Well-to-wheel analysis of future trains and fuels

in the Dutch context

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Client
This report is prepared on request of the **Province of Groningen**, The Netherlands.

Goal of study
This study aims to provide an objective comparison of the sustainability performance of future powertrain and fuel technologies for passenger rail transport. The context for the study is taken to be the Northern Netherlands with a 2020 – 2025 timeline.

Contact persons
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Timeline. The research has been performed between **November 2013** and **April 2014**.

Disclaimer. The verbal additions and explanations given during the sessions and presentations are part of the results. The figures in this report are based upon verified data, documented sources or author estimates.

Information from this report can be used if sourced and referred to as *Duinn, Well-to-wheel analysis of future trains and fuels in the Dutch context, version 1.0, 2014*.

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Key definitions

AC means alternating current

biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste [2009/28/EC]

catenary-diesel powertrain means in this study a powertrain that, for the purpose of mechanical propulsion, draws energy from both of the following:
— an on-board diesel engine using a consumable fuel,
— an off-board electricity supply (i.e. catenary system).

compression ignition means the process in which the fuel in a diesel engine is ignited by compression in the cylinder [Volvo 2007]

DC means direct current

diesel-hybrid vehicle means a hybrid-electric vehicle powered by a compression ignition engine.

distribution relates to the final stages required to distribute the finished fuels from the point of import or production to the individual refuelling points (e.g. road transport) and available to the vehicle tank (e.g. compression in the case of natural gas) [JEC 2007]

driving cycle means a sequence consisting of an engine start, an operating period (of the vehicle), an engine shut-off, and the time until the next engine start [582/2011/EC]

energy efficiency means the ratio of output of performance, service, goods or energy, to input of energy [2012/27/EU]

extraction includes all operations required to extract, capture or cultivate the primary energy source. In most cases, the extracted or harvested energy carrier requires some form of treatment or conditioning before it can be transported conveniently, economically and safely [JEC 2007]

gas-hybrid vehicle means a hybrid-electric vehicle powered by a spark ignition engine in which the consumable fuel is a gas which consists predominantly of methane.

greenhouse gases (GHG) means those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere and clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere [IPCC 2013].

hybrid-electric vehicle means a hybrid vehicle that, for the purpose of mechanical propulsion, draws energy from both of the following on-vehicle sources of stored energy/power:
— a consumable fuel,
— an electrical energy/power storage device (e.g. battery, capacitor, flywheel/generator, etc.) [2007/46/EC]

pathway means a route, formed by a chain [Oxford Dictionary 2013] an "energy pathway" means in this study a chain from source to end-use of an energy carrier

powertrain means the system of energy storage device(s), energy converter(s) and transmission(s) that converts stored energy to mechanical energy delivered at the wheels for propulsion of the vehicle [UN ECE R 101]

pure-electric vehicle means a vehicle powered by an electric powertrain only [UN ECE R 101]

renewable energy share means the primary renewable energy use as proportion of the total primary energy use.

spark ignition means a process in which the air-fuel mixture in an Otto engine is ignited by a spark plug [Volvo 2007]

tank-to-wheel means an accounting of the energy consumption and GHG emissions resulting from moving a vehicle (through its drive-cycle) [GM 2002]

well-to-tank means an accounting of energy consumption and GHG emissions over an entire fuel pathway, from primary resource to delivery of the fuel to the vehicle [GM 2002]

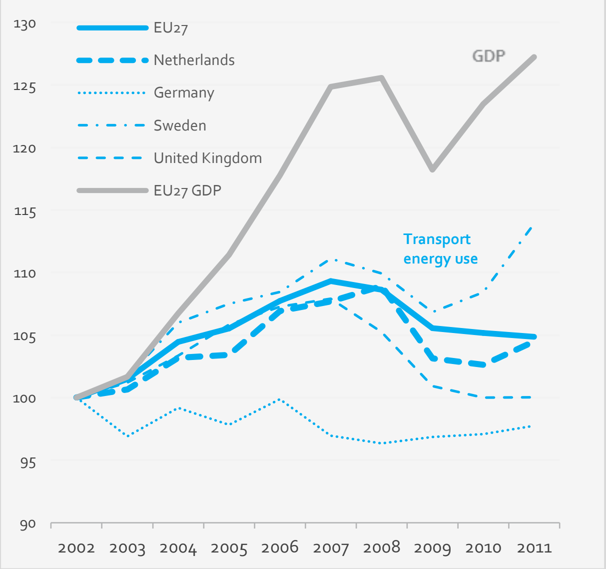
well-to-wheel means an accounting of well-to-tank and tank-to-wheel energy consumption and greenhouse gas emissions.

Rail transport in Europe uses 306 petajoule in energy of which ~80% is electricity and ~20% diesel. Most of the diesel is used in cargo and regional passenger trains. Can new powertrain and fuel technologies contribute to more energy efficient and sustainable regional rail passenger transport?

EU rail transport decreases its energy use…

- European railway passenger transport reached 390 000 mln passenger kilometres in 2007 [EU27, EUROSTAT, 2014].
- EU rail energy use amounted to 7 319 kton oil equivalent or 306 petajoule (2011) [Eurostat 2014] or roughly 2% of total EU energy use in transport.
- Rail energy use is correlated with economic output (see below chart).
- Electricity provided most of the rail energy use at approximately 79%. Diesel provided most of the remainder.

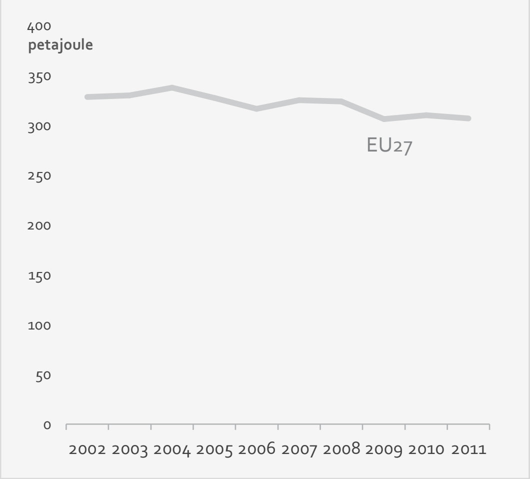
Transport energy use and GDP developments correlated
Index 2002 = 100 [Eurostat 2014]



…in the Netherlands a stabilisation after the crisis…

- Dutch railway passenger transport reached 16 000 mln passenger kilometres in 2007 and 18 000 mln passenger kilometres in 2009 according to [Eurostat, CBS, ministerie V&W, 2013].
- Dutch railway energy use is low at only 0.95% compared to the EU27 average.
- Rail energy use amounted to a growing 1.1 – 1.4 petajoule diesel [CBS, CLO, 2013] and 1.2 TWh electricity [NS, 2013].
- For regional rail passenger transport, the diesel fuel use was 18 – 23 mln litre diesel in 2012 in the Netherlands [CBS, Arriva, Veolia, Syntens, 2013]

Rail energy use in EU27
energy use in terajoule [Eurostat, 2014]

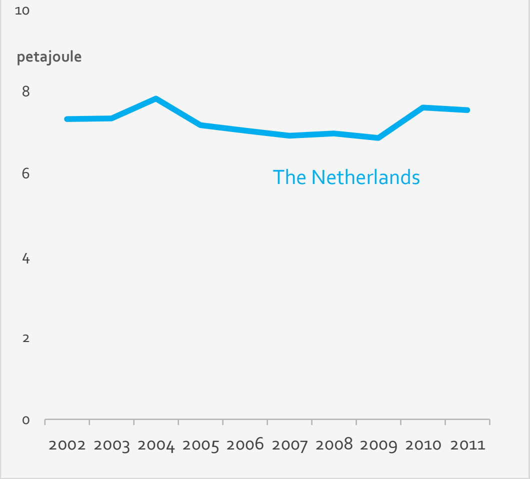


…the Northern Netherlands use 250 – 300 terajoule diesel.

- In the Northern Netherlands, Groningen and Fryslân, the railway passenger kilometres amount to approximately 316 mln kilometre [Arriva 2013].
- An estimated 8.5 mln train kilometres we're produced in the Northern Netherlands according to [Arriva 2013; Province of Groningen 2013] requiring 250 – 300 terajoule energy use in diesel fuel (tank-to-wheel).
- The current direct tank-to-wheel greenhouse gas emissions are estimated to be 18 – 22 mln ton CO_2 equivalent.

Main question: can new powertrain and fuel technologies contribute to more sustainable performance of regional rail passenger transport?

Rail energy use in The Netherlands
energy use in terajoule [Eurostat, 2014]



Energy-efficiency, renewability and greenhouse gas emissions provide a basis for assessing the sustainability performance of trains.

Comparing future train technologies and fuels requires a thorough assessment of availability, reliability, safety, affordability, social acceptability and sustainability. This report does not aim so broadly, but focuses on energy-efficiency, renewability and greenhouse gas performance to assess the sustainability performance of a number of technologies.

To provide insight into the well-to-wheel energy and greenhouse gas performance of train technology…

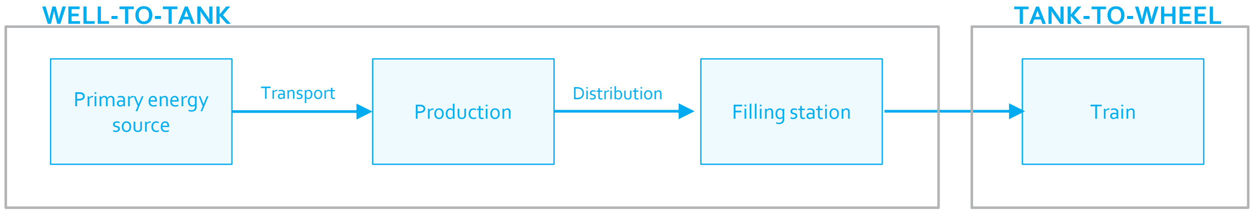
- In 2020 the new train concession is planned to start in the Northern Netherlands. Duinn has been commissioned to look into the (environmental) topics of energy use and greenhouse gas emissions for this new concession.
- To analyse energy use and greenhouse gas emissions a well-to-wheel evaluation is applied. A well-to-wheel evaluation looks at train energy use, the energy required to extract, transport, produce and distribute the fuels to the train and the resulting greenhouse gas emissions. The advantage of this method is that all relevant energy use in the total pathway can be compared between all fuels and powertrains.
- The results are presented in energy use and greenhouse gas emission per train kilometre. Both the current diesel-electric well-to-wheel performance as well as a number of future train and fuel technologies in 2020 - 2025 are assessed.
- Greenhouse gas emissions are taken into the study according to the [IPCC 2007] 100-year time horizon figures and includes the N_2O and CH_4 emissions from combustion when the train uses an internal combustion engine.

…we look into the train technologies in the tank-to-wheel part first…

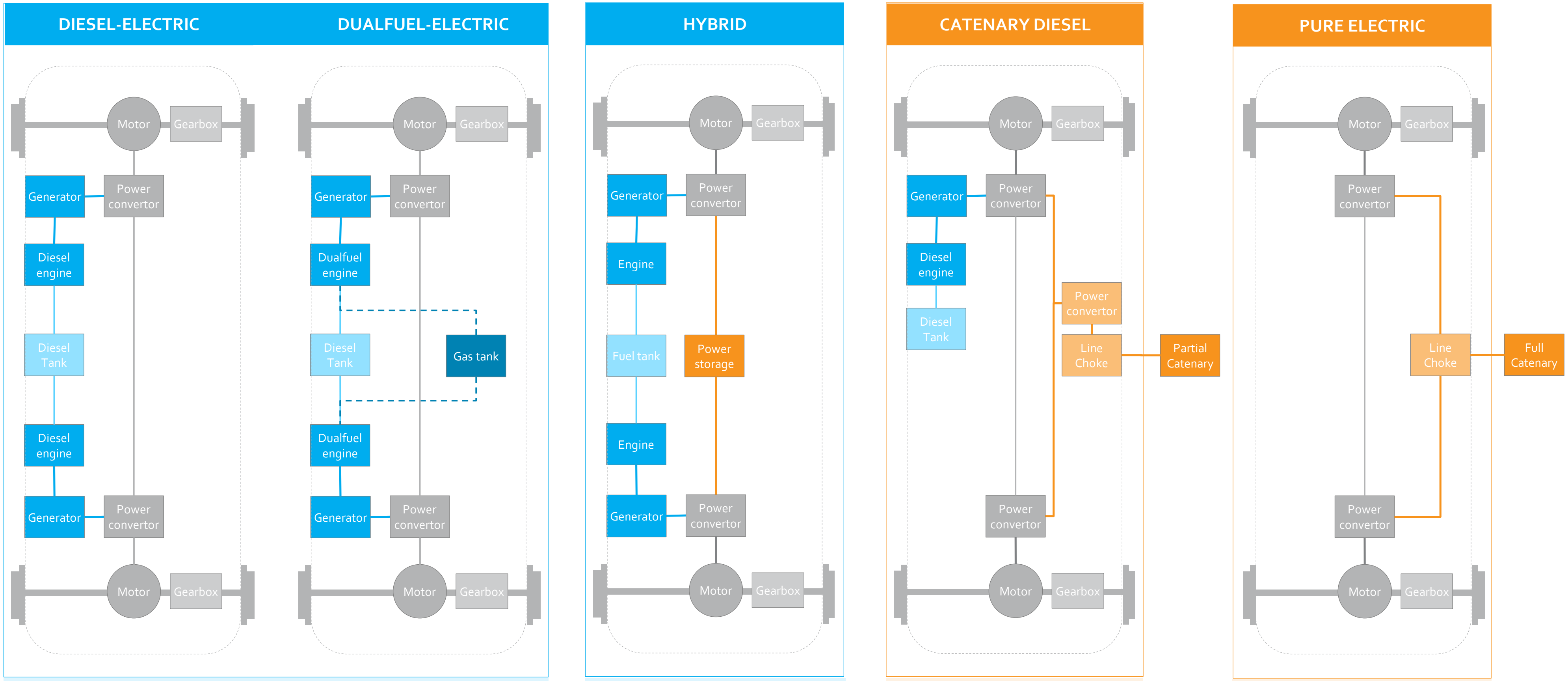
- The following powertrain technologies have been assessed: diesel-electric, hybrid diesel, hybrid gas, catenary-diesel and pure electric (hydrogen is not considered relevant in the 2020 context as too much development and testing work is required for normal train application).
- The fuel and energy storage on-board the train are diesel, compressed natural gas, liquefied natural gas and electricity in batteries (flywheels and supercapacitors are also possible, but outside the scope the study). Off-board energy supply is performed by a catenary system.
- The operating range is taken to be similar to the current ~1 300 kilometres for diesel.
- Outside of scope are engine map simulations due to the proprietary nature of this information.
- Local harmful emissions such as particulate matter, nitrogen oxides and noise are outside the scope of this study. All technologies are modelled to meet the Tier IIIb category L emission standards for non-road engines.

…after which we assess the well-to-tank performance of the fuels and electricity of the primary energy carriers.

- A fuel is an energy carrier derived from resources like crude oil, wind or biomass. These resources constitute the primary energy used to produce the fuel. Understanding the energy used in the production of the fuel and its associated greenhouse gas emissions requires an analysis of how the fuels are extracted, transported, produced and distributed.
- The well-to-tank assessment provides the direct energy use and emissions for extraction/growing, transport, production and distribution of the fuels. The indirect energy contained in commissioning and decommissioning of the installations, machines and trains are not taken into account.
- The following fuels have been found practically relevant for the 2020 - 2025 context: diesel, biodiesel, BTL, GTL, compressed natural gas, biogas, bioLNG, LNG, and electricity.
- For biofuels, the land-use effects of growing crops and perennials are strongly debated in science. The debate considers the long-term uncertainties from land-use changes and its impact on greenhouse gas emissions. Therefore the authors do not take the land-use changes into account in this (version) of the study.
- Energy and GHG savings opportunities in vehicle body, construction, auxiliaries, infrastructure, train scheduling and driving behaviour are expected to be substantial, but are outside the scope of this study.



Future powertrain technologies might be able to improve fuel efficiency. The drivelines considered in this study are: engine-electric, hybrid-electric, catenary-diesel and pure-electric ….



