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Key Points:
- Switching to alternative transport fuels entail land and water tradeoffs
- Solar-powered electric cars have the smallest environmental footprints per km
- Biofuel driven cars have the largest environmental footprints per km

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The Environmental Footprint of Transport by Car Using Renewable Energy

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Abstract Replacing fossil fuels in the transport sector by renewable energy will help combat climate change. However, lowering greenhouse gas emissions by switching to alternative fuels or electricity can come at the expense of land and water resources. To understand the scale of this possible trade-off, we compare and contrast carbon, land, and water footprints per driven km in midsize cars utilizing conventional gasoline, biofuels, bioelectricity, solar electricity, and solar-based hydrogen. Results show that solar-powered electric cars have the smallest environmental footprints per km, followed by solar-based hydrogen cars, and that biofuel-driven cars have the largest footprints.

1. Introduction

Human-driven emissions from fossil fuel combustion are the largest contributor to climate change (Pachauri et al., 2014). Climate change related risks are steering us towards developing innovative strategies and pathways that are quick in reducing greenhouse gas (GHG) emissions. The road to a low carbon world entails making decisions across sectors, with some sectors, such as transport having a large potential because of its large GHG emission contribution. The transport sector is responsible for 8 Gt year^{-1} of CO_2 emissions (a quarter of the global total) and road transport alone is responsible for about 74% of the sector's total emissions (IEA, 2018). More than 1.2 billion cars are currently in operation (OICA, 2019a) while another 100 million new vehicles are produced annually (OICA, 2019b). The motorization rate (number of cars per population) is still higher in developed countries but increasing in all regions of the world (OICA, 2019a). In the last quarter of a century (1990–2016), emissions from the transport sector increased by 71% (IEA, 2018).

Although innovations to limit emissions from the transport sector are emerging, they are not equally efficient in terms of emission reduction and use of natural resources. For example, first generation biofuels require large water (Vanham, Medarac, et al., 2019) and land resources (Holmatov et al., 2019; Rulli et al., 2016). Vehicles that run on electricity or hydrogen can be considered clean technology (IRENA, 2019; TE, 2018) only if the electricity and hydrogen are produced from renewable sources. In terms of market penetration, the number of vehicles using biofuels is not clear cut as the gasoline-biofuel blend ratios vary. In early 2019, the number of electric vehicles (i.e., battery powered electric vehicles, range extenders, plug-in hybrids) was about 5.6 million only, a 64% increase from a year earlier (ZSW, 2019). The number of hydrogen fuel cell electric vehicles (FCEVs) was even less, about 11 200 at the end of 2018, serviced by only 376 refueling stations operating worldwide (IEA, 2019). Together, battery electric vehicles (BEVs) and FCEVs make up less than 0.5% of 1.2 billion cars. It is interesting to compare and contrast environmental (i.e., carbon, land and water) footprints per unit of distance driven in vehicles utilizing alternative fuels or electricity to understand environmental tradeoffs linked to the choice of energy source as we transition towards low-carbon road transport.

Environmental footprint assessment is a common and handy tool to understand direct and indirect natural resources use and emissions related to a product or activity. The carbon, land and water footprint serve as different indicators of human pressure on the environment. Together, the three footprints can provide a broader understanding of environmental tradeoffs. To date, studies have looked at the land and water footprints of biofuels, but a systematic comparison of environmental footprints per unit of distance driven in vehicles using gasoline or a blend of biofuels or in BEVs or FCEVs is missing. Here we calculate the three footprints of midsize cars per unit of distance assuming different energy sources: (1) conventional gasoline; (2) 20% biodiesel blend (B20), with biodiesel from rapeseed; (3) 85% bioethanol blend (E85), with bioethanol from sugar beet; (4) electricity generated from burning sugarcane; (5) electricity generated from photovoltaic (PV) solar panels; and (6) hydrogen, produced through electrolysis using solar electricity. For calculations see Holmatov and Hoekstra (2020).

2. Materials and Methods

Production of gasoline, biofuels, bioelectricity, solar electricity and solar-based hydrogen require energy, land and water during different stages of production. Land footprint, water footprint, and carbon footprint are members of the environmental footprint family (Vanham, Leip, et al., 2019), which includes other footprints not addressed in this study. Carbon footprint (CF) refers to GHG emissions produced in the supply chain of a product (Hoekstra & Wiedmann, 2014). Land footprint (LF) refers to direct and indirect appropriation of land as a resource (Hoekstra & Wiedmann, 2014). Water footprint (WF) refers to direct and indirect appropriation of freshwater and includes a blue component (consumption of surface and groundwater), a green component (consumption of rainwater), and a grey component (water required to assimilate pollution) (Hoekstra et al., 2011).

