease. This scenario also has the smallest LFs and WFs and is therefore the most favorable from a sustainability point of view. If storage is needed and hydrogen is applied, CFs for the most favorable PES, i.e., wind energy, double from 3055 to 7074 kg CO_2e, LFs increase from 15×10^6 to 43×10^6 m^2, and WFs increase from 3×10^6 to 37×10^6 m^3 compared to the electricity scenario.

This case study for The Netherlands shows that the use of less CF-intensive fuels contributes to energy policy aims to decarbonize transport and to substantially decrease emissions. However, trade-offs with land and water resources might occur and these need to be included in the decision-making. Other countries could also adopt these strategies.

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List of Abbreviations and Definitions

BE1W	Bioethanol first generation Wheat
BE1SB	Bioethanol first generation sugar beet
BE2W	Bioethanol second generation wheat
BD1R	Biodiesel first generation rapeseed oil
BGM	Biogas manure
Bio-CNG	Bio-compressed natural gas
CF	Carbon footprint in CO_2e
CO_2e	CO_2-equivalent weighted average of all GHG emissions
EM	Electricity mix
ENG	Electricity natural gas
EC	Electricity coal
EW	Electricity wind
ES	Electricity solar
EW+G	Electricity wind + gasoline
EM+G	Electricity mix + gasoline
EW+B	Electricity wind + bioethanol
EM+B	Electricity mix + bioethanol

Environmental impact parameter	The amount of CO_2, water and land use per unit of energy
GHG	Greenhouse gas
GJ	Gigajoule (10^9 Joule)
H2EM	Hydrogen electricity mix
H2ENG	Hydrogen electricity natural gas
H2EC	Hydrogen electricity coal
H2EW	Hydrogen electricity wind
H2ES	Hydrogen electricity solar
H2GNG	Hydrogen gasification natural gas
H2GC	Hydrogen gasification coal
HFO	Heavy fuel oil
J	Joule
LPG	Liquefied petroleum gas
MDO	Marine diesel oil
MJ	Megajoule (10^6 joule)
Mt	Megaton (10^9 kg)
PES	Primary energy source—energy sources that can be used directly, as they appear in the natural environment
PJ	Petajoule ((10^{15} joule)
PV	Photovoltaics
REF	Reference
TTW	Tank-to-wheels emissions that occur during the combustion of a fuel in a vehicle
WTT	Well-to-tank emissions that occur in the production chain of a fuel
WTW	Well-to-wheels—TTW and WTT emissions combined
WF	Water footprint—the total annual volume of freshwater used to produce the goods and services related to consumption

Appendix A. Specific Carbon Footprints for Transport Fuels

Table A1 gives the specific carbon footprints (kg CO_2e per GJ) for transport fuels, including the well-to-tank (WTT), tank-to-wheels (TTW) and well-to-wheels (WTW) footprints. Data were derived from the Joint Research Center [20] (JRC) and from Turconi et al. [36].

Table A1. Specific carbon footprints, including the well-to-tank (WTT), tank-to-wheels (TTW) and well-to-wheels (WTW) emissions. (Sources: JRC [20]; Turconi et al. [36]).

Fuel Type	**Reference**	**Fuel**	**Carbon Footprint (kg CO_2e/GJ)**		
			WTT	**TTW**	**WTW**
Liquid	[20,36]	Diesel	15.4	73.2	88.6
	[20,36]	Gasoline	13.8	73.4	87.2
	[20,36]	Marine diesel oil (MDO)	15.4	73.0	88.4
	[20]	Biodiesel—rapeseed oil	−23.9	76.2	52.3
	[20,36]	Bioethanol—sugar beet	−33.0	71.4	38.4
	[20,36]	Bioethanol—wheat	−12.0	71.4	59.4
	[20,36]	Bioethanol—wheat straw	−32.2	71.4	39.2
Gaseous	[20]	Liquefied petroleum gas (LPG)	8.0	65.8	73.8
	[20]	Hydrogen electrolysis—natural gas	177.6	0	177.6
	[20]	Hydrogen electrolysis—coal	430.8	0	430.8
	[20]	Hydrogen electrolysis—wind	16.3	0	16.3
	[20]	Hydrogen electrolysis—solar	32.4	0	32.4
	[20,36]	Bio-compressed natural gas (CNG)—manure	−30.0	56.0	26.0
	[20]	Electricity—natural gas	115.8	0	115.8
	[20]	Electricity—coal	277.4	0	277.4
	[20,36]	Electricity—wind	3.3	0	3.3
	[20,36]	Electricity—solar	19.4	0	19.4

Appendix B. Specific Land Footprints for Transport Fuels

Table A2 gives the specific land footprints for transport fuels.

Table A2. Specific land footprints for transport fuels. (Sources: United Nations Convention to Combat Desertification (UNCCD) [50] for typical values; Börjesson and Tufvesson [51] for crops and technologies in Northern Europe; this study; BioEnergyFarm [53]; Kaza and Curtis [52]).

