Ministry of Infrastructure and Water Management

Energy chains for carbon neutral mobility

KiM | Netherlands Institute for Transport Policy Analysis

Stefan Bakker, Saeda Moorman, Marlinde Knoope and Maurits Terwindt

Preface

Conferences in Copenhagen, Paris, Glasgow, *Fit For 55* and the Dutch Climate Act: governments and citizens all over the world are concerned about the consequences of climate change for the planet and mankind and are thinking about solutions. We are faced with huge climate challenges, but what is the best way to solve them? All the paths to the solutions are connected, and these connections are only growing stronger. The Netherlands Institute for Transport Policy Analysis hopes this study will contribute to our understanding of the facts about carbon neutral mobility. To achieve this, we asked ourselves: *What investments and sacrifices will a carbon neutral mobility system require in terms of energy, money and land use?*

We further narrowed down 'mobility' to cover five main modes of transport: cars, and heavy-duty vehicles, inland shipping, maritime shipping and aviation. What will be the consequences and requirements for these modes of transport if they can only run on electricity, hydrogen (H_2), synthetic fuels and biofuels obtained from carbon neutral sources? For each combination of transport mode and energy carrier, we examined the costs, the level of energy efficiency achieved, the amount of land needed for solar panels, wind turbines and other infrastructure , and the availability or scarcity of the required resources.

We applied the results to all travel and transport that now refuels in the Netherlands. It only requires a brief look at the outcome of the study to understand the enormity of the challenges we face. If we want to continue to use cars, trucks, planes and ships as we have always done, we will need to set aside large areas of the Netherlands, including Dutch North Sea waters, to produce the required green energy, and this would be for just the mobility sector alone. Once it is clear which energy carriers will likely be the most suitable for each transport mode, it will be easier to determine what concrete actions are needed today.

Still many questions remain unanswered, such as whether there is enough social and political resolve to achieve the climate targets, and what other opportunities there are. For example: *Are we prepared to make the necessary investments, or would we rather travel and transport less instead? Do we really want to achieve the current climate targets, or is the sacrifice we need to make today too massive, and would we rather invest in much higher dikes when the need arises (with all the costs that entails)? If we do everything we can to meet the 2050 targets, will we also be able to achieve those for 2030, or do these intermediate goals require other measures?*

There are also unanswered questions about the desirability and feasibility of technological developments:
Should we hope for (or trust in) the advent of major technological innovations that will solve all our problems, or should we stick to currently proven technologies and base our plans on these? How can we build the carbon neutral vehicles needed (but not discussed in this report), such as tractors for agriculture and machinery for construction, many of which are used very intensively? There are countless technical questions that require answering and political choices that need to be made. Do we need to develop legislation to allow motorways with electric overhead lines? Should we invest much more in public transport? Or do we need to live closer to our workplaces?

Possibly the most sensitive questions are:
Should we opt for slower but fossil-free mobility solutions at the expense of better fossil-free heating for our homes? Or a fossil-free steel or cement industry? Or vice versa?

KiM hopes this study will help ensure that the urgent political and policy choices that need to be made to achieve carbon neutral mobility can be based on facts. We also hope that it will help to make these facts known to a wider audience and so foster support for the important choices that have to be made. Finally, we hope this brochure will provide a foundation for the development of sensible investment programmes and that it will promote cooperation between policymakers, political players and the industry, nationally and internationally. This is important, because the transition to carbon neutral mobility will affect us all.

Dr. Henk Stipdonk
Director of the Netherlands Institute for Transport Policy Analysis (KiM)

Summary

The production of carbon neutral energy is a crucial step towards achieving carbon neutral mobility in the Netherlands. We look at four potential energy carriers to this end: electricity, hydrogen, synfuels (manufactured from hydrogen and CO_2 or N_2) and biofuels. We focus on the entire energy chain, from production, transport, storage and distribution, and charging or refuelling to the actual use in the vehicle. The questions we ask are: How energy efficient is the solution? What is the cost per distance travelled? How much space will these fuels and their infrastructures require?

In principle, carbon neutrality is feasible for each of these energy chains. However, the chains differ greatly in the way they achieve carbon neutrality and in their degree of suitability for various modes of transport.

Of the options considered, the use of electricity for mobility leads to the lowest energy loss, needs a relatively small land area and has relatively low costs per distance travelled. The energy loss and land use of hydrogen and synfuels are 2-5 times greater.

The land area required by biofuels for mobility depends very much on the origin of the biomass used: if it is sourced from agricultural or other production residues it requires no additional land and therefore has the smallest land use, but if it is obtained from dedicated energy crops it requires the most space of all the options. In terms of costs, biofuels may be able to compete with electric vehicles, although there are many uncertainties.

Like hydrogen, electricity is mainly suitable for road transport and inland shipping, but less for long-distance maritime shipping and aviation. Synfuels and biofuels can be produced in a form that is suitable for all modes of transport without any modifications (this is called a 'drop-in' fuel). Other types of synfuels and biofuels require vehicle engine modifications.

The land required does not necessarily have to be found in the Netherlands; electricity, hydrogen, synfuels and biofuels (or the biomass used to manufacture them) can also be imported from abroad. However, the greater the distance from the Netherlands, the greater the energy losses (and therefore the costs).

Contents

Preface 2

Summary 3

1 Introduction:
5 modes of transport, 4 energy chains, 3 criteria 5

2 Energy efficiency 12

3 Costs 15

4 Land use 19

5 Overview of combinations of energy carriers and modes of transport 24

6 Passenger cars 26

7 Heavy-duty vehicles 28

8 Inland shipping 30

9 Maritime shipping 31

10 Aviation 32

11 Other barriers and uncertainties 33

12 Overall conclusions 35

List of abbreviations 37

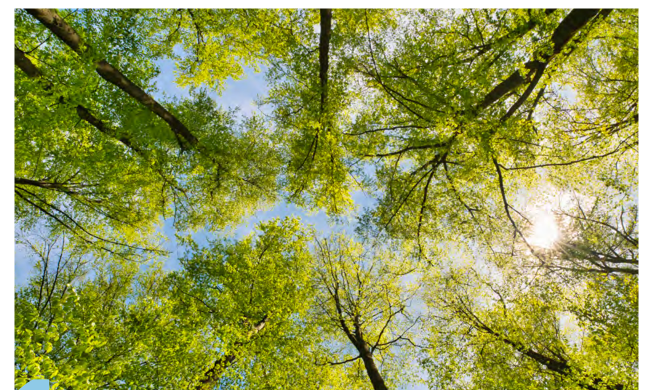
About this publication 38

4 energy chains: electricity, hydrogen, synfuels en biofuels

1 Electricity

2 Hydrogen

3 Synfuels



4 Biofuels

1 Introduction: 5 modes of transport, 4 energy chains, 3 criteria

CO_2 emissions from mobility in the Netherlands have been declining only slowly since 2006. Emissions from fuels bunkered in the Netherlands for international aviation and shipping are actually rising slightly. The goal of achieving carbon neutral mobility by 2050 therefore presents a major challenge. Various strategies can be deployed to achieve this objective. Making energy carriers carbon neutral is one of these, as are reducing the demand for mobility, shifting to other modes of transport and improving energy efficiency.

In this study, we consider four energy carriers that can be used for mobility: electricity, hydrogen, synfuels (synthetic fuels made of H_2 with CO_2 or N_2) and biofuels. With this brochure, the Netherlands Institute for Transport Policy Analysis (KiM) aims to provide an overview of the available knowledge on carbon neutral mobility so that political players and the government can use it to make policy choices.

Modes of transport analysed on a well-to-wheel basis

For each of the four energy carriers, we analysed the entire energy chain (well-to-wheel), i.e. from their production to their actual use in various modes of transport.

Step			
1	Production of energy carrier from raw materials	Well-to-tank (WTT)	Well-to-wheel (WTW)
2	Transport, storage and distribution en route to a fuelling or charging point		
3	Fuelling or charging in the vehicle		
4	Use in the vehicle	Tank-to-wheel (TTW)	

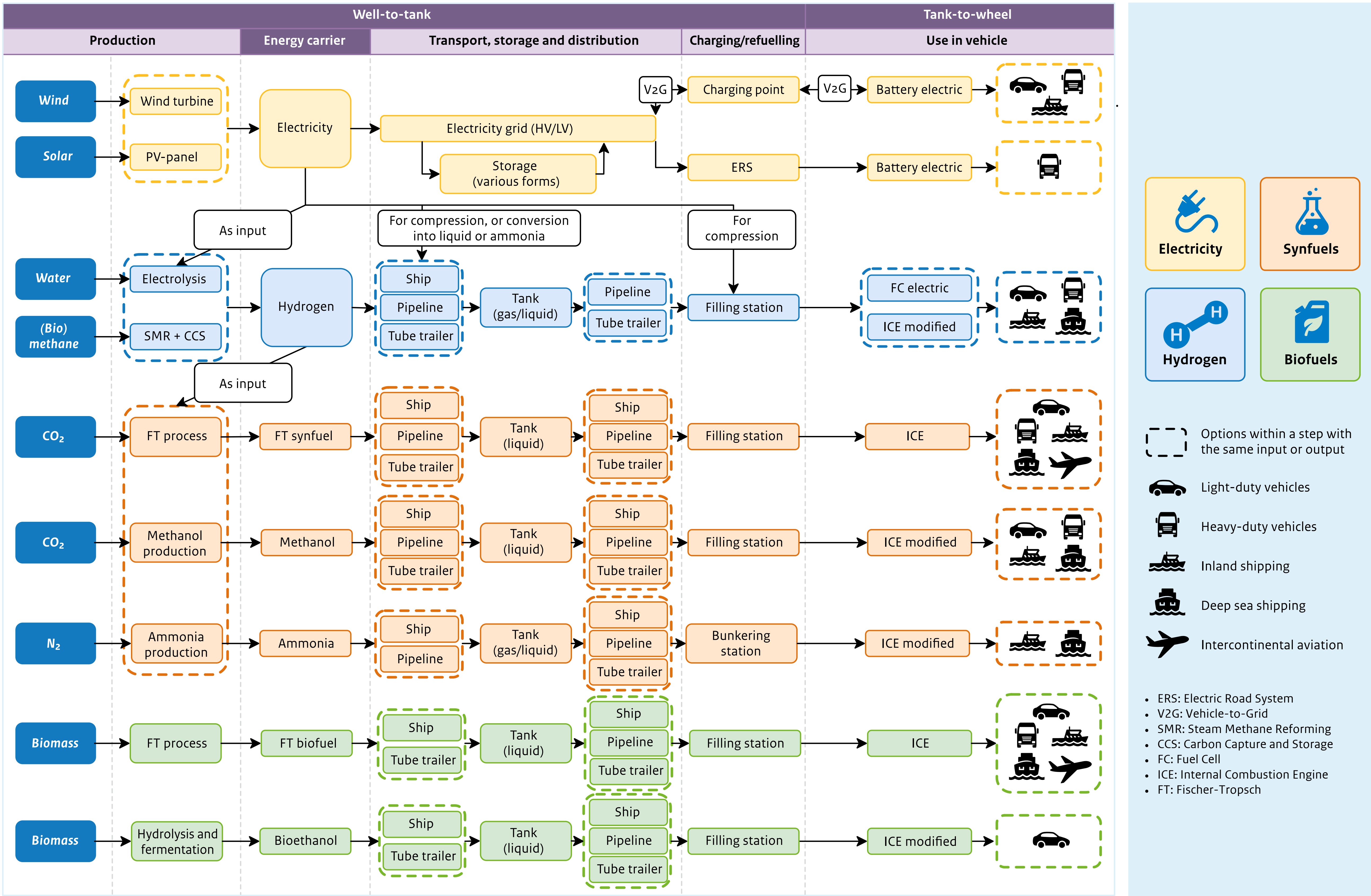
Modes of transport:
- Passenger cars
- Heavy-duty vehicles
- Inland shipping
- Long-distance maritime shipping
- Intercontinental flights

Technological readiness

We considered technologies with a technological readiness level (TRL) of at least 6 (on a scale of 9), i.e. there is at least a full-scale working prototype of the technology.

3 criteria: energy efficiency, costs and land use

The energy chains we analysed are all completely, or nearly, carbon neutral in principle, so they score virtually the same in terms of carbon emissions. We measured all the chains against three criteria: energy efficiency, costs and land use (surface area required on land or at sea to provide the energy for the vehicles). Incidentally, carbon neutral is not necessarily the same thing as climate neutral, as non-CO_2 emissions of can also have a climate impact.