CFs of conventional diesel and gasoline are calculated using data from Zijlema (2018). CFs of biofuels and bioelectricity refer to emissions per unit of net energy output in a circular production system (whereby bioenergy is used to produce bioenergy) (Holmatov et al., 2019) with one adjustment. Specifically, the biofuel related emissions refer to fertilizer production and soil management stages, while the bioelectricity related emissions extend further to include combustion related emissions of nitrous oxide and methane in stationary power plants. CF of PV solar panel generated electricity is assumed zero if existing PV solar modules provide the input energy in a circular PV solar panel production system. CF of hydrogen is based on the total solar electricity consumed in production of hydrogen, thus also zero.

LFs of conventional gasoline and diesel are obtained from Pękala et al. (2010). LFs of biofuels and bioelectricity are calculated using data from Holmatov et al. (2019). LF of solar electricity is calculated as the inverse of annual electricity generation per m^2. Annual electricity generation assumptions are: average PV solar module efficiency is 16%, solar insolation 1700 kWh m^2 $year^{-1}$, and performance ratio is 75% (for clarifications see Bhandari et al. (2015)). LF of hydrogen is based on the LF of total solar electricity consumed in the production of hydrogen.

WF of oil (assumed same as conventional gasoline or diesel) and solar electricity from PV modules are calculated using data from Mekonnen et al. (2015). WFs of biodiesel, bioethanol and bioelectricity are calculated using data from Holmatov et al. (2019) assuming rapeseed as the biodiesel feedstock, sugar beet as the bioethanol feedstock, and sugarcane as the bioelectricity feedstock. Footprint calculations of B20 and E85 fuels assume the following composition: 20% biodiesel and 80% conventional diesel in B20, and 85% bioethanol and 15% gasoline in E85. WF of hydrogen production through electrolysis is calculated in two steps as the direct WF, that is water as feedstock for electrolysis, and the indirect WF of solar PV generated electricity. Direct WF is based on the theoretical hydrogen gas produced when splitting water molecules, i.e. 112 g $liter^{-1}$ of water (8.9 liters kg^{-1} hydrogen). Indirect WF is linked to the WF of solar electricity from PV, where the electricity requirements are assumed as 47 kWh kg^{-1} hydrogen (Züttel et al., 2010) and the average of 3.1 kWh kg^{-1} hydrogen (USDOE, 2009) required for compression at the fueling station.

Energy contents (lower heating values) of biodiesel, bioethanol and hydrogen are obtained from USDOE (2014). Energy content (lower heating value) of conventional diesel and gasoline is calculated using data from IEA and OECD (2010). For comparison we assumed fuel efficiency of "midsize" sedan cars, which are defined as cars with passenger and cargo volume of 110-119 $feet^3$ ~ 3.1-3.4 m^3 (USDOE, 2019a).

Fuel efficiency of an FCEV is obtained from USDOE (2019b) that corresponds to a 2019 Honda Clarity. Fuel efficiencies of all other vehicles are obtained from USDOE (2019c). Fuel efficiency of a conventional gasoline car corresponds to a 2019 Kia Forte FE or 2019 Toyota Camry. Fuel efficiency of a B20 vehicle corresponds to a 2019 Chevrolet Cruz Hatchback or 2019 Jaguar XF, while the fuel efficiency of an E85 vehicle corresponds to a 2016 Mercedes-Benz E350. The fuel efficiency of BEV corresponds to 2019 Honda Clarity EV or 2019 Nissan Leaf (40 kWh battery pack).

Table 1
Carbon, Land and Water Footprint per km and per Capita Year^{-1} of Driving a Car Fuelled by Conventional Gasoline, Biodiesel Blend B20, Bio-Ethanol Blend E85, Bio-Electricity, Solar Electricity or Solar-Based Hydrogen

		Biofuel blend		Electricity		Hydrogen
	Gasoline	B20[1,a]	E85[2,a]	Bio[3,a]	Solar (PV)[c]	
Carbon footprint (g CO_2eq/km)	165	185[b]	80.2[b]	7.3[b]	0	0
Land footprint (m^2/km)	0	0.37	0.21	0.028	0.00091	0.0023
Water footprint (L/km)	0.25	170	163	40	0.12	0.39
Carbon footprint (kg CO_2eq/driver/year)	3579	4010	1739	158	0	0
Land footprint (m^2/driver/year)	0	7977	4463	611	20	50
Water footprint (m^3/driver/year)	5	3685	3534	859	3	8

Notes: [1] 20% biodiesel from rapeseed and 80% conventional diesel; [2] 85% bioethanol from sugar beet and 15% conventional gasoline; [3] from sugarcane's biomass;
[a]assuming circular production (using bioenergy to produce bioenergy);
[b]the CF of biofuels originates from nitrogen fertilizer production and soil management while the CF of bioelectricity also includes nitrous oxide and methane emissions during combustion;
[c]assuming circular production (using solar PV panels to make solar PV panels). Fuel efficiencies refer to: 2019 Kia Forte FE or 2019 Toyota Camry for conventional gasoline; 2019 Chevrolet Cruze Hatchback for B20; 2016 Mercedes-Benz E350 for E85; 2019 Honda Clarity EV or 2019 Nissan Leaf (40kWh battery pack) for electric; and 2019 Honda Clarity for hydrogen. We assume here the average annual travel distance as in the US (FHWA, 2018), which is 21687 km.