DIESEL

Train tare weight : 87 000 kg
Diesel fuel : 1 300 litre
Tank weight : 350 kg
Traction power : 600 kW

DUAL FUEL

Train tare weight : 87 700 kg
Diesel fuel : 1 300 litre
Diesel tank weight : 350 kg
Gas fuel : 1 230 kg
LNG tank weight : 700 kg

HYBRID

Train tare weight : 89 000 kg
Diesel fuel : 1 300 litre
Diesel tank weight : 350 kg
Power storage : lithium-ion power
Power storage weight : ±2 000 kg

CATENARY DIESEL

Train tare weight : 87 000 kg
Diesel fuel : 1 300 litre
Diesel tank weight : 350 kg
Power storage : *optional*
Second engine : *optional*
Power elec. weight : ± 1 500 kg

PURE ELECTRIC

Train tare weight : 83 000 kg
Power storage : *optional*

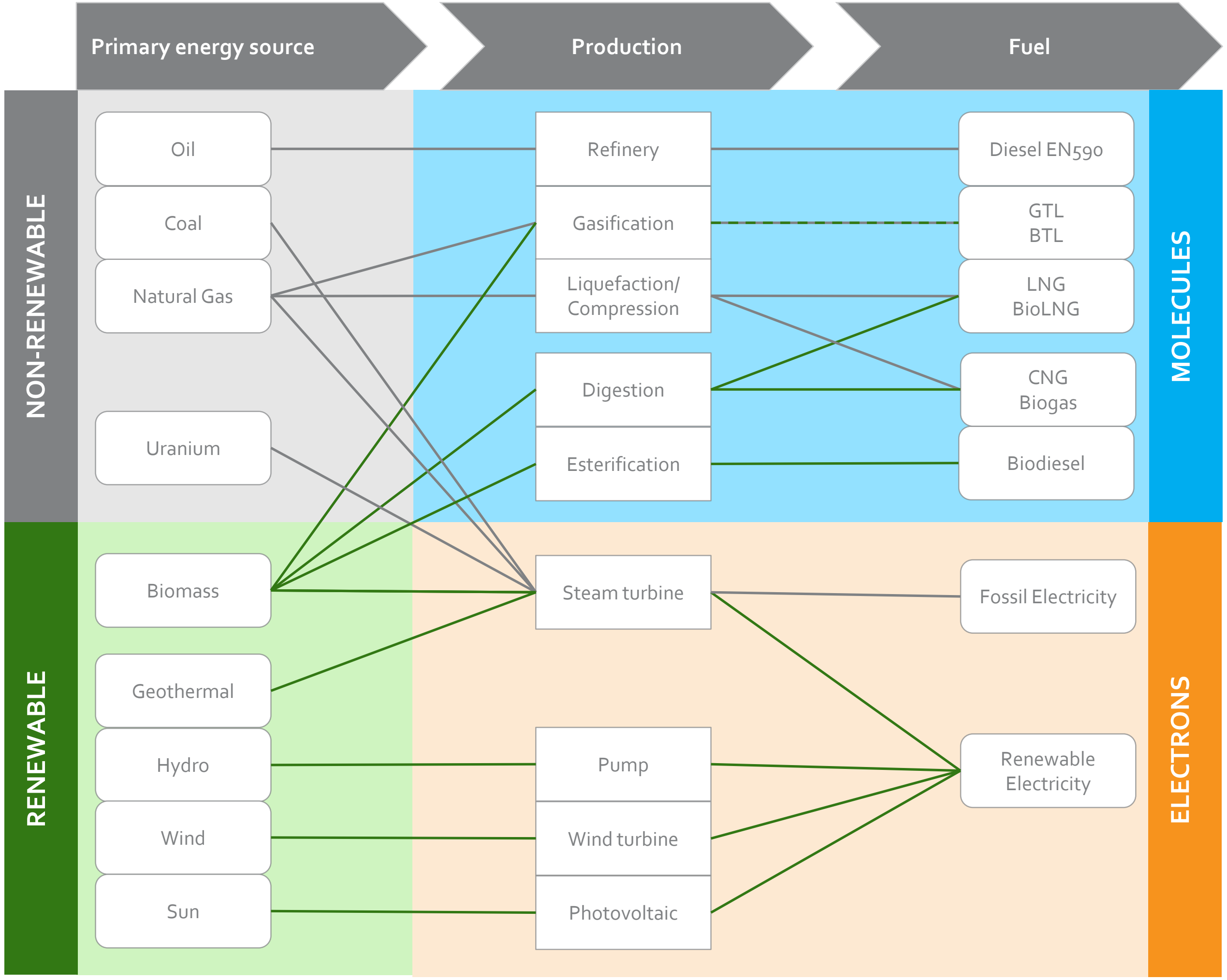
… which in this study are powered by the following fuels: diesel, biodiesel, GTL, BTL, compressed gas, liquefied gas and electricity….

Fuel	Definition	Density	Energy content		CO_2-emission
		kg/m^3	MJ/litre, *LHV*	MJ/kg, *LHV*	gram/MJ, *TTW*
Diesel	gas oils falling within CN codes 2710 00 66 and used for self-propelling vehicles meeting EN590 specification	832 - 845	35.9	43.1	73.2
GTL	a synthetic hydrocarbon or mixture of synthetic hydrocarbons produced from natural gas	780	34.3	44.0	70.8
BTL	a synthetic hydrocarbon or mixture of synthetic hydrocarbons produced from biomass	780	34.3	44.0	70.8
Biodiesel	methyl-ester produced from vegetable or animal oil, of diesel quality, to be used as biofuel (such as FAME, RME, REE)	883	32.5	36.8	76.2
CNG Dutch	compressed natural gas meeting Dutch vehicle specifications	0.83	31.6	38.1	55.8
CNG Sweden	compressed natural gas meeting Swedish vehicle specifications	0.75	34.8	46.2	56.5
Biogas	a fuel gas produced from biomass and/or from the bio degradable fraction of waste, that can be purified to natural gas quality […]	0.83	31.6	38.1	55.8
LNG	liquefied natural gas from natural gas meeting vehicle specifications	432	21.4	49.5	55.9
BioLNG	liquefied biogas meeting vehicle specifications	418	20.7	49.5	55.1

Note: according to DIN norms, in agreement with 2009/28/EC. Compressed gas according to Dutch 'Slochteren' gas specifications. LNG according to 'ethane rich' Qatar LNG specifications with 90% methane. BioLNG is taken to have 99.5% methane. Fatty acid methyl ester (FAME) to represent biodiesel. Swedish compressed gas according to SS 155438. TTW means tank-to-wheel. CO_2 emissions show emissions from complete combustion of the fuel.

… these fuels are produced from different renewable and non-renewable primary energy sources.

The nine main primary energy sources available are: oil, coal, natural gas, uranium, biomass, geothermal, hydro, wind and the sun. The first four are non-renewable, the five last are renewable.



Note: CTL, hydrogen and power-to-gas are not shown in this overview

From primary energy resource to fuel

All fuels are energy carriers. This means that fuels are produced from a primary energy source. The nine main primary energy sources available are: oil, coal, natural gas, uranium, biomass, geothermal, hydro, wind and the sun. The first four are non-renewable, the five last are renewable.

The energy carriers included in the well-to-wheel analysis are diesel, GTL, BTL, LNG, bioLNG, CNG, biogas, biodiesel and electricity. Most of these fuels can be produced from either renewable or non-renewable sources. The choice to produce a fuel from a specific source is determined by its comparative availability and affordability. Are the resources and technology available? Can it be produced and brought to market at competitive prices?

Health and climate considerations are focussing attention to the local and global emission performance of a fuel. To assess each fuel for its sustainability performance we look into the energy efficiency of the production steps, i.e. how efficient a fuel is produced. In addition, we investigate the greenhouse gas emissions that occur in the pathway from extraction to end use in the train.

Comparing train technologies requires a baseline scenario situation.
The baseline in this study is the 2014 diesel-electric train as it operates in the Northern Netherlands.

Source: Prorail 2013

A driving cycle for the Northern Netherlands simulates the current and future powertrain tank-to-wheel energy use.

The driving cycle is developed to describe the current time table, track specifications and train operation in the Northern Netherlands. The measured speeds and accelerations are used to determine the required power demand of the (future) train technologies.

Driving cycle Northern Netherlands

A driving cycle is a sequence consisting of an engine start, an operating period (of the vehicle), an engine shut-off, and the time until the next engine start [582/2011/EC]. To describe the real-life usage of the diesel-electric trains in the Northern Netherlands, we develop a driving cycle that accurately describes the current train operation.

The driving cycle is based upon the: (1) time table (see Annex 2), (2) track information, (3) maximum track speeds [Prorail 2013] and (4) Duinn train measurements.

The real-life measurements register the train movements during operation on different lines. This provides the speed, acceleration and deceleration profiles of the current diesel-electric trains. All the data was combined to build a driving cycle reflecting the real-life train use in the Northern Netherlands. The trains were measured from September to November 2013 using the Duinn vehicle logger.

Driving cycle validation

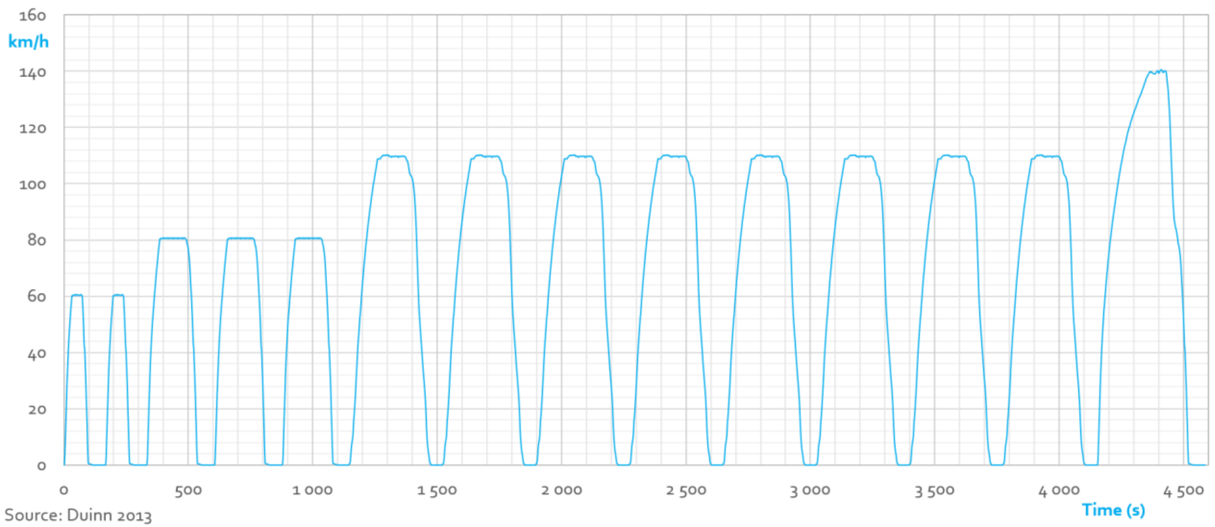
The driving cycle was checked and validated in three steps: power requirement check, validation with Stadler models and verification with Arriva fuel consumption.

The power requirement involved checking whether the driving cycle required more power output than the maximum traction power of the current trains (see appendix 3). The train input figures were verified and provided by Stadler; making the model more accurate, but at the cost of having to keep the information confidential. Real-life fuel usage was obtained from Arriva, the current operator, and found to be similar and within 4% of the model output.

Altogether, the authors assume the driving cycle to be valid and representable for the current real-life train operation in the Northern Netherlands and suitable for powertrain comparisons.

Northern Netherlands driving cycle

Speed-time profile based upon current timetable, track specifications and measured accelerations

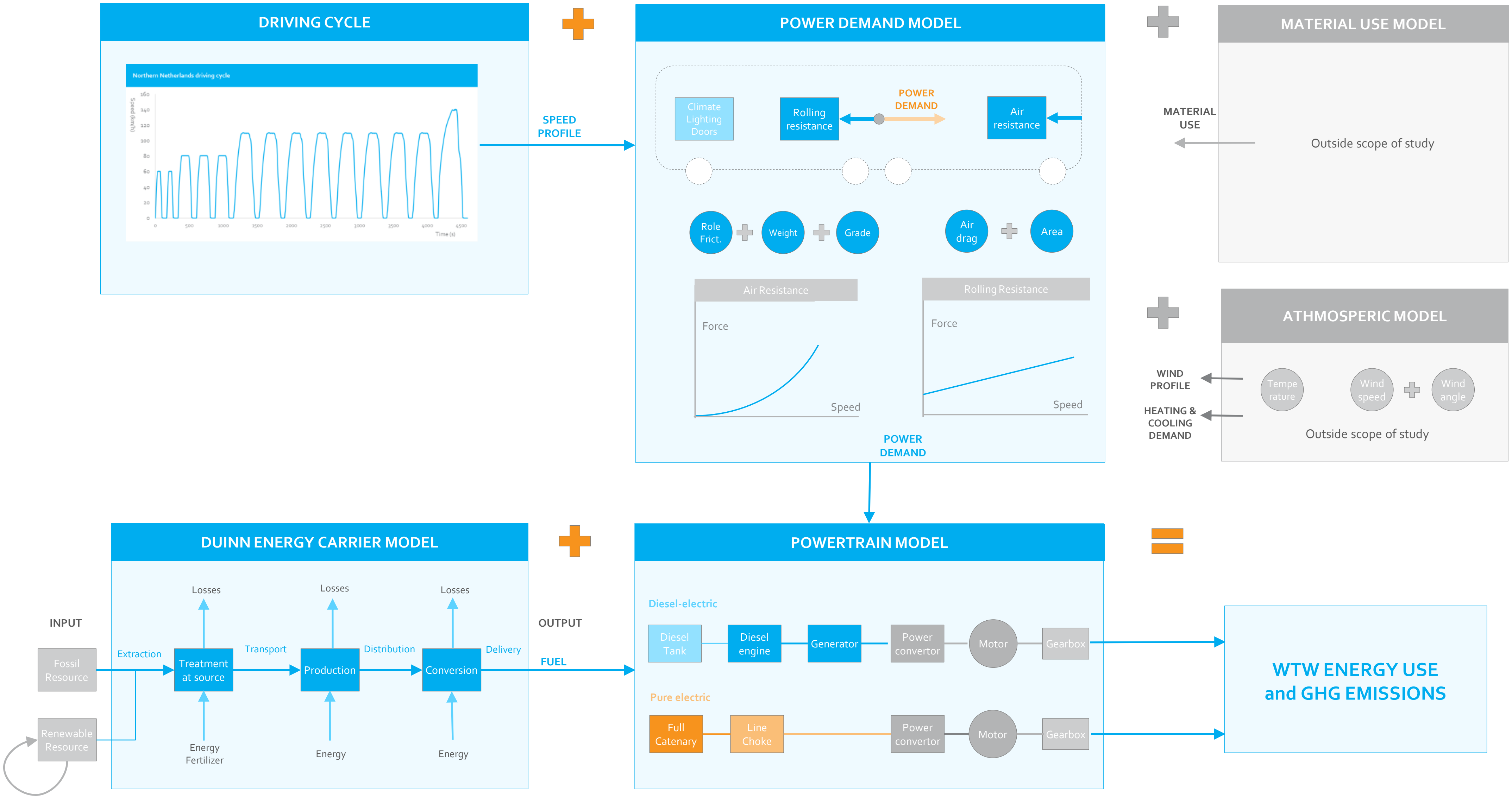


Source: Duinn 2013

Driving cycle specifications

parameter	unit	value
distance	km	81.0
trip duration	s	4587.0
average speed	km/h	63.6
standard deviation of speed	km/h	44.1
max speed	km/h	140.6
max acceleration	m/s²	0.9
max deceleration	m/s²	-1.0
average acceleration	m/s²	0.2
average deceleration	m/s²	-0.2
total time of acceleration	s	819
total time of deceleration	s	710
number of stops	#	13.0
total duration of stops	s	659.0
average duration of stops	s	50.7

…which is used in the Duinn Train Model and Energy Carrier Model, to simulate energy use and greenhouse gas emissions.



DRIVING CYCLE

SPEED PROFILE

POWER DEMAND MODEL

Climate Lighting Doors

Rolling resistance

POWER DEMAND

Air resistance

Role Frict. + Weight + Grade

Air drag + Area

Air Resistance

Force

Speed

Rolling Resistance

Force

Speed

POWER DEMAND

MATERIAL USE MODEL

MATERIAL USE

Outside scope of study

ATHMOSPERIC MODEL

WIND PROFILE

HEATING & COOLING DEMAND

Tempe rature

Wind speed + Wind angle

Outside scope of study

DUINN ENERGY CARRIER MODEL

INPUT

Fossil Resource

Renewable Resource

Extraction

Losses

Treatment at source

Energy Fertilizer

Transport

Losses

Production

Energy

Distribution

Losses

Conversion

Energy

Delivery

OUTPUT

FUEL

POWERTRAIN MODEL

Diesel-electric

Diesel Tank — Diesel engine — Generator — Power convertor — Motor — Gearbox

Pure electric

Full Catenary — Line Choke — Power convertor — Motor — Gearbox

WTW ENERGY USE and GHG EMISSIONS

Note: the shown model is a abstract representation of reality and a simple representation of the modelling
A minimum power is required for a powertrain to meet the current train table requirements, this is taken to be 600 kW traction.

Main findings

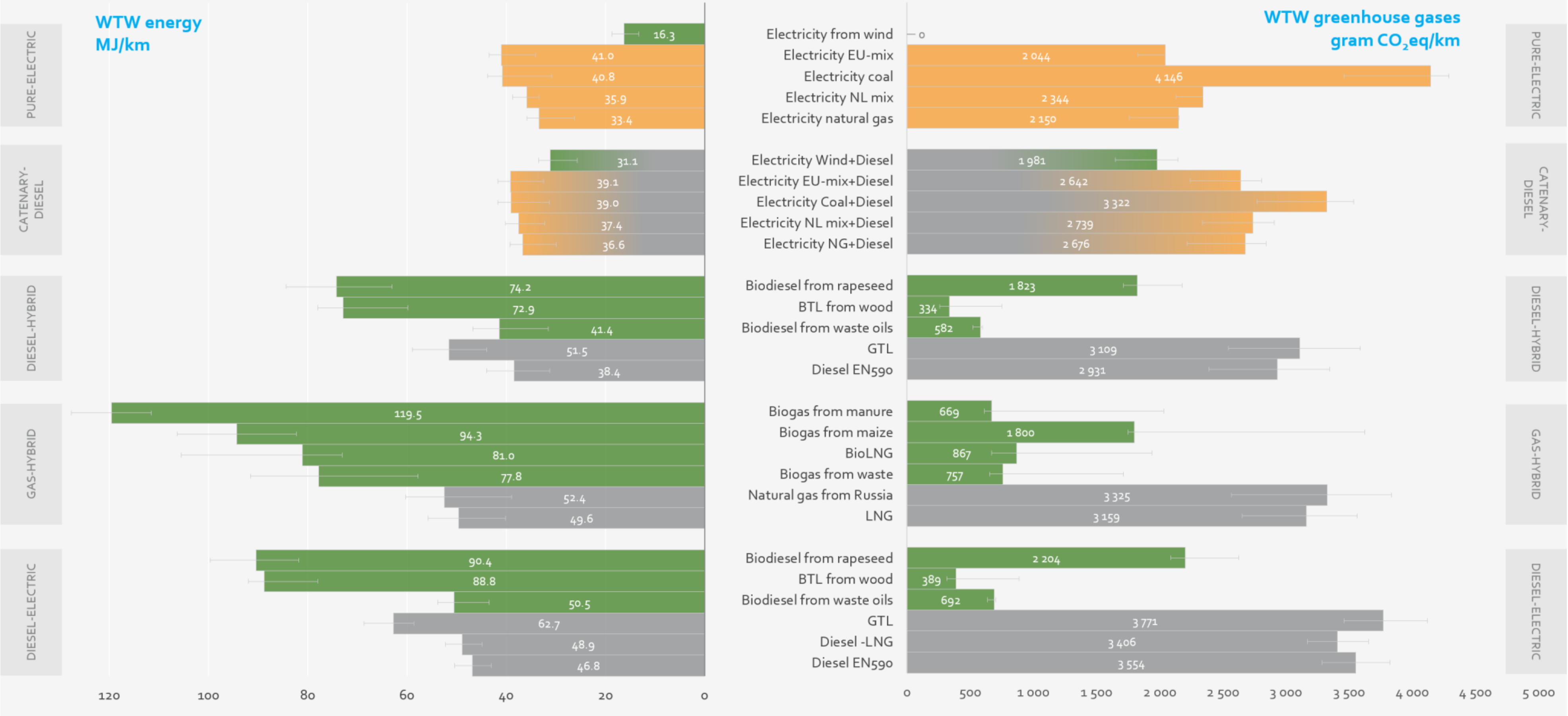
Compared to the current diesel-electric trains, the hybrid-diesel shows a 15 – 25% well-to-wheel energy and GHG saving. The fossil gas pathways show a slight GHG reduction, but at the cost of higher energy use. Biofuels provide good GHG performance but also at the cost of higher energy use. The catenary-diesel pathways show higher potential savings at 17 – 34% for energy and 23 – 46% for GHG (7% for coal). The pure-electric fossil pathways show 12 – 29% energy saving. Only with the electricity from wind pathway do WTW energy savings increase to 65% and GHG savings to 100% (see page 35 – 36 for more conclusions).