Well-to-tank
Tank-to-wheel
Production
Energy carrier
Transport, storage and distribution
Charging/refuelling
Use in vehicle
Wind
Solar
Wind turbine
PV-panel
Electricity
Electricity grid (HV/LV)
Storage (various forms)
V2G
Charging point
V2G
Battery electric
ERS
Battery electric
As input
For compression, or conversion into liquid or ammonia
For compression
Water
(Bio) methane
Electrolysis
SMR + CCS
Hydrogen
Ship
Pipeline
Tube trailer
Tank (gas/liquid)
Pipeline
Tube trailer
Filling station
FC electric
ICE modified
As input
CO_2
FT process
FT synfuel
Ship
Pipeline
Tube trailer
Tank (liquid)
Ship
Pipeline
Tube trailer
Filling station
ICE
CO_2
Methanol production
Methanol
Ship
Pipeline
Tube trailer
Tank (liquid)
Ship
Pipeline
Tube trailer
Filling station
ICE modified
N_2
Ammonia production
Ammonia
Ship
Pipeline
Tank (gas/liquid)
Ship
Pipeline
Tube trailer
Bunkering station
ICE modified
Biomass
FT process
FT biofuel
Ship
Tube trailer
Tank (liquid)
Ship
Pipeline
Tube trailer
Filling station
ICE
Biomass
Hydrolysis and fermentation
Bioethanol
Ship
Tube trailer
Tank (liquid)
Ship
Pipeline
Tube trailer
Filling station
ICE modified
Electricity
Synfuels
Hydrogen
Biofuels
Options within a step with the same input or output
Light-duty vehicles
Heavy-duty vehicles
Inland shipping
Deep sea shipping
Intercontinental aviation
ERS: Electric Road System
V2G: Vehicle-to-Grid
SMR: Steam Methane Reforming
CCS: Carbon Capture and Storage
FC: Fuel Cell
ICE: Internal Combustion Engine
FT: Fischer-Tropsch

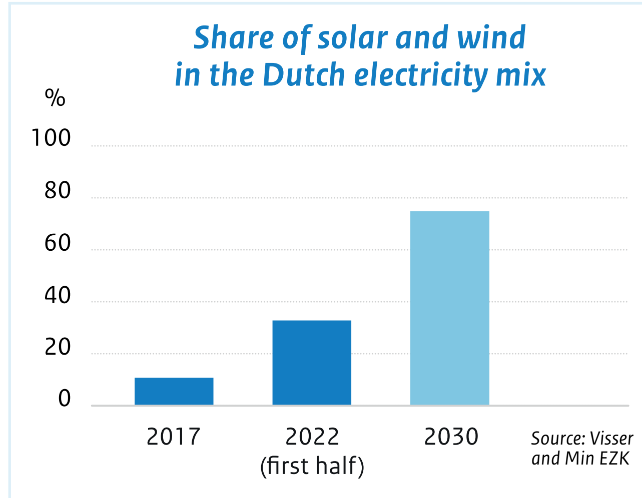
Electricity

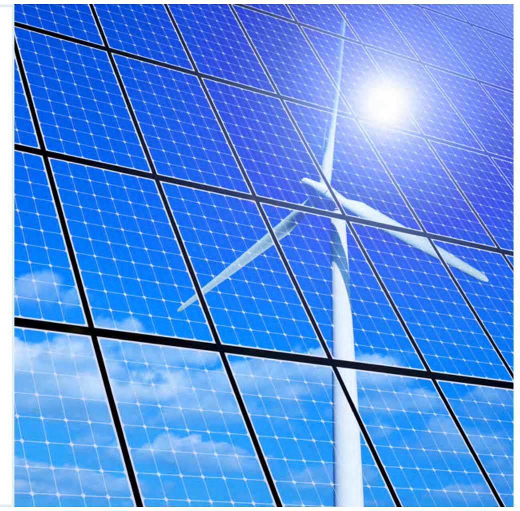
This energy chain begins with the generation of electricity from wind and solar energy using wind turbines or photovoltaic cells (solar panels). This electricity is then transported and distributed through the electricity grid to the charging infrastructure to charge vehicle batteries. In the period between its generation and use, it is possible to store the electricity for a short time in stationary batteries, or for a longer time by converting it into hydrogen, for example.

Electricity as an energy carrier is suitable for light vehicles (passenger cars), heavy-duty vehicles (trucks) and inland shipping (barges). For the purposes of this report, we have excluded battery-powered maritime shipping and aviation, because insufficient technological progress has been made for their use over long distances (TRL<6); moreover, the great weight of the batteries required is a major bottleneck for intercontinental flights. For heavy vehicles, it could be an option to charge the vehicles while on the road using a pantograph system. Such systems are known as Electric Road Systems (ERS) or dynamic charging systems.

In the first five months of 2022, 18% of all new passenger cars sold and 3% of all passenger cars then in use in the Netherlands were fully electric. Source: RVO

Renewable electricity is important not only for the electricity chain, but also for the hydrogen and synfuels chains, because electricity is a resource for hydrogen production (by electrolysis). In turn, hydrogen is a material input for synfuels (also called e-fuels because the chain is electricity-hydrogen-synfuels). Electricity also plays a role in other parts of the energy chain, for example to compress hydrogen or for the extreme cooling required to transport it in liquid form.





Storage medium for electricity?

Electricity is difficult to store. It can be done using stationary batteries, but this is a relatively expensive solution. Like hydrogen, synfuels are sometimes seen as an option to temporarily store surplus electricity from variable sources (solar and wind), however it is unclear to what extent the process of producing synfuels is suitable in combination with a variable supply.

Electric charging

An average electric passenger car uses about 0.2 kWh/km, which is about 2,600 kWh per year for an average mileage. This is comparable to the average electricity generation of 9 solar panels. An offshore wind turbine with a capacity of 11 MW can produce enough energy for 15,000 cars, 250 heavy trucks or 3 million electric bicycles. The capacity of a standard public charging point for two vehicles is 22 kW, or 11 kW per outlet. This is 220 volts and 48 amps, which means a 50 kWh battery can be charged in about 4-5 hours.

Hydrogen

There are two methods for producing hydrogen, both of which we describe in this report: 1) from electricity via electrolysis and 2) from biomethane (or an alternative) via Steam Methane Reforming (SMR).

In **electrolysis**, water molecules are separated into hydrogen and oxygen atoms using electricity. In **SMR**, methane is converted into hydrogen via a number of chemical process steps, whereby CO_2 is also produced. To produce carbon neutral hydrogen, this CO_2 must be captured and stored. This is called carbon capture and storage (CCS). In current practice, often up to 90% of the CO_2 produced in SMR is captured and further processed (for example by the soft drinks industry). However, in order to achieve carbon neutral hydrogen, this captured CO_2 would have to be stored permanently. The remaining 10% of the CO_2 can be 'neutralised' by mixing the natural gas with 10% biomethane.

Hydrogen colour codes	Manufactured from/using	Carbon neutral?
Grey	Natural gas	No
Blue	Natural gas combined with carbon capture and storage	Only in combination with biomethane for the uncaptured CO_2
Green	Renewable electricity	Yes

A lot of hydrogen is already being produced for industrial applications. SMR is the most widely used production method to this end and natural gas the most commonly used fuel: about 75% of all hydrogen is produced by SMR using natural gas.

Source: Shell

How much additional volume is required to produce the same amount of energy as diesel?

	Volume compared to diesel (=1)	
	Excl. container	Incl. container
Hydrogen @700 bar	6	16
Cryogenic hydrogen (-253°C)	4	8
Electricity in battery	50	100
Diesel	1	1

Source: TNO

Hydrogen can be transported and stored as a gas under high pressure, as a liquid (at an extremely low temperature of -253°C), or in the form of ammonia (NH_3), i.e. chemically bonded to nitrogen. Liquefying hydrogen and producing ammonia both require a lot of energy. Hydrogen can be converted into electricity for an electric motor by using a fuel cell (FC). However, the hydrogen must be purified before it can be used in an FC, which requires extra energy. Hydrogen can also be used as a fuel in an internal combustion engine (ICE), provided that the engine has been modified to this end. Both options can be used for light and heavy-duty vehicles and inland and maritime shipping. The TRL is too low for intercontinental flights using hydrogen (moreover, as with batteries, there is the problem of the extra weight and space required on board), so we do not investigate this option here.

Synfuels

Synfuels (synthetic fuels) come in various types. These fuels can be used in vehicles with an ICE (modified or unmodified). In this report, we distinguish between Fischer-Tropsch synfuels (FT fuels), ammonia (NH_3) and methanol (CH_3OH). The production of synfuels always requires hydrogen as a material input. This hydrogen must necessarily be obtained in a carbon neutral manner. CO_2 is also required as a material input for FT synfuels and methanol. It can be captured from so-called point sources, such as industries (Carbon Capture, or CC), or extracted from the air (Direct Air Capture, or DAC).

Fuel of the future?

Although synfuels sound like something from the future, they have actually been around for a while. In 1997, over 150,000 cars in the state of California were running on pure methanol or a mixture of petrol and methanol. This was in response to the high price of petrol. Methanol was available at more than 100 filling stations. When petrol prices fell, methanol lost its popularity. All in all, Californians drove more than 300 million kilometres using methanol.

Fischer-Tropsch: climate-friendly fuel based on CO_2

Fischer-Tropsch fuels are produced by the chemical process of the same name. In this process, carbon-rich sources such as CO_2, wood or organic residues are converted into carbon monoxide which is then transformed into syngas using steam. Hydrocarbon chains can be formed from this syngas, and because these chains have varied lengths, several types of fuel are created. As they are chemically identical to fossil fuels (diesel, petrol, kerosene), they are also known as 'drop-in fuels': they can be used as direct replacements for fossil fuels. Depending on the material input (biomass or hydrogen with CO_2), either FT biofuels or FT synfuels are produced.

Three types of synfuels in this study

Synfuels	Produced from		Application in vehicle
FT synfuel	H_2 from renewable electricity	CO_2	**Drop-in fuels** can be used in ICEs without engine modification
Methanol			Engine needs to be modified and fuel must be mixed with diesel or H_2
Ammonia		N_2	

Compared to electricity and hydrogen, synfuels are easy to store. The **FT synfuels** (FT petrol, FT kerosene, etc.) are chemically identical to their fossil counterparts and can therefore be used in the same transport infrastructure and combustion engines as fossil fuels. They are therefore also called drop-in fuels.

In principle, it is possible to make suitable FT synfuels for all modes of transport. **Ammonia** is volatile and toxic, which poses safety risks and makes storage and transport more complicated. Ammonia is only considered suitable as a transport fuel for inland and maritime shipping. This requires both a modified combustion engine as well as mixing with a second fuel, such as diesel or hydrogen, because ammonia is highly flammable. This means that two fuel tanks are required in the vessel or vehicle. Finally, **methanol** is also toxic, requires a modified engine and can be used in all modes of transport except aviation.

Biofuels and synfuels are carbon neutral but do cause NO_X emissions

Biofuels contain the element carbon (C) and therefore emit CO_2 when combusted. Synfuels that contain carbon (FT synfuels and methanol) do the same. Despite this, these carbon-based fuels could be suitable for carbon neutral mobility:

- The plants that provide the biomass for biofuels extracted the CO_2 from the air in a process called photosynthesis.
- In synfuels in combination with DAC, as much CO_2 is removed from the atmosphere as is emitted during combustion.
- In synfuels in combination with CC, the premise is that if the CO_2 were not used for mobility it would be emitted by the industry sector. The use of these fuels for mobility therefore only delays the industrial emissions. The question is whether there will still be point sources available for this capture in the medium to long term.
- The electricity and any hydrogen required must also be carbon neutral.

Synfuels and biofuels have the disadvantage over electricity and hydrogen as an energy carrier for mobility that their combustion generates NO_X. This is harmful to humans (air pollution) and the environment (nitrogen deposition). However, the NO_X emissions produced during the combustion of methanol are 60% lower than those from diesel due to a lower combustion temperature than in a regular diesel engine.

Biofuels

The FT process can be used not only for converting H_2 and CO_2 into synfuels, but also for converting biomass into transport fuels. The biofuels manufactured with this process are called FT biofuels. Another biofuel discussed in this report is bioethanol. The biomass (feedstock) for these FT biofuels and bioethanol can consist of lignocellulose, wood, or residues from various crops such as maize, coconut or sugar cane.

Raw material for fuel

The Renewable Energy Directive II (RED II) provides targets and guidelines for renewable energy, including the use and production of biofuels in transport. Annex IX covers raw materials (also called 'feedstocks') for biofuels. Part A includes feedstocks that should be used more (agricultural residues, dedicated energy crops) and part B lists feedstocks that should be used less (cooking oil and animal fats). The underlying goal is to preserve biodiversity and safeguard the food supply and sustainability in general.

FT biofuels and bioethanol can be transported, stored and refuelled using the existing fuel infrastructure. Like FT synfuels, FT biofuels are chemically identical to their fossil counterparts, which means that they can be used in regular combustion engines. However, engines need to be modified in order to use pure bioethanol. For the purposes of this report, we studied FT biofuels in combination with all modes of transport. We consider bioethanol only as an energy carrier for light vehicles, because this fuel is a petrol substitute and petrol is currently only used in these vehicles.

In 2021, 86% of biofuels in the Netherlands were sourced from waste streams, half of which were used cooking oil. Source: NEa

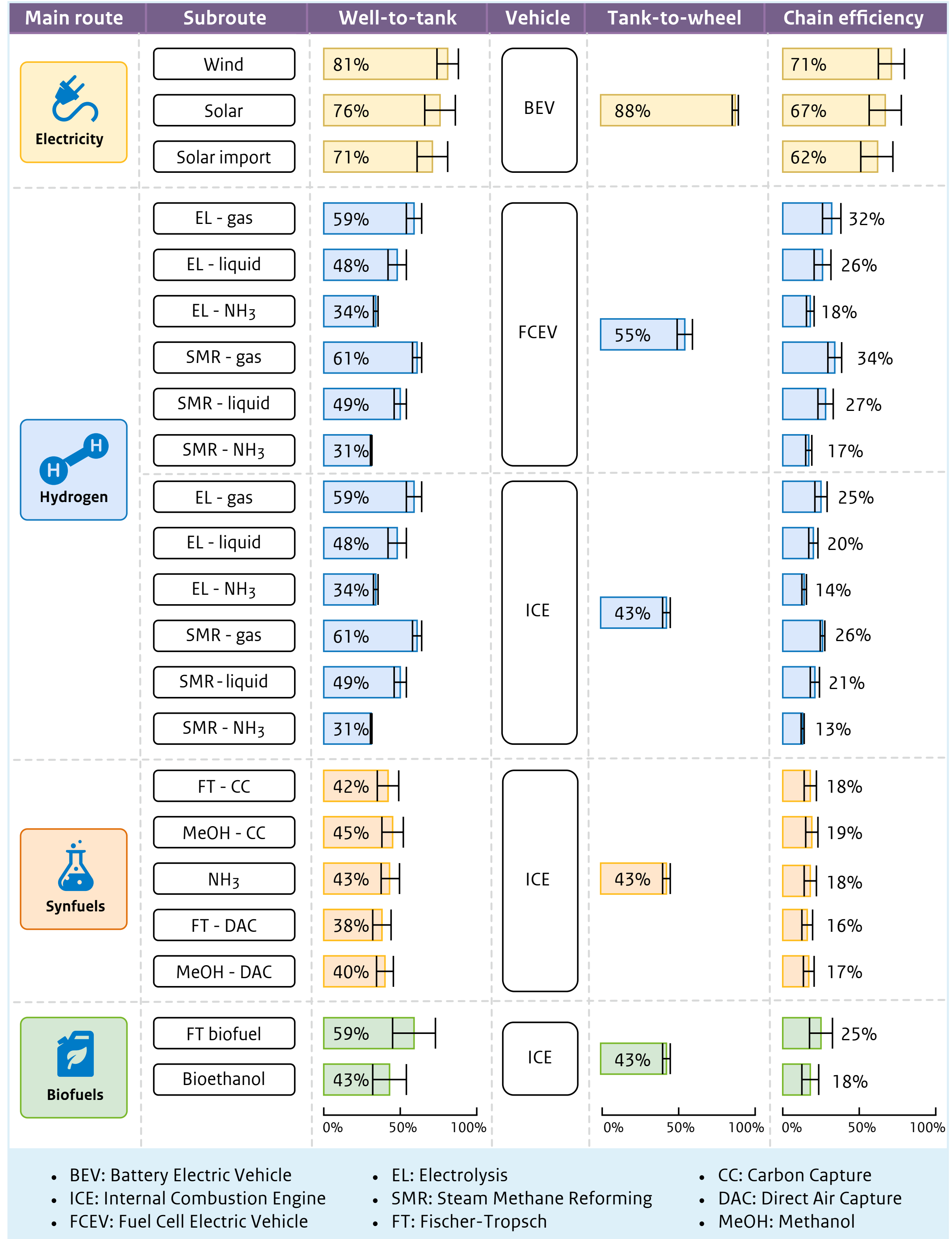
Physical characteristics of all fuels

	Calorific value	Mass density	Liquid under atmospheric pressure and at room temperature?
	MJ/kg	kg/m³ (*)	
Hydrogen @1 bar	120	0.09	No, liquifies at -253ºC
Hydrogen @350 bar		31**	
Hydrogen @700 bar		42**	
Liquid hydrogen		71	
Ammonia	18.6	758	No, liquifies at -33ºC
Methanol	19.9	794	Ja
Synthetic and oil-based petrol	41.5	747	Ja
Synthetic and petrol-based diesel	44.0	780	Ja
Synthetic and petrol-based kerosene	44.1	755	Ja
Bioethanol	30.0	790	Ja

