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Land use of energy supply for carbon neutral mobility: a well-to-wheel analysis

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Abstract

Background The transition to carbon neutral mobility will require a lot of carbon neutral energy, but a lot of space as well. In many countries, it will be a challenge to find this space or to import enough energy. Land use indicators related to sustainable mobility usually focus on space for transport infrastructure and parking, i.e. direct land use, and do not include energy supply. Existing literature on the emerging research field of 'energy landscapes' has not covered the transport sector.

Objective The aim of this paper is to estimate the order of magnitude of land or sea area required for carbon neutral mobility.

Method In a well-to-wheel analysis, we investigate the land use for the production, transport, storage, distribution, and charging/refuelling of carbon neutral energy carriers for various modes of transport. The analysis focuses on the Netherlands, but part of the results are expected to be broadly applicable to other countries as well.

Findings The results show that electricity from wind or solar energy supplied to electric vehicles is the most space efficient. Use of hydrogen and synthetic fuels in vehicles takes 2–5 times more land, while use of biofuels from energy crops takes 100 times more land compared to the electricity route. We also conclude that the indirect land use for energy supply for carbon neutral road transport in the Netherlands is in the same order of magnitude as the current direct land use of road mobility.

Keywords Land use, Energy landscapes, Carbon neutral energy, Mobility, Well-to-wheel, Sustainable transport, Electricity, Hydrogen, Synthetic fuels, Biofuels

1 Introduction

Making mobility systems carbon neutral is a major challenge. It fits in with the European Green Deal's goal of carbon neutrality by 2050 and reducing transport CO_2 emissions by 90% 1. Such a large CO_2 reduction requires a comprehensive transition with major investments, policy choices and behavioural changes. This transition also has substantial spatial consequences. It is not only about how we will produce the necessary carbon neutral energy for mobility, but also where we will do this: will there be a few large production locations or many small ones? And how do we organise transport, storage and distribution to the end-users in the mobility sector? This paper aims to shed light on the spatial implications of the transition to carbon neutral mobility, an issue which so far has received limited attention in academic literature. The objective is to assess and compare the land use of several energy chains for carbon neutral energy for mobility and to evaluate the options that the Netherlands has to achieve carbon neutral mobility. In addition, we discuss to what extent the results may be applicable to other countries. The main research question of our research is:

> *What are the net and gross land use of electricity, hydrogen, synthetic fuels and biofuels, when used for*

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carbon neutral mobility in the Netherlands?

In this paper we analyse 4 energy carriers for mobility (electricity, hydrogen, synthetic fuels and biofuels) in terms of the space used in their respective 'energy chains' in 2030. This year was chosen as assumptions for technology development after that are too uncertain. An energy chain consists of the following steps:

1. Production of the energy carrier from raw materials and other inputs.
2. Transport, storage and distribution of the energy carrier. The difference between transport and distribution is that transport (for electricity: transmission) refers to long distances and distribution to the supply to the end-user.
3. Bringing the energy carrier in the vehicle by refuelling or charging.
4. Use in the vehicle: conversion of the energy carrier into vehicle propulsion.

The 4 selected energy carriers can be produced from carbon-neutral sources 2. A complete chain is also called "well-to-wheel" (WTW). The first 3 steps are well-to-tank (WTT) and the last step is tank-to-wheel (TTW). For the TTW step we analyse 5 different modalities, that together make up over 90% of the mobility emissions in the Netherlands, including those from bunker fuels 3 (with the latter largely used by international shipping and aviation). These are: light duty vehicles, heavy duty vehicles, inland shipping, maritime shipping and (intercontinental) aviation. Not all vehicle-energy carrier combination are investigated, as some have a technological readiness level (TRL) that is too low to be implemented on a large scale by 2050 or involve practical barriers. The land use is determined through literature research and data from previous primary research. Our research is embedded in literature on 'energy landscapes', which concerns the study of the correlation between the physical characteristics of energy commodities (including their spatial footprints) and the societal implications of the energy commodities 4, 5. Our research does not consist of a life cycle analysis (LCA), as we do not take the production of the required installations or facilities into account (e.g. the land required to provide the energy or steel to build wind turbines). The research is validated through expert interviews and expert reviews.

This paper contributes to filling two knowledge gaps. First, the results provide a rough picture of the surface of land or sea taken up by the energy chains in relation to each other, which can be important when considering policy—alongside other aspects such as costs, environmental impact, security of supply, safety and so on. In recent literature, the link between land use and climate policy is explored for the energy or electricity sector [6–9 (see for an overview Guillot et al. 10). This paper therefore specifically provides insights into the spatial aspects of energy in the mobility sector.

Second, this paper adds to literature on indicators for land use of mobility. Several articles and reports [11–14 review and develop sets of indicators for sustainable mobility. In such indicator sets, land surface required (phrased for example as "land use", "land consumption", "land take", "space consumption", and "space usage") for transport road infrastructure is considered, as is space used for parking of vehicles, fuel stations, logistics centres, ports and airports. One example of a land use indicator is "per capita land devoted to transport facilities" 11. Land use for the energy supply has, to our knowledge, not yet been considered in land use indicators for mobility.