Primary energy use WTW

Total energy use for the pathways in megaJoule per train kilometre

Greenhouse gas emissions WTW

Total GHG emissions for the pathways in grams CO_2-equivalent per train kilometre



Note: please observe that hydrogen has not been included within this version of the study.

TANK-TO-WHEEL

Energy source
Transport
Production
Distribution
Usage

The reference diesel-electric powertrain requires 38.8 MJ_{TTW} per train kilometre.

The tank-to-wheel energy use is similar to figures provided by Stadler and Arriva.

Powertrain description

Currently in the Northern Netherlands, 51 diesel-electric trains are in operation. These diesel-electric trains are powered by two synchronous diesel generators which supply electricity to the electric motors of the train.

The diesel engines are MAN D2676 LE121 engines with both 380kW power output, connected to their own generator. The generators in turn power the IGBT power converters which convert the frequency of the AC power from the generators to the frequency fitting the train speed. After conversion, the electricity is supplied to the electric motors. The motors are connected by a gearbox to the drive axles. In total, the powertrain can provide a maximum of 600 kW to the drive axles.

A diesel tank of 1 300 litre is installed, as the trains use on average about 1 litre diesel per kilometre the range of the diesel-electric trains is about 1 300 km [Arriva, 2014].

Diesel-electric model

The energy use is obtained by the efficiencies of the gearbox, electric motor, power converters, generators and finally the diesel engine to determine the energy use. Since the engines are idling during stops and decelerations, idling energy use is applied to these events, a share of the idling energy use supplies the auxiliary systems.

Results diesel-electric

The energy use of the diesel-electric powertrain on the Northern Netherlands driving cycle is found to be 38.8 MJ per kilometre. This energy use is in line with the data provided by Arriva and Stadler and hence forth the energy use per kilometre for baseline comparison with other powertrains .

Dual-fuel powertrain

In dual-fuel diesel engines it is possible to fuel the engine with a mixture of LNG and diesel or CNG and diesel. The amount of LNG or CNG that can be used depends on the power and torque demand. For application of dual-fuel in the diesel-electric powertrain, a mixture of 50% LNG and 50% diesel is assumed for the dual-fuel powertrain.

Since an additional LNG tank is necessary, the weight of the dual fuel powertrain is 700 kg higher. LNG tanks are about four times heavier per energy unit than diesel tanks [JEC; 2013], The 1 300 litre diesel tank which is currently installed on the Stadler GTW DMU [Arriva; 2014], weights about 350 kg. Therefore, when requiring 50% of the energy content of the diesel tank in the form of LNG, the additional weight of the LNG tank will be about 700 kg.

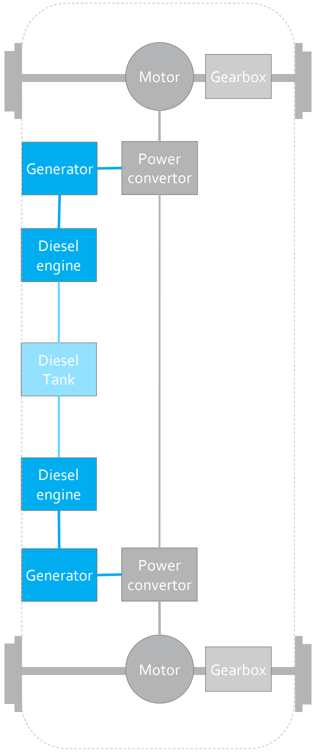
Results dual-fuel

Due to the lower efficiency of the dual-fuel engine and higher weight the energy use of the dual-fuel powertrain is slightly higher and found to be 39.9 MJ/km. Which is 3% higher than the baseline diesel-electric powertrain.

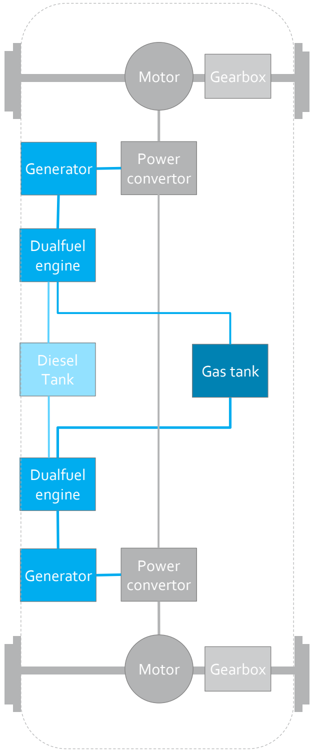
Greenhouse gas emissions

Consist of the CO_2 from complete combustion, and resulting N_2O and CH_4 exhaust gas emissions. The CO_2 emissions for each fuel are provided on page 7.

The diesel-electric powertrain emits 2 838 gram CO_2 per kilometre, 0.18 gram CH_4 per kilometre and 0.38 gram N_2O per kilometre.



diesel-electric powertrain



dual fuel-electric powertrain

Hybridisation results in an energy use of 31.8 MJ_{TTW} per train kilometre for the diesel-hybrid, and a increased energy use compared to the baseline for the gas-hybrid.

The compressed gas-hybrid powertrain uses 40.1 MJ_{TTW} per train kilometre, while the liquid gas hybrid powertrain uses 39.8 MJ_{TTW} per train kilometre.

Powertrain description

In the hybrid powertrain, apart from the two engines and the generators, a energy storage is installed to (a) store braking energy and (b) power the traction motors during acceleration.
Since (part of) the kinetic energy of the train can be regenerated by the hybrid powertrain, the train can be operated more efficiently than the diesel-electric powertrain. The energy savings potential depends on the usage of the train, optimisation of the driving behaviour can thus be beneficial.
The energy storage makes it possible to lower the engine power without affecting the acceleration capabilities of the train, which makes it possible to use gas engines instead of diesel engines. Therefore, two hybrid options are considered: a hybrid powertrain with a diesel engine and hybrid with an spark-ignited engine running on gas.

Model description

Hybridisation increases the weight of the train due to the additional batteries. The hybrid powertrain is designed to be able to store as much braking energy as possible and should therefore be proportional to the regenerative braking power of the train. In the train the regenerative braking power is limited to 600 kW, according to the maximum power of the electric motors. We assume that the battery state of charge stays between 50% and 70% since it increases the lifetime of the battery. With state of the art batteries we find that the weight of the battery, energy management systems and power equipment with a suitable power and energy density weights 2 000 – 3 000 kg.

The energy supply to the wheels of the hybrid powertrain is simulated by using a control strategy similar to that of a Toyota Prius. Meaning that the engine is engaged above a certain threshold speed and power demand. The battery is used to add power to the electric motors during accelerations, this makes it possible to decrease the power requirement of the engine substantially. For regenerative braking a 50% efficiency is used.

Results diesel-hybrid powertrain

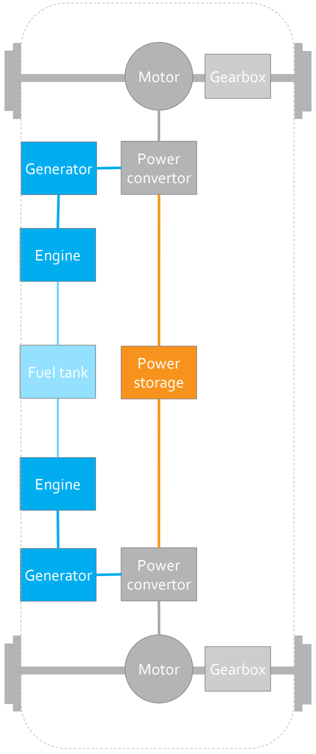
For the diesel-hybrid powertrain we found an energy use of 31.8 MJ/km, which is 18% less than the diesel-electric powertrain. The energy use might be further optimised by adapting drive style to the new technology. This is reflected in a large negative margin of uncertainty (see results pages).

Results gas-hybrid powertrain

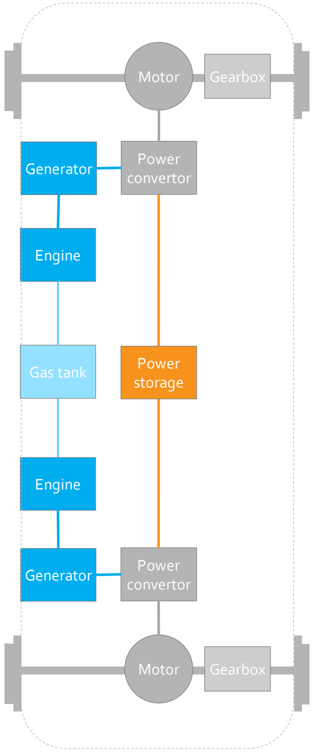
In the gas-hybrid powertrain the Diesel engine is replaced by a gas engine. The powertrain comes in two types, the only difference being the fuel storage. The first is the one with an LNG storage tank which is assumed to be four times heavier than a diesel tank [JEC 2013]. The 1300 litre diesel tank is assumed to be 350 kg, the LNG tank would then be 1400 kg. Since the diesel tank will be removed the effective mass increase will be 1050 kg. The energy use of the hybrid spark-ignited powertrain fuelled by liquid gas is 39.8 MJ/km which is 2.5% more than the baseline energy use.

To fuel the gas-hybrid powertrain with compressed gas, the diesel tank is removed and CNG type IV cylinders are installed on the train. The equivalent of 1 300 litre diesel, 1 230 kg of CNG has to be stored.

To store 1 230 kg CNG, a total of 3 320 kg of cylinders have to be installed. Without the removed diesel tank, the gas-hybrid powertrain on CNG is around 3 000 kg heavier than the diesel-hybrid powertrain. The energy use of the gas-hybrid powertrain on compressed gas is 40.1 MJ/km.



diesel-hybrid powertrain



gas-hybrid powertrain

Pure electric powertrains use only 35% of the diesel-electric powertrain TTW energy use. The main reason is the high energy efficiency of the powertrain, with its lower weight also providing an advantage.

Pure-electric uses a low 13.4 MJ per train kilometre.
However the electricity production is not taken into account in the TTW energy use, see therefore the WTW assessment.

Powertrain description

A pure-electric powertrain, draws energy through a catenary system to power the electric traction motors. The powertrain has no on-board energy storage for traction purposes.

In this study, regenerative braking with a pure electric powertrain is not taken into accounts due to large amounts of single tracks and low voltages characteristic to the Dutch catenary system, which negatively affects the useful application of the regenerated energy, because the energy can only rarely be delivered to another train.

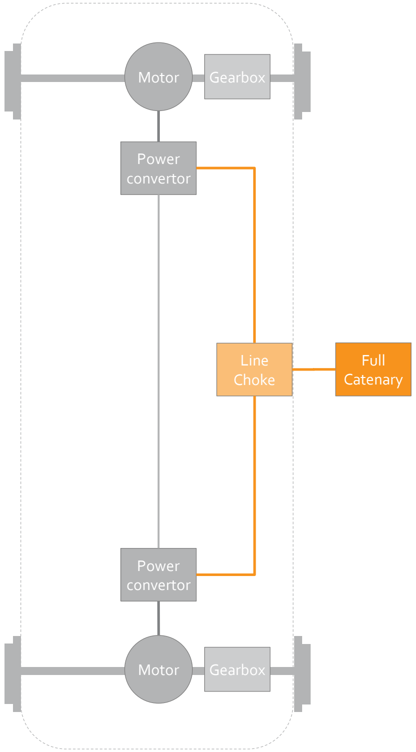
Model description

The electric train model uses the weight and vehicle characteristics of the Stadler GTW Electric Multiple Unit (EMU) [Stadler, 2014]. The electric system of the EMU is different from the Diesel multiple unit (DMU), since it is developed for the 1.5 kV DC in the Netherlands. Where the DMU contains two diesel engines and generators, the EMU has a pantograph which takes energy from the catenary system. In addition, a line choke is installed, which 'filters' the DC power from the catenary to prevent damage to the power-electronics on the train. The weight of the powertrain is about 4 000 kg lower than the diesel-electric powertrain [Stadler 2013].

Results pure-electric powertrain

The TTW energy use of the pure electric powertrain on the Northern Netherlands driving cycle is 13.4 MJ/km, which is 35% of the diesel-electric energy use. This appears low in comparison with the baseline, however, electricity is not a primary energy source. In the WTW part the primary energy use of all different powertrains is presented.

Stadler GTW EMU 2/8 [Stadler 2014]



pure-electric powertrain

The catenary-diesel powertrain, uses 25.7 MJ_{TTW} per kilometre.

The energy use of the catenary-diesel powertrain decreases further as more of the track would be electrified.

Powertrain description

The catenary-diesel powertrain (or partial-electric powertrain) consists of a combined pure-electric and diesel-electric powertrain. Like in a pure-electric train, the pantograph draws energy from a partial catenary system and the diesel-electric powertrain supplies energy when no catenary system is available. Authors suggest (from an energy saving perspective) to provide a catenary that covers the length of track for the distance the train is accelerating. When the cruising speed is reached the diesel engine takes over.

Dependent on the catenary system it is possible to regenerate braking energy, and store it in a land-based energy storage system and re-use the energy when the train departs from the station. In this study the authors assume a land based energy storage which stores braking energy. For a system overview see appendix 5.

It is considered possible to remove one of the diesel engines to save weight, since one diesel engine can provide enough power for cruising. Note that with the current MAN engines the maximum cruising speed will be lower than 140 km/h, however, in the new Stadler trains, Deutz TCD 16.0 V8 engines are installed and one of the new Deutz engines will be able to generate enough power to cruise at 140 km/h.

Since an additional pantograph and power-electronics need to be installed on the train this weight saving largely evaporates. Therefore, in our model we choose to keep the weight of the powertrain equal to the diesel-electric powertrain.

Model description

The catenary-diesel powertrain is modelled to be electric for the first kilometre prior to all stations and the first kilometre after all stations. As soon as the train comes within range of the catenary system, it acts like a pure-electric train, however, the diesel-engine is still running when the train is under the catenary. This strategy is chosen to extend the engine lifetime and to prevent cold starts. Therefore an idling energy use of the diesel engines is applied when under catenary.

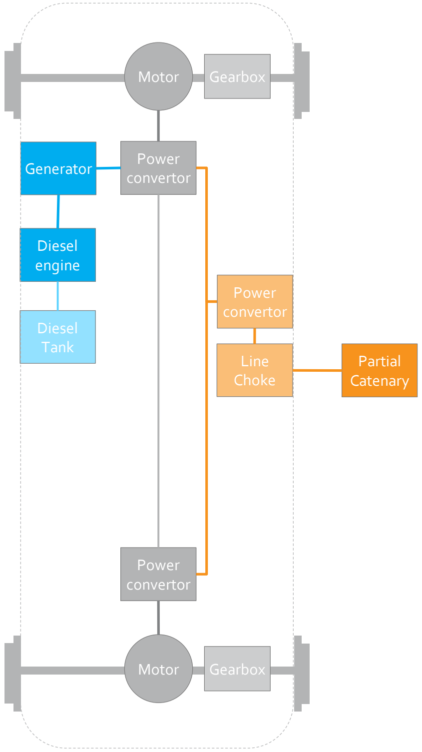
When the train decelerates under the catenary system, 50% of the braking energy with a maximum of 600 kW is fed back into the catenary. During acceleration the train acts as a pure electric train and accelerates till the train reaches the required cruising speed. When the end of the 1000 metre catenary is reached the diesel-engine starts to generate electricity to keep the required train speed.

Results catenary-diesel powertrain

For the Northern Netherlands driving cycle the catenary-diesel powertrain requires on average 4.3 MJ/km electricity and 21.4 MJ/km in the form of diesel. This TTW energy use of 25.7 MJ/km is 34% less than the energy use of the diesel-electric powertrain.

The energy use of the catenary-diesel powertrain depends strongly on the length of the catenary system and the driving strategy. If for example the train is operated in such a way that during acceleration enough speed is gained to coast to the next station, the diesel consumption would be lower.

However, our goal is to objectively compare powertrains and therefore we choose to keep the driving cycle constant. Larger error margins in the total energy use account for the potential energy savings in the driving strategy and the possibility to coast instead of cruise.



catenary-diesel powertrain

Compared to the diesel-electric powertrain, the diesel-hybrid powertrain has the potential to reduce tank-to-wheel energy use by 15-25%, the catenary-diesel powertrain by 30 – 40% and the pure-electric by 60 – 70%.