** Under atmospheric pressure and at room temperature*
*** At the stated pressure*

2 Energy efficiency

We will first compare the energy efficiency of the various energy chains. This characteristic provides information on how efficiently energy is used in the chain to propel the relevant means of transport. The higher this efficiency, the fewer means of production (wind turbines, electrolysis units, fuel plants, etc.) are needed at the beginning of the chain.



WTT, TTW and energy chain efficiency in 2030

WTT efficiencies are considered under conditions of optimal vehicle dynamic behaviour and engine load (dynamic versus non-dynamic, high load versus low load). What constitutes optimal conditions differs per powertrain type (Battery Electric Vehicle (BEV), Fuel Cell Electric Vehicle (FCEV) or Internal Combustion Engine (ICE)). 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. Based on our study, the synfuel NH_3 is only an option for maritime and inland shipping. In the 'SMR-NH_3' sub-chain, methane is converted to ammonia and the ammonia is later converted to hydrogen. This is not done using SMR, so the designation is actually incorrect. However, we have left it as it is for the purpose of comparison with the other methane-based sub-chains.

- WTT: this is the energy efficiency of the combined steps of production, transport/storage/distribution and refuelling/charging. This efficiency is often independent of the mode of transport for which the energy is ultimately used, but sometimes efficiency differences occur in the refuelling or charging process and in the length of the transport and distribution chain. This results in lower or higher energy losses depending on the mode of transport.
- TTW: this is the efficiency with which the energy obtained by refuelling or charging is converted into propulsion. The efficiency here depends on the type of energy and on the drivetrain in the vehicle (electric or combustion engine). For the efficiency of each vehicle type, we have assumed optimum conditions in terms of driving profile and engine load. In the case of a BEV and FCEV, these are a low engine load and dynamic vehicle behaviour. In an ICE it is the other way round: a high load and non-dynamic vehicle behaviour.
- Chain efficiency: this is the multiplication of the above two energy efficiencies and describes the proportion of energy in the chain that is ultimately used for propulsion.

Battery electric vehicles in combination with wind energy most efficient

The most efficient combination is that of wind energy with battery electric vehicles (BEVs). The energy chain efficiency is 71%, i.e. the energy input is approximately 1,4 times greater than the energy that is eventually given to the wheels. The other electric sub-chains (locally generated solar energy and imported solar energy) are also energy efficient: they all show relatively low losses from the point of electricity generation to the charging point (i.e. well-to-tank). In addition, they achieve the most efficient energy conversion in the vehicle (tank-to-wheel efficiency).

Regenerative braking

Vehicles with an electric motor (BEV and FCEV) can achieve high energy efficiency in a dynamic driving pattern (different speeds and many start-stops) because braking energy is recovered. In combustion engine only vehicles, all braking energy is lost.

Hydrogen driving lags behind battery-electric driving in terms of efficiency

Hydrogen is the most efficient fuel after wind-powered battery electric vehicles. More specifically, it is the variant: production from electrolysis, transported to the refuelling point in gaseous form and used in a fuel cell vehicle (FCEV). The difference, however, is considerable: the 'BEV on wind energy' sub-chain is more than twice as efficient as the 'FCEV on H_2 from electrolysis' sub-chain, namely 71% and 32% respectively. If H_2 is used in an internal combustion engine (ICE) instead of an FCEV, the difference is even greater: 71% versus 25%. So, the total energy input is 3 to 4 times greater than the energy that eventually is used for propulsion.

If the hydrogen is transported by ship, the efficiency is even lower: 18-26% when used in an FCEV, and 13-21% when used in an ICE. This is because hydrogen needs to be liquified by means of extreme cooling before transporting it by ship. Another option is to transport hydrogen in the form of liquid ammonia. The conversion to liquid hydrogen or ammonia (NH_3) is relatively energy-consuming, while in the case of NH_3, the step of reconverting it to gaseous hydrogen is also energy intensive.

In the hydrogen energy chain, electricity is an input in the production step and an input in other steps of the chain. The steps of compression and extreme cooling consume a particularly large amount of electricity.

Synfuels the least energy efficient

In general, the chain efficiency of synfuels is lower, and thus results in higher energy consumption, when compared to the hydrogen and electricity energy chains. An exception is when the hydrogen is transported in the form of ammonia and then converted back into hydrogen. This reconversion results in an energy loss compared to the direct use of ammonia as a synfuel.

The energy chain efficiency of the three synfuels is less than 20%. This relatively low efficiency is primarily due to the energy loss in the production process in which the synfuels are manufactured from hydrogen and CO_2 or nitrogen. Secondly, they are used in the vehicle in an ICE which has a much lower energy efficiency than an electric motor in combination with a battery (BEV) or a fuel cell (FCEV). All in all, running a vehicle on methanol, ammonia or FT synfuels is 3 to 4 times less energy efficient than using electricity. In all cases, these differences apply under optimal driving conditions.

Biofuels score only average for energy efficiency

In the biofuel energy chain, the greatest energy losses occur during the production process. Both the cellulosic ethanol production process and the Fischer-Tropsch process are very energy intensive. Cellulosic ethanol production has an average efficiency of 30%, but it is expected this can be increased to 40%. The production of FT biofuels, with an energy efficiency of between 45% and 73%, also involves significant energy losses, partly because some of the carbon in the biomass is released in the form of CO_2.

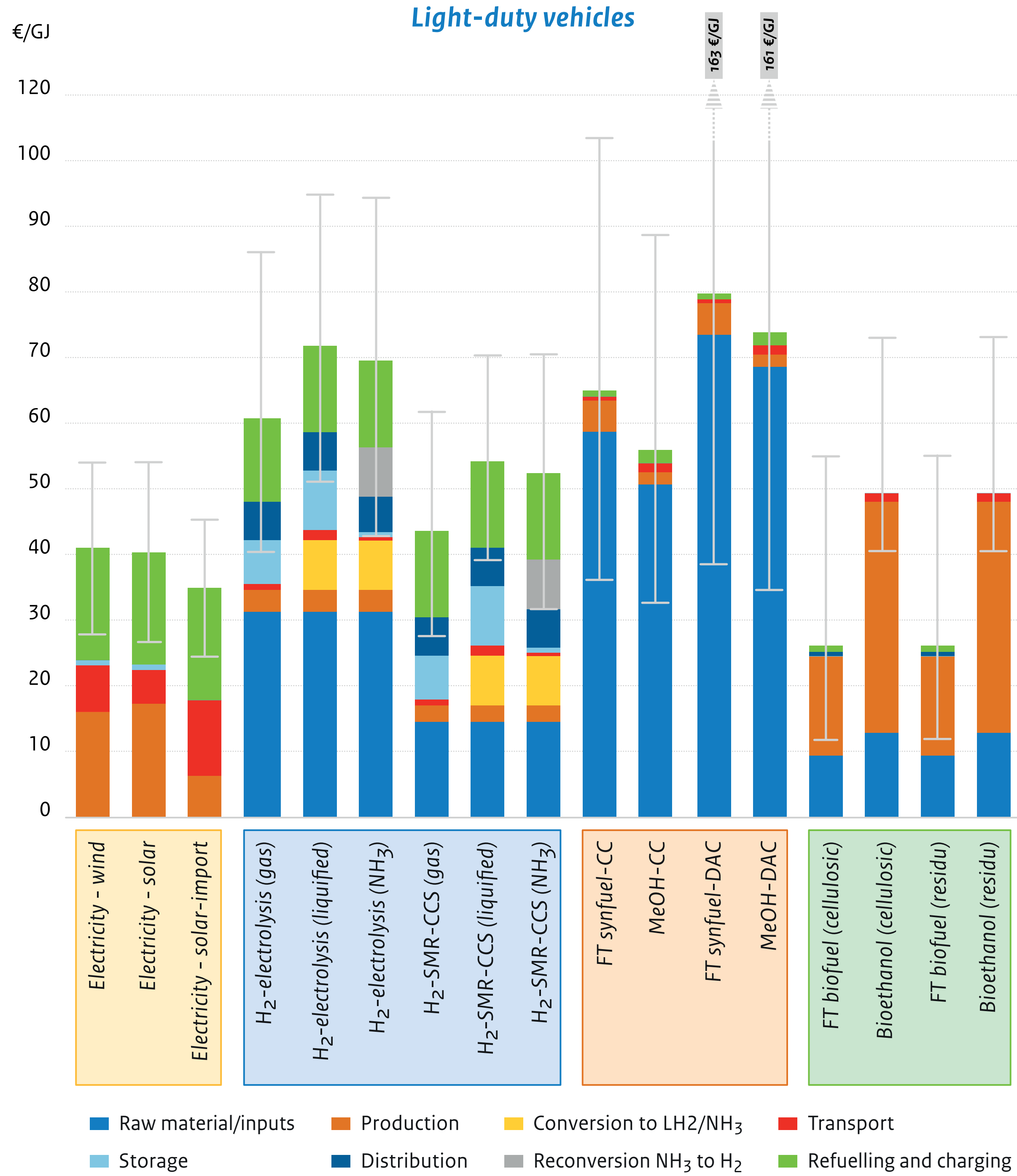
In the case of biofuels, it is possible to make use of the existing efficient fuel infrastructure, where there are little transport losses. They are used in vehicles with combustion engines that have an optimal energy efficiency of 40-45%.

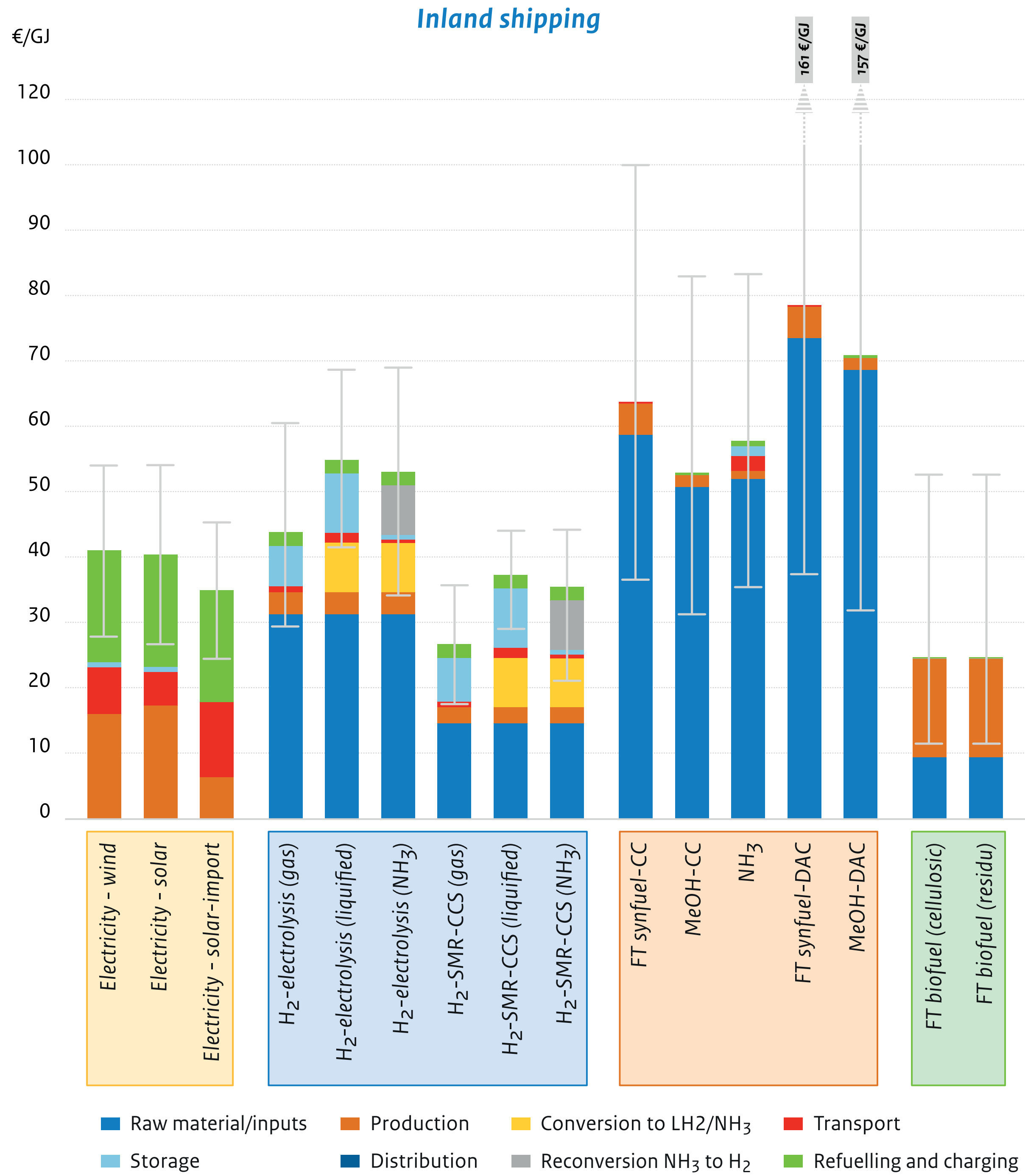
3 Costs

The next criterion involves the costs of each of the energy chains. We will focus first on the costs at the refuelling or charging point, since fuel costs are dominant for most modes of transport. Then we will look at the cost per distance travelled, including vehicle costs (excluding maintenance costs, insurance and taxes). As the costs in 2050 are too uncertain, in this study we will only look at the projected costs in 2030. In fact, the uncertainties are already large even for that year, as shown by the uncertainty margins in the figures below.