2 Method

2.1 Overview of energy chains

An energy chain starts, according to our definition, with energy production and ends with using the energy carrier in a vehicle, i.e. a well-to-wheel approach. We consider 5 modes of transport, each with its own reference vehicle, see Table 1. The reference vehicles are selected in such a way that they are typical for the transport modes and are responsible for a significant amount of CO_2 emissions of each mode. For instance, for aviation we have selected a large aircraft suitable for international flights which can

Table 1 The 5 modalities considered and their reference vehicles 16

Mode	Reference vehicle	Land use determined on the basis of
Light duty vehicles	Passenger car	Distance per year (13,000 km)
Heavy duty vehicles	Tractor-trailer (up to 40 t including cargo)	Distance per year (87,000 km)
Inland shipping	Ship similar to a large Rhine vessel (110 m in length)	Distance per year (70,000 km)
Maritime shipping	General cargo ship for long distance	Total amount of maritime fuel bunkered in the Netherlands
Aviation	Boeing 787 for 300+ passengers	Total amount of aviation fuel bunkered in the Netherlands

accommodate more than 300 passengers. The focus on international flights is based on the fact that flights longer than 4000 kms emit more than half of the CO_2 emissions of the flights to and from EU airports 15.

The 4 energy carriers are not equally suitable for all reference vehicles. Table 2 gives an overview of the combinations of energy carriers and vehicles considered in this study. As selection criteria we have applied 1) a technological readiness level (TRL) greater than 6 for the vehicle-energy carrier combination, i.e. the technology has been demonstrated 17 and 2) practical applicability.

Based on the second criterion, the synthetic fuel (synfuel) ammonia, which is highly toxic, has only been considered for inland and maritime navigation and not for road transport 18. In intercontinental aviation, we only see drop-in fuels as an option: fuels that are chemically similar to kerosene, which means that no modifications to the aircraft and to the fuel infrastructure are necessary. Other options (battery-electric and hydrogen) have been excluded for intercontinental aviation because of their low TRL and their unpractical weight and volume characteristics.

Within each energy chain, multiple technologies can be used to produce and transport the energy carriers. Table 3 gives an overview of the options per energy chain and subtypes considered in this study.

2.2 Definition and scope of land use

In this paper, we consider land use from a quantitative point of view. We first analyse the use of space per unit of energy produced, transported and finally distributed to a vehicle or vessel. This is a unit of energy at the point of charging or refuelling. We subsequently translate this, via energy consumption per vehicle, into usage of space for 2 different scopes:

(1). Per vehicle:

- (a) A passenger car
- (b) An inland vessel

(2) Total:

- (a) Total for distance travelled in Dutch road transport
- (b) Total for aviation and maritime transport on the basis of what these modes bunker within the Netherlands

Land use per vehicle [m^2] = land use per unit of energy at the point of charging/refuelling [m^2/GJ] x energy charged or tanked by the vehicle [GJ].

For the per vehicle approach, we selected the 2 modes that have the highest number of feasible energy carriers from Table 2. This will be sufficient to show the relative land use results, as the relative values are rather similar across all modes (see Chapter 3). For the energy consumption of a vehicle, we take its annual consumption; the land use is the space required to produce this amount of energy in a year.

We estimate the use of space in 2 ways, in accordance with for example [20] and [21]. The *net* land use is the above-ground land or sea area that is used primarily (i.e. as the main purpose) for energy production, for example the area of land occupied by a wind turbine, without taking into account the fact that wind turbines must be placed hundreds of metres away from each other to avoid interference with each other. The *gross* land use (sometimes called "total land use") indicates the total area required to produce a certain amount of energy. The space between the turbines, or air capture units, for

Table 2 Selection of energy carrier-vehicle combinations in this study based on the criteria TRL > 6 17, 19 and practical applicability

Energy chain	Subtype	Conversion in vehicle	Light duty vehicles	Heavy duty vehicle	Inland shipping*	Maritime shipping	Intercontinental aviation
Electricity		Battery-electric	O	O	O		
Hydrogen		FC electric	O	O	O		
		ICE adapted	O	O	O		
Synfuels	Drop-in (FT)	ICE	O	O	O	O	O
	Ammonia	ICE adapted			O	O	
	Methanol	ICE adapted	O	O	O	O	
Biofuel	Drop-in (FT)	ICE	O	O	O	O	O
	Bioethanol**	ICE adapted	O				

O=included

* Including shipping for short and medium distances

** Ethanol is a gasoline substitute

FC Fuel cell, *ICE* Internal combustion engine, *FT* Fischer-Tropsch, *Drop-in* Composition comparable to Fossil.