A gas engine or dual-fuel engine increases energy use compared to the diesel engine.

Key findings

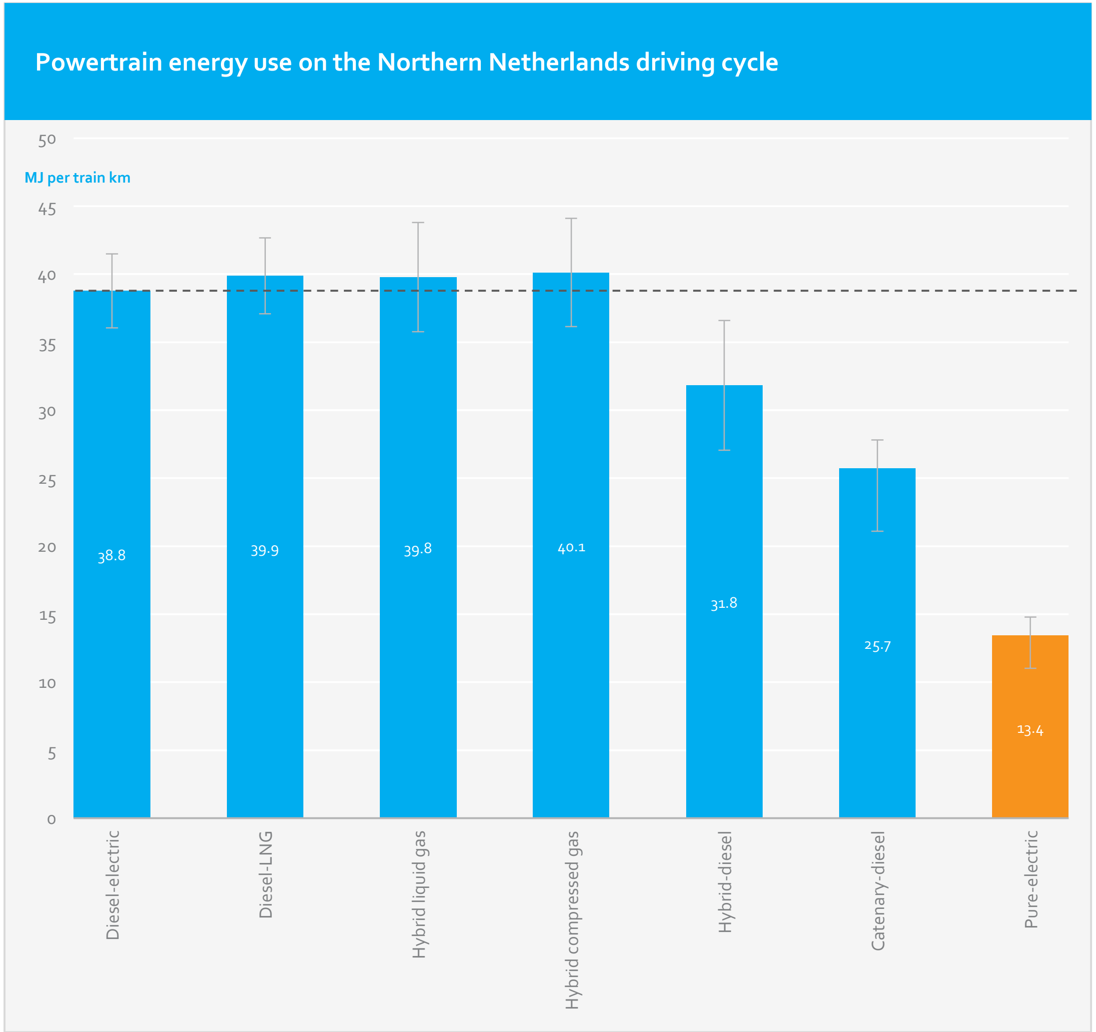
1. A **pure-electric powertrain** reduces 65% of the TTW energy use of the diesel-electric powertrain on the Northern Netherlands driving cycle. Please note that the TTW energy use does not account for the primary energy use.

2. The TTW energy use of the **catenary-diesel** powertrain is 34% lower than the diesel-electric powertrain energy use, in this study it is assumed that per station two times 1000 metre catenary system is present in combination with a land based energy storage to power the train electrically during acceleration.

3. The **diesel-hybrid** powertrain reduces the TTW energy use by about 18%; assumed is that the train can regenerate its braking energy and can store this energy in the on-board battery. Since apart from the engines the battery can also supply power to the wheels the engine can be used less intensively.

4. The **diesel-electric** powertrain uses 38.8 MJ/km_{TTW}, this figure is in line with Stadler and Arriva.

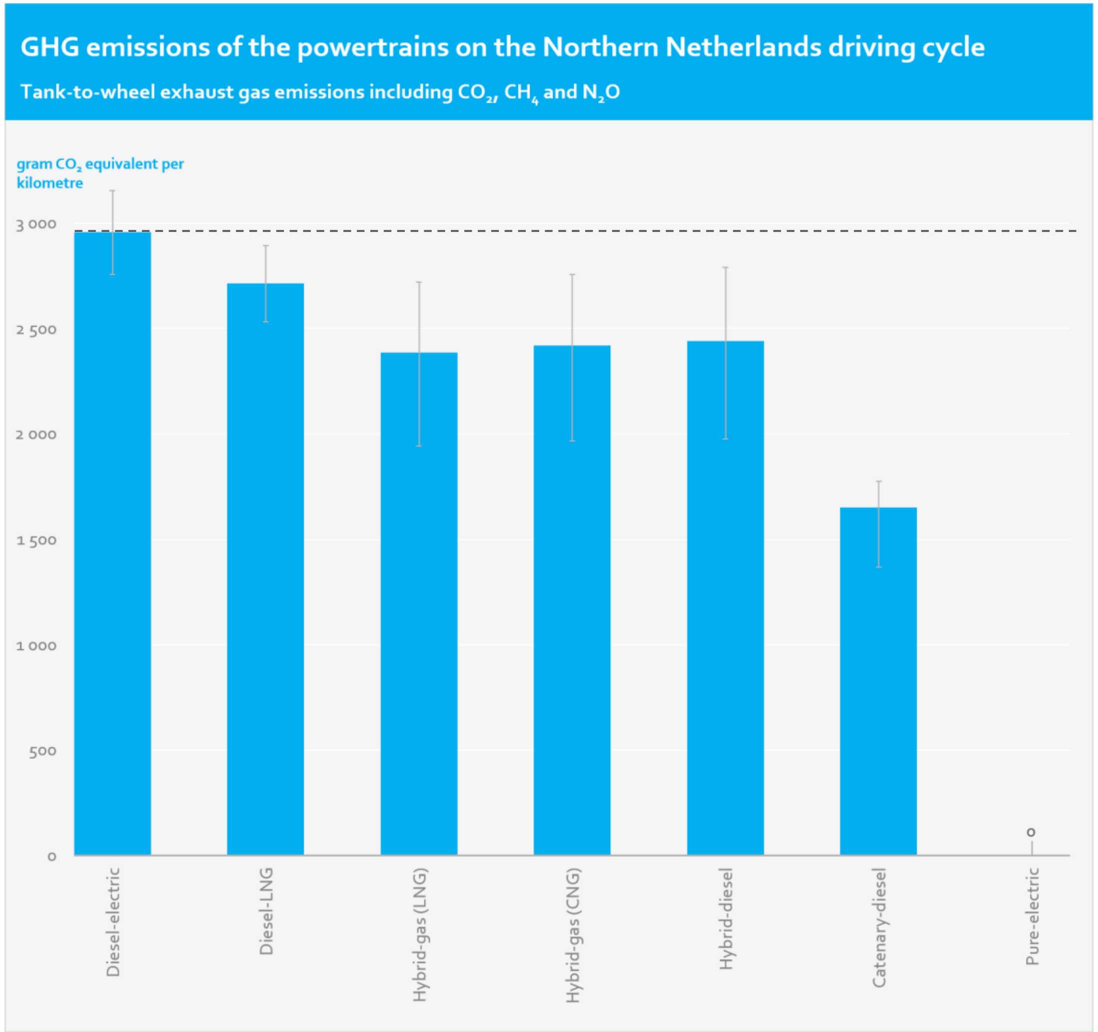
5. Applying a **gas engine** increases the TTW energy use.


Powertrain energy use on the Northern Netherlands driving cycle

The diesel-electric powertrain emits 2 960 gram CO_2-equivalents per train kilometer (tank-to-wheel). Diesel-LNG can reduce GHG emissions by 8%, with hybrid-diesel and hybrid-gas showing comparable GHG reductions of approximately 18%. The pure-electric does not emit tank-to-wheel greenhouse gases.

Key findings

1. The **pure-electric powertrain** reduces tank-to-wheel greenhouse gas emissions with 100% to zero grams per kilometre.
2. The **diesel-LNG** powertrain has 8% lower TTW greenhouse gas emissions than the diesel-electric powertrain.
3. The **gas-hybrid** fuelled with LNG and the gas-hybrid fuelled CNG powertrains both have slightly lower emissions compared to the diesel-hybrid powertrain.
4. The **catenary-diesel** powertrain emits 44% less tank to wheel greenhouse gases per kilometre than the diesel-electric powertrain.
5. The **pure-electric** powertrain does not emit any tank-to-wheel greenhouse gas emissions, all emissions are generated in the well-to-tank part of the pathway.



GHG emissions of the powertrains on the Northern Netherlands driving cycle

Tank-to-wheel exhaust gas emissions including CO_2, CH_4 and N_2O

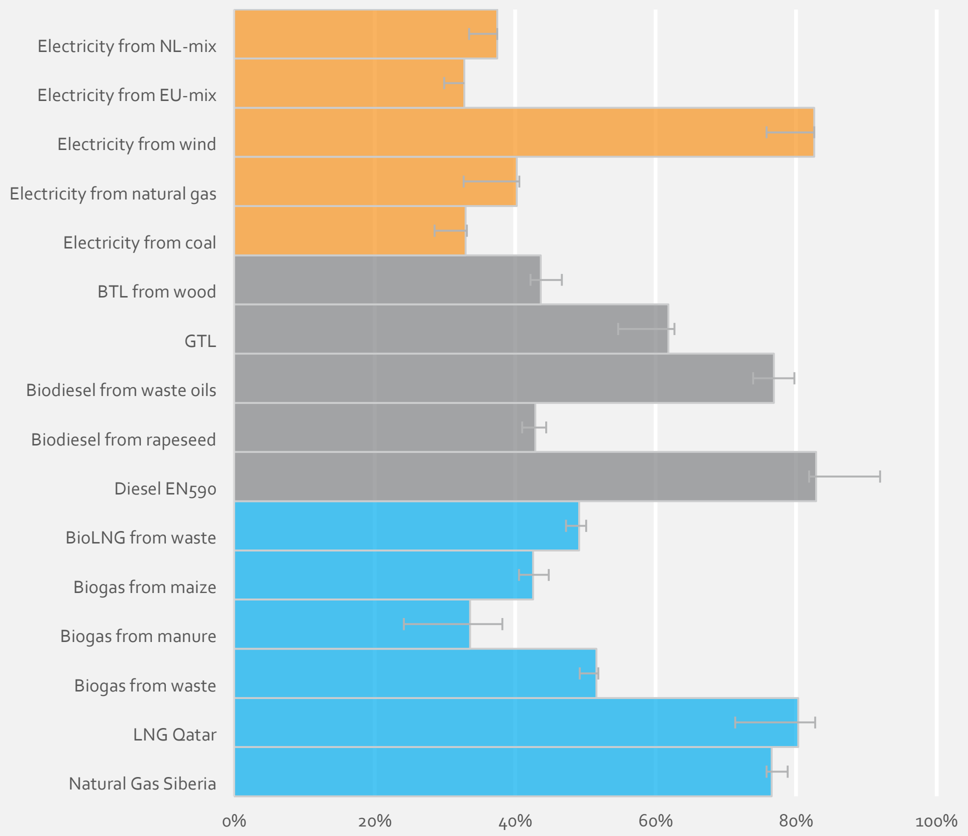
WELL-TO-TANK

- Energy source
- Transport
- Production
- Distribution
- Usage

Electricity from wind, natural gas from the Netherlands and diesel from crude oil have the highest well-to-tank energy efficiency at about 80%. Biogas from maize and biodiesel from rapeseed have well-to-tank efficiencies between 50 and 60%. Fossil electricity production shows an even lower efficiency at 40%.

Well-to-tank energy efficiency

η; in total energy efficiency for the pathway; grey for diesel pathways, blue for gaseous pathways and orange for electricity.



Source: Duinn, 2014
Note: efficiency means the ratio of output of performance, service, goods or energy, to input of energy [2012/27/EU]

Key findings

1. **Electricity produced from wind** has the best well-to-tank performance at 83%. In other words, uses the least primary energy to produce the energy carrier.
2. **Diesel EN590** produced from crude oil has a similar performance to wind. Although more energy is required in production, the losses in transport and distribution are quite a bit lower resulting in 83%.
3. **Natural gas from Russia** and **LNG from Qatar** have rather similar pathway efficiencies at respectively 77% and 80%.
4. **GTL** requires less transport and storage energy compared to natural gas and LNG. Still the higher energy use during production results in a lower figure at 62%.
5. **Biodiesel from waste oils** is the best performing biofuel in this study with an efficiency at 77%.
6. **BioLNG** and **biogas from waste and maize,** as well as **BTL from wood** and **biodiesel from rapeseed** score relatively similar at around 43 – 46%. This means that more than twice the primary energy input is required to produce one unit of fuel.
7. **Electricity from fossil sources** score a lowly 33 – 40%. The primary causes are: (1) the low production efficiency of thermal conversion and (2) high losses in the grid. The relatively low performance of the EU and NL mix is a cause of the older and less efficient installed capacity and aging of the plants (for natural gas and coal the figures reflect state-of-the-art technology).
8. **Biogas from manure** requires the most primary energy to be produced. This mainly reflects the low conversion efficiency of manure (not all energy in the manure is turned into biogas). Since manure can be considered waste, this low score is not relevant for making policy choices whether to produce biogas. The score would be relevant when comparing competing application of the biogas outside transport.

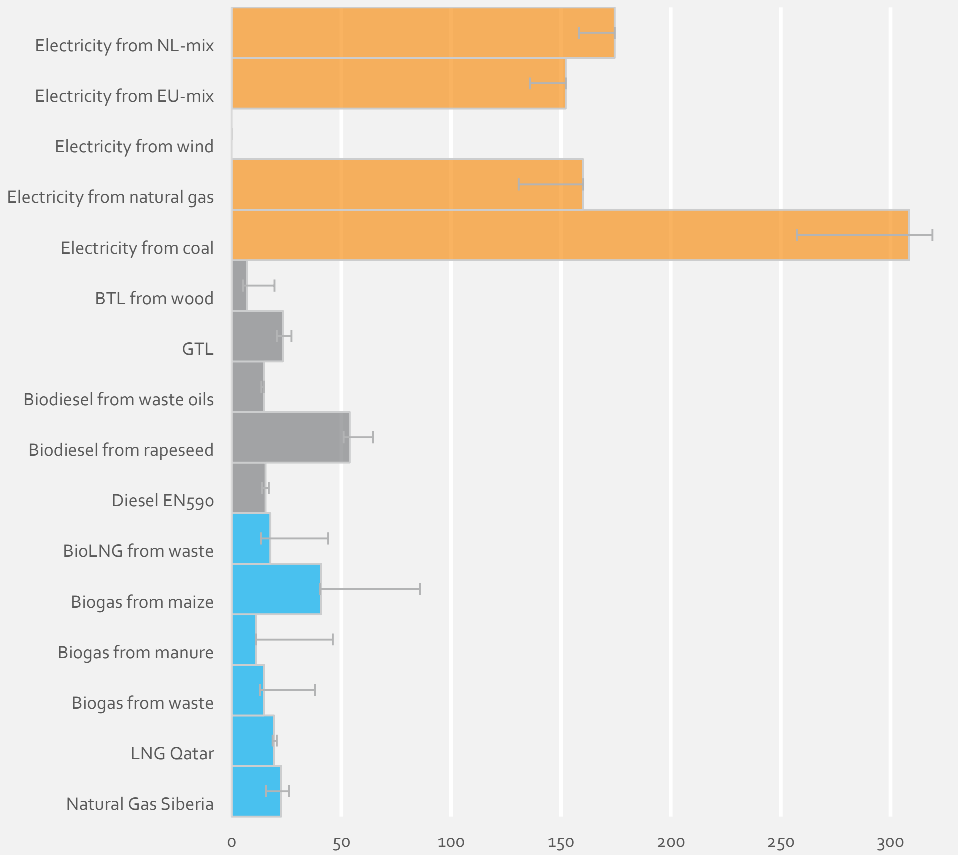
Electricity from wind, BTL from wood, biodiesel and biogas from waste all show good greenhouse gas performance. Biofuels from crops compare less favourably mainly due to the emissions from cultivation. Fossil electricity has much higher emission due to the lower energy efficiency of the thermal conversion.