Costs are not the same as prices, i.e. no profit mark-ups, subsidies, taxes and duties have been included. The latter three are possible policy levers that the government could deploy to make one energy carrier more attractive than the other, or balance out the cost differences for the user. Although profit margins may vary from one energy carrier to another, the cost ratios do give an idea of the price relationships (without policy measures) between the energy carriers.

Energy costs at the fuel station or charging point





Cost overview of the various energy carriers at the fuel station or charging point for road vehicles (previous page) and shipping (above) in 2030. The uncertainties reflect the uncertainty of the fixed and variable costs, and not the uncertainty of the energy efficiency. For synfuels, CO_2 can be captured directly from the air (DAC) or at point sources (CC). For hydrogen, we assume that the hydrogen is transported from North Africa to the EU. In the case of gaseous hydrogen, we assume it is transported by pipeline over a distance of 1,500 km. In the case of NH_3 and liquid hydrogen, we assume transport by ship.

Electricity and biofuel are the cheapest per energy unit at the fuel station/charging point

FT biofuels and electricity are among the cheapest options per energy unit at the charging or refuelling point. The uncertainty is mainly related to the production costs, as the production of FT biofuels is a relatively new technology that has not yet been applied on a large scale. In addition, raw materials prices are also uncertain. However, for the purposes of this study we have applied a fixed price of €5,5/GJ of biomass for both woody (cellulosic) biomass and residues.

For electricity, the import option can be slightly cheaper than local generation, provided that the electricity is purchased from regions where production is cheap (for example because of the amount of sunshine and/or the favourable wind conditions). However, transport costs are higher.

When used for road vehicles, hydrogen is more expensive than for shipping

When used for vehicles, hydrogen is more expensive per unit of energy at the filling station than for shipping by about €17(11-25)/GJ. This is because road vehicles require a much more extensive distribution network than shipping. In addition, the storage tank and the compressor needed to increase the pressure of the hydrogen to 350-700 bar at the filling station are expensive pieces of equipment. For the other energy carriers, there is only a small difference in refuelling costs between the modes of transport.

Hydrogen based on natural gas and biogas (SMR with CCS) is about €18/GJ cheaper than hydrogen produced using electrolysis. This is because the production and materials input costs for SMR-CCS are about 50% lower than for electrolysis. We have taken into account natural gas costs of €10 (5-15)/GJ and electricity costs of €75 (50-100)/MWh. Around 30-60% of these electricity and gas costs for the hydrogen energy chain are for production and input materials. The remaining costs are for transport, storage, distribution and refuelling.

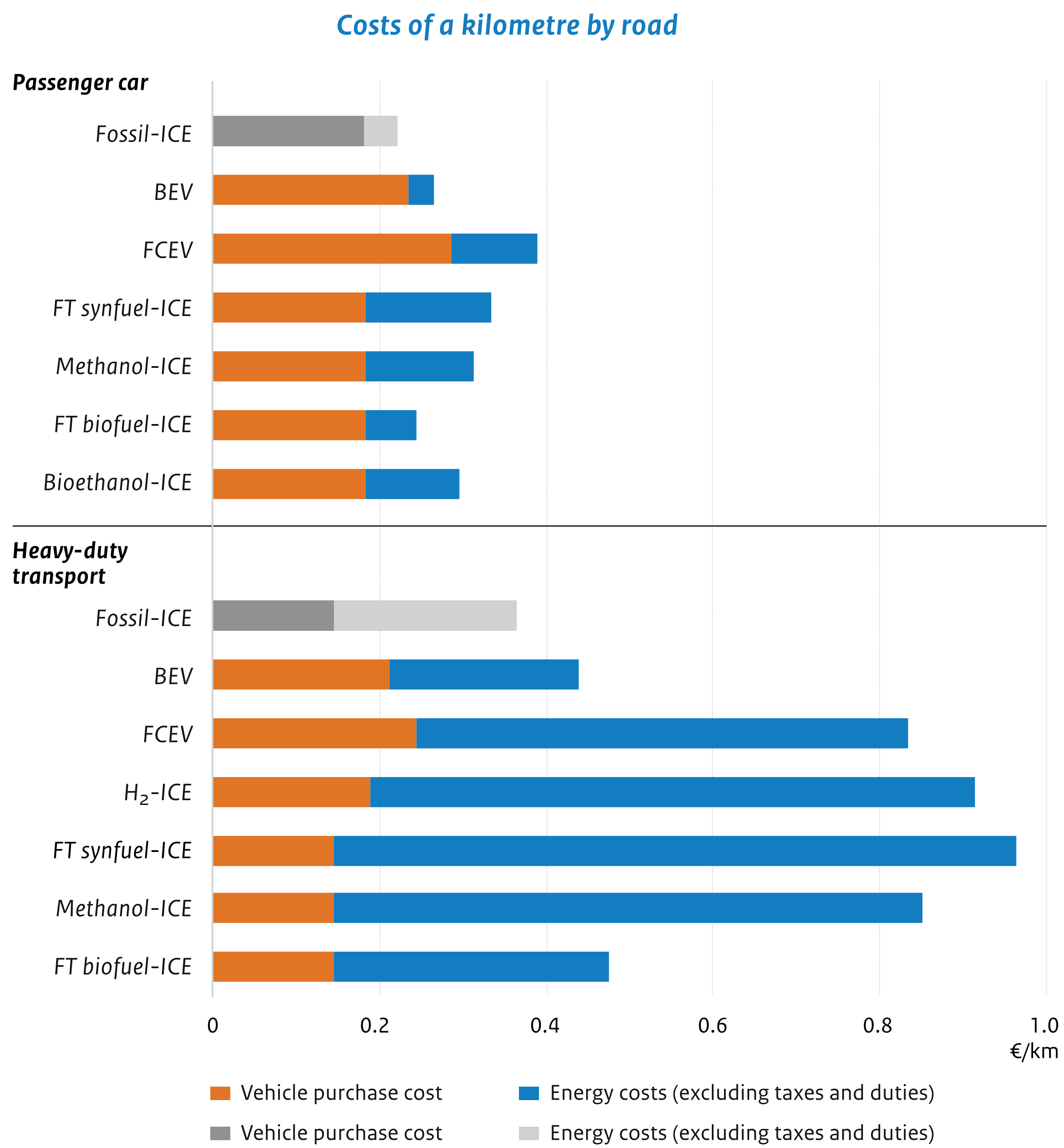
Transport, storage and distribution amount to 10-30% of the total costs, while the refuelling costs for road traffic amount to about 20-30% of the costs per unit. If the hydrogen is transported by ship, the additional step of liquefying the hydrogen adds about 11-14% to the costs and that of converting it into NH_3 and back adds 22-29%. In our calculations, we assumed a distance comparable to transport by ship from North Africa to the EU and a pipeline of 1,500 km. For longer distances, the cost of transport by pipeline increases more than the cost of transport by ship, regardless of whether a new gas pipeline has to be built or an existing one is used.

Synfuels are expensive, but do have other advantages

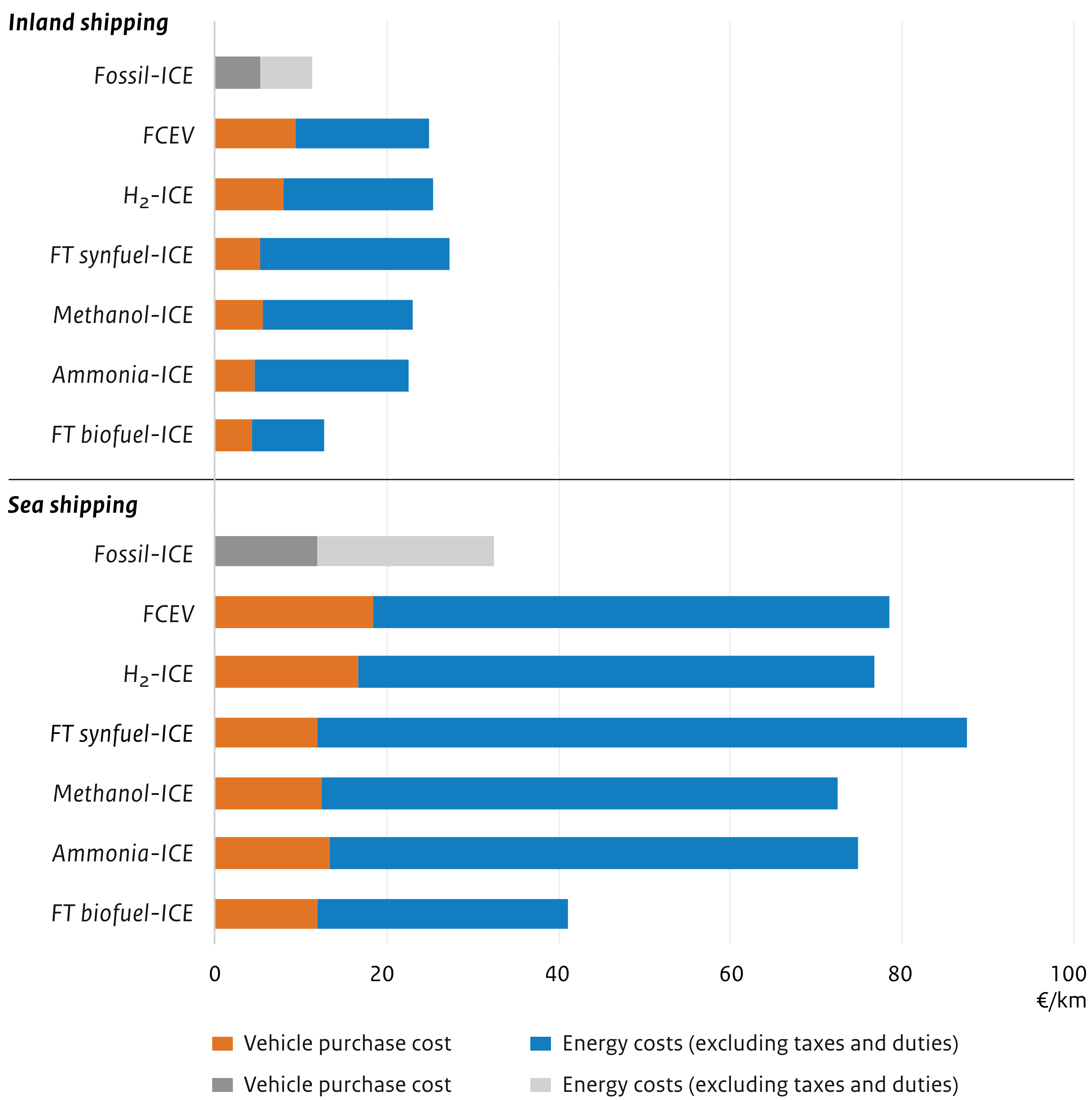
The material inputs for synfuels (hydrogen and CO_2) are expensive. For methanol and FT synfuels, we distinguish between fuels where CO_2 is captured directly from the air (DAC) and CO_2 obtained from point sources (CC). The latter option is approximately €200 cheaper per tonne of CO_2 (€15-20/GJ). By 2050, it is likely that CO_2 will have to be captured directly from the air, as there will be few, if any, large-scale point sources left by that time (but they will most likely still be available in 2030). However, the costs of DAC are very uncertain.

An advantage of both synfuels and biofuels is that the costs of transport, storage, distribution and refuelling are relatively low. All the existing infrastructure can be reused for FT fuels. For the other non-FT biofuels and synfuels, a large part of the existing infrastructure can probably be reused with some minor adjustments.

Costs in the total energy chain



Costs of a kilometre across the water



Battery electric heavy-duty vehicles the cheapest carbon neutral option per distance travelled

For trucks, battery electric is the cheapest of the 4 carbon neutral options. This is mainly due to the low energy costs, which are dominant in the total cost per km (the purchase costs of an electric truck are higher than for a truck with a combustion engine). In principle, this also applies to cars, although here the cost per distance travelled is slightly lower for a FT biofuel vehicle than for a BEV.

For heavy-duty vehicles, hydrogen is slightly cheaper when used in a fuel cell (FCEV) than in an internal combustion engine (H_2-ICE). For both alternatives, this only applies if the powertrains operate under optimal conditions. In the case of an FCEV, these conditions are a low engine load and highly dynamic vehicle behaviour. The energy costs of an FCEV increase under a high engine load and non-dynamic behaviour, while an ICE performs optimally under these conditions. The situation is then reversed and FCEV will be more expensive than H_2-ICE.

Biofuels are the cheapest per distance travelled for all other modes of transport

For inland and maritime shipping, FT biofuels, when used in an internal combustion engine ('FT biofuel ICE' option), are cheaper than the other carbon neutral alternatives. As mentioned, however, there is much uncertainty regarding the cost of the biofuels. There are only minor cost differences between the other alternatives (ammonia, methanol and FT synfuels, and H_2-ICE and FCEV for inland shipping).

We were not able to find a reliable cost estimate for electric barges, and this option is therefore not included in the figure.

We do not know what the costs are of purchasing aircraft, which is why aviation is not included in the cost overview above. The fuel options for aviation are FT synfuels and FT biofuels, both of which can be used in existing aircraft engines. FT biofuels are cheaper per kilometre than FT synfuels.