Table 3 Techniques considered for each stage in the chain

Energy carrier	Input into production process	Production	Transport, storage, distribution	Refuelling, charging	Use in vehicle
Electricity		Wind turbines; Solar panels on roofs, on land (solar farms), infrastructure or water bodies	Electricity grid, system batteries, possible storage in other form (e.g. H_2)	Charging points	Battery with electric motor
Hydrogen	Electricity	Electrolysis using renewable electricity (mix of solar and wind)	Transport can take place either via tube (gaseous under high pressure) of via ship (cryogenic H_2 or in the form of ammonia). Distribution by pipeline, road tanker or by ship	Gas fuelling under pressure (incl. compression); purification	Fuel cell + (small) battery + electrical motor; Modified ICE
Hydrogen	Natural gas and bio-methane	SMR based on natural gas with 90% CCS and 10% biomethane			
Synfuels: FT-liquids	Hydrogen and CO_2	FT plant	Identical to current	Identical to current	Identical to current
Synfuels: ammonia	Hydrogen and nitrogen	Ammonia plant	Existing fuel transport, storage and distribution infrastructure can be adapted to make it suitable for ammonia	Adapted: ammonia has to be pressurised or cooled to liquefy it.	Adapted ICE
Synfuels: methanol	Hydrogen and CO_2	Methanol plant	Conventional transport, storage and distribution infrastructure can be adapted to make it suitable for methanol	Adapted. Due to the low dew point of methanol, toxic methanol vapours can easily occur, which need to be avoided	Adapted ICE
Biofuel: bio- FT-liquids	Energy crops or residues	Bio-FT plant	Identical to current	Identical to current	Identical to current
Biofuel: bioethanol	Energy crops or residues	Ethanol plant	Conventional transport, storage and distribution infrastructure can be adapted to make it suitable for bioethanol	Identical to current	Adapted ICE

example, also counts as land use for energy production, even though it is or can be used for other purposes. For instance, cattle can graze between the wind turbines. However, this space between turbines must be present in order to be able to place the turbines at a distance from each other and is therefore indispensable. This gross measure is useful to determine what the spatial possibilities and limitations are to generate a certain quantity of energy.

Combinations of energy production can also take place on the same surface, for example biomass cultivation between the turbines of a wind farm 9, but this will not be considered here.

Table 4 shows what is included and excluded in the land use for the production of electricity and biomass (as a raw material for biofuels). A general assumption here is that for the net land area, the primary purpose of the land area is leading, and that when energy production is a secondary purpose of the land area used, the net usage is zero. The latter also applies to solar energy on roofs and biomass from agricultural residues.

Storage of CO_2 and transport of natural gas take place underground and as such do not require significant amounts of land. The required biomethane can be extracted from waste (sewage sludge) or residual flows from agriculture or livestock and therefore we allocate no land area for that either.

In addition to hydrogen, the production of synfuels requires CO_2. This CO_2 can be either captured from point sources via carbon capture (CC) or directly from the air. With carbon capture it is questionable if it fits in a CO_2 neutral society in the longer term 22. Nevertheless, if there are still point sources (which is very likely in 2030) it is more cost-effective to capture the CO_2 there than from the air. Carbon capture installations are not very space intensive but have to be placed next to existing industrial facilities, where space may be scarce 23. Direct air capture (DAC) installations require more space than CC units. In addition, there is some uncertainty about the land use for DAC in the literature 24, 25.

3 Data

The reference year is 2030 for all technologies in the energy chains. In the analysis for the total use of space, this has been combined with the *current* mobility demand (in pre-COVID year 2019). Tables 5, 6, 7 and 8 show the data sources used for the first step in the energy chain, the production of the energy carriers, broken down into land use per unit of energy carrier production and the inputs required to produce hydrogen and 3 subtypes of synfuels.

For hydrogen production with electrolysis, it is assumed that the electrolyser uses a mix of 76% electricity from wind turbines and 24% electricity from solar panels in the Netherlands (based on [48]), where electricity from solar panels can be split into 9% on roofs and 15% solar farms on land, water or infrastructure 32.

For the land use of the electricity network of the Netherlands, we have taken the current land take of the high-voltage grid (150 km^2) and transformer substations (15 km^2), plus the expansion that is expected to be needed until 2050: 40–70 km^2 for the high-voltage grid and 3 km^2 for transformer substations, as well as 20–50 km^2 for the required flexibility (hydrogen storage, stationary batteries and gas-fired power stations) 49. Based on the average electricity demand in 2050 in four scenarios for carbon-neutral energy 50, the land use amounts to 1 m^2 per MWh per year.

Table 4 Demarcation of land use for the production of energy carriers in this study. *Source* authors, based on [7] and [20].