3. Results

Results show that solar-powered BEVs have the smallest environmental footprints per km (Table 1), while biofuel-driven cars have the largest footprints. Driving a car with B20 blend has the worst environmental performance. Driving a car with E85 blend gives the second-largest land and water footprints, while conventional gasoline gives the second-largest carbon footprint. Interestingly gasoline-based cars have the smallest associated land footprint per driven km and the second smallest water footprint.

Switching from gasoline to BEV cars gives an emission saving per km of 96% in case of bioelectricity and 100% in case of solar electricity. Driving a B20 fueled car will actually increase emissions per km by 12% while requiring 683 times more water than a gasoline car. A E85-based car can cut emissions by half but will require 655 times more water compared to gasoline. A solar-based FCEV can achieve 100% emission reduction but requires 58% more water than driving a gasoline car. The indirect water footprint of a solar-based FCEV (i.e., the water consumed in the supply chain of solar electricity) is over three times larger than its direct water footprint (the water used to produce hydrogen) (Figure 1).

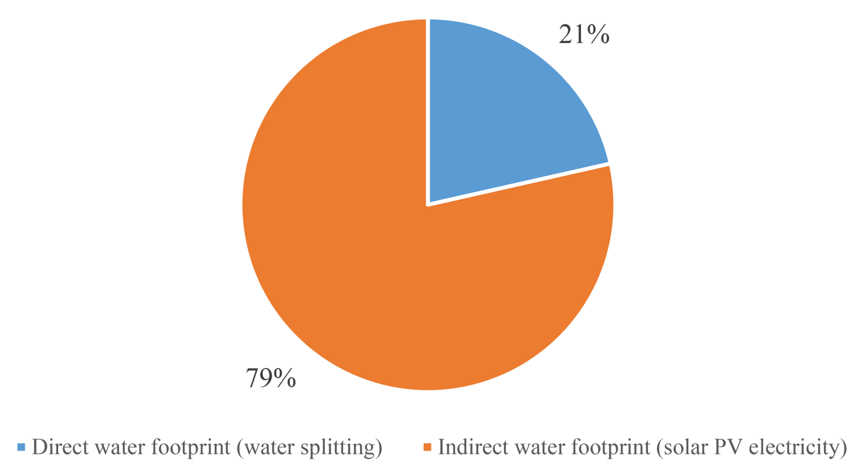

Figure 1. Breakdown of the water footprint of hydrogen production using solar based electricity.

Gasoline has the smallest land footprint (related to land occupied by mining and refineries), thus switching from gasoline to any of the considered alternative energy sources will increase the land requirement. A solar-based BEV or FCEV has an order of magnitude smaller land footprint than a bio-based vehicle.

To put things into perspective, the average annual driving distance per car driver in the US is 13 476 miles (FHWA, 2018) or 21 687 km. Driving a gasoline car translates into 3.58 tonnes of CO_2eq emissions and 5 m^3 of water consumption per year. From the GHG emissions perspective, using solar-based BEV or FCEV emits 0 kg of CO_2eq. A BEV powered by bioelectricity emits 158 kg of CO_2eq per year. If we add the water perspective, a solar-based BEV requires only 3 m^3 of water per year, followed by a solar-based FCEV (8 m^3), while a bioelectricity based BEV requires 859 m^3 and an E85-powered car 3534 m^3. A B20 fuelled car has the worst performance, emitting over 4 tonnes of CO_2eq year^{-1} while requiring 3685 m^3 of water and 7977 m^2 every year.

The least GHG emissions can be achieved driving a solar-based BEV or FCEV. If we add the land and water perspective, a solar powered BEV becomes the most resource efficient vehicle per unit of distance.

4. Conclusions

The environmental performance of different cars depends on the choice of energy source. We show inherent tradeoffs between land use, water use and carbon emissions. From the environmental footprint perspective, solar-powered battery-electric vehicles are the most resource efficient per unit of distance, followed by solar-based hydrogen-driven vehicles. Biodiesel has the worst resource use efficiency per unit of distance while bioethanol has smaller emissions compared to fossil fuels but has extremely large land and water requirements. The logical choice of future transport is thus diffusion of electric and hydrogen vehicles based on (non-biomass) renewable energy sources.

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