4 Land use

Land availability is limited and thus important to consider

Because land is a scarce resource, land use is an important criterion when considering carbon neutral mobility options. A decision to use land for a specific purpose (such as energy production) can limit the availability of that piece of land for other functions (such as housing or nature).

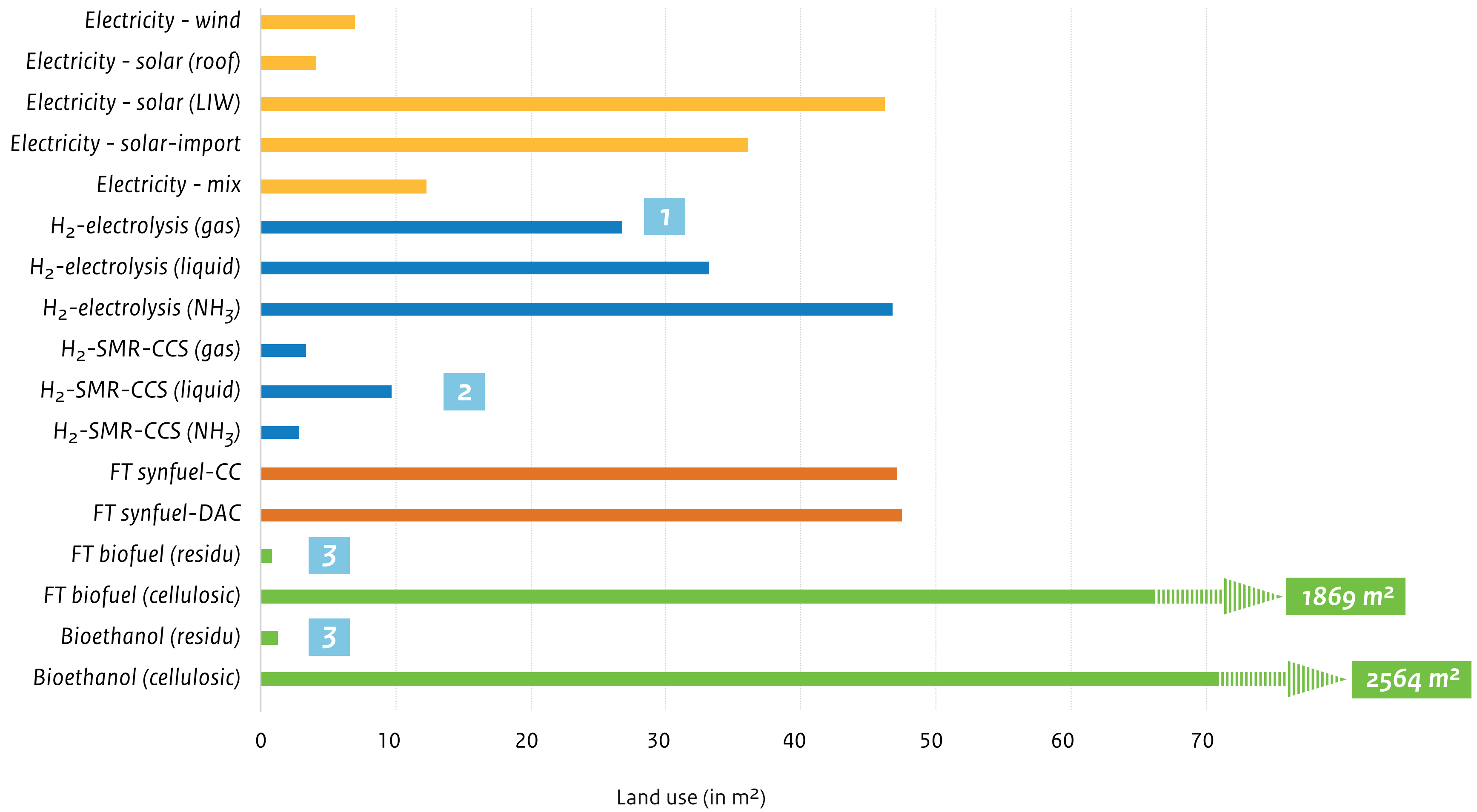
We quantitatively analysed space or land use requirements – also called ‘land take’ – of the energy chains per vehicle, expressed in square meters of land or sea surface (below we use ‘land’ to also include sea area). We did not consider qualitative aspects (such as the visual impact of wind turbines). Nor did we distinguish between land use in the Netherlands versus abroad, be it on land or at sea, or in an urban or rural area. Only surface land use was estimated, so subsurface CO_2 storage and power lines are not included.

Difference between net (direct) and gross land use

First of all, we report the net (direct) land use in m² for energy supply for a passenger car (13,000 km/year) and for an inland barge (70,000 km/year). For example, for wind energy we take into account the area of land or sea that cannot be used for other purposes due to the presence of a turbine or other infrastructure. For biofuels from agricultural or forestry residues, the land take is close to zero, as no additional land is required than is already used for the primary product, such as maize (the production process of the bio-fuel does takes land, which is visible in the graph).

However, in the case of wind energy, the gross land use is also important, because various climate neutral scenarios for the Netherlands assume the majority of electricity will come from this source. Gross land use is then the total area required to build a wind farm, including the space between the turbines.

Net land use for the energy supply for 1 passenger car



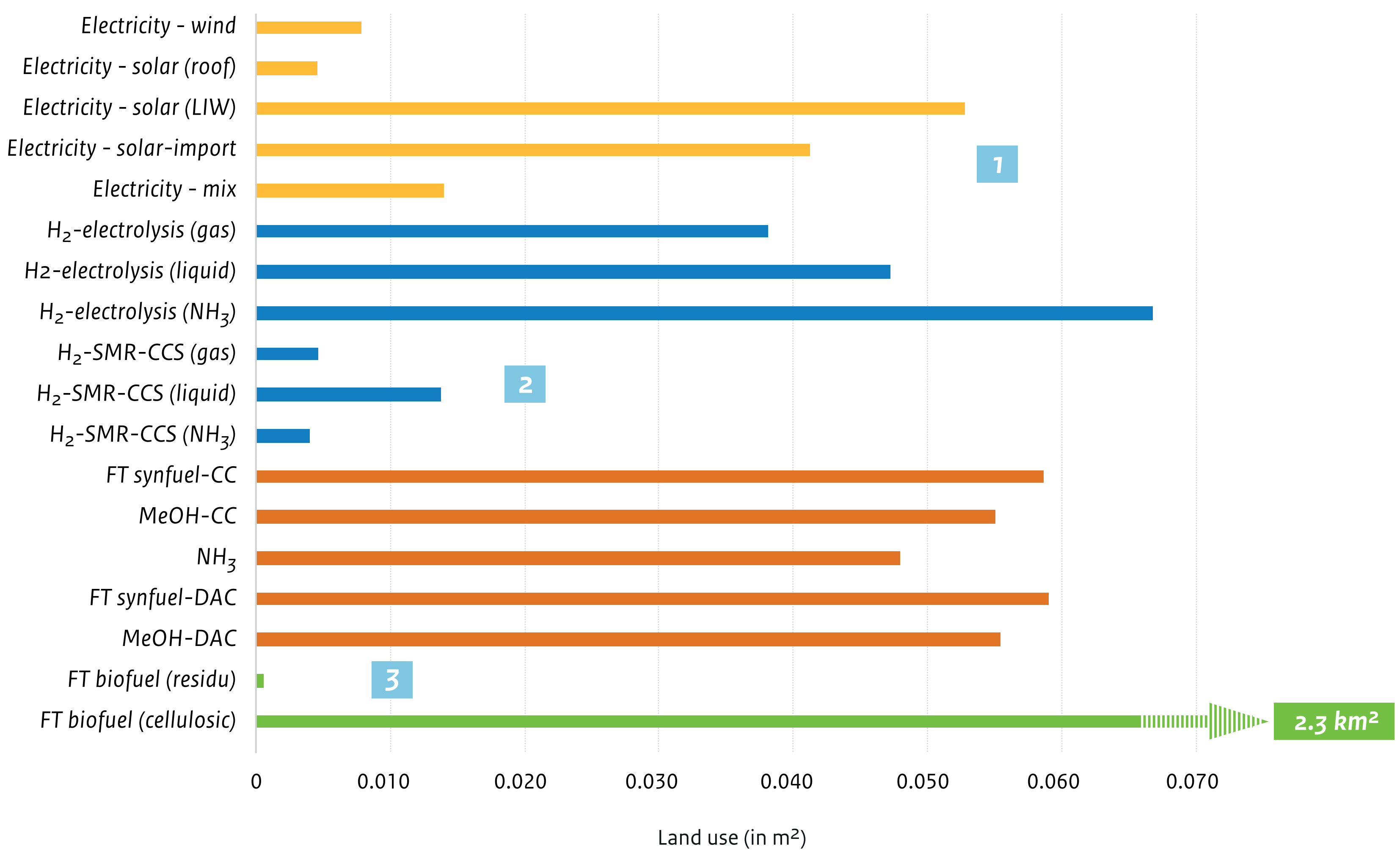
1 For electricity - mix and for the electricity for electrolysis a share of 76% wind and 24% solar energy applies.

2 H_2-SMR-CCS: no land use attributed to biomethane use.

3 No land use attributed to biomass from residues.

Abbreviations:
LIW: Landscape, infrastructure, water
CCS: Carbon Capture & Storage
CC: Carbon Capture
FT: Fischer-Tropsch
DAC: Direct Air Capture

Net land use for the energy supply for 1 inland vessel (Large Rhine class barge M8, 110m)



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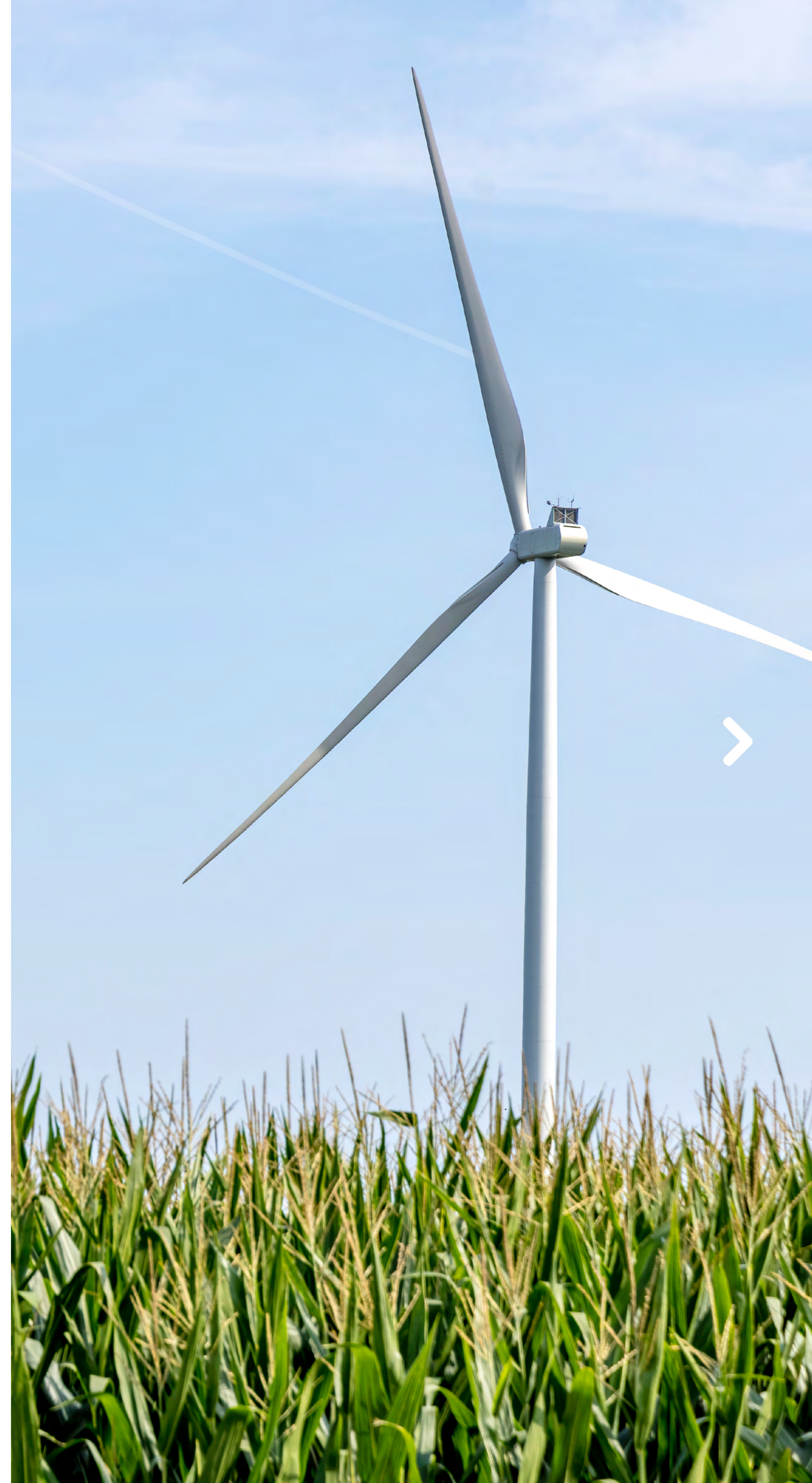


Battery-electric transport uses the least land

Due to the difference in efficiency, hydrogen produced by electrolysis and synfuels requires more than 2-5 times more electricity from wind power than when using electricity alone.

These differences are also reflected in the net land area required to supply one passenger car with carbon neutral energy: for electricity this is about 12 m^2 per vehicle, for hydrogen from electrolysis and synfuels this is 25-45 m^2. The land area required for biomass obtained from energy crops is much higher than that of the other options.

Hydrogen obtained through SMR-CCS uses less space than hydrogen produced by electrolysis, and is therefore more suitable for the Dutch situation. An SMR plant takes up little space, as does the requisite natural gas infrastructure. We assume the use of waste streams (such as animal manure and sewage sludge) to produce the 10% biomethane needed to make the SMR-CCS process carbon neutral. This therefore requires no extra land.