	Net	Gross
Wind energy	Land or sea area for turbines + any additional infrastructure (access roads, transformer platform at sea)	Surface area of wind farm
PV (on roofs)	No use of space	The roof area used
PV (on land, water or infrastructure)	Surface area of solar panels + space between panels	Equal to net
Biofuels (energy crops)	Area of land needed to produce woody biomass	Equal to net
Biofuels (residues)	No land use	Area of land from which the residue is extracted
Hydrogen from electrolysis	Net area required for production electricity for electrolysis	Gross area of electricity requirement
Hydrogen from SMR with CCS and 10% biomethane	Net area required for SMR and CCS and natural gas transmission	Equal to net
Synfuels	Net area required for hydrogen production from electrolysis + DAC	Gross area of electricity requirement + DAC

PV Photovoltaic, *SMR* Steam methane reforming, *CCS* Carbon capture and storage, *DAC* Direct air capture.

Table 5 Land use of electricity production

	Land use per unit of energy or power	Sources	Notes
Wind (net)	0.9 m^2/MWh electricity per year (0.3-2.3)	Average of 4 sources from the Netherlands [26, 27], the EU [28] and the US [29]	No difference assumed between on-shore and off-shore wind.
Offshore wind (gross)	0.2 km^2/MW installed capacity (0.1–0.3)	Average of 3 sources [29–31]	
Solar (on land, water or infra-structure)	12 m^2/MWh electricity per year (6–25)	Average of 5 sources [6, 31–34]	3 sources for solar farms, 2 for various surface types

Table 6 Land use for synfuel production inputs

	Land use per unit of captured CO_2 or energy	Sources	Notes
DAC	1.5 (0.04-25) km^2/Mt CO_2 per year	[24, 25, 35, 36]	Due to the large spread in the literature, a value in the middle, as reported by [36], is used for the calculations.
Carbon capture at point sources (post-combustion)	13,000 m^2/Mt CO_2 per year	[23]	Questionable whether this space is available at industrial facilities.
FT-synfuel production	0.03 m^2/ GJ synfuel per year	[37]	Based on the Yinchuan FT-plant, which runs on coal.
Methanol production	0.06 m^2/GJ synfuel per year	[38]	Based on demonstration plant in Iceland that produces 4 kt methanol on a surface of approximately 5,000 m^2.
Ammonia production (including N_2 production)	<0.04 m^2/GJ synfuel per year	[39]	Based on an industrial complex where among others ammonia is produced. As the entire surface of the complex is used, the surface is an upper limit.
Ammonia storage	$8*10^{-5}$–$5*10^{-3}$ m^2/GJ synfuel per year	[40, 41]	Large economies of scale
Ammonia transport and tank infrastructure	No land use is assigned to these components. Probably diesel infrastructure could be used after adaptations. Land use will increase due to lower energy density and larger safety distances 42.		
FT storage, transport and tank infrastructure	No land use is assigned to these components. Similar to current diesel infrastructure.		
Methanol storage, transport and tank infrastructure	No land use is assigned to these components. Probably diesel infrastructure could be used after adaptations 43. Land use will increase due to lower energy density.		

Table 7 Land use of biofuel production

	Land use per unit of energy	Source	Notes
Biomass (cellulose) for Biofuel production	57 m^2/GJ biomass per year (15-99)	[7]	Bioethanol from cellulose: 35-230 m^2/GJ per year. Conversion of biomass into ethanol: 43% efficiency.
Biofuel production facility	0.03 m^2/GJ biofuel per year	[37]	Assumed to be equal to synfuel production facility.

Table 8 Inputs for the production of energy carriers

	Input	Sources
Hydrogen production (electrolyser)	50 kWh electricity per kg H_2	[44]
Hydrogen production (SMR-CCS)	0.17 GJ natural gas per kg H_2	[44]
Hydrogen other chain steps:		
Liquefaction (if any)	15 kWh electricity per kg H_2	[44]
Conversion to NH_3 (if any)[a]	43 kWh electricity per kg H_2	[44]
Conversion of NH_3 to H_2 (if any)	Efficiency 66%	[45]
Compression and purification at filling station	4 kWh electricity per kg H_2	[44]
FT-liquids	Input of 11.7 kg H_2/GJ Input of 78 kg CO_2/GJ	[46]
Ammonia	12.5 kg H_2/GJ	[47]
Methanol	Input of 10.8 kg H_2/GJ Input of 94 kg CO_2/GJ	[46]

[a] Electricity use for conversion of hydrogen to ammonia (NH_3) is additional to the energy use in electrolysis of water to produce hydrogen. Total electricity use for producing NH_3 by electrolysis is therefore 93 kWh (50 kWh + 43 kWh) (overall efficiency ~54%).

For the production of hydrogen from electrolysis, we do not allocate land use to transport and distribution of electricity, under the assumption that the electrolyser can be connected relatively close to the electricity production sites (wind turbines and solar panels). Further land requirements for hydrogen are partially underground (pipelines, for example), which we do not count as land use, in storage tanks similar to those currently used for fossil fuels and in electrolysers. The land use of electrolysers and storage tanks is small 44 compared to the land use associated with the electricity supplied to the electrolysers.

Charging stations are needed for electric vehicles. These are mainly located on private property and partly in the (semi-)public space: on the street, at parking lots and at fast-charging stations or in business parks. The surface area required for these charging stations is small compared to the production and transport of electricity 16. The same applies to filling stations for hydrogen, biofuels and synfuels; their land take is comparable to that of existing filling stations for fossil fuels.