Key findings

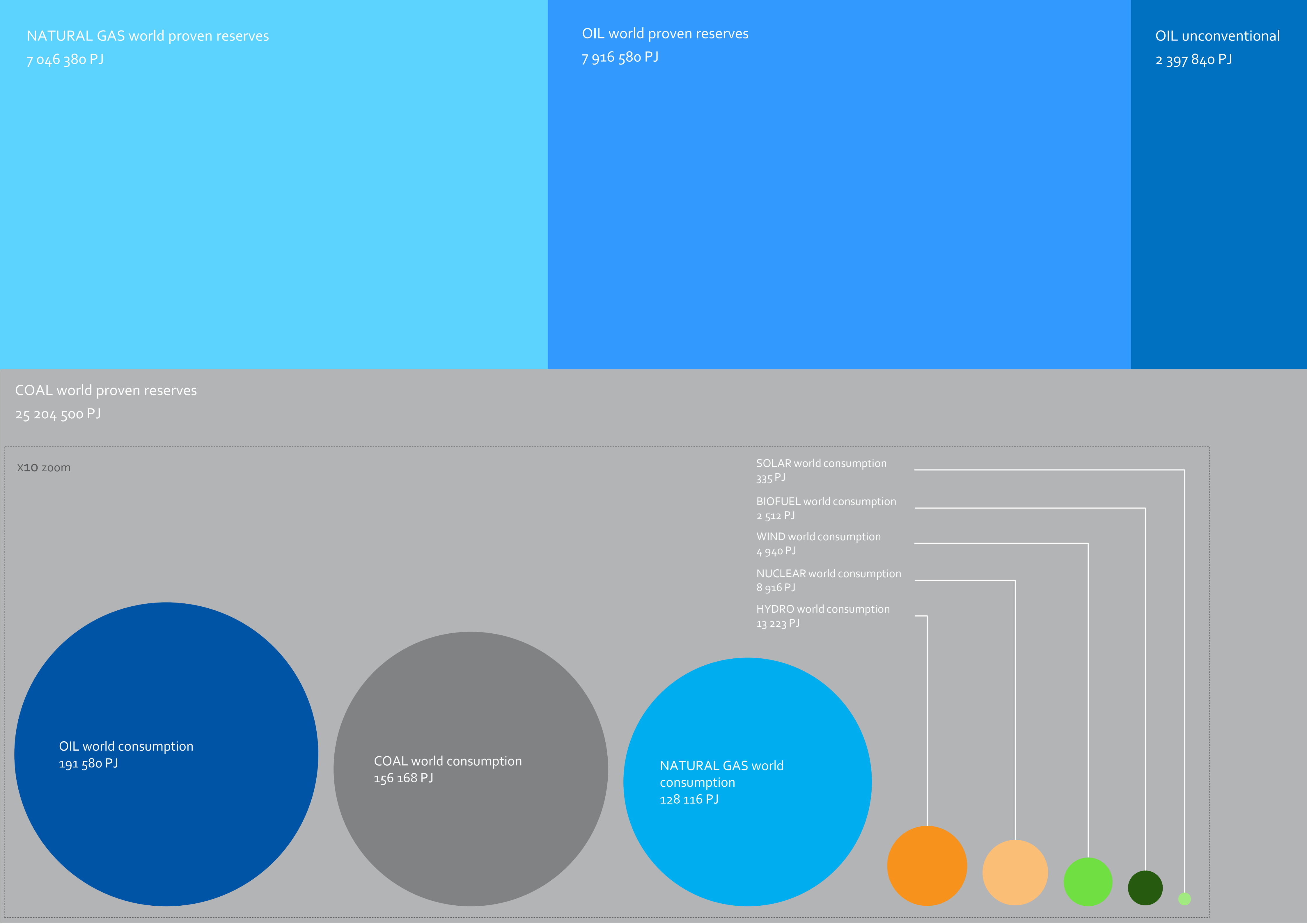
1. **Electricity produced from wind** has the best GHG well-to-tank performance emitting zero grams of CO$_2$eq per MJ. In other words, no non-renewable energy is used from production to the catenary.
2. **BTL from wood** shows the best performance after wind at 7 gram CO$_2$eq per MJ. During production a part of the wood is used to fuel and power the production process. Only during transport and distribution, a small amount of fossil fuel is used.
3. **Biogas, bioLNG and biodiesel from waste** show a low 11 – 15 gram, similar to diesel, but much better than biofuels from crops. These values are similar to the typical savings in the Renewable Energy Directive [EU 2009]. Important to note is the high uncertainty for the biogas and bioLNG due to methane emissions (the higher band reflects open digestate storage).
4. **Natural gas from Russia** and **LNG from Qatar** have rather similar GHG emissions at 19 – 23 gram per MJ. Although it requires more energy to cool down the gas to form LNG, this is more than compensated by the savings in long distance transport where pipelines require more energy than sea transport.
5. **GTL** performs similar to natural gas from Russia.
6. **Biogas from maize** emits 41 gram CO$_2$eq per MJ.
7. **Biodiesel from rapeseed** has higher WTT emissions at 54 gram. Here the result deviates from the typical emissions of 46 gram in the Renewable Energy Directive. The reason is that authors take into account evidence for higher emissions during cultivation.
8. **Electricity from natural gas** shows much higher GHG emissions at 160 gram for natural gas. The average EU and NL mix are close to the emissions of a state-of-the-art natural gas plant. EU average marginal emissions are taken to be 152 gram. The Dutch average, marginal emissions in 2011 is slightly higher at 174 gram per MJ.
9. **Electricity from coal** emits a planet melting 309 gram, caused by a combination of low efficiency, high carbon content and high transport losses.

Well-to-wheel greenhouse gas emissions

gram CO$_2$eq per MJ of fuel; in total energy efficiency for the pathway; grey for diesel pathways, blue for gaseous pathways and orange for electricity.



Source: Duinn, 2014
Note: for the GHG emissions a GWP value of 1 is taken for CO$_2$, 25 for CH$_4$ and 298 for N$_2$O [IPCC 2007]


NATURAL GAS world proven reserves
7 046 380 PJ
OIL world proven reserves
7 916 580 PJ
OIL unconventional
2 397 840 PJ
COAL world proven reserves
25 204 500 PJ
X10 zoom
SOLAR world consumption
335 PJ
BIOFUEL world consumption
2 512 PJ
WIND world consumption
4 940 PJ
NUCLEAR world consumption
8 916 PJ
HYDRO world consumption
13 223 PJ
OIL world consumption
191 580 PJ
COAL world consumption
156 168 PJ
NATURAL GAS world consumption
128 116 PJ

Diesel produced from crude oil is the baseline scenario

The diesel pathway starts with crude oil from the Middle-East which is transported over sea to a European refinery. From the refinery it is distributed to filling stations at the train depots

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Diesel EN590	Oil field Middle-East	Oil tanker	Oil refinery EU	Train transport	Diesel depot	Truck 27 ton payload 300 km	Diesel filling station	Rail transport

Diesel is still a common fuel for regional trains…

In the European Union the energy used in rail transport is approximately 78% electricity and 22% being predominantly diesel [Eurostat, 2013]. Here we look into the reference fuel for current and 2020 trains for regional transport: diesel.

Diesel is produced from crude oil. The first step in the production process is the extraction of the oil in the Middle-East. The Middle-East is currently, and expected to be in 2020, a major supplier of crude oil to Europe and the Netherlands. The North Sea was the main supplying region for Europe, however production in the North Sea is declining and will soon drop below 20% of the total oil supply. The African coast and Caspian sea area are relevant new supply regions relatively close to Europe. Russia is besides a large gas supplier, a large supplier of oil, mainly to Eastern Europe.

During the extraction of crude oil, both oil and natural gas are used as process energy. In addition, a part of the product is lost which produces emissions. The emissions to air are the most important of these emissions [OGP, 2011; IEA, Brandt, 2011].

..which is produced from crude oil in European refineries…

After extraction, the crude oil is transported by sea in very large and ultra large crude oil carriers to North Western Europe, mainly Rotterdam. These ships run on heavy fuel oil. The ship fuel use depends mainly on the water displacement.

The crude oil is processed in the major harbour regions of Europe into finished products such as gasoline and diesel. The energy use and emissions related to the diesel product depends on the energy allocation across products.

In this report we follow the 'substitution method' and 'reference method' as described by [LBST, 2007; LBST 2011; ECN, PBL, CBS, 2012] to allocate the energy and emissions of additional diesel production. In our view this best reflects the 'opportunity effect' of a marginal increase or reduction in the diesel consumption (for it tries to capture the impact on the refinery's operation). For large changes in diesel output the substitution method breaks-down as this amount is expected to be supplied from refineries or GTL plants outside Europe.
The diesel emerges from the refinery, meeting the EN590 specification after which it is transported by train from the refinery to the depot for storage.

…after which it is distributed and stored at a diesel filling station.

At the depot, the diesel can be blended to contain renewable fuels such as biodiesel (FAME, RME, REE) while keeping within the EN590 specifications. From the depot the diesel is transported by truck to the filling station. The logistical route for the truck amounts to 300 km. A truck which transports 27 ton diesel uses about 25 – 40 litres of diesel per 100 kilometre.
In case of train fuels, the filling station is located at the train depot. It stores the diesel and dispenses it to the train. A small amount of energy is used to pump the diesel into the train.

Total diesel use in regional rail transport in the Netherlands is stable at 18 – 23 mln litre diesel per year [Vivens, Arriva, Veolia, Syntus, 2013]. In the Northern Netherlands about 8.5 million litre of diesel is used per year [Arriva 2014].

Biodiesel from rapeseed and waste oils can sometimes be used as diesel substitute (blend or pure)

Two pathways are assessed: biodiesel from rapeseed and biodiesel from waste cooking oils. The production, distribution and storage steps are broadly similar.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Biodiesel from rapeseed	Rapeseed cultivation	Truck 20 tons	Estrification			Truck 27 ton payload 300 km	Biodiesel filling station	Rail transport
Biodiesel from waste oils	Waste cooking oil collection	Truck 20 tons	Estrification			Truck 27 ton payload 300 km	Biodiesel filling station	Rail transport

Vegetable oils can be esterified into biodiesel.

Across Europe rapeseed and sunflower are cultivated for their oil containing seeds. Since the 90's these seeds are increasingly used for biodiesel production, mainly in Germany. The reason being the European Renewable Energy Directive [2009/28/EC]. European biodiesel production capacity has reached 23.5 mln ton in 2012, however current biodiesel output is only 8.6 mln ton [EurObserver, 2013] with biodiesel consumption at 13.5 mln ton, the balance being supplied by imports.

Growing the seeds requires agricultural energy use in the form of diesel, fertilizers and some pesticides. An important emission in the growing step are the emissions resulting from the ploughing, tiling and growing of the crops during which nitrous oxide and some methane are emitted from the field.

After harvesting, the crops are transported from the field to the biodiesel plant (or pre-processing plant) where they are pressed, steamed, and cleaned after which the vegetable oil is ready to be 'esterified'.

Waste cooking oils are also a feedstock.

Besides using virgin vegetable oils, used cooking oils and animal fats can be used as feedstock. The used oils are collected as part of the standard waste collection, for example from caterings and restaurants. Instead of incinerating the oils, they are transported to the biodiesel plant where they are cleaned and refined after which they are ready for esterification.

Next the biodiesel is produced through esterification

Esterification is a process which increases the fuel stability and burning properties of the oils. It removes the fatty acids from the oils to yield a stable methyl ester fuel such as FAME (fatty acid methyl ester). This is achieved by reacting the oils with an alcohol, predominantly methanol.

The resulting biodiesel has to meet the minimum EN 14214 norm requirements. Application as pure fuel in diesel engines remains a problem as the fuel does not fully meet the EN590 diesel specifications. Engine manufactures have to provide a 'clearance' for the fuel to be used, otherwise engine warranty is no longer valid. Currently, the earlier mentioned EN590 norm allows for up to 7% of biodiesel blending by volume.

Distribution and storage is very similar to diesel

The distribution and storage of biodiesel is similar to diesel. In case of a neat 100% biodiesel fuel, it is transported directly from the plant by road to the filling station. By far the largest part of the biodiesel is used in blends with diesel. In this case the biodiesel is blended with diesel at the depots when it is supplied to the distribution trucks.

Biodiesel plant Neste Oil in Rotterdam

GTL (gas-to-liquid) and BTL (biomass-to-liquid) are synthetic diesel fuels produced from respectively natural gas and biomass

Both GTL and BTL are called synthetic fuels since they are both produced from intermediary synthetic gas. The synthetic gas is in turn produced from different hydrocarbon feedstocks such as natural gas and biomass.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
GTL	Production stranded gas field	-	GTL plant	Oil tanker	Depot	Truck 27 ton payload 300 km	GTL filling station	Rail transport
BTL from wood	Wood plantation and chipping	Truck transport	BTL plant			Truck 27 ton payload 300 km	BTL filling station	Rail transport

GTL is produced from natural gas

Gas-to-liquid uses gas from remote gas fields to produce mainly naphtha and diesel. The technology allows remote fields that are 'stranded', i.e. have no access to a pipeline to reach the market. The alternative route to the market that avoids pipelines is LNG (*see LNG and bioLNG*).

The production of GTL started in the 90's when Shell pioneered the Bintulu project in Malaysia. In 2011, world-wide production of GTL amounted to 76 000 barrels per day [IEA, 2012]. When the large-scale Qatar based GTL plant 'Pearl' will reach full production the GTL production will more than double. This is still modest looking at world oil production levels, however growth is expected and the IEA predicts 900 000 barrels per day in 2035.

The production process consists of natural gas being gasified/reformed to yield a synthetic gas which is reacted over a catalyst to produce a range of middle-distillates and base oils. Already invented in 1925, this Fischer-Tropsch process has received renewed interest when oil is not available or relatively expensive. Currently, the interest is driven by relatively cheap gas versus crude oil and the possibility to produce high-grade (high-value) products.

The relatively low energy efficiency of GTL production remains a drawback compared to conventional oil production.

BTL is produced from biomass, mainly wood

Biomass-to-liquid substitutes the natural gas feedstock for biomass. The mostly woody biomass, is grown as (perennial) energy crop, however also waste wood or pruning's are envisioned as feedstock. This study takes a fast growing perennial such as willow, grown on non-prime agricultural land as feedstock. Wood from forest clearings and pruning are not assessed since authors observe that most existing gasifiers have difficulty to produce a high quality syngas to use in the Fischer-Tropsch process (the input is too heterogeneous). Still, it remains promising and a great deal of R&D is going into the utilisation of low value inputs in gasifiers such as the Dutch Biorefinery Initiative from WUR and ECN.

The energy used in growing the woody perennials comes in the form of agricultural inputs amounting to about 6 - 10% of the yield. This compares favourable to yearly crops such as maize at 10 - 15% and rapeseed at 20 - 30% [KTBL 2006; JRC, EFMA 2008]

The energy efficiency of the gasification, cleaning and catalytic step is low as about 50% of the biomass input being used as process energy.

After production the BTL is transported to end-markets and sold as a premium diesel fuel, mostly for fleets.

GTL and BTL as fuel

The end-products GTL and BTL are chemically almost identical, a clean burning diesel fuel. However it does not meet the EN590 diesel specification at one characteristic: density. Blending GTL in diesel up to 30 – 40% allows the resulting blend to still meet the EN590 specification.

Application of the pure fuel has been running in small and large-scale pilot projects since 10 – 15 years. The pilot projects mostly involving captive fleets such as taxies and buses. Application in trains can similarly be envisioned.

GTL plant 'Pearl' in Qatar [Shell, 2012]

Compressed natural gas is produced from natural gas

The production pathway for CNG is straightforward, natural gas is cleaned, pressurized and transported to filling stations where it is further compressed to 250 bar to be utilized by natural gas powered vehicles.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Natural gas Russia	Siberian Gas field	-	Gas cleaning and processing	High-pressure grid 40 bar	Seasonal storage (small % of gas)	Low-pressure pipeline	Pressurized container 250 bar	Rail transport

Natural gas as vehicle fuel

Natural gas can be used as vehicle fuel and currently more than 16 million road vehicles run on natural gas [NGV Global, 2014].

For Europe, the gas is extracted in Norway, the Netherlands and mainly Russia. The gas is cleaned and higher alkanes, such as ethane and propane, are removed. The energy consumption of this extraction and cleaning step are minor.

Transporting the natural gas to market is more energy intensive as the gas needs to be pressurized for pipeline transport. The energy requirement for transport for various distances is given below [JEC, 2013]:

European sources	2 500 km	0.06 MJ/MJ_{CNG}
Middle Eastern fields	4 000 km	0.10 MJ/MJ_{CNG}
Russian fields	7 000 km	0.18 MJ/MJ_{CNG}

Arriving in Europe, some seasonal storage is performed in underground caverns and depleted gas fields. The storage amounts are still very small and the energy use is not included in this study.

Natural gas infrastructure [ENTSOG, 2010]

Distribution and CNG filling stations

To deliver gas to trains, the gas is first transported by high pressure pipeline and then through low pressure pipeline until it reaches the CNG filling station. The transport in the low pressure (8 bar) pipeline does not require additional energy since enough pressure is available in the high pressure grid (40 bar).

The filling station compresses the natural gas to around 250 bar. This pressure is needed to be able to supply the vehicles with enough energy for an acceptable range. At higher pressure more energy can be stored in a given volume. Compression of the gas to 250 bar requires a sizable amount of 0.1 kWh/Nm^3_{CNG} electricity to drive the compressor.

Natural gas from the Netherlands

For completeness, an additional indicative pathway is included for Dutch low calorific (Slochteren) gas. Please note that this L-gas pathway is not comparable to the other pathways under the applied marginal/substitution method. The main reason being that additional L-gas demand is expected to generate an equivalent increase in H-gas demand from the North Sea, Norway, Russia and/or LNG.

Authors assume that, for the indicative pathway, 2/3 of the L-gas originates from the Slochteren field with 1/3 being high calorific North Sea gas blended with nitrogen to meet the L-gas specification. Please see appendix 6 for more information on natural gas from the Netherlands.

Liquefied natural gas (LNG) is produced from remote natural gas fields in the Middle East after which it is shipped to Europe.

Natural gas is extracted, cleaned and liquefied to LNG after which it is shipped at low temperature to Europe.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
LNG Qatar	Peshawar gas field	Pipeline	Large-scale LNG production plant	LNG carrier	Large scale LNG terminal Zeebrugge/GATE	Truck 300 km	Steel containers -155° -160° C 1-10 bar	Rail transport

LNG production from natural gas

Bringing natural gas to market by pipeline and in the form of GTL has already been described. Since the 60's natural gas is also transported in a liquid state. At -162°C, the gas becomes liquid and can be transported at higher density thereby reducing transport costs.