The net land use of electric road vehicles is equivalent to 1/5 of all roads and parking spaces in the Netherlands

If all road vehicles in the Netherlands had been electrified in 2019, it is estimated that it would have taken 40 TWh of electricity to run all these vehicles, with a net land take of about 250 km^2. This is equivalent to about one-fifth of the current surface area of the road and parking infrastructure.

The gross land use of all road vehicles is equivalent to the size of the province of Utrecht, the land use for bunker fuels is nine times this size

A wind farm the size of the province of Utrecht would be needed to power all the road vehicles in the Netherlands in case these are all BEVs. This is the gross land use, including the space between the wind turbines.

Manufacturing synfuels for the aircraft and ships currently bunkering in the Netherlands would require wind farms of an area of nine times the province of Utrecht, or a quarter of the Dutch Continental Shelf in the North Sea (gross land use). Setting aside such a huge area for wind farms would be a major challenge, as other sectors will also need electricity and the potential area for wind farms is limited to about one-third of the Dutch Continental Shelf. Most of the available space will therefore be needed for power generation for aviation and maritime bunker fuels (in case the energy were to be produced in the Netherlands).

Biofuels sourced from energy crops required a large land area

If all the fuel currently bunkered in the Netherlands for aviation and shipping were to be biofuel from energy crops (not residues), this would require a land area approximately twice the size of the Netherlands. If the biomass was sourced from crop residues there would be no additional land required, and the net land use would be zero. In the long term, it is likely that both energy crops and residues will be needed to meet the demand for biomass from all sectors.

Energy can be produced in the Netherlands or abroad

Energy production does not necessarily have to take place on Dutch land or sea; the energy can also be imported from abroad. Although the energy losses increase with distance, production abroad can sometimes be more efficient. For example, a PV panel in North Africa produces twice as much electricity as in the Netherlands. Hydrogen, biofuels (or the required biomass) and synfuels could be produced abroad using solar or wind energy, and then transported to the Netherlands by ship or pipeline. There are various reasons for the energy losses per energy carrier and mode of transport. In the case of hydrogen transported by ship, for example, the energy losses are mainly due to the liquefaction of the hydrogen, whereas the transport by ship itself requires relatively little energy. For gaseous hydrogen transported by pipeline, compressor stations are required at regular intervals, and these use a lot of power. In principle, the longer the pipeline, the more compressor stations are needed.

Which medium is suitable to transport energy?

	Electricity cable	Pipeline	Ship	Tube trailer
Electricity	√			
Compressed H_2 (gas)		√*		√
Liquid H_2 (cryogenic)			√**	√
NH_3 (liquid)		√***	√	√
FT fuels		√***	√	√
Methanol, bioethanol		√***	√	√

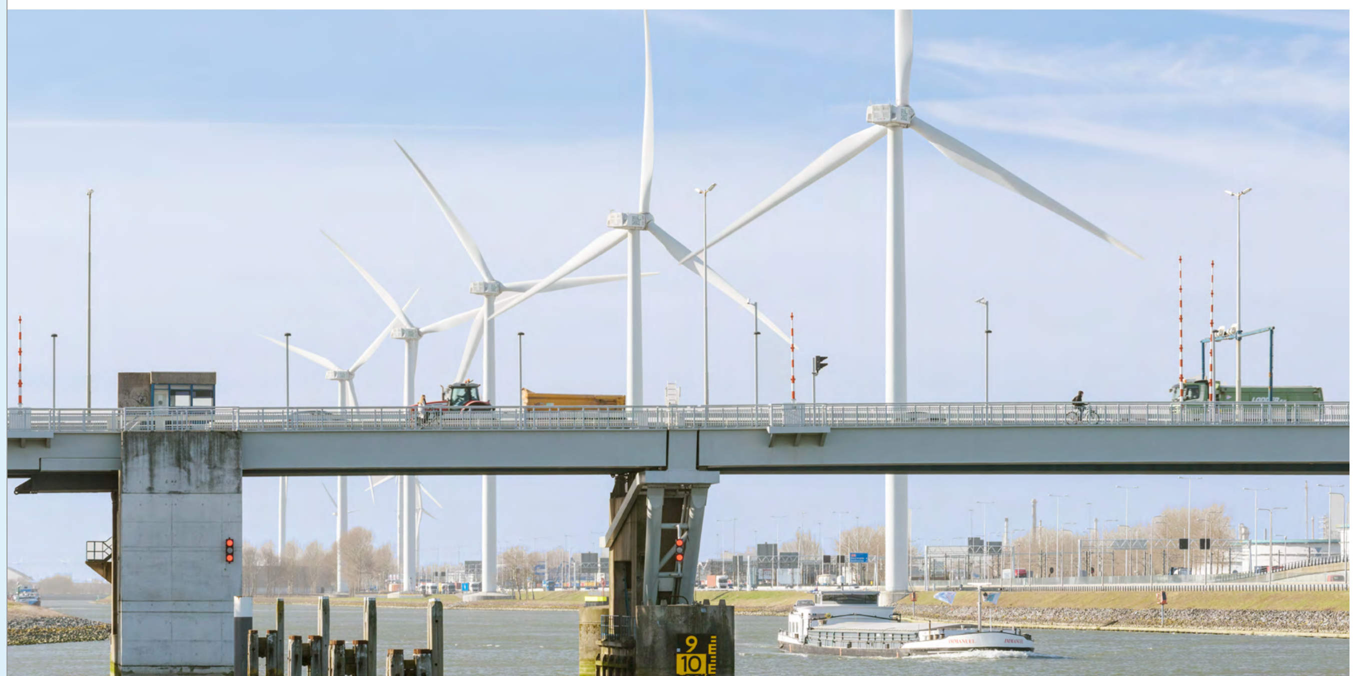
** With compressor stations at regular intervals (energy consumption relatively high)*
*** In a special ship similar to an LNG tanker, of which only one exists in the world (capacity 75 tonnes of H_2)*
**** With pump stations at regular intervals (energy consumption lower than for compressor station)*

Infrastructure for transport, distribution and charging also has spatial consequences

In all four energy chains, the production of energy (including the raw materials required) is the step that uses by far the most space. However, the other steps in the energy chain can also form land-use bottlenecks, particularly in urban environments. Examples are high-voltage cables and transformers for the transport and distribution of electricity, and pipelines for the transport and distribution of hydrogen. The charging and refuelling infrastructure also requires space, often in places where there is already a lot of competition for that space. It is easier to integrate synfuels and biofuels (that chemically resemble their fossil counterparts) into the spatial plan than it is for electricity and hydrogen.

5 Overview of combinations of energy carriers and modes of transport

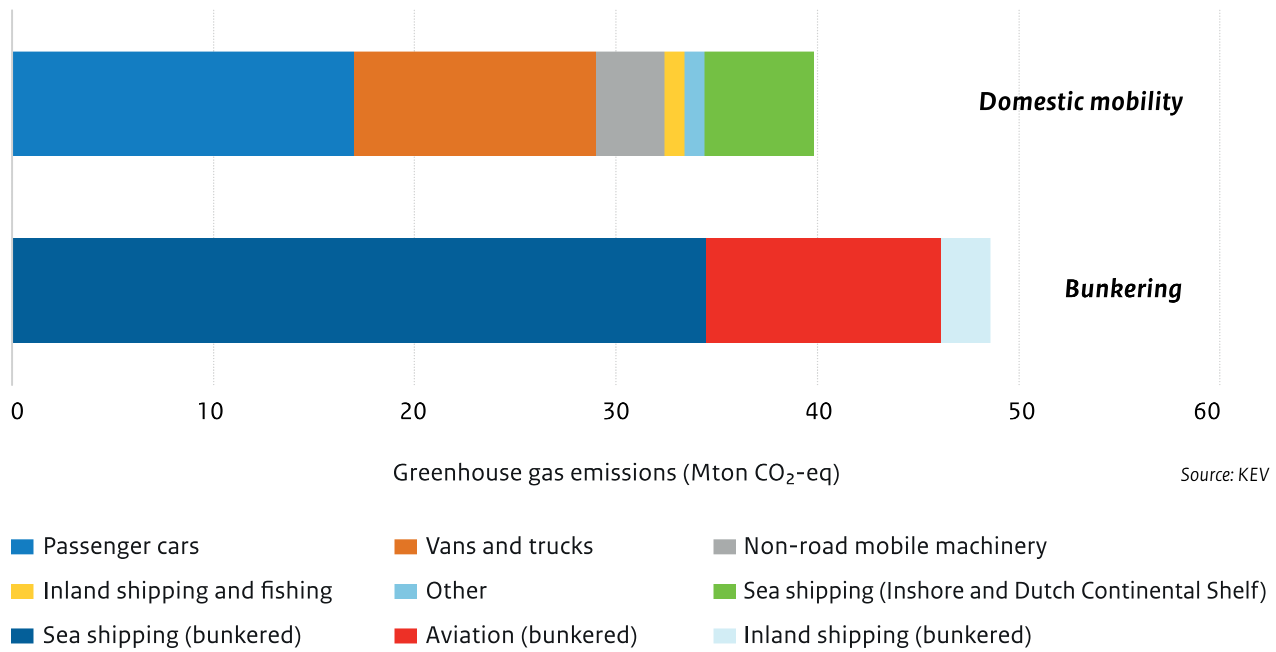
In this study, we discuss the five modes of transport that emit the most CO_2 in the mobility sector (excluding non-road mobile machinery). This concerns both domestic emitters such as road vehicles, and international maritime shipping and aviation, which refuel (bunker) in the Netherlands without their emissions necessarily having to take place on Dutch territory. The analysis of the modes of transport focuses on the following reference vehicles.



Mode of transport	Reference vehicle	Comments
Light-vehicles	Passenger cars	Vans are also included under light-duty vehicles, as they often have similar characteristics
Heavy-duty vehicles	Tractor-trailer	This is the heaviest category of trucks (up to 40 tonnes)
Inland shipping	Ships similar to a Large Rhine class barge (110 m)	
Maritime shipping	General cargo ship for long distances	
Aviation	Boeing 787 for about 300 passengers and intercontinental flights	Of all flights to and from EU airports, flights longer than 4,000 km account for 52% of CO_2 emissions; flights longer than 1,500 km account for 75% of emissions*

** Source: Eurocontrol*

Greenhouse gas emissions from domestic mobility and bunkering (2019)



The emissions of domestic mobility are the national emissions according to the IPCC guidelines, with the addition of the emissions of maritime shipping, both in port and on the Dutch Continental Shelf. Emissions from bunkering are the emissions from fuels that are stored in the Netherlands for aviation and shipping. These emissions may occur partly on Dutch territory and partly on foreign territory. The two categories of emissions therefore differ in their dimensions and cannot simply be added up.

We have not included all energy carriers for each mode of transport; the combinations indicated in black in the figure fall outside the scope of the study. This is due to the criteria of TRL ≥ 6 and practical applicability.

Energy chain	Sub-type	Conversion in vehicle	Light-duty vehicles	Heavy-duty vehicles	Inland shipping*	Sea shipping	Aviation
Electricity		Battery-electric					
		ERS					
Hydrogen		FC electric					
		ICE modified					
Synfuels	Drop-in (FT)	ICE					
	Ammonia	ICE modified					
	Methanol	ICE modified					
Biofuels	Drop-in (FT)	ICE					
	Bio-ethanol**	ICE modified					

** Also shipping on short and medium distances*
*** Ethanol is a gasoline substitute*

6 Passenger cars

There are plenty of opportunities to achieve carbon neutrality in the passenger car fleet by 2050. For this report, we examined battery electric vehicles, hydrogen vehicles (with a combustion engine or fuel cell system), drop-in synthetic fuels, methanol and biofuels (both drop-in and ethanol). Only ammonia as a fuel was excluded (because of the safety factor).

Electricity has advantages over hydrogen

Electric vehicles have advantages over hydrogen vehicles across the board: the costs of the energy chain are lower and the efficiency across the energy chain is two to five times higher. In the case of hydrogen, the total energy chain losses are lowest if it is transported in gaseous form and highest if it is (temporarily) chemically bound as NH_3 during transport.

Battery electric vehicles (BEVs) also have the advantage of ‘smart charging’ and Vehicle-to-Grid (V2G) systems. Smart charging varies the charging speed in order to optimise the load on the electricity grid. V2G systems temporarily store electricity in the vehicle battery and then feed it back into the grid when it is convenient. Both options can play an important role in the future electricity system, particularly in that they can reduce the need for capacity expansion inthe medium and low voltage grids.

The safety risks of BEVs compared to petrol and diesel vehicles appear limited. Moreover, these can be countered by effective regulation. BEVs produce no combustion emissions and the emissions caused by wear and tear are similar to those of diesel cars: there is slightly more tyre wear due to the extra weight of the battery, but less particulates emitted during braking.

Number of BEVs rising rapidly

In May 2022, there were 527 hydrogen-powered passenger cars with a fuel cell in the Netherlands, compared to approximately 275,000 fully electric passenger cars.

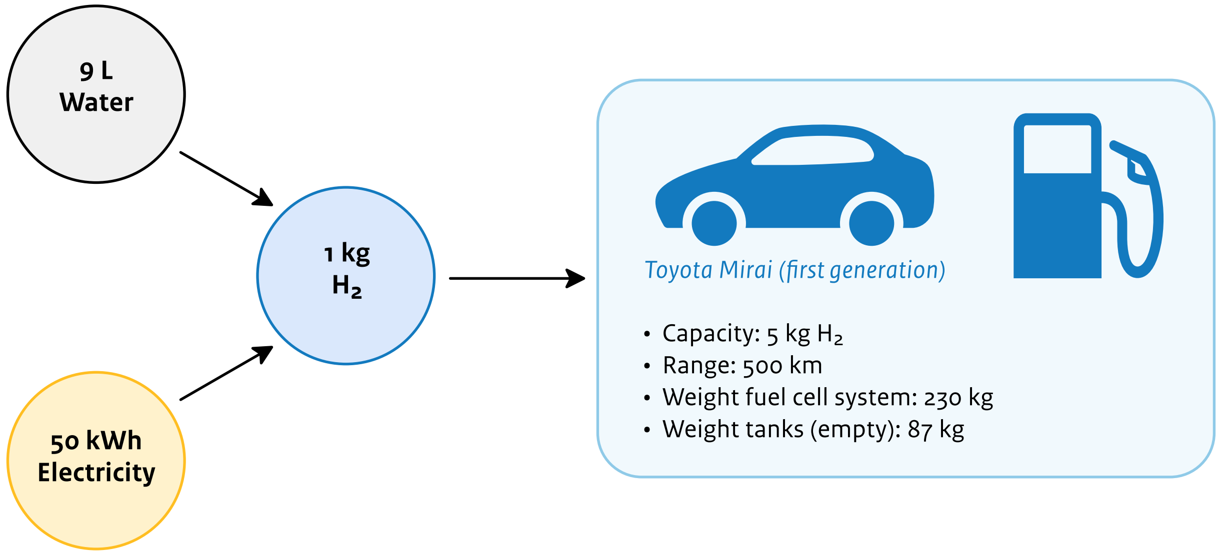
Source: RVO

By the end of 2021, there were 13 hydrogen refuelling points in the Netherlands, compared to 85,000 public (or semi-public) charging points for electric vehicles.