Table 9 shows the energy efficiency of the various energy chains, split into well-to-tank (from production to loading/fuelling) and tank-to-wheel (use in vehicle) and well-to-wheel (entire chain). These are used to calculate energy consumption, and thus land use per vehicle.

Data on total energy consumption and distance travelled by the various transport modes in 2019 are taken from Statistics Netherlands 67, and data on specific energy consumption was analysed by the Netherlands Organisation for Applied Scientific Research 16.

4 Results

4.1 Land use per vehicle or vessel

Due to the electricity demand in the different steps of the hydrogen chain and further energy losses in the production of synfuels from hydrogen (see Tables 6 And 8), the use of hydrogen from electrolysis and synfuels costs over 2 to 5 times more electricity than the use of pure electricity in vehicles. These differences are also reflected in the net land use to supply 1 passenger car with carbon neutral energy (see Fig. 1). For a mix of 76% electricity from wind turbines and 24% electricity from solar panels, this is about 12 m^2 per car, based on annual distance travelled of 13,000 km. For hydrogen from electrolysis and FT-liquids it is 25–45 m^2 per vehicle, the variant in which hydrogen is transported in the form of ammonia (which is then converted back into hydrogen) at the upper limit of this range due to the lower efficiency of this energy chain. The space consumption of biomass from energy crops is much higher than that of the other options, around 2500 m^2.

For a truck, the space required is 600 m^2 for electricity and 1300–2300 m^2 for hydrogen and synfuels. For a tractor-trailer to run completely on solar energy, a PV panel area of about 200 m^2 is required.

An inland vessel requires about 0.01 km^2 for electricity and 0.02–0.04 km^2 for hydrogen and the various synfuels (FT-liquids, methanol and ammonia) (Fig. 2).

Hydrogen from SMR-CCS takes up less space than hydrogen from electrolysis and therefore fits better in the Netherlands. The SMR-CCS installation takes up little above-ground space as does the natural gas required for it (we assume gas pipeline lie underground). For the required 10% biomethane to make the SMR-CCS process carbon neutral, we assume residual flows, as mentioned earlier, which does not require any additional space. Thus, the only considered use of space comes from the electricity required for the production and above-ground transport and distribution of the hydrogen.

Table 9 Energy efficiencies of the chains

	Energy efficiency			Sources	Remarks
	WTT (%)	TTW (%)	WTW (%)		
Electricity (wind)	81	89	71	[31, 51-56]	Included are energy losses due to transport & distribution, charging/discharging and electric motor efficiency (including brake energy recovery)
Electricity (solar)	76	89	67		Equal to wind + efficiency of PV inverter
H_2 electrolysis (transport in gaseous form)	59	55	32	[44, 45, 57]	
H_2 electrolysis (transport in liquid form)	48	55	26		The differences in WTT efficiency are explained by the mode of transport of H_2; Application in a fuel cell vehicle (FCEV)
H_2 electrolysis (transport as NH_3)	34	55	18		
H_2-SMR-CCS (transport as gas)	61	55	34		For SMR-CCS, an efficiency of 69% has been taken into account; The differences in WTT efficiency are explained by the way the hydrogen is transported from a production location to a refuelling station; Application in a fuel cell vehicle (FCEV)
H_2-SMR-CCS (transport in liquid form)	49	55	27		
H_2-SMR-CCS (transport as NH_3)	31	55	17		
H_2 electrolysis (gas)	59	43	25		Same as above, but application in vehicle with (modified) internal combustion engine
H_2 electrolysis (liquid)	48	43	20		
H_2 electrolysis (NH3)	34	43	14		
H_2-SMR-CCS (gas)	61	43	26		Same as above, but application in vehicle with (modified) internal combustion engine
H_2-SMR-CCS (liquid)	49	43	21		
H_2-SMR-CCS (NH_3)	31	43	13		
Synfuel-NH_3	43	43	18	[47, 58-61]	The efficiency of NH_3 production is 67% 47. In addition, energy is used for storage (37.8 kWh/t NH_3) 58. The energy required for transport (0.03 GJ/GJ_{fuel}) and tank infrastructure (0.01 GJ/GJ) are assumed to be the same as for methanol. The efficiency of an ICE is assumed to be similar to that of a diesel engine [59-61.]
Synfuel-FT-DAC	38	43	16	[46, 52, 62]	FT synfuels are produced with an efficiency of 69% 46. In addition, energy is used for CO_2 capture (1.5 MWh/tCO_2) 62, transport (0.03 GJ/GJ_{fuel}), distribution (0.01 GJ/GJ_{fuel}), storage (0.0025 GJ/GJ) and tank infrastructure (0.01 GJ/GJ) 52.
Synfuel-MeOH-DAC	40	43	17	[46, 52, 62, 63]	Efficiency of MeOH production is 80% 46. In addition, energy is used for CO_2 capture (1,5 MWh/tCO_2) 62, transport (0.07 GJ/GJ_{fuel}), storage (0.01 GJ/GJ) and tank infrastructure (0.01 GJ/GJ) 52. The ICE efficiency is similar to that of a diesel engine 63.
Bio-FT-liquids (cellulose)	59	43	25	[64, 65]	Based on a range of efficiencies: 45–73%
Bioethanol (cellulose)	43	43	18	[66]	Based on a range of efficiencies: 32–54%

The ICE efficiency of 43% applies to a large diesel engine, for example in a heavy-duty vehicle or a barge. In general, the smaller the engine, the lower its efficiency.