Type	References	Fuel	Land Footprint (m^2/GJ Final Fuel)
Liquid	[50]	Diesel	0.001
	[50]	Gasoline	0.001
	[50]	Marine diesel oil (MDO)	0.001
	[51]	Biodiesel—rapeseed oil	125
	[51]	Bioethanol—sugar beet	95
	[51]	Bioethanol—wheat	83
	[51]	Bioethanol—wheat straw	21
Gaseous	[50]	Liquefied petroleum gas (LPG)	0.011
	[this study]	Hydrogen electrolysis—electricity mix	0.004
	[this study]	Hydrogen electrolysis—natural gas	0.003
	[this study]	Hydrogen electrolysis—coal	0.005
	[this study]	Hydrogen electrolysis—wind	0.099
	[this study]	Hydrogen electrolysis—solar	0.590
	[this study]	Hydrogen thermal—coal	0.005
	[this study]	Hydrogen thermal—natural gas	0.003
	[53]	Bio-compressed natural gas (CNG)—manure *	0.040
	[52]	Electricity—natural gas	0.002–0.005
	[52]	Electricity—coal	0.002–0.008
	[52]	Electricity—wind	0.286–0.897
	[52]	Electricity—solar	0.046–0.153

* Average measurement of a biogas digester is 240 m^3 with an overall capacity of 335 MWh per year; 335 MWh is 1205 GJ per year (BioEnergyFarm [53]). Assuming that an average bio digester has a height of 5 m, this leaves a ground surface of 48 m^2. Dividing the surface by the amount of energy generated in the digester in one year gives an environmental impact parameter of 0.04 m^2/GJ.

Appendix C. Specific Water Footprints for Fuels

Table A3 gives the specific water footprints for fuels.

Table A3. Specific water footprints for fuels. (Sources: Williams and Simons [55]; Mekonnen and Hoekstra [60]; Mathioudakis et al. [58]; this study; Mekonnen et al. [17]).

Type	References	Fuel	Water Footprint (m^3/GJ Final Fuel)		
			Blue	green	grey
Liquid	[55]	Diesel	0.06	0	n.d *
	[55]	Gasoline	0.06	0	n.d *
	[55]	Marine diesel oil (MDO)	0.06	0	n.d *
	[60]	Biodiesel—rapeseed oil	0	75	5
	[60]	Bioethanol—sugar beet	0	21	5
	[60]	Bioethanol—wheat	0	50	18
	[58]	Bioethanol—wheat straw	0	4	1
Gaseous	[55]	Liquefied petroleum gas (LPG)	0.06	0	n.d *
	[this study]	Hydrogen electrolysis—natural gas	0.46	0	n.d *
	[this study]	Hydrogen electrolysis—coal	0.88	0	n.d *
	[this study]	Hydrogen electrolysis—wind	0.08	0	n.d *
	[this study]	Hydrogen electrolysis—solar	0.32	0	n.d *
	**	Bio-compressed natural gas (CNG)—manure	0.41	0	n.d *
	[17]	Electricity—natural gas	0.24	0	n.d *
	[17]	Electricity—coal	0.50	0	n.d *
	[17]	Electricity—wind	0.01	0	n.d *
	[17]	Electricity—solar	0.15	0	n.d *

* n.d. = no data. ** See calculation below in Table A4.

Table A4. Calculation water footprint Bio-compressed natural gas (CNG)—manure.

Water Use Bio-CNG (Sources: BioEnergyFarm [53])		
Input Capacity Installation: 15,000 kg Water Input (15 m^3). Output: 1000 m^3 CNG Energy Content CNG: 37 MJ/m^3 = 37,000 MJ		
Calculation	0.000405405	m^3/MJ
	0.405405405	m^3/GJ

Appendix D. Scenarios 1–4

Appendix D gives the carbon footprint (CO_2e emissions in kt), land footprint (10^6 m^2) and water footprint (10^6 m^3) for the four scenarios. Table A5 shows the energy use, CO_2e emissions, land and water footprints per fuel for scenario 1, the reference scenario, i.e., the fuel use in The Netherlands in 2016.

Table A5. Energy use and carbon, land and water footprints for scenario 1, the reference scenario, i.e., fuel use in The Netherlands in 2016.

Fuel	Energy Use (PJ)	Carbon Footprint (Mt)	Land Footprint (10^6 m^2)	Water Footprint (10^6 m^3)
Diesel	302.2	26.775	0.33	17.38
Gasoline	163.0	14.214	0.18	9.37
Bioethanol	6.8	308	647.62	176.80
Biodiesel	5.0	259	618.83	395.92
Bio-compressed natural gas (CNG)	0.45	12	0.02	0.18
Liquefied petroleum gas (LPG)	6.0	443	0.01	0.35
Electricity (mix)	7.4	1.777	0.03	2.75
Marine diesel oil (MDO)	13	1.149	0.01	0.75
Total	503.8	44.936	1266.83	603.50

Table A6 shows the carbon, land and water footprints for scenario 2, the hydrogen scenario.

Table A6. Carbon, land and water footprints for scenario 2, the hydrogen scenario.

Fuel	Carbon Footprint (Mt)	Land Footprint (10^6 m^2)	Water Footprint (10^6 m^3)
Electrolysis—natural gas	77.078	1.4	197.8
Electrolysis—coal	186.967	2.2	381.1
Electrolysis—wind	7.074	43.2	36.8
Electrolysis—solar	14.061	256.8	138.4

Table A7 shows the carbon, land and water footprints for scenario 3, the electricity scenario.

Table A7. Carbon, land and water footprints for scenario 3, the electricity scenario.

Fuel	Carbon Footprint (Mt)	Land Footprint (10^6 m^2)	Water Footprint (10^6 m^3)
Electricity—natural gas	19.705	0.5	37.0
Electricity—coal	43.622	0.8	76.3
Electricity—wind	3.055	14.7	2.6
Electricity—solar	5.438	87.6	24.3

Table A8 shows the carbon, land and water footprints for scenario 4, the biofuels scenario.

Table A8. Carbon, land and water footprints for scenario 4, the biofuels scenario.

Fuel	Carbon Footprint (Mt)	Land Footprint (10^6 m^2)	Water Footprint (10^6 m^3)
Bioethanol—first generation wheat	29.462	40,935	33,728
Bioethanol—first generation sugar beet	19.046	47,238	12,896
Bioethanol—second generation wheat straw	19.443	10,417	2622
Biodiesel—first generation rapeseed oil	25.941	62,000	39,680

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