Liquefied Natural Gas (LNG) constituted only a minor part of the total natural gas production, however has seen enormous growth driven by new gas reservoirs in Qatar and more recently Australia. Total LNG trade amounted to 328 billion cubic metres in 2012 [GIIGNL, Waterborne, 2013].

The natural gas is extracted and cleaned after which it is liquefied in a cryogenic installation. Liquid nitrogen is used to cool-down the natural gas. This process requires a large amount of energy mostly in the form of electricity. After liquefaction the LNG is stored at a loading terminal awaiting transport to markets in Europe, Asia and South America.

Transport of LNG

LNG transport is performed by dedicated gas carriers which can hold between 140 000 and 266 000 m^3 of LNG. Most of these gas carriers use a part of the LNG that boils off to power the ship.

LNG carrier Arctic Princess with 147 000 m^3 capacity [HŐEGH LNG, 2013]

LNG methane emissions

An important property of the LNG is that its temperature increases. From -162°C the liquid slowly attracts heat which causes the temperature and pressure to rise. This results in a small part of the LNG 'boiling off' in the form of gas. Keeping the gas cool requires properly insulated storage and in some cases energy for re-liquefaction. Crucially, when the LNG is not stored and transported properly, the temperature and pressure build-up can result in a part of the LNG being vented to the atmosphere to reduce the pressure in the tanks.

This results in large greenhouse gas emissions since methane is a strong greenhouse gas. In this study a small amount of losses are taken into account [Shell, 2002; Total 2001; LBST 2013]:

Extraction	0.08 gram CH_4/MJ
Production	0.04 gram CH_4/MJ
Sea transport	negligible
Terminal	negligible
Distribution	0.1 gram CH_4/MJ
Filling station	0.001%

The total greenhouse gas emissions amount to 5 – 7 gram CO_2eq/MJ of CNG. Others have reported higher emissions [TNO 2012; Duinn 2013] of 1 - 3% from terminal to vehicle.

From terminal to vehicles

Arriving at the unloading terminal in Europe, the LNG is pumped into large steel and concrete holding tanks such as GATE in Rotterdam, the Netherlands and Fluxys in Zeebrugge, Belgium.

The terminals were originally built to supply the natural gas grid, but have obtained loading bays to be able to deliver LNG directly to trucks with LNG trailers. The trailers have a capacity of 20 ton LNG when loaded to 90%. The trailers are not fully unloaded to keep the trailers cool.

At the train depot, LNG is stored in 40 – 100 m^3 double-hulled vacuum-isolated containers. Some electricity is use for pumping, but in much lower quantities compared to a CNG filling station.

Biogas is produced by bacterial degradation or 'fermentation' of biomass. Manure, waste and maize are widely used feedstocks.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Biogas from waste	Digestion	Vacuum pipeline	Fermentation and upgrading	-	-	Low pressure pipeline	Pressurized container 250 bar	Rail transport
Biogas from manure	Digestion	Truck 20 tons	BTL plant	-	-	Low pressure pipeline	Pressurized container 250 bar	Rail transport
Biogas from maize	Maize cultivation	Road transport	Fermentation and upgrading	-	-	Low pressure pipeline	Pressurized container 250 bar	Rail transport

Biogas from bacteria

Organic material in waste yields a gas mixture rich in methane when fermented by bacteria. The bacteria work at higher temperature in the absence of oxygen where they decompose the material over a period of 15 – 40 days.

The biogas yield from the biomass depends on the amounts of fatty acids, carbohydrates and proteins which can be transformed to methane. Fatty substances give high biogas yields of 700 – 900 m^3_{biogas} per ton material. Maize yields 150 – 250 m^3_{biogas} and manure at only 30 – 120 m^3_{biogas}. [IEA, 2009; WUR, 2008].

The energy efficiency of the whole process is low because not all biomass is converted and the bacteria consume a part of the energy in the biomass. For waste this is deemed non-relevant, however for energy-grown crops this matters since input energy is required and emissions from the cultivation can be sizable. The electricity use is estimated at 20 – 30 kWh/ton_{input} with a small part of the biogas used for heating the digester.

Total biogas production for the EU27 amounted to 3.5 bcm_{biogas} or 70 petaJoule in 2011 [ECN, 2011]

In landfills, the bacteria operate naturally and cause the landfill to emit methane. In most cases this methane has to be captured and flared for environmental reasons. Since the 80's this methane is increasingly used as energy in combined heat and power systems. More recently, the raw biogas is upgraded to natural gas specification for application in the gas grid (Netherlands, Germany) or for application in vehicles (Sweden).

Upgrading the biogas

When the raw biogas is produced it consists of only 50% – 65% methane and still contains a large share of CO_2 (30 – 45%) and some inert gasses such as nitrogen and hydrogen sulphide. To use the biogas as a fuel requires removal of most of the CO_2 and all of the hydrogen sulphide. This 'upgrading' of the biogas can be performed through either washing the biogas with water or an amine containing liquid or filtering the biogas through a membrane. 'Waterscrubbing' is the most common technology, with membrane being mostly applied in smaller plants. In Germany a lot of amine-based washing systems are used.
The energy use in the form of electricity and in some cases heat amounts to 0.18 – 0.30 $kWh/Nm^3_{biogas.}$ The greenhouse gas emission are strongly influenced by methane losses. Authors have taken a closed digester storage. An open digester storage emits more compared to a closed storage.

Meeting vehicle specification

The goal of upgrading the gas is to meet the specifications required for gas grid and/or vehicle application. In practice this amounts to more than 97.5% methane content for most high calorific gases 'H-gases' such as required. For low calorific 'L-gas' meeting the German G260/G262 standard this amounts to 87 – 98.5% methane, (for French low calorific gas even lower values are allowed) [IEA, 2006]. For the Netherlands, the minimum L-gas specification for biogas is 88% methane.

Before adding the biogas to the grid an odorant is added and in some cases pressurized. The filling station is taken as similar to compressed natural gas.

Biogas plant in Sweden, Linkoping [Svensk Biogas, 2008]

BioLNG is liquefied biogas

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
BioLNG from waste	Digestion	Pipeline	Fermentation, upgrading and cooling	-	-	Truck 21 ton payload	Cryogenic container	Rail transport

BioLNG production

BioLNG extraction and production are similar as for biogas. After cleaning and upgrading, the biogas is liquefied by cooling it to -162°C. Usually a liquefied nitrogen cycle is use as cooling agent in a heat exchanger [Wärtsila, Linde, 2013]. This process step is similar to the large scale LNG production. The energy requirement is relatively high at 0.70 – 0.90 kWh/$\mathrm{Nm}^3_{\mathrm{biogas}}$ [Lund, 2008].

An alternative process to produce bioLNG is by combining the upgrading and liquefaction step [GtS, 2012]. Since CO_2 has a higher boiling point at -78.5°C than methane, it can be separated through cooling thereby removing a separate upgrading step. This has the potential to save a part of the upgrading energy requirement.

In Europe, very little bioLNG is being produced as the technology emerges from the development stage. Authors estimate that only 6 - 11 small to medium scale plants are in operation at the time of writing in Europe, with the majority in Sweden. However, interest in the technology is large and the production capacity is set to rise in the coming years.

Transporting liquid biogas

Liquefied gas can be transported by cryogenic tankers with a relatively high energy density. However, the energy use in transport is higher compared to pipeline transport.

BioLNG filling station

At the filling station the LNG is stored in a double hulled vacuum insulated storage tank. This is similar to the LNG filling station described in the LNG pathway. Energy use in storing and pumping the LNG amounts to around 0.03 – 0.07 kWh/$\mathrm{kg}_{\mathrm{LNG}}$.

BioLNG quality

As with all fuels, bioLNG has to meet engine manufacturers fuel specification. Currently, no DIN or NEN EN norms have been established and temporary specifications are used. The main requirements for LNG are the heating value, Wobbe Index and Methane Number [CARB, 2005]. BioLNG has no problem meeting the current temporary specifications.

BioLNG production plant in Sweden [Greenlane 2013]

Fossil electricity can be generated from coal and natural gas. Renewable electricity is taken from wind sources as it is the largest source of renewable electricity in Europe.

The coal pathway shows low efficiency, natural gas has moderate efficiency for electricity production, with wind power scores the highest efficiency.

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Electricity from coal	Hard coal	Shipping	Steam turbine 600 - 1 500 MW	High+medium-voltage grid	-	1.5 kV DC rail grid	-	Rail transport
Electricity from natural gas	Digestion	Truck 20 ton	Combined cycle 450 MW	High+medium-voltage grid	-	1.5 kV DC rail grid	-	Rail transport
Electricity from wind	-	-	Wind turbine 5 MW	Medium-voltage grid +step up losses	Storage, mainly pumped hydro	1.5 kV DC rail grid	-	Rail transport

Electricity as energy carrier

Electricity can be produced from a large number of primary energy sources. We describe three common sources in the EU being coal, natural gas and wind. Nuclear and solar are not taken into the study due to the small share of nuclear and its uncertain future and the performance of solar and wind being relatively similar.

Coal to power

Coal is mostly produced in open pit or shaft mining. The coal is dug from the ground, grinded and shipped to the power plant. Two types of coal power plant are in operation, a conventional thermal plant and an integrated combined cycle. A conventional state-of-the art plant burning hard coal is assumed to have an life-time efficiency of 43% and a IGCC plant an efficiency of 48% [JEC, 2013]. Older coal plants will have lower efficiencies.

Natural gas to power

Natural gas is extracted in Norway, the Netherlands, the UK and especially Russia (see natural gas pathway). Burning natural gas in considered to occur in a combined cycle gas turbine. These installations have a much higher efficiency at 65%.

Power production from natural gas has been dropping lately due to relatively high renewable energy production and low CO_2-prices which favours power production from coal over natural gas.

Wind to power

Wind power has been the fastest growing renewable energy source in Europe. Installed capacity reached 109 GW in Europe in 2012 [BP, 2013]. Dutch installed capacity reached 2.5 GW (1% of world total).

Wind power uses the ‘free’ wind so assigning an efficiency figure is meaningless. In most literature sources a efficiency 100% value is applied. In some cases the kinetic to electric conversion efficiency is applied (~33%). This report sticks with the 100% efficiency figure (R = 1). The authors have chosen to account for the ‘step up losses’ of 2% in the power transformers when the generated electricity is fed into the high or medium voltage grid [NREL 2007].

Transporting power to the rail grid

While most observers focus on the generation efficiency of the turbines and combustion plants, it is meaningful to focus to the same degree on the transport of electricity. Transport losses can be substantial for electricity. The grid losses result from resistance in the power cables which dissipates the electricity as heat. For the grid the losses are taken as [ENTO-E 2011; AEEG 2012]:

High voltage	380 kV, 220 kV, 110 kV	1.5%
Medium voltage	10 – 20 kV	3.8%
Low voltage	0.4 kV	6.4%

The authors assume that transport via high and medium voltage (10 kV) cables is used to supply the rail grid.

The losses in the ‘rail grid’ depend chiefly on the voltage, catenary material and thickness, the distance to the substation and the power demand. For the Netherlands with its 1.5 kV DC grid the losses are high and taken to be 10% on average [Railforum Working Group, May 2013; Matlab 1988]. Higher voltages would substantially reduce losses in this part of the pathway.

The average EU and Dutch electricity mix have been added for comparison reasons

	Extraction	Transport	Production	Transport	Storage	Distribution	Storage	End-use
Electricity EU-mix	Multiple sources	-	Actual EU average 2009 [JRC 2012]	High+medium-voltage grid	Storage, mainly pumped hydro	1.5 kV DC rail grid	-	Rail transport
Electricity NL-mix	Multiple sources	-	Actual NL averages [ECN, PBL 2012]	High+medium-voltage grid	-	1.5 kV DC rail grid	-	Rail transport

EU electricity production mix

For comparison reasons, the authors have included the current EU and Dutch electricity mix. The mix contains all generating assets, their operating hours and efficiencies. Based upon [JRC 2013] the EU-mix is provided for the EU27 member states. The gross electricity production in 2009 amounted to 3 170 TWh while emitting on average 134 gram $CO_2eq/MJ_{net\ produced\ electricity}$.

The thermal electricity plants require a part of their electricity (±4%) for running the plant which gives the difference between gross and net electricity production. Finally, some storage is performed, mostly in the form of pumped hydro which involves some losses.

NL electricity production mix

The reference Dutch electricity mix is based upon [ECN, PBL, 2012] and takes the marginal method since the aim is to compare different fuels for trains. The energy efficiency of the average *net* electricity production is slowly rising and now stands at 42.7% for 2010. The CO_2-emission factor is given at 158 gram CO_2eq/MJ which is slightly worse than the EU-mix, but this includes distribution losses.

Electricity transport and losses

The authors estimate the high- and medium voltage grid losses for Europe at 5% and for the Netherlands at 1.5 – 2.5%.

For a 1.5 kV DC grid the losses are higher and are taken to be 10% for the dedicated rail grid [Railforum Working Group 2013; Matblad 1988]. This is a greatly more than figures for a standard local grid in which losses are estimated at between 4.4 – 6.4% [ECN 2013, NMA 2010, Enexis 2012]. The reason for the high value, is the relatively high power demand for the Voltage resulting in a high Amperage and thus high losses

Which voltage?

Higher voltages, thicker cables and more closely spaced connecting stations would reduce the electricity losses since the Ohm loss is proportional to the formula I^2R. This means that electrification of the rail grid at 3.0 kV DC would cut the Ohm losses by a factor 4 (all other things being equal). However, Corona losses would rise slightly [KEMA 2009, 2010]. At 25 kV alternating current, the total losses would be reduced to around 1 – 2%.

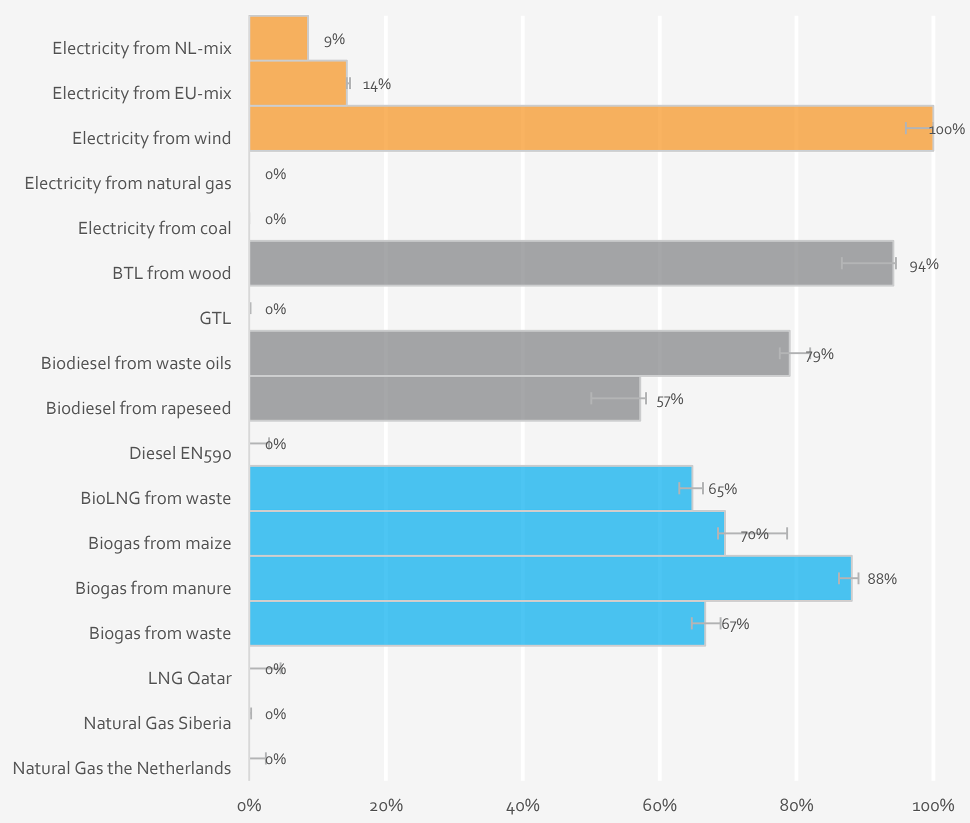
Catenary 1.5 kV DC

Fossil pathways use no renewable energy (from well-to-tank). BTL from wood, biogas from manure and biodiesel from waste contain a ~75% renewable share. BioLNG and biogas from waste and maize show 60 – 70% of the primary energy coming from renewables. Wind electricity is 100% renewable (from well-to-tank).

The renewable energy share means the primary renewable energy use as proportion of the total primary energy use.

Renewable energy share of well-to-tank pathway

share of total well-to-tank energy expended being renewable; grey for diesel pathways, blue for gaseous pathways and orange for electricity.



Source: JEC, 2013; Duinn, 2014
Note: EU electrictricy mix applied to calculate electricity renewability share in extraction, transport, production and distribution.

Key findings

1. The fossil pathways **Diesel EN590, Natural Gas Siberia and the Netherlands, LNG, GTL** and **Electricity from Natural Gas and Coal** have negligible amounts of renewable energy use in their pathway. The authors do not take the renewable energy obligation into account [Renewable Energy Directive 2009/28], to keep the assessment of renewable energy share transparent.
2. **Electricity from NL-mix** contained 8,6% renewable electricity share in 2010 and this amount is rising.
3. **Electricity from EU-mix** shows a higher share at 14% which is expected to rise rapidly.
4. **BTL** has a high share of renewable energy use since very little fossil fuel is used in production. Most of the fossil energy is consumed in transport and distribution.
5. **Biogas and BioLNG** show a renewable share of 65 – 70 %. The high score for biogas from manure is mainly the result of the high energy use during production when compared to the other biogas pathways. For all biogas pathways the fossil energy use is similar in absolute terms.
6. **Biodiesel from waste** has a good performance at 79% renewable energy share, with **biodiesel from rapeseed** has a much lower share at 57%.