4.2 Total land use

As explained in Sect. 2.2 we also explore, based on assumptions in Chapter 3, the total land use for road-based mobility and bunker fuels. If all road mobility in the Netherlands had been electric in 2019, it is estimated that electricity demand at the charging points would have been 40 TWh, with a net land take of about 250 km^2. For comparison, this corresponds to about 1/5 of the existing surface for road infrastructure and (outdoor) parking.

A wind farm of the size of 4% of the land surface of the Netherlands is needed to power all road vehicles in the Netherlands. This is the gross land take, including the space between the wind turbines.

Wind farms with a surface area of almost 40% of the Dutch land surface, or 1/4 of the Dutch Continental shelf (NCP), are needed to produce synfuels for the aircraft and sea-going vessels currently bunkering in the Netherlands. Again, this is the gross surface area. Realising such an area of wind farms would be a major challenge, because other sectors also need electricity and the potential space for wind farms at sea is limited to approximately 1/3 of the NCP 6.

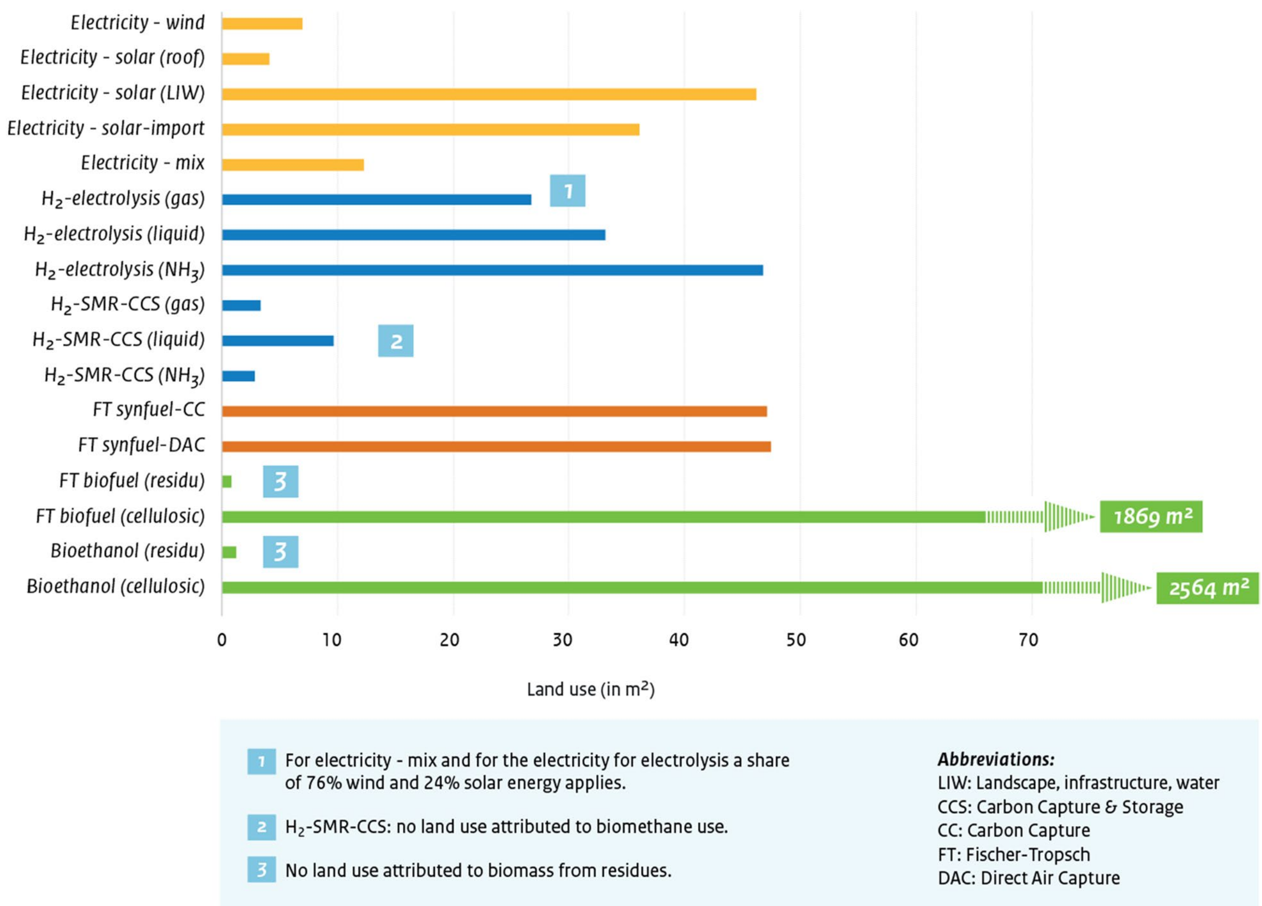

Fig. 1 Net land use for the energy supply of 1 passenger car.