Yet hydrogen also has its pros

Hydrogen vehicles have advantages in terms of refuelling time (compared to charging time), range and the space requirements on board the vehicle. A battery takes up 6 to 12 times more space per unit of energy than a hydrogen tank. Hydrogen itself weighs little per unit of energy (about 3 times less than petrol and diesel). However, the hydrogen tank and the fuel cell system add a lot of weight to the car.

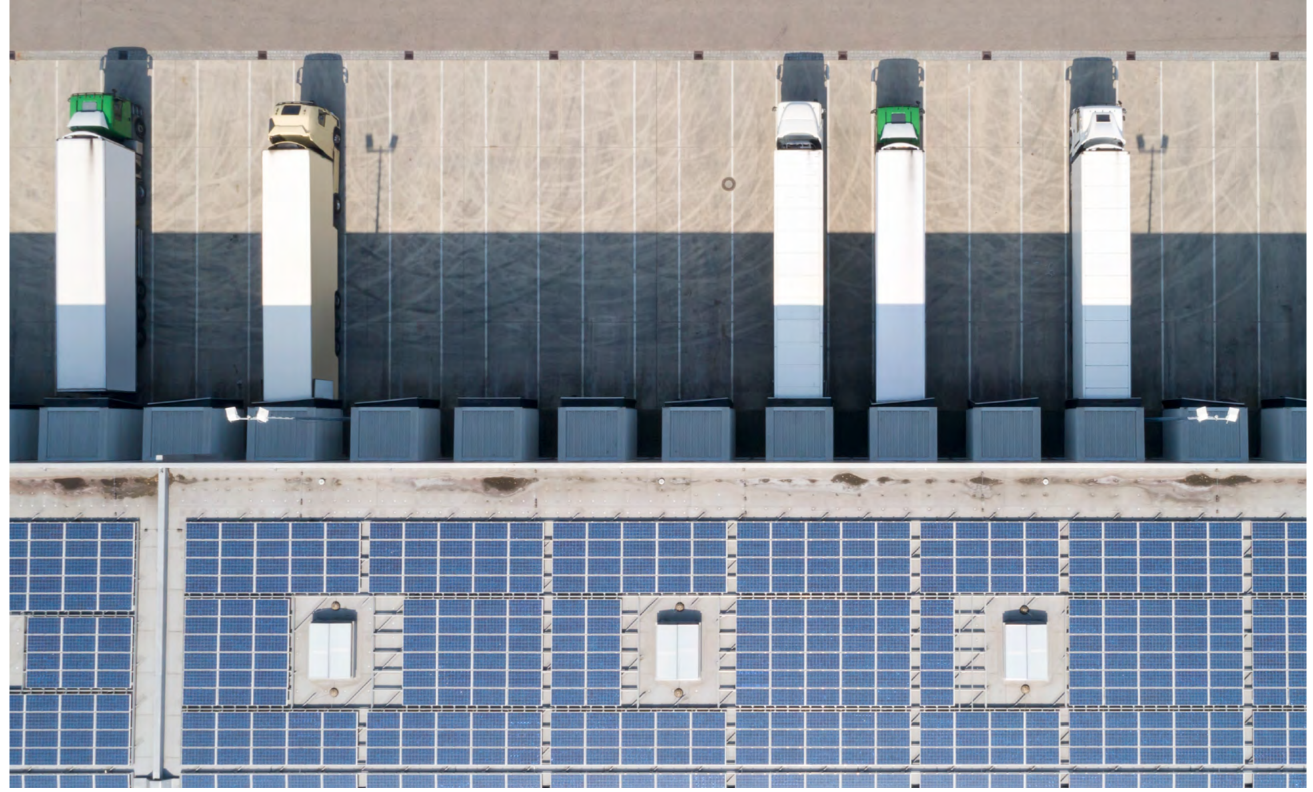
Hydrogen can be used not only in a fuel cell, but also in an internal combustion engine. This has the advantage of lower costs (no expensive fuel cell system needed) and the hydrogen does not have to be as carefully purified. On the other hand, the energy efficiency is lower and NO_X is emitted (how much depends on the combustion temperature and how the NO_X is treated, as is the case for all engines).



Drop-in fuels: no need for modifying vehicles and refuelling infrastructure

The drop-in biofuels and synfuels have the benefits of a high energy density and no engine modification is required. The drawback of the synfuels is that the energy is expensive to produce. The total costs of vehicle and energy are higher than for battery electric vehicles, but lower than for hydrogen in combination with a fuel cell. Drop-in biofuels are relatively cheap (comparable to battery electric vehicles). For biofuels, the availability of sufficient sustainably grown or advanced biomass may be an issue (see further under Aviation).

7 Heavy-duty vehicles



Battery electric vehicles have important advantages but there are also potential bottlenecks

For the heaviest category of road transport (tractor-trailer combinations), battery electric vehicles score favourably for all three criteria compared to the other energy carriers. However, some energy carriers score as good or better than battery electric vehicles for a specific criterion.

For example, FT biofuels may have a cost advantage over battery electric vehicles. In addition, if manufactured from waste streams, land use is lower. The energy chain with hydrogen from SMR-CCS is more expensive and less energy-efficient than the battery electric chain, but it also requires less land.

Battery electric vehicles also face potential bottlenecks that the other energy carriers do not (or only to a lesser extent). For example, electric long-range trucks are currently being developed, but the batteries required for this are heavy (about 4 tonnes for 800 kWh and a range of 400-600 km) and large, which reduces the cargo capacity. A battery is heavier than a system with fuel cells and a hydrogen tank that can cover the same distance. Moreover, ultra-fast charging during stops of 30-45 minutes at a time will need to be facilitated (this time corresponds to the break a driver has to take every 4.5 hours). Furthermore, charging infrastructure will be required at the depots of the transport companies and along motorways. The electricity demand for both fast and regular charging will require adjustments to the electricity grid.

Here is an example of two trucks that can cover the same distance			
BEV	800 kWh battery	Efficiency 88%	Battery weighs 4 tonnes
FCEV	38 kg H_2 tank	Efficiency 55%	FC+tank weighs 2,3 tonnes

The weight of the FC + tank is calculated based on the ratio of 1:60 of the Toyota Mirai (see Passenger cars). Fuel cell stacks and hydrogen tanks are built into trucks as modular systems. Note: BEVs and FCEVs do not require an internal combustion engine, which results in weight savings of 1 to 1.5 tonnes. The weights must be seen in the context of the total weight of the truck (fully loaded) of 40 tonnes.

The current trucks can run on biofuel and synthetic FT diesel, using the existing transport and refuelling infrastructure. Trucks with different engines will be needed to run on methanol and hydrogen. Quite drastic modifications are particularly needed when hydrogen is used in combination with a fuel cell: both the FC system and the hydrogen tank take up a lot of space and add weight. Hydrogen in combination with a fuel cell has the advantage of higher energy chain efficiency and lower costs than when used in an internal combustion engine (in both cases if optimal vehicle dynamic behaviour and engine load conditions apply).

Hydrogen, and to a lesser extent methanol, requires a different kind of refuelling station. This is because hydrogen is used in gaseous or liquid form and must be highly compressed or cooled.

BEV trucks require a number of scarce materials. In particular, the long-term availability of lithium, nickel, cobalt and rare earth metals are uncertain.

Dynamic charging has benefits and drawbacks

An electric road system (ERS) that supplies electricity to trucks while they are on the road can overcome some of the drawbacks of BEVs: a smaller battery will suffice and there is no need for charging stops. However, the investment costs are substantial and it will take time to plan and build the infrastructure. There are also environmental issues such as copper wear and adverse effects on the quality of the landscape.

Source: Siemens

8 Inland shipping

With approximately 5,000 vessels in the Netherlands, the inland shipping sector is a relatively small market when it comes to developing carbon neutral options. The Dutch fleet is relatively old, with the exception of the barges for wet bulk shipping. The vessels are often also the home of the ship owners, who are typically self-employed. Engines are replaced after 20-40 years.

All options still open

The transition in the inland shipping sector towards carbon neutral propulsion is in a less advanced stage than for road transport and is dependent on developments in the much larger sectors of maritime shipping and non-road mobile machinery. All options, including electric, hydrogen FC or ICE, drop-in fuels, methanol and ammonia, are still open. Each option has its benefits and drawbacks in terms of energy chain costs, energy efficiency, land use and commercial and socio-economic impact.

Biodiesel and FT diesel do not require modification of the vessel or the fuel infrastructure

Biodiesel and synthetic FT diesel have almost no practical drawbacks: the propulsion systems in the ships do not need to be modified and the refuelling infrastructure is already in place. Hydrogen, ammonia and methanol do require a dedicated distribution and refuelling infrastructure.

Ammonia and methanol also require modifications to the vessel itself: ammonia requires refrigerated storage and a wide safety zone around the tank. The latter measure complicates the design of smaller vessels such as inland barges. Methanol is volatile, which means the tank seals need to be strengthened. These options are therefore less favourable from the point of view of energy efficiency and land use of the energy chain.

As an energy carrier, hydrogen is suitable in principle for ships that travel short and medium distances. Hydrogen is cheaper when used in the form of a compressed gas (in order to avoid the necessity of cryogenic cooling to -253°C). The required safety zone on board is smaller than for ammonia (see Maritime shipping).

Energy chain costs uncertain

Using the synfuels methanol and ammonia for powering ships involves some additional costs, as an additional tank for the 'ignition fuel' and a catalyst are required on board. There is still much uncertainty about the costs of other carbon neutral alternatives. Hydrogen fuel cell and ICE vessels are considerably more expensive to build than diesel and electric vessels, even when taking the costs of the battery into account. Because this market is still in its infancy, it is not yet possible to compare the energy chain costs of these alternatives per distance travelled.

Battery swapping systems could be an interesting option

Electric barges could be an interesting option from an efficiency point of view. Currently, the focus is on container ships and battery swapping systems, in which an empty battery the size of a shipping container is swapped out for a charged one in the port. The ship owner does not have to invest in the purchase of a battery, but instead leases it. On-board batteries should be technically feasible for bulk carriers. There is also a chicken and egg problem: charging infrastructure or a network of battery swapping stations will be required to make electric shipping attractive, but the investment will only become worthwhile if enough vessels use the system.

9 Maritime shipping

Hydrogen and electricity not suitable for long distances

There are various fuel options for long distance shipping. In this report, we considered Fischer-Tropsch biofuels and synthetically produced ammonia, methanol, and FT diesel.

Hydrogen and electricity are not suitable for long distances by sea, as such vessels need to be able to sail for 30-60 days without refuelling or charging. Hydrogen tanks or batteries that can do that would be so large that it would take up too much load capacity. This means electricity is only suitable for short distances by sea and inland shipping.

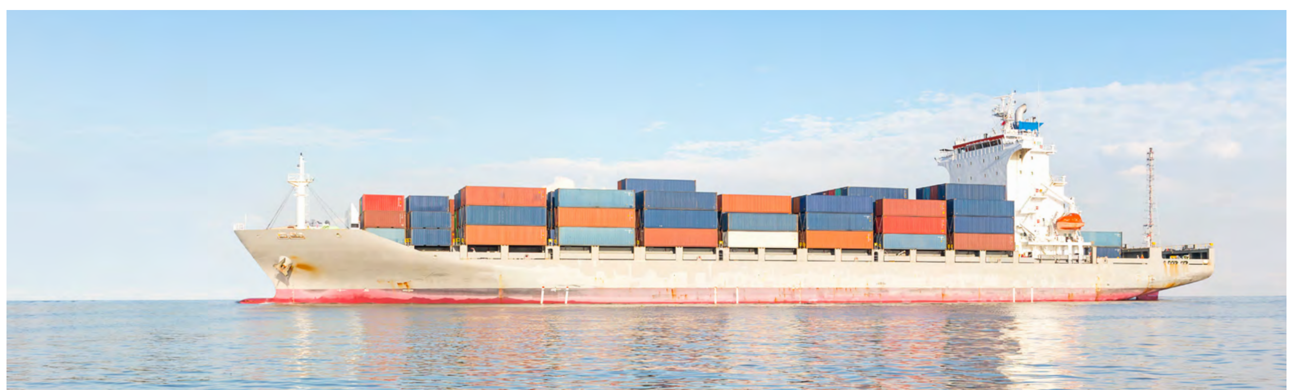
FT biofuels appear to be the cheapest option, but synfuels may also be an interesting alternative

FT biofuels are cheaper than synfuels per energy unit and on a chain level, although uncertainties about the costs of both fuel types are large. Should biofuels prove more expensive or not sufficiently available, synfuels will be a good (although inefficient) option for the maritime sector. Which synfuel (methanol, ammonia or FT synfuels) is the most favourable is unclear.

A concern with ammonia and FT fuels is the NO_x emissions during combustion. Catalytic converters can greatly reduce these emissions, but have the drawback of emitting a small amount of N_2O (nitrous oxide), which is a strong greenhouse gas. The advantage of FT fuels is that they have twice the energy density of methanol and ammonia, which roughly doubles the range of a ship for a given tank capacity. FT fuels also have the advantage that they can be used in current combustion engines without modification and without compromising on range.

With ammonia and methanol, as with inland navigation, the engine and vessel have to be adapted: two fuel tanks are required and, because of the volatility of methanol, the seals have to be improved. In addition, ammonia has to be kept slightly cooled, which places demands on fuel storage. Also, compared to the use of (FT)diesel, the range will decrease if the bunker volume remains the same. Another option is to install additional fuel tanks on board, but this is at the expense of cargo capacity.