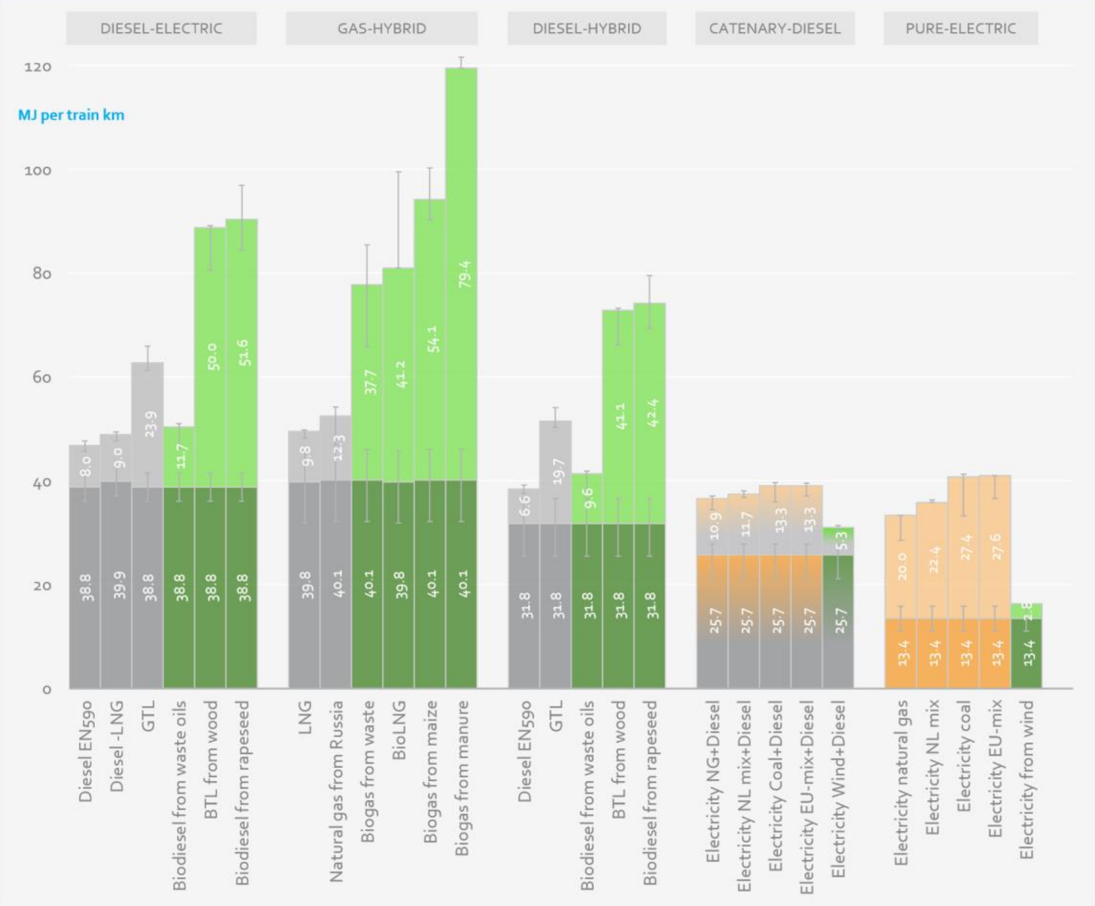
WELL-TO-WHEEL

- Energy source
- Transport
- Production
- Distribution
- Usage

Compared to the current diesel-electric trains, the gaseous pathways use 4 – 12% more well-to-wheel primary energy. Hybrid-diesel reduces WTW energy use by 15 – 25%, while catenary-diesel shows energy saving at 17 – 34%. Pure-electric trains using electricity from fossil sources and the EU- and NL-mix show savings of 12 – 29%. With wind energy, the pure-electric trains provide the highest WTW energy saving at 65%. Biofuels increase WTW energy use, except for biodiesel from waste.

Primary energy use WTW

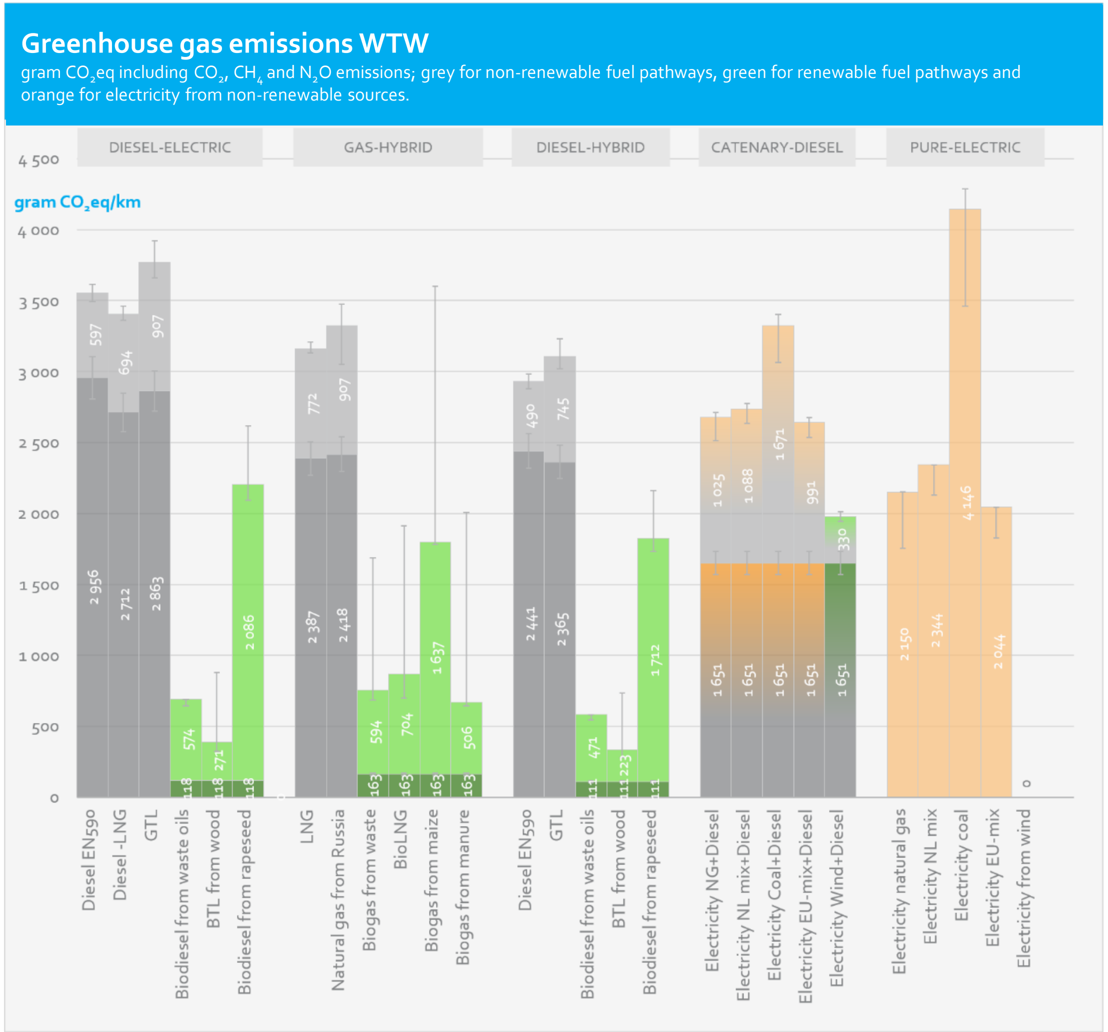
Grey for non-renewable fuel pathways, green for renewable fuel pathways and orange for electricity from non-renewable sources
Bottom part of the bars is the TTW energy use, the upper part the WTT.



Key findings

1. The reference **diesel-electric** pathway fuelled with EN590 diesel uses 47 MJ per kilometre in primary energy when simulated on the Northern Netherlands driving cycle.
2. **Diesel-LNG** requires ~4% more energy compared to the diesel-electric, mainly due to the lower dual-fuel engine efficiency and higher energy use in the LNG pathway.
3. Hybridisation with a diesel engine reduces the WTW energy use by 15 – 25%.
4. The **gas-hybrid** fossil pathways show a 4 – 12% higher primary energy use, as the increased train weight and lower efficiency of the gas engine offsets the hybrid savings. The gas-hybrid biogas pathways require roughly double the primary energy use due to the low conversion efficiency of the digester.
5. **Biodiesel from waste** requires 8% more well-to-wheel energy.
6. **Biodiesel from rapeseed** increases energy use, almost doubling the energy required.
7. **Catenary-diesel** shows a WTW energy saving potential of 17% when carbon intensive electricity is used. Utilising wind energy results in savings of 34% compared to the diesel reference.
8. **Pure-electric** powered by fossil electricity shows similar performance to the catenary-diesel pathways at 12 – 29% WTW energy savings. Most of the primary energy use results from low energy efficiency in the thermal power plants and electricity losses during transport and distribution.
9. **Pure-electric** powered by wind electricity shows the lowest WTW energy use at ~16 MJ/km –or 65% below the reference diesel.

Compared to the current diesel-electric trains, hybrid-diesel reduces well-to-wheel greenhouse gas emissions by 15 – 25%. The diesel-LNG and gas-hybrids using LNG and natural gas show GHG reduction of 4 – 11%. Catenary-diesel reduces GHG emissions by 23 – 46% (7% for coal). Pure-electric trains using natural gas, NL-mix or EU-mix show GHG savings of 34 - 42%. The coal pathway shows an *increase* in GHG emission of 17%. Pure-electric trains powered by wind energy show the highest WTW greenhouse gas savings at 100%.



Greenhouse gas emissions WTW

gram CO_2eq including CO_2, CH_4 and N_2O emissions; grey for non-renewable fuel pathways, green for renewable fuel pathways and orange for electricity from non-renewable sources.

Key findings

1. The GHG performance of a pathway is most strongly determined by: (1) the energy conversion efficiencies, (2) fuel carbon content and (3) train energy use.
2. The reference **diesel EN590** emits 3553 gram CO_2eq per kilometre.
3. The **diesel-hybrid** reduces the GHG emissions by 15 – 25%, taking 18% as the mean expected value.
4. **Diesel-LNG** and **gas-hybrid** LNG and natural gas have a slightly better GHG performance at 4 – 11% reduction due to the lower carbon content of the natural gas.
5. **GTL** has one of the highest GHG emissions (6% above diesel) due to the high energy use and resulting emissions during GTL production.
6. **Biofuels from dedicated grown crops** can reduce GHG emissions by 38 – 49%, but these contain large uncertainty and authors have to note that indirect land-use effects are not taken into account at this point.
7. **Biodiesel, biogas and bioLNG from waste** show similar and good reduction potential at 76 – 81%.
8. **BTL** has a favourable performance at 89% reduction since little fossil fuel is used in production.
9. **Electricity from coal** shows 17% higher greenhouse gas emissions per km, making it the worst GHG performing pathway. The high emissions are mainly caused by the high carbon content of coal and the relatively low energy efficiency of a state-of-the-art coal plant.
10. **Electricity from natural gas** scores in between the EU and NL electricity mixes – all three pathways emitting 34 – 42% less compared to diesel-electric. Wind electricity and pure-electric trains show a 100% reduction in GHG emissions.
11. For electricity, the authors chose to use figures that are at the high end of the uncertainty range due to the relatively high losses in the rail grid.
12. Uncertainty in the results are largest for biogas and LNG which reflects the potential methane losses during production, distribution and use.

Discussion of results

Tank-to-wheel results

1. **Train energy use** is affected by more factors than just powertrain and fuel. Other train elements such as body design and weight are critical elements not investigated. However, these factors could impact energy use strongly and have different effects on different powertrain technologies. For example, a low air drag train would show higher energy savings for the catenary-diesel powertrain than for the pure electric.
2. The **Northern Netherlands driving cycle** attempts to reflect the way trains are operated under the current time schedule, track length, number of stations and speed limits. These were determined by the 2014 time table and train measurements from September to November 2013. The driving cycle strongly determines the energy use of the powertrains. Duinn observes that energy savings are possible by relatively simple adjustments in operation, mainly by adjusting stops and driving pattern.
3. The **pure-electric and catenary-electric** trains are simulated to run according to the Northern Netherlands driving cycle. However, the potential higher power and torque of these trains allows for faster acceleration which allows for an optimization of the driving pattern, especially for the catenary-diesel since it is dependent on the length of the catenary.
4. **Auxiliary energy use** for on-board systems has been included in this study. Authors observe that heating is a large auxiliary energy requirement and here the performance of the engine and electric powertrains differ. For the engine heat can be used to warm (and cool) the passenger cabins cutting auxiliary heating demand. Something pure electric cannot do. The difference for a regional passenger train are estimated at 0.5 – 1.5 MJ per kilometre on average.

1. **Hybrid powertrains** come in many configurations and this is reflected in the broad definition used by the UN and EU. In this study the choice has been made to apply a state-of-the art lithium-ion battery with high power density. The dimensioning of the system reflects the maximum regeneration potential of the electric engines. As such the battery size is taken to maximise energy saving potential. For reliability, safety or economic reasons, different storage and dimensioning choices could be made, such as capacitors or flywheels. A sensible choice could be to use smaller batteries which supply the on-board systems with electricity.
2. The catenary-diesel is designed in this study to *not* contain on-board electricity storage. The rationale is to reduce train weight and complexity and to reduce total system cost. The electricity is fed back to the catenary and stored close to the train station, ready for use during the next acceleration. Still, an on-board energy storage would be technically feasible and such a powertrain would be defined by authors as catenary-hybrid.

Well-to-tank results

1. Many **powertrain and fuels choices** can be included in a well-to-wheel study. The authors have endeavoured to choose the most relevant powertrains and fuels for the 2020 – 2025 timeframe. A rationale for the choice has been to *not* combine multiple untested technologies. For example, a dual-fuel engine running on both biodiesel and bioLNG, using a catenary power supply in the urban area is deemed technically feasible, but not practically useful. In practice one innovation would be applied at a time to keep development manageable and reduce risk. An exception here has been the gas-hybrid powertrain, which is taken to be achievable in the timeframe if great effort would be undertaken.

1. **Hydrogen** is the obvious missing technology and has been omitted for time and resource constraints. Authors suggest to add three hydrogen pathways: (1) hydrogen from natural gas which is reformed at the train depot and compressed to 350 bar. (2a) hydrogen from electricity applying electrolysis centrally and trucking it to the train depot, and (2b) applying the electrolysis at the train depot avoiding the trucking and supplying it at 350 bar.
2. The **marginal method** (or substitution method) is chosen as it is deemed to best reflect the opportunity energy use in the trains. For the results, a key choice has been to take Russian natural gas as the marginal supply source. Since natural gas use is currently stable or slowly declining, a case could be made that Norwegian gas or the new found shale gas could be the marginal supply. This would reduce upstream energy use and emissions. To reflect the impact an additional pathway could be added which uses European natural gas in the WTT analysis.

Disclaimer

1. **Modelling** in this study is performed using two in-house models to simulate reality: for the train energy use the DuinnTrainModel v1.3 is used, for the fuels and electricity the DuinnEnergyCarrierModel v2.7 is applied. As always when modelling, the quality of the input determines the quality of the output. Many choices have to be made at each step and the authors have made an effort to be as clear as possible in their considerations and provide insight into the choices made and inputs used. Unfortunately, some inputs cannot be shared due to their confidential nature, mentioning others would be trivial since they hardly affect results. As reader or interested observant, feel free to contact Duinn to discuss the input or provide feedback via age.vandermei@duinn.nl.