If all the fuel currently bunkered in the Netherlands by air and sea transport were biofuel from energy crops (non-residues), this would require a land area approximately twice that of the Dutch land surface. In the case of biomass from residues, there is no additional land take, so the net land take is zero, even if the primary crop does require space.

4.3 Space comparison of the chain steps

Production of energy carriers (including the inputs it requires) is the step that uses by far the most space in all four chains. This does not alter the fact that the other chain steps also need space and this can be a major challenge, especially in urban environments.

The transport, storage and distribution step takes up considerable space in the electricity chain, more than in the other chains. In fact, this step accounts for all the space consumed by the 'electricity-solar-on-roof' option, because we do not allocate any net land take to the solar panels themselves (and assume the electricity is taken from the grid and no application of vehicle-to-grid). The main issue is the land use of high-voltage cables and transformer substations for electricity transmission and distribution 49. Transformer stations are usually located in or on the outskirts of urban areas. In addition, flexibility in the electricity system is needed to accommodate fluctuations in solar and wind energy. The installations needed for this—stationary batteries, hydrogen storage—also take up space 49.

In the case of the hydrogen, synfuels and biofuel chains, we have considered the space requirements in the transport, storage and distribution step to be negligible compared to the production step (and the inputs for production).

The charging and refuelling infrastructure also requires space, often in places where space is scarce. In the Netherlands an estimated 1.4 million public and semi-public charge points are needed to accommodate the current fleet of 9 million electric cars 68, many of which will be sited at pavements or parking lots. In addition, fast chargers will be located along motorways or arterial roads. In the case of hydrogen, the filling stations will have to be

Fig. 2 Net land use of energy supply for 1 inland vessel (Large Rhine class vessel, 110 m).

well fitted into the local area for safety reasons (hydrogen is used under high pressure, is highly flammable and has an ignition energy 10 times lower than that of natural gas 69). For the synfuels and biofuels that are chemically equivalent to their fossil counterparts, the spatial integration of charging/refuelling infrastructure is easier than for electricity and hydrogen.

5 Discussion

For the preceding analysis we make a few comments on the methodology, uncertainties, interpretation of the results, the relevance for other countries and finally, some implications for policy.

5.1 Method

Net land use is the surface area that cannot be used, or only used to a limited extent, for other purposes. For solar energy this may be a somewhat strict approach: we also count the space under and between solar panels in the landscape or on infrastructure as space for energy production, while this space could also be used for other purposes, such as livestock grazing 70.

For biofuels from energy crops we count all the space of the energy crops, although this space may also contribute to biodiversity or be suitable for recreation. In the case of biofuels from residues, on the other hand, we do not allocate land use to these residues, residues and waste streams from agriculture and forestry, but allocate 100% of the land use to the primary product, such as maize or sugar cane. The EU Renewable Energy Directive 71 uses a similar approach to determine greenhouse gas emissions. However, the residue does have an economic value. This is why land use can also be allocated on the basis of economic value 72. The results with respect to land use will then be substantially different, but we have not found any literature that quantitatively applies this approach.

5.2 Uncertainties

The results are shown without uncertainty margins, but there are of course uncertainties. These uncertainties do not affect the ratio of land use between the various chains much—as this is determined mainly by the energy efficiency values, which are relatively certain and correspond well with existing research 51, 52—but do affect the absolute values. The uncertainty is mainly caused by the dispersion in the literature on the use of space for energy production (see Table 5, 6 and 7). The literature on solar and wind energy is mainly from the Netherlands, because the yield per unit of space differs between countries, but we have also used some international sources. For wind energy and biomass production, for example, we found a factor of 8 between the lowest and highest values for net land take. For wind, the spread in gross land use is less: a factor of 2.5. We did not further investigate the reasons for this difference in spread for wind energy, but an explanation may be that definitions of gross land use are better defined than for net land use 8. The result that large-scale demand for wind-based electricity in ambitious climate mitigation scenarios will need a large land or sea area corresponds with recent literature 20.

For electricity transmission and distribution, we examined the electricity grid as a whole, without distinguishing between user sectors, such as electric mobility versus households or industry. This is a simplification of reality as the user profile of mobility is different from other sectors, which also means that the adjustments needed in the electricity grid are different, especially if, for example, all road mobility becomes electric.

5.3 Interpretation

The quantitative analysis we have used in this paper has the advantage of providing an insightful measure into the land use of energy for mobility. The limitation is that no attention is given to the qualitative side. As noted in literature on energy landscapes [4–6, Qualitative aspects effects on the landscape can be very important, for example from the point of view of social acceptance and combining it with other functions and social goals, such as nature and liveability.