> Hydrogen could be an option for dredgers. The advantage of this fuel option over ammonia for dredgers is that a smaller safety zone will be required on board (9 m instead of 25 m), so a hydrogen tank will be easier to integrate in the ship design.



10 Aviation

Long-haul flights powered by hydrogen or electricity will not yet be possible in 2050

The aviation sector will likely have few options for carbon neutral long-haul flights in 2050. The weight and space requirements of the batteries for electric aeroplanes, or the tanks and fuel cell systems for hydrogen aeroplanes, will make it impossible for large aircraft (such as the current Boeing 787 with 330 seats) to fly long distances. In addition, these technologies have a low TRL.

For this study we therefore focussed only on biokerosene and synthetic kerosene manufactured from hydrogen and CO_2.

Biokerosene has advantages

Biokerosene and synthetic kerosene have the advantages of a high energy density and that the tanks and engines of the aircraft do not need to be modified. Of the two options, biokerosene has lower fuel costs and therefore the costs of the energy chain are lower. The fuel costs of biokerosene depend largely on biomass and production costs, both of which are highly uncertain.

But synfuels may also be attractive

The costs of synthetic kerosene are also uncertain, as the technology is still under development. In the long run, it could prove that synthetic kerosene is more economical to use than biokerosene. The availability of sufficient sustainably grown and advanced biomass may be an issue, particularly if other sectors also require this biomass to become carbon neutral. This applies to residues but also to woody energy crops, as the latter require a lot of land area.

Because synthetic and biokerosene are physically interchangeable, both could be used alongside or in combination with each other in aviation by 2050

11 Other barriers and uncertainties

In the previous chapters, we looked into the efficiency, costs and land use of options for achieving carbon neutral mobility by 2050. Now we will briefly discuss other potential bottlenecks and uncertainties in the four energy chains.

Electric energy chain:

- The limited availability of **raw materials** for batteries (and to a lesser extent for solar panels and wind turbines), particularly lithium, cobalt, nickel and some rare earths such as neodymium and praseodymium, as well as the environmental and social impacts of their extraction. Strategies for recycling materials are being developed, but fully circular batteries are still a long way off.
- In the case of electric road systems (ERS), high levels of **copper** may be released into the environment through the wear of the overhead wires.
- The volume and weight of **batteries for heavy-duty vehicles** reduces the vehicle's capacity or, if a smaller battery is used to save weight and volume, the vehicle's range.
- In electric transport, the **charging time** is longer than the refuelling time of the other energy carriers. This applies to all modes of transport, but it is particularly relevant for heavy-duty vehicles.
- The required expansion of the **electricity grid** in various scenarios for electrified mobility. This applies to low and medium voltage grids (particularly for electric cars, but potentially to chargers for trucks as well). It could also possibly apply to to higher voltage levels. Additionally, it is still unclear what impact ERS will have on the electricity grid.
- The lack of qualified **technicians** in the Netherlands to install the charging infrastructure and expand and upgrade the electricity grid. This lack of technicians may also apply to other energy chains.

Hydrogen energy chain:

- The **scarcity** of raw materials described for electricity production also applies to electrolysis, because this technique requires a high-capacity connection to the grid (about 1.4 GWe per GW of electrolysis capacity). Other parts of the hydrogen energy chain also require a lot of power for compression, cooling, conversion to ammonia, etc. On the other hand, hydrogen can be used to buffer temporary electricity surpluses.
- Electrolysers **require scarce raw materials**, such as platinum and iridium.
- Electrolysis requires large amounts of **water**. This can be a problem if this process takes place in regions with water scarcity or in periods of drought.
- **Methane leakages** in the SMR-CCS sub-chain during the transport of natural gas from the gas field to the production site. The greenhouse effect of methane is 23 times greater than that of CO_2.
- Risk of **leakage of CO_2** in CCS (in the SMR-CCS sub-chain).
- Contaminations in H_2 can cause the rapid degradation of fuel cells.
- **Leakage of H_2** in various parts of the energy chain (H_2 is not a greenhouse gas itself, but it does augment the greenhouse effect of methane and ozone).
- Potentially rapid **degradation of fuel cells** in general.
- Just as fossil fuels, the combustion of H_2 produces **NO_X**.

Synfuels energy chain:

- Ammonia and methanol are volatile and **toxic** substances, requiring additional safety measures during storage, bunkering and on board. If additional measures are taken, the risks will be similar to those of fossil fuels.
- The **transport of ammonia** by tankers and trains is a socially sensitive issue due to the **safety risks**. For this reason, this transport is carefully regulated and discouraged. There does not seem to be any societal resistance to the transport of ammonia by ship and its storage in ports, but it is unclear whether this will remain the case if ammonia is transported on a large scale by inland vessels and stored near inland transhipment points.
- Synfuels are most efficiently produced in a **continuous process**, whereas the availability of renewable electricity fluctuates.
- It is unclear whether there will still be enough **CO_2 point sources** in 2050, and, if there are, whether they can be used for the purposes of climate neutral mobility.
- The combustion of synfuels leads to emissions of **NO_X** and **particulates**.
- The use of synfuels in aircraft causes other **non-CO_2 climate effects**.

Biofuels energy chain:

- The **availability** and supply of feedstock for advanced biofuels are uncertain, both for crop residues and for energy crops. Moreover, other sectors than transport will also require biomass for energy.
- Soil **degradation** (along with the residues, organic matter that is important for good soil quality is also removed).
- Possible harmful environmental effects due to the use of **water** for the cultivation of energy crops.
- The combustion of biofuels leads to emissions of **NO_X** and **particulates**.
- The use of biofuels in aircraft causes other **non-CO_2 climate effects**.

12 Overall conclusions

Electric energy chain is efficient in terms of energy, land use and costs

On a well-to-wheel basis, the electric mobility energy chain will be relatively efficient in terms of energy, land use and costs when compared to hydrogen and synfuels. Electric vehicles only use about 1.4 times the energy put into the chain. When using hydrogen and synfuels, three to six times more energy needs to be produced than is ultimately used by the vehicle to drive the wheels (or propeller). This means that two to three times more wind turbines would be needed to produce hydrogen using electrolysis or manufacture synfuels than would be required to generate electricity to power BEVs. In the case of biofuels, land take will depend strongly on the source of the biomass. The land use can vary from smallest (for crop residues) to largest (for energy crops).

Looking at the three main criteria, the energy chains for hydrogen and synfuels for mobility are less attractive than the energy chain for electricity. They will only become feasible if their higher costs, poorer energy efficiency and larger land use still outweigh the disadvantages of the electric energy chain, such as the long charging time (if not factored into the costs), the consumption of scarce raw materials for batteries, and the complexity of matching the supply and demand of power from carbon neutral sources. Hydrogen and synfuels in particular could provide a solution for the latter problem, for example for the storage of excess electricity produced by solar panels in the summer for use in the winter (seasonal storage). Biofuels have the advantage of being 'stand-alone', i.e. not dependent on electricity as a raw material.

Land use of sustainable energy carriers for mobility is a challenge

A wind farm the size of the Dutch province of Utrecht would be needed to power all the road vehicles in the Netherlands by electricity. Manufacturing synfuels for the airplanes and ships that currently refuel in the Netherlands would require wind farms with a cumulative area of nine times the province of Utrecht, or a quarter of the Dutch Continental Shelf.

Agricultural crop residues could be used to meet part of the demand for biofuels, without requiring additional land use. In contrast, biofuels from energy crops require a large amount of land. An area twice the size of the Netherlands would be needed to replace all bunker fuels with biofuels from energy crops.

Should it be impossible or undesirable to produce all this energy in the Netherlands, it could be an option to import it, for example in the form of hydrogen and synfuels (which are produced from electricity elsewhere). This should be feasible at the global scale: an area four times the size of France covered with solar panels would theoretically be sufficient to meet the current global energy demand.

Importing energy carriers effectively entails 'exporting' the land take of a carbon neutral energy chain. Importing carbon neutral energy has the advantage that its production can take place in sparsely populated or uninhabited areas where space is less scarce and negative effects such as noise and visual pollution may play a lesser role. In addition, the production of electricity from solar energy becomes less land-intensive the closer it is located to the equator. A disadvantage is the loss of energy during transport.

Synfuels and biofuels can be deployed with limited infrastructure modifications

An advantage of both synfuels and biofuels is that the costs of transport, storage, distribution and refuelling are relatively low. In the case of FT fuels (which are chemically almost identical to their fossil counterparts), the entire existing infrastructure can be reused. For the other biofuels and synfuels, a large part of the existing infrastructure can probably be reused with some minor adjustments. The FT fuels also have the benefit of being usable in regular combustion engines.

Large-scale production of synfuels requires CO_2 capture from the air

The carbon neutral production of FT synfuels and methanol will require a climate neutral carbon source, in addition to hydrogen. This could be an industrial CO_2 point source or direct air capture (DAC). As there will be far fewer point sources in a climate neutral 2050 than exist today, DAC will probably be unavoidable. However, DAC is much more expensive than point source capture and the technology is still in its infancy.

Costs are uncertain: various options could benefit from R&D

Many of the technologies discussed are still in the development phase and therefore uncertain. For example, methanol based on DAC could become more cost-effective by 2050 than in 2030, while the cost of electricity will not necessarily decrease in the same period. On the other hand, the higher efficiency of the electric energy chain also means that this chain is less sensitive to energy price fluctuations. All in all, this means that it is too early to conclude that any one energy chain does not have a future because of the costs. Given the major challenges of achieving carbon neutral mobility, we cannot afford to write off any of the options yet, so it is worthwhile investing in relevant, solution-oriented R&D programmes.

Potential bottlenecks: lack of qualified technicians and scarce raw materials

A lack of qualified technicians is a potential bottleneck for all energy chains, and the electric, hydrogen and synfuel options in particular. These experts will be required to manufacture and install the charging infrastructure, wind farms and electrolysers, and upgrade the power grid, for example. However, electric vehicles require less maintenance than vehicles with combustion engines, which means fewer mechanics will be required for this purpose. The scarcity of technicians could increase the cost of the transition to sustainable mobility.

The long-term availability of scarce raw materials is uncertain. This applies to lithium, cobalt, nickel and some rare earths such as neodymium and praseodymium, among others. The environmental and social impact of raw materials extraction also needs to be taken into account.

Careful comparison of the costs and benefits of each chain needed

The energy chain for a given mode of transport is not necessarily unsuitable if it scores ‘poorly’ for one of the three criteria, because many other aspects also play a role. It is crucial to consider all the costs and benefits, among others because the various energy carriers in a carbon neutral energy system will become increasingly interconnected. For example, vehicles will also contribute to the energy system through bidirectional (V2G) charging, and hydrogen will also play a dual role as a fuel for vehicles and as a storage medium in the energy system. Other criteria also need to be considered in the cost-benefit analysis, such as security of supply (e.g. diversification of energy sources and suppliers), the distribution system, the synergy between the sectors, or the user-friendliness of a given option.

Reducing energy consumption remains important to save land and resources

Carbon neutral mobility can be achieved by deploying carbon neutral energy carriers and energy-efficient drivetrains in vehicles. However, it is also important to continue to look for ways to reduce the energy consumption per distance travelled (e.g. through aerodynamic modifications and lighter vehicles) and to limit the total distance travelled. This will save both land and material resources.

List of abbreviations

Energy units

W: watt (1 watt is 1 joule per second)
J: joule
kWh: kilowatt-hour (1 kilowatt-hour is 3,6 megajoules)

Chemical compounds

CH_3OH: Methanol (aka MeOH)
CO_2: Carbon dioxide
H_2: Hydrogen
N_2: Nitrogen
NH_3: Ammonia
NO_x: Nitrogen oxides (generic term; x is variable)

SI prefixes

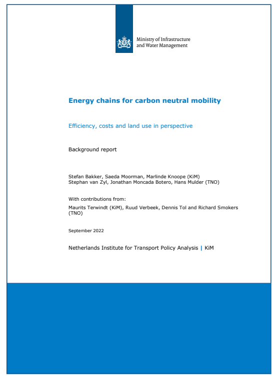
k: kilo, factor 10^3 (thousand)
M: Mega, factor 10^6 (million)
G: Giga, factor 10^9 (billion)
T: Tera, factor 10^{12} (trillion)

Other abbreviations

BEV: Battery Electric Vehicle
CC: Carbon Capture
CCS: CO_2 Capture and Storage
DAC: Direct Air Capture
EL: Electrolysis
ERS: Electric Road System
FC: Fuel Cell
FCEV: Fuel Cell Electric Vehicle
FT: Fischer-Tropsch
ICE: Internal Combustion Engine
IPCC: Intergovernmental Panel on Climate Change
LH2: Liquid hydrogen
NCP: Dutch Continental Shelf (North Sea)
PV: Photovoltaic
SMR: Steam Methane Reforming
TRL: Technology Readiness Level
TTW: Tank-to-wheel
V2G: Vehicle-to-grid
WTT: Well-to-tank
WTW: Well-to-wheel

About this publication

This brochure summarises the insights of the study into energy chains for carbon neutral mobility conducted by the Netherlands Institute for Transport Policy Analysis (KiM) in collaboration with TNO. Please refer to this study for the methods, data, assumptions and references used. In this version of the brochure, costs for fossil-ICE vehicles have been corrected in the graphs on page 17 and 18.


Ministry of Infrastructure and Water Management

Energy chains for carbon neutral mobility

Efficiency, costs and land use in perspective

Background report

Stefan Bakker, Saeda Moorman, Marlinde Knoope (KiM)
Stephan van Zyl, Jonathan Moncada Botero, Hans Mulder (TNO)

With contributions from:

Maurits Terwindt (KiM), Ruud Verbeek, Dennis Tol and Richard Smokers (TNO)

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Ministry of Infrastructure and Water Management

KiM Netherlands Institute for Transport Policy Analysis

www.kimnet.nl
info@kimnet.nl

Postal Box 20901 | 2500 EX The Hague
www.rijksoverheid.nl/ienw

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Authors
Stefan Bakker, Saeda Moorman, Marlinde Knoope and Maurits Terwindt

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