Appendix

1. Definitions
2. Train operation within the Northern Netherlands
3. Power curve for a Stadler GTW DMU 2/8 on the Northern Netherlands driving cycle
4. Acceleration curves Stadler GTW DMU and EMU
5. Duinn publication on catenary-diesel trains, January 2013
6. Well-to-wheel findings including natural gas from the Netherlands

Definitions

anaerobic digestion is a biological process in which organic material is broken down, primarily into methane and carbon dioxide [Volvo, 2007]

biodiesel (methyl-ester produced from vegetable or animal oil, of diesel quality, to be used as biofuel [2009/28/EC]

biofuels means liquid or gaseous fuel for transport produced from biomass [2009/28/EC]

biogas means a fuel gas produced from biomass and/or from the biodegradable fraction of waste, that can be purified to natural gas quality, to be used as biofuel, or wood gas [2009/28/EC]

biomass means the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste [2009/28/EC]

container (or cylinder) means any vessel used for the storage of compressed natural gas [UN ECE R 110]

diesel fuels means gas oils falling within CN codes 2710 00 66 and used for self-propelling vehicles as referred to in Directive 70/220/EEC and Directive 88/77/EEC [98/70/EG]

electric power train means a system consisting of one or more electric energy storage devices (e.g. a battery, electromechanical flywheel or super capacitor), one or more electric power conditioning devices and one or more electric machines that convert stored electric energy to mechanical energy delivered at the wheels for propulsion of the vehicle [UN ECE R 101]

electrolysis The breakdown of a substance using electrical current; in this context, the breakdown of water into hydrogen and oxygen [Volvo, 2007]

energy from renewable sources means energy from renewable non-fossil sources, namely wind, solar, aero thermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases [2009/28/EC]

engine means the motive propulsion source of a vehicle for which type-approval as a separate technical unit, as defined in point 25 of Article 3 of Directive 2007/46/EC, may be granted;

esterification is a chemical process in which the properties, particularly the stability, of raw vegetable oils are improved [Volvo, 2007]

fermentation is a biological process in which material containing sugar is broken down into ethanol and carbon dioxide. For use as a feedstock, cellulose must first be hydrolysed into sugar using enzymes or acids [Volvo, 2007]

gasification means that organic material, such as biomass, is converted into synthetic gas, which is a mixture of hydrogen gas and carbon monoxide. The synthetic gas is then used to produce various synthetic fuel components [Volvo, 2007]

greenhouse gas emissions per unit of energy means the total mass of CO_2 equivalent greenhouse gas emissions associated with the fuel or energy supplied, divided by the total energy content of the fuel or energy supplied (for fuel, expressed as its low heating value) [2009/30/EC]

GTL (gas-to-liquid) means a synthetic hydrocarbon or mixture of synthetic hydrocarbons produced from natural gas

hybrid motor vehicle means a vehicle with at least two different energy converters and two different energy storage systems (on-vehicle) for the purpose of vehicle propulsion; [2007/46/EC]

maximum mass means the technically permissible maximum mass declared by the vehicle manufacturer (this mass may be greater than the maximum mass authorised by the national administration [ECE R 83]

power train means the system of energy storage device(s), energy converter(s) and transmission(s) that converts stored energy to mechanical energy delivered at the wheels for propulsion of the vehicle [UN ECE R 101]

pressure means relative pressure versus atmospheric pressure, unless otherwise stated [UN ECE R 110]

unladen mass means the mass of the vehicle in running order without driver, passengers or load, but with the fuel tank 90 per cent full and the usual set of tools and spare wheel on board, where applicable [ECE R 83]

synthetic diesel means Fischer-Tropsch diesel a synthetic hydrocarbon or mixture of synthetic hydrocarbons produced from biomass [2009/28/EC]

railway system means the totality of the subs systems for structural and operational areas, as defined in Directives 96/48/EC and 2001/16/EC, as well as the management and operation of the system as a whole [2004/49/EC]

train path means the infrastructure capacity needed to run a train between two places at a given time [95/19/EC]

reference mass means the "unladen mass" of the vehicle increased by a uniform figure [ECE R 83]

2. Train operation within the Northern Netherlands

Train operations for one week within the Northern Netherlands

From	To	length (km)	Number of stations (stop-	Number of stations (express trains)	number of stop-trains per	number of expres	km/week	total number of stops/week	km/stop	Traveltime	Average speed	Section speed
Groningen	Grijpskerk	18.5	2	0	426	208	11729	852	13.8	49.0	22.7	100
Grijpskerk	Veenwouden	21.7	3	1	426	208	13758	1486	9.3	49.0	26.6	140
Veenwouden	Leeuwarden	15.3	3	1	426	208	9700	1486	6.5	49.0	18.7	100
Groningen	Zuidbroek	21.8	5	0	911	0	19860	4555	4.4	22.0	59.5	100
Leeuwarden	Sneek	21.7	3	0	570	0	12369	1710	7.2	19.0	68.5	100
Sauwerd	Delfzijl	27.9	6	0	442	0	12332	2652	4.7	27.0	62.0	100
Sauwerd	Roodeschool	26.9	7	0	444	0	11944	3108	3.8	34.0	47.5	80
Leeuwarden	Harlingen-haven	24.9	5	0	440	0	10956	2200	5.0	25.0	59.8	100
Groningen	Sauwerd	10.9	2	0	886	0	9657	1772	5.5	9.0	72.7	100-120
Sneek	Stavoren	28.5	5	0	252	0	7182	1260	5.7	26.0	65.8	100
Zuidbroek	Winschoten	12	2	0	460	0	5520	920	6.0	11.0	65.5	100
Winschoten	Nieuweschans	12.2	1	0	286	0	3489	286	12.2	9.0	81.3	100
Zuidbroek	Veendam	7.5	1	0	445	0	3338	445	7.5	7.0	64.3	80
		249.8				total	131833	22732	5.8			

Duinn 2014

Train operation

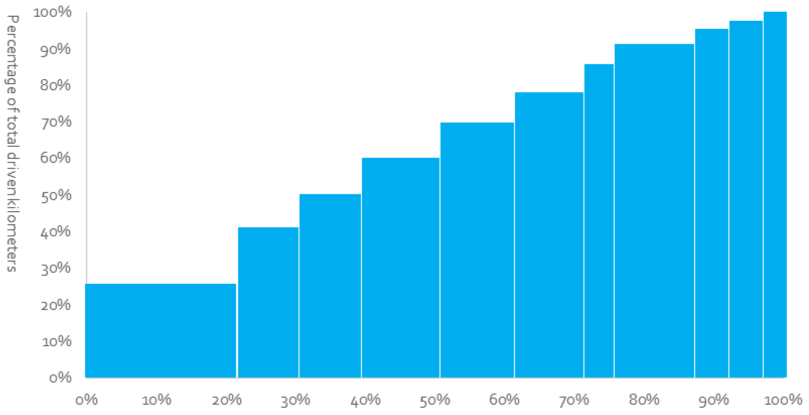
The train operation in the Northern Netherlands is performed on seven different railways. The timetables were studied to determine the number of kilometres driven, the average number of stops per kilometre, the speed of operation and the total number of stops. This appendix shows the results of this part of the study which was helpful in developing the Northern Netherlands driving cycle.

Train movements per week

	Stop-trains			express trains		
traject	Sunday	Weekdays	Saturday	Sunday	Weekdays	Saturday
Groningen leeuwarden	34	66	62	22	32	26
groningen zuidbroek	75	141	131	0	0	0
zuidbroek winschoten	39	71	66	0	0	0
winschoten nieuweschans	23	44	43	0	0	0
zuidbroek veendam	36	69	64	0	0	0
groningen sauwerd	74	136	132	0	0	0
sauwerd roodeschool	36	68	68	0	0	0
sauwerd delfzijl	38	68	64	0	0	0
leeuwarden harlingen-haven	48	66	62	0	0	0
leeuwarden sneek	34	95	61	0	0	0
sneek stavoren	28	38	34	0	0	0

Source: timetables Arriva, 2014

40% of the total driven kilometers is performed on 30% of the railroads



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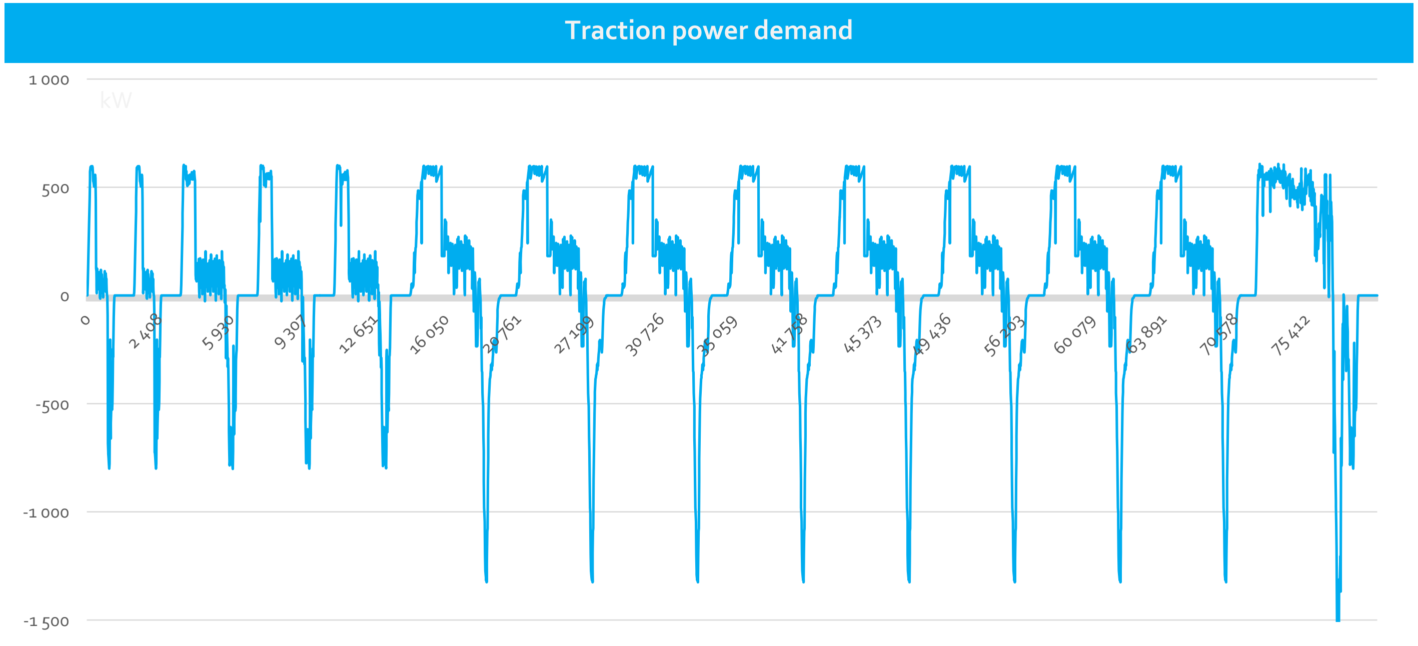
3. Power curve for a Stadler GTW DMU 2/8 on the Northern Netherlands driving cycle



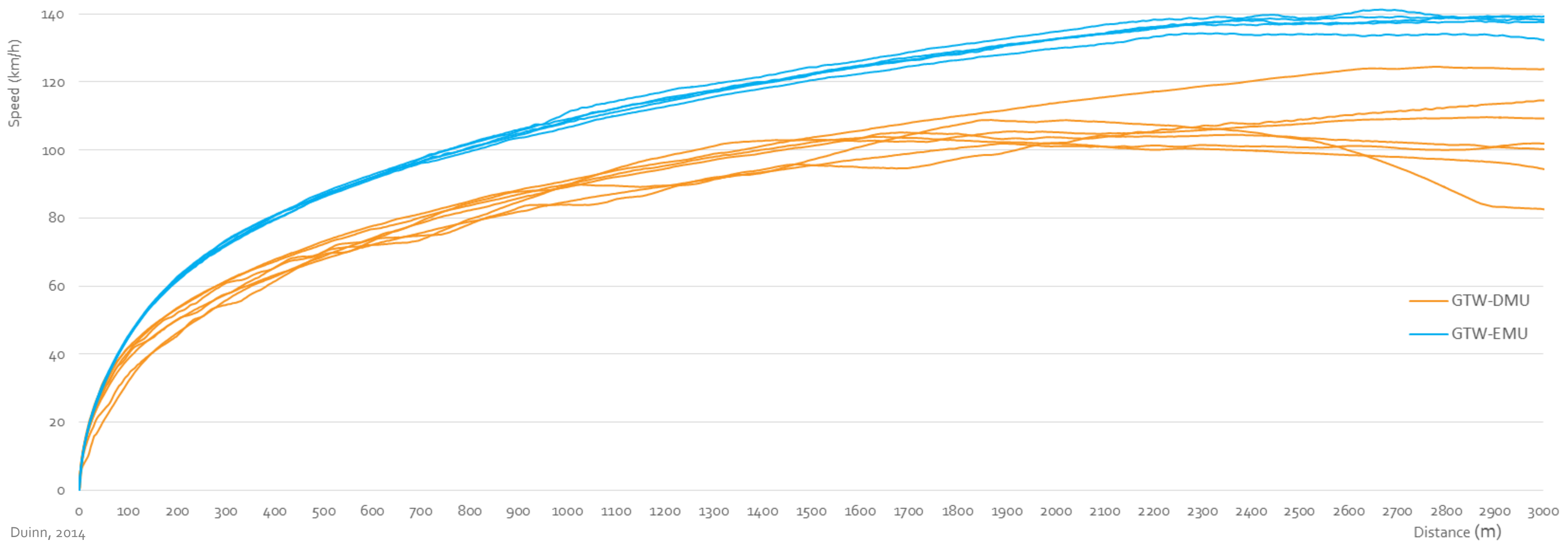
Traction power demand

4. Acceleration curves Stadler GTW DMU and EMU

Acceleration curves

Due to the more powerful traction motors in the Stadler GTW Electric multiple unit (EMU) compared to the Stadler GTW Diesel multiple unit (DMU), 1100 kW and 600 kW respectively. As can be seen in the figure below, the EMU reaches it's top speed earlier than the DMU.

A Stadler GTW-EMU requires 500 meter less distance to reach 100 km/h than a Stadler GTW-DMU



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5. Duinn publication on catenary-diesel trains January 2013 (Infografic in Dutch)

INNOVATIVE TRANSPORT

Duinn
Duurzaam Innoveren

Het beste van twee werelden: *diesel en elektrisch*

Schone en duurzame treinen door partiëel elektrificeren en lokale opslag

Google earth rit *Groningen-Nieuweschans*

Versnellingsfrequentie Stadler GTW

Huidige situatie

Optie: Elektrificeren

Idee Duinn: Partieel elektrificeren en opslag

Cijfers en tabellen

Nederland

17	Aantal treintrajecten	23	Aantal treintrajecten mln liter per jaar
± 60	Totaal broeikasgassen kiloton CO2 per jaar	47	Aantal stations Noord-Nederland

Per trein

63-95	Gewicht ton	70-75	Geluid dB(A)
32-40	Energieverbruik per trein megajoule per km	350 - 700	Remenergie benodigd vermogen kw
2.300 - 2.900	CO2-uitstoot CO2eq per km (TTW)	20 % - 50 %	Energiebesparing terugwinbaar tractie-energie (afhankelijk van inzet)

Voordelen

Huidig

- + Kosteneffectief
- + Hoog verbruik
- + Geluidsemissie in stedelijke omgeving

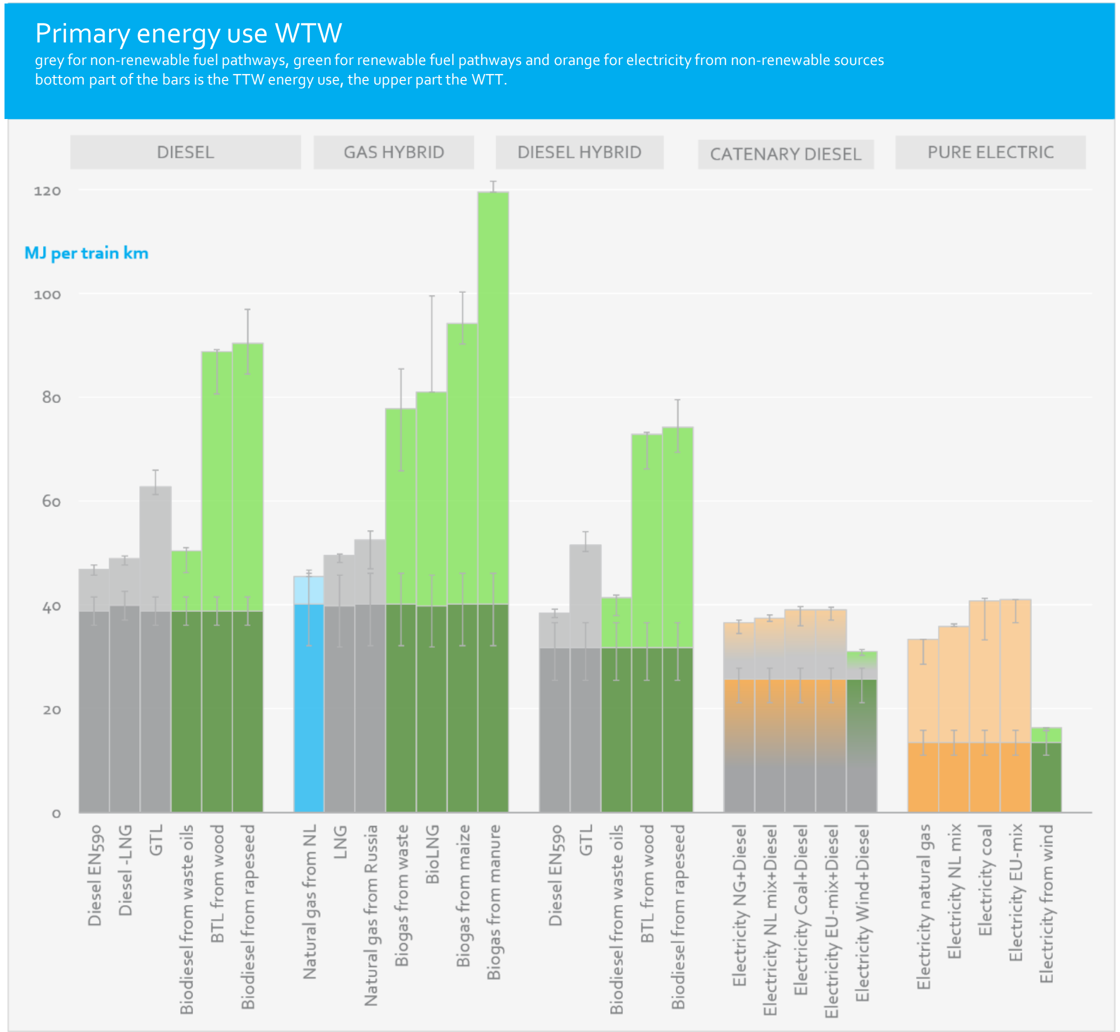
Elektrificeren

- + Relatief stille treinen
- + Energieterugwinning alleen gebruikt wanneer andere trein wegrijdt
- + Hoge investeringskosten
- + Hoog onderhoud

Partieel elektrificeren en opslag

- + Energiebesparing
- + Lokale opslag
- + Koppeling aan stroomnet
- + Inzet renewables mogelijk
- + Stille treinen in stedelijke omgeving
- + Lagere investeringskosten dan volledig elektrificeren
- + Bovenleiding niet per se nodig

6. Well-to-wheel findings including natural gas from the Netherlands



Primary energy use WTW

grey for non-renewable fuel pathways, green for renewable fuel pathways and orange for electricity from non-renewable sources
bottom part of the bars is the TTW energy use, the upper part the WTT.

Key findings

1. Dutch Natural Gas in the compressed gas-hybrid, is with a WTW energy use of 45.5 MJ/km more efficient than the baseline diesel-electric energy use.
2. Due to the limited production capacity of Dutch natural gas, the marginal substitution method does not allow Dutch natural gas to be taken as an alternative fuel. Therefore, the figures of Dutch natural gas on this page should be considered as a reference fuel and not as alternative for the trains in the Northern Netherlands.

Duinn is an independent research and consultancy firm for energy systems and sustainable mobility. We provide expert services that cover the entire energy value chain, from production to end-user. Our approach combines system expertise and in-depth knowledge with clarity in presentation and pragmatism in solutions. Clients can expect an creative and independent solution. Founded in 2006, Duinn is a private company with two offices in The Netherlands and Sweden.

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