We can illustrate this with wind energy. Quantitatively, we can get a good insight into the net and gross land take, in the measure m^2 or km^2, as we have shown above. In qualitative terms, however, the presence of the turbines is a factor in limiting users of the space between them. In addition, the wind turbines have a subjective (scenic) impact, for example in the form of sight obstruction. The quality of space is thus affected by the presence of the wind turbines.

The qualitative aspects of land use are also influenced by the exact location and its relationship to other land users. In areas with a high population density or high nature value, different quality requirements will generally apply to land use than to areas with low population density or low nature value.

5.4 Applicability of the results to countries other than the Netherlands

Although we have done this analysis only for the Netherlands, it gives an idea about the space needed for carbon neutral mobility and the differences in space use between energy carriers. The results are not intended to provide exact numbers, but rather reasonable estimates that can be used to compare different energy carriers. Therefore, we believe the results are also broadly applicable to other countries, while noting the following. Net land use per vehicle may be lower if wind and solar power have a higher yield per m^2 than in the Dutch situation. For example, in Northern African countries electricity production per m^2 solar panel is about double of that in the Netherlands 73. On the other hand, if the share of non-roof solar power compared to wind power is higher than assumed for the Netherlands, the land use for the electricity mix will be higher. Globally, the main carbon neutral sources of electricity are projected to be wind and solar in 2050, for example approximately 70% in the IEA Net Zero Scenario 18, however this share may be lower or higher depending on each countries' natural conditions.

For total gross land use, expressed in percentage land use for energy supply for mobility, the results are rather specific to the Dutch situation. For example, less densely populated countries such as Australia, Sweden or the United States may have substantially lower energy consumption for mobility relative to their land surface, therefore also a lower relative land use for the energy supply. For bunker fuels for maritime transport, the Netherlands is in an exceptional position, having the 3rd largest bunker fuel port in the world, and being one of the six countries that together make up 60% of the global bunker fuel market 74. Most other countries will therefore have a much smaller gross land use for carbon-neutral bunker fuels.

5.5 Policy implications

Our analysis shows that use of electricity in vehicles is the most space-efficient option. However, when choosing an energy carrier for vehicles, other aspects are also important, such as cost, flexibility, security of supply and impacts on other areas such as biodiversity and nature. In terms of flexibility, electricity has the disadvantage that its supply depends on variable sources: solar and wind energy and that it is more difficult to store than the other energy carriers. Hydrogen seems to be the second-best option, if direct electrification is not possible. What the carbon neutral energy carriers have in common is that the land take will soon exceed the available space in densely populated countries such as the Netherlands. Multifunctional land use can tackle part of this problem 9, but energy imports will probably become necessary. Strategies for this and international cooperation may be required. For other countries, on the other hand, opportunities for export arise. When considering biofuels for transport, biomass from agricultural residues has the lowest footprint, however is unlikely to be sufficient to meet demand 72. Producing biofuels from energy crops requires consideration of biodiversity and soil erosion impacts. And last but not least a strategy to reduce the energy demand of mobility, for example through lighter vehicles or a shift to less energy intensive modes, is another way of saving space.

6 Conclusion

Carbon neutral mobility can be achieved by using electricity, hydrogen synfuels or biofuels as energy carriers. The analysis shows that the use of electricity in vehicles leads to lower land use than that of hydrogen or synfuels. The land use of synfuels and hydrogen is several times (2–5) higher than that of electricity. The land use of biomass is very low if the fuel is made from residues. However, the land use of biofuels is much higher if the fuel is produced from dedicated energy crops, by 2 orders of magnitude, than the electricity route.

If in 2019 all road mobility in the Netherlands were electric based on solar and wind energy, it is estimated that this would mean a net land use of approximately 250 km^2. This corresponds to about 1/5th of the existing land surface taken by road infrastructure and parking. This means that even the most efficient carbon neutral energy chain has a land use in the same order of magnitude as that of transport facilities. Therefore, when looking at the indicator of land use for transport in the context of sustainable mobility, the land use of energy could be taken into account. The gross land use is much higher: in total, electric road mobility requires wind farms the size of 4% of the Netherlands' land surface.

If aviation and shipping were to bunker in the Netherlands in the form of synfuels, this would require wind farms 40% of the land surface of the Netherlands (gross land use). If biofuels from energy crops were to be used for this, an area approximately 0.5 to 3 times the size of the Netherlands would be required.

Besides the production of energy, the transport, storage and distribution of energy carriers also requires space. The spatial integration of these may be challenging, especially in urban environments.

In densely populated countries, space requirements may exceed available land or sea area. Strategies for multifunctional land use and energy imports may become necessary.

The choice of energy carriers for mobility must also take into account factors other than energy and space efficiency, such as cost, flexibility, security of supply, use of materials, and impacts on biodiversity and nature.

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